SIMULATION OF PERFORMANCE OF CHLORINE-FREE FLUORINATED ETHERS AND FLUORINATED HYDROCARBONS TO REPLACE CFC-11 AND CFC-114 IN CHILLERS

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ABSTRACT

Chlorine-free fluorinated ethers and fluorinated hydrocarbons are being considered as potential long-term replacements for R-11 and R-114, both CFCs. Simple cycle modeling has been done with in-house refrigeration models based on the Carnahan-Starling-DeSantis (CSD) equation of state (EOS) to determine the performance of these chlorine-free compounds in a variety of refrigeration applications. In the future, a standard compressor calorimeter using an oil-free diaphragm compressor will be used to evaluate the performance of these chlorofluorocarbons (CFCs) and their proposed alternatives at the Stratospheric Ozone Refrigeration Laboratory of the U.S. Environmental Protection Agency (EPA).

INTRODUCTION

In the mid-1970s, concern mounted over the depletion of stratospheric ozone by fully halogenated chlorofluorocarbons (CFCs) and halons. Ozone depletion leads to increasing ultraviolet (UV) radiation, which in turn increases incidents of cataracts, skin cancers, immune system deficiencies, and other human and ecological problems. To prevent the potential disasters of stratospheric ozone depletion, an international agreement entitled the "Montreal Protocol for Substances that Deplete the Ozone Layer," hereafter referred to as the Montreal Protocol, was signed to reduce consumption of CFCs and halons (UNEP 1987).

In June 1990, in London, participants at a United Nations Environmental Programme (UNEP) meeting reassessed the phaseout schedule for CFCs and discussed future reductions and/or phaseout of hydrogenated chlorofluorocarbons (HCFCs). The current schedule listed by the Montreal Protocol and the Clean Air Act Amendment (1990) dictates CFC phaseout by the year 2000. The Clean Air Act Amendment also dictates phaseout of HCFCs by the year 2015 unless the HCFCs are recycled, entirely consumed in the production of other chemicals, or "used as refrigerants in appliances manufactured prior to January 1, 2020." Total HCFC production phaseout is scheduled for the year 2030. Requirements are in place for the evaluation and reassessment of each of these schedules.

Based on scientific findings by the UNEP International Ozone Assessment and the U.S. Airborne Arctic Stratospheric Expedition that ozone depletion was occurring at a much more rapid pace than expected, the president of the United States in a press release in February 1992 called for a unilateral acceleration of the phaseout of ozone-depleting substances, including a CFC phaseout, by the end of 1995 (White House 1992). The president also announced a reevaluation of the phaseout schedule of HCFCs.

CFCs, halons, and HCFCs are used for a variety of functions including refrigeration, foam-blowing, solvents, aerosols, and fire extinguishants. This paper will concentrate on substitutes for CFCs and HCFCs related to refrigeration.

Finding an alternative refrigerant for any of the CFCs and HCFCs is a difficult task. A variety of tests and analyses must be performed to evaluate flammability, stability, toxicity, energy efficiency, material compatibility, oil solubility, environmental effects, and cost. Often the testing sequence is an iterative route based on the cost-effectiveness and perceived outcome and impacts of each test. In addition to selection based on the performance within the system, regulations relating to health, safety, and environmental issues such as stratospheric ozone and global warming may also have an impact upon refrigerant selection.

Industry, academia, and government laboratories have all been striving to find replacements for CFCs, but in 1987, for many of the CFC replacements that had undergone at least a screening of the above factors, there were still questions or concerns related to efficiency, health, safety, or the environment. Because of the issues surrounding the top candidates in 1987, an expert panel suggested that EPA investigate "backup" or second-generation replacements to utilize in the event that the top candidates for specific applications were later deemed unacceptable. At that time, partially halogenated CFCs were not subject to regulation. Since 1987, atmospheric scientists have discovered increasing ozone depletion, beyond their earlier predictions, and it has become apparent to the signatories of the Montreal Protocol that HCFCs must now be included in the phaseout schedule. R-123, the leading replacement for R-11, and R-124, the leading replacement for R-114, are

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both partially halogenated compounds that are subject to future phaseout. Consequently, long-term research must continue to focus on chlorine-free replacements for R-11 and R-114.

EPA and a panel of experts recommended a list of second-generation replacements that would be particularly applicable for refrigerants. Because it was recognized that the ideal refrigerant would be safe, environmentally friendly, energy-efficient, and inexpensive, the assembled experts considered estimates of the following properties for the selection process: thermodynamic properties, global-warming potential, ozone-depletion potential, ease of manufacture, toxicity, and flammability. The panel of experts decided that the most promising chemical classes to pursue would be the fluorinated ethers and fluorinated propanes (Bare et al. 1989).

After the selection process, the synthesis and property determinations of the leading candidates were required. At one university, the fluorinated ethers were synthesized with direct fluorination of the foundation ethers. At another university, the fluorinated propanes were manufactured by using a variety of established fluorination methods. Property measurements taken at these universities included critical temperature, critical pressure, normal boiling point, freezing point, liquid density, vapor pressure, liquid-phase heat capacities over a range of temperature, vapor density, and hydrolytic stability (Adcock et al. 1991; Beyerlein et al. 1991). Table 1 lists the boiling points and critical temperature for these new compounds as well as the CFCs and HCFCs and other proposed replacements.

DESCRIPTION OF IN-HOUSE MODEL

To obtain a preliminary assessment of the performance of chlorine-free replacements as refrigerants in R-11 and R-114 chillers, computer modeling was performed using an in-house, FORTRAN-based model, which allows analysis of simple theoretical vapor compression cycles that consist of constant pressure evaporation, compression at a specified compressor efficiency (in this case, compressor efficiency was assumed to be 1.0), constant pressure condensation, and adiabatic expansion. The model allows analysis of systems that do not have internal heat exchange but may have imposed evaporator superheat, imposed condenser subcooling, and suction line gains. The model is designed to analyze refrigerants that may or may not experience wet compression.

The model is based on the Carnahan-Starling-DeSantis (CSD) equation of state, which requires specific refrigerant parameters. The CSD coefficients of some of the more common refrigerants were adopted from previous work at the National Institute of Standards and Technology (NIST), which involved calculations using properties data for each refrigerant (McLinden and Morrison 1989). Additional CSD coefficients were added based on properties determinations (Salvi-Narkhede et al. 1993; Beyerlein et al. 1991) and CSD coefficient calculations (McLinden 1992). Critical points, liquid and vapor densities, vapor pressures, and calculated ideal gas heat capacities were used to determine the CSD coefficients for these fluorinated ethers and fluorinated propanes. The refrigerant properties necessary for the refrigerant modeling are identified in Tables 2a (SI units) and 2b (I-P units). The CSD coefficients for the equation of state are listed in Table 3. All simulations were done based solely on these thermodynamic properties; refrigerant transport properties were not factored into this work.

In addition to inputs relating to imposed superheat, subcooling, and suction line gains, other inputs required for the model are specific refrigerant or refrigerant mixture, mass fraction of refrigerants (for mixtures), interaction parameters (for mixtures), evaporating temperature, and condensing temperature.

Outputs include temperature, pressure, enthalpy, volume, entropy, and quality at the following points: evaporator out, compressor in, compressor discharge, condenser vapor saturated state, condenser liquid saturated state, condenser out, evaporator in, and evaporator vapor saturated state. Outputs also include: coefficient of performance (COP), volumetric capacity, and pressure ratio (Gage 1992).

SIMULATION CONDITIONS

Each of the new chemicals was compared to the compound it was replacing at current operating conditions. These simple cycle conditions correspond to 4.4°C (40°F) evaporating temperature with and without 2.8°C (5°F) superheating in the evaporator and condensing conditions ranging from 20°C to 60°C (68°F to 140°F) with and without subcooling in the condenser. Temperature extremes on the condensing side such as these may be experienced in cooling aboard surface ships and submarines. The assumed compressor isentropic efficiency chosen for this analysis was 1.0.

Nonazeotropic refrigerant mixtures (NARMs) were not included in this simulation because centrifugal chillers operate with flooded evaporators that would experience mixture separation and compositions shifting with large temperature glides.

Suction line heat exchangers were not simulated even though previous work had shown that more complex molecules, such as the fluorinated propanes and ethers, could show greater benefits with suction line heat exchange (McLinden 1990). Suction line heat exchangers would require significant design changes because they involve a huge volume of low pressure vapor going into the compressor and the potential for large pressure drops at these conditions.

DISCUSSION OF RESULTS

Tables 4a (SI units) and 4b (I-P units) show the conditions and results of these runs. Some of the more

TABLE 1
Physical Properties of Various Alternative Refrigerants

Refrigerant	Chem. Form.	BPt. °C	BPt. (°F)	Crit.T. °C	Crit.T. (°F)	Comm.
CFC-12	CCl_2F_2	-29.8	(-21.6)	112.0	(233.6)	
HFC-134a	CF_3CFH_2	-26.1	(-15.0)	101.1	(214.0)	
HFC-152a	CF_2HCH_3	-24.2	(-11.6)	113.3	(235.9)	
E-143a	CF_3OCH_3	-24.1	(-11.4)	106.1	(223.0)	*+
HFC-227ea	CF_3CFHCF_3	-15.2	(4.6)	103.5	(218.3)	*+
HFC-227ca	$CF_3CF_2CF_2H$	-16.3	(2.7)	106.3	(223.3)	*+
HFC-245cb	$CF_3CF_2CH_3$	-18.3	(-1.0)	108.5	(227.3)	*+
CE-216	$-CF_2CF_2OCF_2-$	-29.9	(-21.8)	88.7	(191.7)	*
CEE-216	$-CF_2OCF_2OCF_2-$	-22.1	(-7.8)	90.0	(194.0)	*
CFC-114	$CClF_2CClF_2$	3.8	(38.8)	145.7	(294.3)	
HCFC-124	$CClFHCF_3$	-12.1	(10.2)	122.5	(252.5)	
HFC-254cb	$CF_2HCF_2CH_3$	-0.8	(30.6)	146.1	(295.0)	*+
HFC-236ea	CF_3CFHCF_2H	6.5	(43.7)	141.1	(286.0)	*+
HFC-236fa	$CF_3CH_2CF_3$	-1.1	(30.0)	130.6	(267.1)	*+
HFC-236cb	$CF_3CF_2CFH_2$	-1.2	(29.8)	130.1	(266.2)	*+
E-134	CF_2HOCF_2H	4.7	(40.5)	153.5	(308.3)	*+
CFC-11	CCl_3F	23.8	(74.8)	198.0	(388.4)	
HCFC-123	CCl_2HCF_3	27.9	(82.2)	183.8	(362.8)	
HFC-245ca	$CF_2HCF_2CFH_2$	25.0	(77.0)	178.4	(353.1)	*+
HFC-245fa	$CF_3CH_2CF_2H$	15.3	(59.5)	157.5	(315.5)	*+

*These compounds were synthesized and the properties tested under EPA/EPRI joint funding at the University of Tennessee and Clemson University.
+CSD coefficients were calculated from EPA/EPRI data at the National Institute of Standards and Technology.

TABLE 2a (SI Units)
Refrigerant Properties for New CFC-11 and CFC-114 Alternatives

Refrigerant	Molecular Weight	Critical Pressure (kPa)	Critical Volume (m^3/kmol)
HFC-236ea	152.04	3533	0.26259
HFC-236fa	152.04	3177	0.27345
HFC-236cb	152.04	3118	0.27897
HFC-254cb	116.06	3753	0.24852
HFC-245ca	134.05	3855	0.25340
HFC-245fa	134.05	3644	0.25197

TABLE 2b (I-P Units)
Refrigerant Properties for New CFC-11 and CFC-114 Alternatives

Refrigerant	Molecular Weight	Critical Pressure (psia)	Critical Volume (ft^3/mol)
HFC-236ea	152.04	512.4	9.2734
HFC-236fa	152.04	460.8	9.6569
HFC-236cb	152.04	452.2	9.8518
HFC-254cb	116.06	544.3	8.7765
HFC-245ca	134.05	559.1	8.9488
HFC-245fa	134.05	528.5	8.8983

TABLE 3
Carnahan-Starling-DeSantis Equation of State Coefficients for New CFC-11 and CFC-114 Alternatives

HFC-236ea
a_o, a_1, a_2 = 5.922310E+03, -2.692871E-03, -1.431562E-06
b_o, b_1, b_2 = 1.922947E-01, -1.541316E-04, -1.775514E-07
c_o, c_1, c_2 = 2.326170E+01, 4.086750E-01, -2.204540E-04

HFC-236fa
a_o, a_1, a_2 = 6.051133E+03, -3.335808E-03, -1.666967E-07
b_o, b_1, b_2 = 2.042306E-01, -2.492263E-04, -2.064470E-08
c_o, c_1, c_2 = 3.436030E+01, 3.802440E-01, -2.052500E-04

HFC-236cb
a_o, a_1, a_2 = 1.638596E+04, -9.100785E-03, 8.156970E-06
b_o, b_1, b_2 = 3.852408E-01, -1.299857E-03, 1.498284E-06
c_o, c_1, c_2 = 1.550780E+01, 5.108440E-01, -2.850690E-04

HFC-254cb
a_o, a_1, a_2 = 7.295989E+03, -5.394319E-03, 3.667774E-06
b_o, b_1, b_2 = 2.195130E-01, -4.653994E-04, 3.842990E-07
c_o, c_1, b_2 = 1.079330E+01, 3.887900E-01, -2.089020E-04

HFC245ca
a_o, a_1, a_2 = 8.510839E+03, -4.498621E-03, 1.782586E-06
b_o, b_1, b_2 = 2.343665E-01, -4.192604E-04, 2.416012E-07
c_o, c_1, c_2 = 4.959730E+00, 4.537480E-01, -2.747960E-04

HFC-245fa
a_o, a_1, a_2 = 8.729749E+03, -5.020118E-03, 2.332009E-06
b_o, b_1, b_2 = 2.358726E-01, -4.540089E-04, 2.967103E-07
c_o, c_1, c_2 = 1.729200E+01, 3.561620E-01, -1.910170E-04

representative conditions without imposed subcooling or imposed superheat are plotted in Figures 1a through 4b. Figures 1a and 1b allow performance ranking by COP/COP Carnot, but the tables must be consulted to determine if a retrofit situation is possible (i.e., capacity and pressure in the system). The R-114 replacements, listed in order of COP at condensing temperatures shown for simple cycle analyses, are E (fluorinated ether)-134, R-254cb, R-236ea, R-236fa, and R-236cb. The R-11 replacements, listed in order of COP at condensing temperatures shown, for simple cycle analyses, are R-123, R-245ca, and R-245fa. Only E-134 has a higher modeled COP than the CFC it replaces.

Qualities less than 1.0 in the last column (Quality @ Comp. Disch.) of Tables 4a and 4b represent the possibility of operating in wet compression under these modeling conditions, but in real-world operation, they may not experience wet compression. The modeling presented is ideal (and thus unrealistic) in many ways (e.g., compressor efficiency equal to 1.0, no pressure drops in the heat exchangers or lines) and in real operation, refrigerants such as R-114, which is shown to require superheat, do not require imposed superheat at all and do not experience wet compression. To determine the extent to which a refrigerant may be expected to experience superheat without experimental data is difficult, but it is anticipated that at least those refrigerants with qualities greater than those of R-114 would have no problems with wet compression. Figures 2a and 2b present the qualities at the compressor discharge for R-11, R-114, and their replacements. Only R-11 and E-134 maintain qualities of 1.0 at the modeling conditions plotted.

Figures 3a and 3b show the volumetric capacity and Figures 4a and 4b show the discharge pressures of the refrigerants modeled at the conditions presented in the previous figures. This information is especially important when considering a retrofit or "drop-in" situation. At least one refrigerant, R-236ea, has simulated volumetric capacities and discharge pressure that so closely match the refrigerant it replaces (R-114), it may be a "drop-in" replacement if material compatibility testing does not become a stumbling block.

CONCLUSIONS

Chlorine-free replacements operating with similar conditions to R-11 and R-114 in chiller applications are probable, based on simulations of several fluorinated propanes and ethers. Based on these simple cycle simulations, at least one of these replacements (R-236ea) operates so much like the CFC it is intended to replace (R-114) in capacity, performance, and system pressures that it may be considered as a possible retrofit or "drop-in" candidate if material compatibility does not become a stumbling block.

Additional property testing and experimental performance tests are being performed for the fluorinated ethers and fluorinated propanes. Larger quantities (3 kg [6.6 lb]) of many of the highest priority compounds are being produced, and EPA is funding atmospheric lifetime testing and limited acute toxicity testing. Flammability and materials compatibility testing (including the materials of construction for the oil-free compressor and calorimeter) and oil/refrigerant miscibilities are being conducted by EPA/AEERL's Stratospheric Ozone Protection Branch. No results are available at this time, but future papers should include details of the above work.

As mentioned before, many other tests must be completed before these compounds can be considered for commercialization. Larger quantities are required for further toxicity, lubrication, property, and performance testing. Industry's involvement will be invaluable to further research and development of any of these replacements.

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TABLE 4a (SI Units)
Modeled Performance of CFC-11 and CFC-114 Replacements

Refrigerant	COP	Vol. Capacity (kJ/m^3)	Pressure Ratio	Suction Pressure (kPa)	Discharge Pressure (kPa)	Quality @ Comp. Disch.
Condensing Temp = 30.0°C, Imp.Superht = 2.8°C, Imp.Subcool = 2.8°C						
CFC-11	10.208	497	2.60	48.7	127	1.000
HCFC-123	10.148	423	2.75	39.9	110	1.000
HFC-245ca	10.046	462	2.84	42.8	122	1.000
HFC-245fa	10.012	665	2.75	63.8	175	1.000
E-134	9.998	949	2.68	93.5	250	1.000
CFC-114	9.892	913	2.39	104	250	0.987
HFC-254cb	9.877	1100	2.42	124	298	0.998
HFC-236ea	9.868	892	2.61	92.6	242	0.990
HFC-236fa	9.756	1100	2.45	125	307	0.978
HFC-236cb	9.674	1090	2.42	127	308	0.962
Condensing Temp = 40.0°C, Imp.Superht = 2.8°C, Imp.Subcool = 2.8°C						
CFC-11	7.110	470	3.60	48.7	175	1.000
HCFC-123	7.021	396	3.87	39.9	155	1.000
HFC-245ca	6.900	428	4.03	42.8	173	0.995
HFC-245fa	6.870	614	3.86	63.8	246	1.000
E-134	6.861	878	3.73	93.5	249	1.000
CFC-114	6.733	835	3.22	104	336	0.972
HFC-254cb	6.719	1000	3.25	124	402	0.986
HFC-236ea	6.697	812	3.62	92.6	335	0.975
HFC-236fa	6.575	994	3.33	125	416	0.958
HFC-236cb	6.492	971	3.26	127	414	0.933
Condensing Temp = 45.0°C, Imp.Superht = 2.8°C, Imp.Subcool = 2.8°C						
CFC-11	6.128	457	4.20	48.7	204	1.000
HCFC-123	6.026	382	4.56	39.9	182	1.000
HFC-245ca	5.897	411	4.76	42.8	204	0.990
HFC-245fa	5.869	589	4.53	63.8	289	1.000
E-134	5.862	841	4.36	93.5	408	1.000
CFC-114	5.724	795	3.71	104	387	0.963
HFC-254cb	5.710	953	3.75	124	463	0.980
HFC-236ea	5.682	771	4.22	92.6	391	0.967
HFC-236fa	5.554	938	3.84	125	481	0.946
HFC-236cb	5.469	913	3.76	127	477	0.916
Condensing Temp = 20.0°C, Imp.Superht = 0.0°C, Imp.Subcool = 0.0°C						
CFC-11	17.030	517	1.83	48.7	89.2	1.000
HCFC-123	16.934	442	1.90	39.9	75.7	1.000
HFC-245ca	16.806	486	1.94	42.8	83.1	0.996
HFC-245fa	16.765	700	1.90	63.8	121	1.000
E-134	16.756	1000	1.87	93.5	175	1.000
CFC-114	16.607	965	1.74	104	181	0.984
HFC-254cb	16.589	1160	1.75	124	216	0.992
HFC-236ea	16.586	945	1.84	92.6	170	0.986
HFC-236fa	16.444	1180	1.77	125	221	0.979
HFC-236cb	16.332	1160	1.75	127	222	0.968
Condensing Temp = 30.0°C, Imp.Superht = 0.0°C, Imp.Subcool = 0.0°C						
CFC-11	10.069	490	2.60	48.7	127	1.000
HCFC-123	9.957	415	2.75	39.9	110	0.999
HFC-245ca	9.819	452	2.84	42.8	122	0.990
HFC-245fa	9.786	649	2.75	63.8	175	0.998
E-134	9.781	928	2.68	93.5	250	1.000
CFC-114	9.629	886	2.39	104	250	0.970
HFC-254cb	9.613	1070	2.42	124	298	0.982
HFC-236ea	9.595	865	2.61	92.6	242	0.974
HFC-236fa	9.455	1070	2.45	125	307	0.960
HFC-236cb	9.350	1040	2.42	127	308	0.942

(Continued)

TABLE 4a (SI Units) (Continued)
Modeled Performance of CFC-11 and CFC-114 Replacements

Refrigerant	COP	Vol. Capacity (kJ/m^3)	Pressure Ratio	Suction Pressure (kPa)	Discharge Pressure (kPa)	Quality @ Comp. Disch.
Condensing Temp = 40.0°C, Imp.Superht = 0.0°C, Imp.Subcool = 0.0°C						
CFC-11	7.003	463	3.60	48.7	175	1.000
HCFC-123	6.873	388	3.87	39.9	155	0.995
HFC-245ca	6.726	417	4.03	42.8	173	0.981
HFC-245fa	6.696	598	3.86	63.8	246	0.993
E-134	6.693	856	3.73	93.5	349	1.000
CFC-114	6.531	807	3.22	104	336	0.954
HFC-254cb	6.516	969	3.25	124	402	0.970
HFC-236ea	6.485	784	3.62	92.6	335	0.958
HFC-236fa	6.340	954	3.33	125	416	0.939
HFC-236cb	6.239	927	3.26	127	414	0.911
Condensing Temp = 45.0°C, Imp.Superht = 0.0°C, Imp.Subcool = 0.0°C						
CFC-11	6.031	450	4.20	48.7	204	1.000
HCFC-123	5.892	374	4.56	39.9	182	0.993
HFC-245ca	5.741	399	4.76	42.8	204	0.976
HFC-245fa	5.711	573	4.53	63.8	289	0.990
E-134	5.708	819	4.36	93.5	408	.000
CFC-114	5.539	766	3.71	104	387	0.945
HFC-254cb	5.526	920	3.75	124	463	0.963
HFC-236ea	5.489	742	4.22	92.6	391	0.949
HFC-236fa	5.339	897	3.84	125	481	0.926
HFC-236cb	5.239	868	3.76	127	477	0.893
Condensing Temp = 50.0°C, Imp.Superht = 0.0°C, Imp.Subcool = 0.0°C						
CFC-11	5.268	436	4.87	48.7	237	1.000
HCFC-123	5.120	360	5.33	39.9	213	0.990
HFC-245ca	4.964	381	5.58	42.8	239	0.970
HFC-245fa	4.935	547	5.29	63.8	337	0.986
E-134	4.933	782	5.07	93.5	474	1.000
CFC-114	4.755	726	4.26	104	444	0.935
HFC-254cb	4.743	870	4.29	124	530	0.955
HFC-236ea	4.700	700	4.89	92.6	454	0.940
HFC-236fa	4.545	840	4.42	125	552	0.913
HFC-236cb	4.445	809	4.31	127	548	0.874
Condensing Temp = 60.0°C, Imp.Superht = 0.0°C, Imp.Subcool = 0.0°C						
CFC-11	4.145	409	6.46	48.7	315	1.000
HCFC-123	3.979	331	7.17	39.9	286	0.983
HFC-245ca	3.812	346	7.55	42.8	323	0.955
HFC-245fa	3.783	494	7.08	63.8	451	0.977
E-134	3.782	708	6.73	93.5	630	0.998
HFC-254cb	3.676	771	5.55	124	685	0.936
CFC-114	3.586	643	5.52	104	576	0.913
HFC-236ea	3.521	615	6.49	92.6	601	0.918
HFC-236fa	3.354	724	5.75	125	719	0.883
HFC-236cb	3.250	689	5.60	127	712	0.832

TABLE 4b (IP Units)
Modeled Performance of CFC-11 and CFC-114 Replacements

Refrigerant	COP	Vol. Capacity (Btu/ft^3)	Pressure Ratio	Suction Pressure (psia)	Discharge Pressure (psia)	Quality @ Comp. Disch.
Condensing Temp = 86.0°F, Imp.Superht = 5.0°F, Imp.Subcool = 5.0°F						
CFC-11	10.208	13.3	2.60	7.06	18.4	1.000
HCFC-123	10.148	11.4	2.75	5.79	15.9	1.000
HFC-245ca	10.046	12.4	2.84	6.21	17.6	1.000
HFC-245fa	10.012	17.9	2.75	9.25	25.4	1.000
E-134	9.998	25.5	2.68	13.6	36.3	1.000
CFC-114	9.892	24.5	2.39	15.1	36.2	0.987
HFC-254cb	9.877	29.4	2.42	17.9	43.3	0.998
HFC-236ea	9.868	24.0	2.61	13.4	35.1	0.990
HFC-236fa	9.756	29.6	2.45	18.1	44.5	0.978
HFC-236cb	9.674	29.2	2.42	18.4	44.7	0.962
Condensing Temp = 104°F, Imp.Superht = 5.0°F, Imp.Subcool = 5.0°F						
CFC-11	7.110	12.6	3.60	7.06	39.9	1.000
HCFC-123	7.021	10.6	3.87	5.79	22.4	1.000
HFC-245ca	6.900	11.5	4.03	6.21	25.1	0.995
HFC-245fa	6.870	16.5	3.86	9.25	35.7	1.000
E-134	6.861	23.6	3.73	13.6	36.1	1.000
CFC-114	6.733	22.4	3.22	15.1	48.8	0.972
HFC-254cb	6.719	26.9	3.25	17.9	58.3	0.986
HFC-236ea	6.697	21.8	3.62	13.4	48.6	0.975
HFC-236fa	6.575	26.7	3.33	18.1	60.4	0.958
HFC-236cb	6.492	26.1	3.26	18.4	60.1	0.933
Condensing Temp = 113°F, Imp.Superht = 5.0°F, Imp.Subcool = 5.0°F						
CFC-11	6.128	12.3	4.20	7.06	29.6	1.000
HCFC-123	6.026	10.3	4.56	5.79	26.4	1.000
HFC-245ca	5.897	11.0	4.76	6.21	29.6	0.990
HFC-245fa	5.869	15.8	4.53	9.25	41.9	1.000
E-134	5.862	22.6	4.36	13.6	59.1	1.000
CFC-114	5.724	21.4	3.71	15.1	56.2	0.963
HFC-254cb	5.710	25.6	3.75	17.9	67.1	0.980
HFC-236ea	5.682	20.7	4.22	13.4	56.7	0.967
HFC-236fa	5.554	25.2	3.84	18.1	69.7	0.946
HFC-236cb	5.469	24.5	3.76	18.4	69.2	0.916
Condensing Temp = 68.0°F, Imp.Superht = 0.0°F, Imp.Subcool = 0.0°F						
CFC-11	17.030	13.9	1.83	7.06	12.9	1.000
HCFC-123	16.934	11.9	1.90	5.79	11.0	1.000
HFC-245ca	16.806	13.1	1.94	6.21	12.1	0.996
HFC-245fa	16.765	18.8	1.90	9.25	17.6	1.000
E-134	16.756	26.9	1.87	13.6	25.4	1.000
CFC-114	16.607	25.9	1.74	15.1	26.3	0.984
HFC-254cb	16.589	31.2	1.75	17.9	31.4	0.992
HFC-236ea	16.586	25.4	1.84	13.4	24.7	0.986
HFC-236fa	16.444	31.6	1.77	18.1	32.0	0.979
HFC-236cb	16.332	31.2	1.75	18.4	32.2	0.968
Condensing Temp = 86.0°F, Imp.Superht = 0.0°F, Imp.Subcool = 0.0°F						
CFC-11	10.069	13.2	2.60	7.06	18.4	1.000
HCFC-123	9.957	11.1	2.75	5.79	15.9	0.999
HFC-245ca	9.819	12.1	2.84	6.21	17.6	0.990
HFC-245fa	9.786	17.4	2.75	9.25	25.4	0.998
E-134	9.781	24.9	2.68	13.6	36.3	1.000
CFC-114	9.629	23.8	2.39	15.1	36.2	0.970
HFC-254cb	9.613	28.6	2.42	17.9	43.3	0.982
HFC-236ca	9.595	23.2	2.61	13.4	35.1	0.974
HFC-236fa	9.455	28.6	2.45	18.1	44.5	0.960
HFC-236cb	9.350	28.0	2.42	18.4	44.7	0.942

(Continued)

TABLE 4b (IP Units) (Continued)
Modeled Performance of CFC-11 and CFC-114 Replacements

Refrigerant.	COP	Vol. Capacity ✓ (Btu/ft^3)	Pressure Ratio	Suction Pressure (psia)	Discharge Pressure (psia)	Quality @ Comp. Disch.(Continued)
Condensing Temp = 104°F, Imp.Superht = 0.0°F, Imp.Subcool = 0.0°F						
CFC-11	7.003	12.4	3.60	7.06	25.4	1.000
HCFC-123	6.873	10.4	3.87	5.79	22.4	0.995
HFC-245ca	6.726	11.2	4.03	6.21	25.1	0.981
HFC-245fa	6.696	16.1	3.86	9.25	35.7	0.993
E-134	6.693	23.0	3.73	13.6	50.6	1.000
CFC-114	6.531	21.7	3.22	15.1	48.8	0.954
HFC-254cb	6.516	26.0	3.25	17.9	58.3	0.970
HFC-236ea	6.485	21.1	3.62	13.4	48.6	0.958
HFC-236fa	6.340	25.6	3.33	18.1	60.4	0.939
HFC-236cb	6.239	24.9	3.26	18.4	60.1	0.911
Condensing Temp = 113°F, Imp.Superht = 0.0°F, Imp.Subcool = 0.0°F						
CFC-11	6.031	12.1	4.20	7.06	29.6	1.000
HCFC-123	5.892	10.0	4.56	5.79	26.4	0.993
HFC-245ca	5.741	10.7	4.76	6.21	29.6	0.976
HFC-245fa	5.711	15.4	4.53	9.25	41.9	0.990
E-134	5.708	22.0	4.36	13.6	59.1	1.000
CFC-114	5.539	20.6	3.71	15.1	56.2	0.945
HFC-254cb	5.526	24.7	3.75	17.9	67.1	0.963
HFC-236ea	5.489	19.9	4.22	13.4	56.7	0.949
HFC-236fa	5.339	24.1	3.84	18.1	69.7	0.926
HFC-236cb	5.239	23.3	3.76	18.4	69.2	0.893
Condensing Temp = 122°F, Imp.Superht = 0.0°F, Imp.Subcool = 0.0°F						
CFC-11	5.268	11.7	4.87	7.06	34.4	1.000
HCFC-123	5.120	9.67	5.33	5.79	30.8	0.990
HFC-245ca	4.964	10.2	5.58	6.21	34.7	0.970
HFC-245fa	4.935	14.7	5.29	9.25	48.9	0.986
E-134	4.933	21.0	5.07	13.6	68.7	1.000
CFC-114	4.755	19.5	4.26	15.1	64.4	0.935
HFC-254cb	4.743	23.4	4.29	17.9	76.9	0.955
HFC-236ea	4.700	18.8	4.89	13.4	65.8	0.940
HFC-236fa	4.545	22.6	4.42	18.1	80.1	0.913
HFC-236cb	4.445	21.7	4.31	18.4	79.5	0.874
Condensing Temp = 140°F, Imp.Superht = 0.0°F, Imp.Subcool = 0.0°F						
CFC-11	4.145	11.0	6.46	7.06	45.6	1.000
HCFC-123	3.979	8.89	7.17	5.79	41.5	0.983
HFC-245ca	3.812	9.29	7.55	6.21	46.9	0.955
HFC-245fa	3.783	13.3	7.08	9.25	65.5	0.977
E-134	3.782	19.0	6.73	13.6	91.3	0.998
HFC-254cb	3.676	20.7	5.55	15.1	99.4	0.936
CFC-114	3.586	17.3	5.52	17.9	83.5	0.913
HFC-236ea	3.521	16.5	6.49	13.4	87.1	0.918
HFC-236fa	3.354	19.4	5.75	18.1	104	0.883
HFC-236cb	3.250	18.5	5.60	18.4	103	0.832

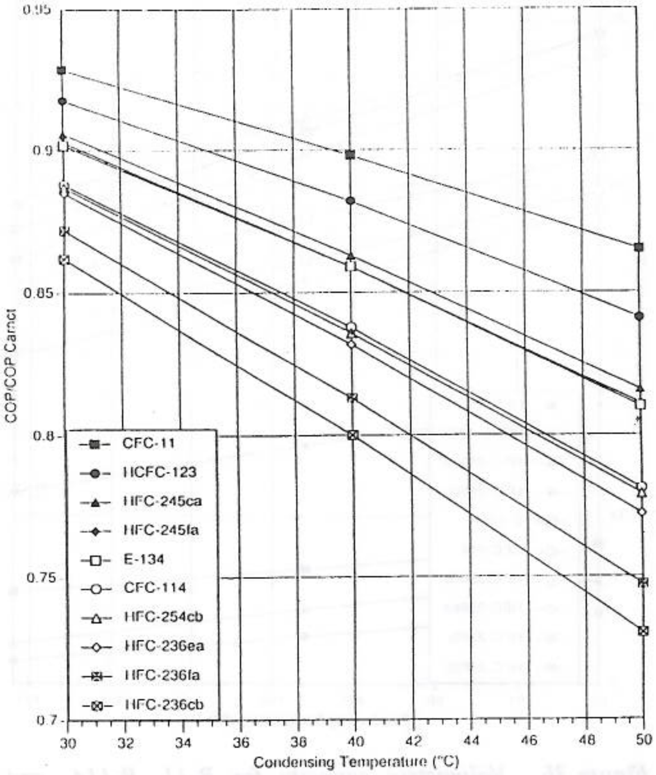

Figure 1a ***Relative performance of R-11, R-114, and replacements with various condensing temperatures, 4.4°C evaporating temperature, and isentropic compression.***

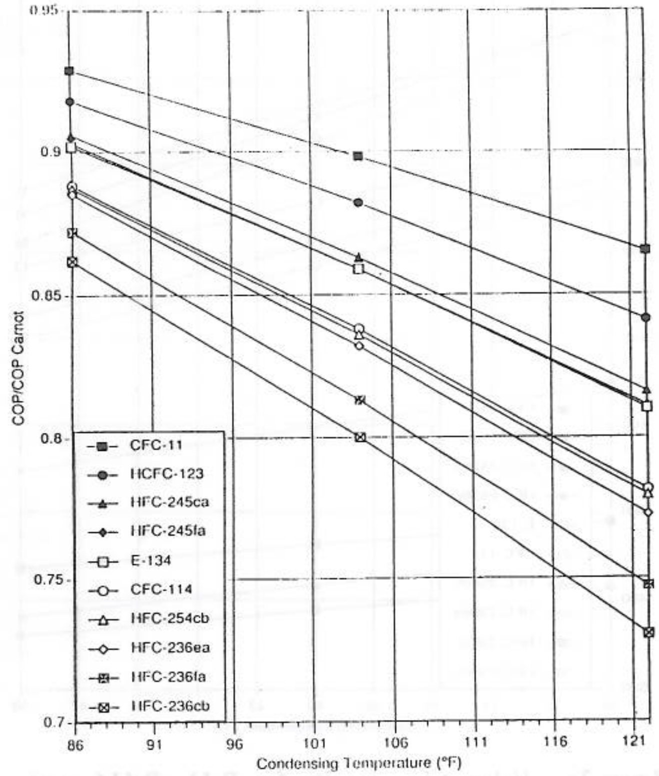

Figure 1b ***Relative performance of R-11, R-114, and replacements with various condensing temperatures, 40°F evaporating temperature, and isentropic compression.***

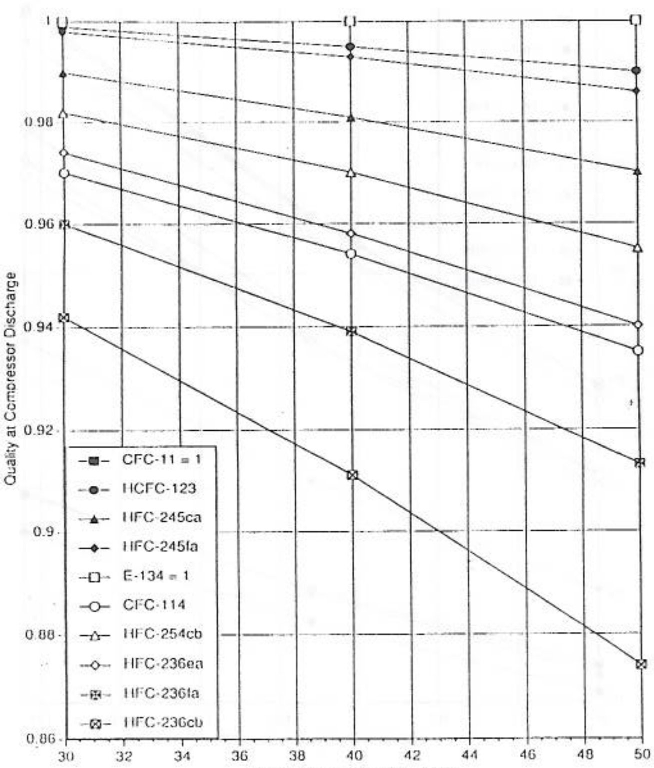

Figure 2a ***Quality at compressor discharge for R-11, R-114, and replacements at various condensing temperatures, 4.4°C evaporating temperature, and isentropic compression.***

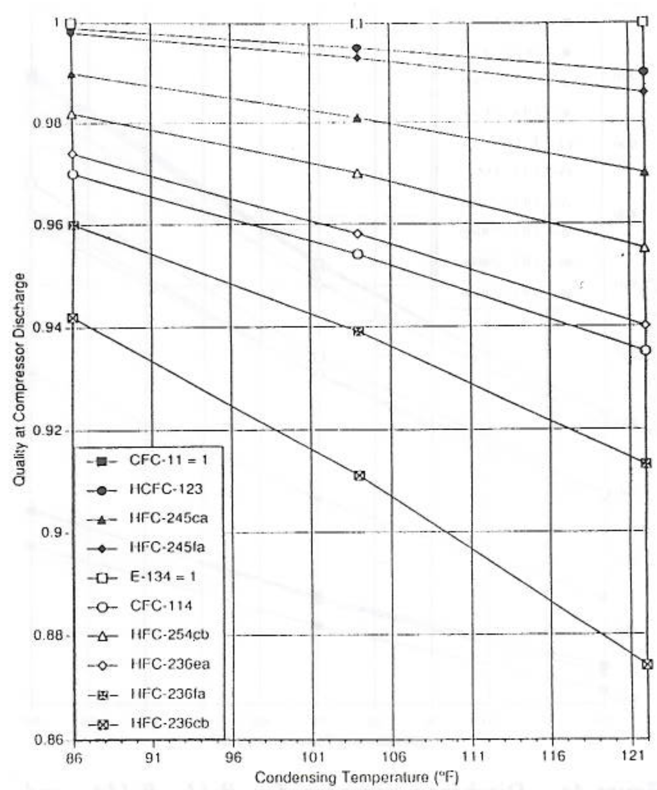

Figure 2b ***Quality at compressor discharge for R-11, R-114, and replacements at various condensing temperatures, 40°F evaporating temperature, and isentropic compression.***

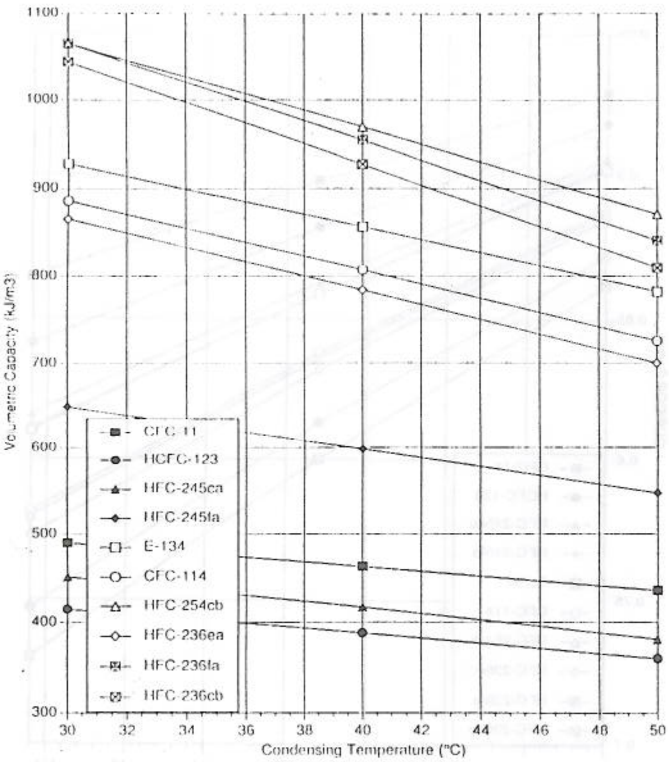

Figure 3a *Volumetric capacity for R-11, R-114, and replacements at various condensing temperatures, 4.4°C evaporating temperature, and isentropic compression.*

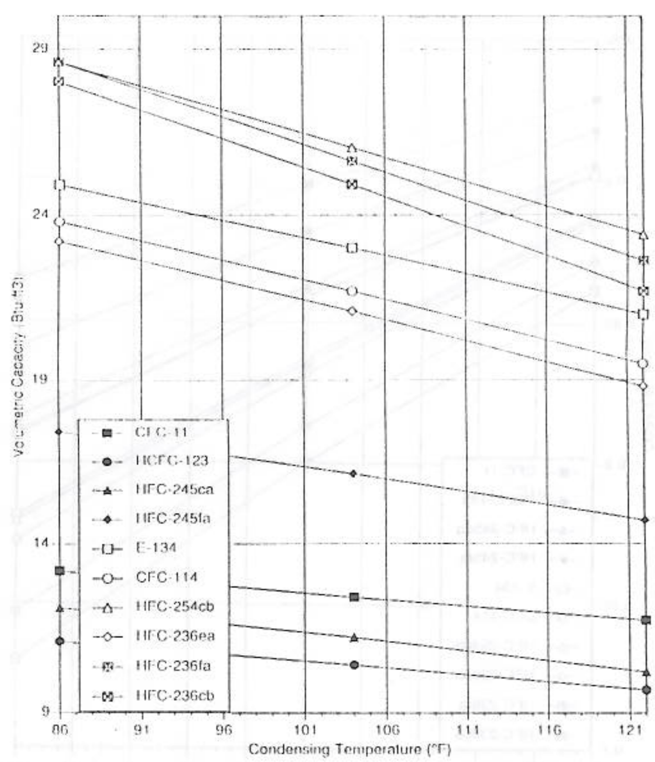

Figure 3b *Volumetric capacity for R-11, R-114, and replacements at various condensing temperatures, 40°F evaporating temperature, and isentropic compression.*

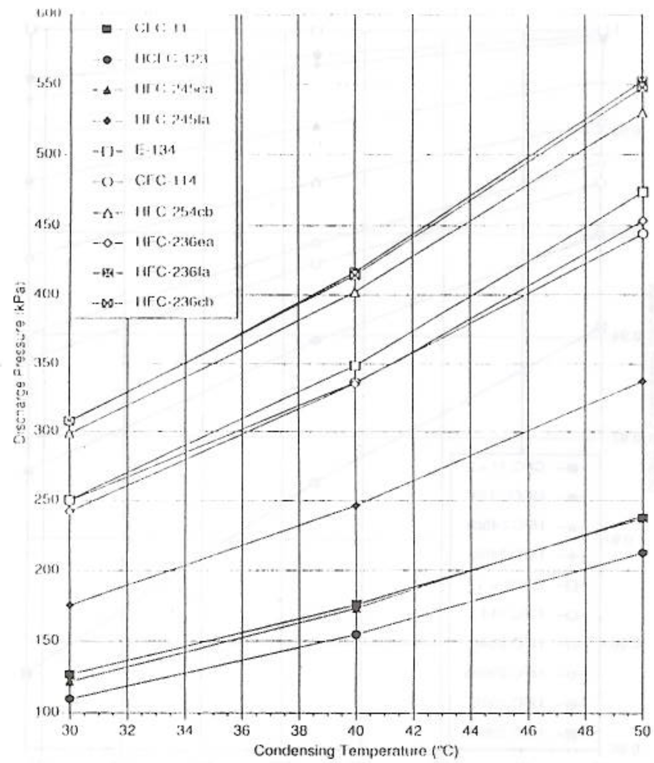

Figure 4a *Discharge pressure for R-11, R-114, and replacements at various condensing temperatures, 4.4°C evaporating temperature, and isentropic compression.*

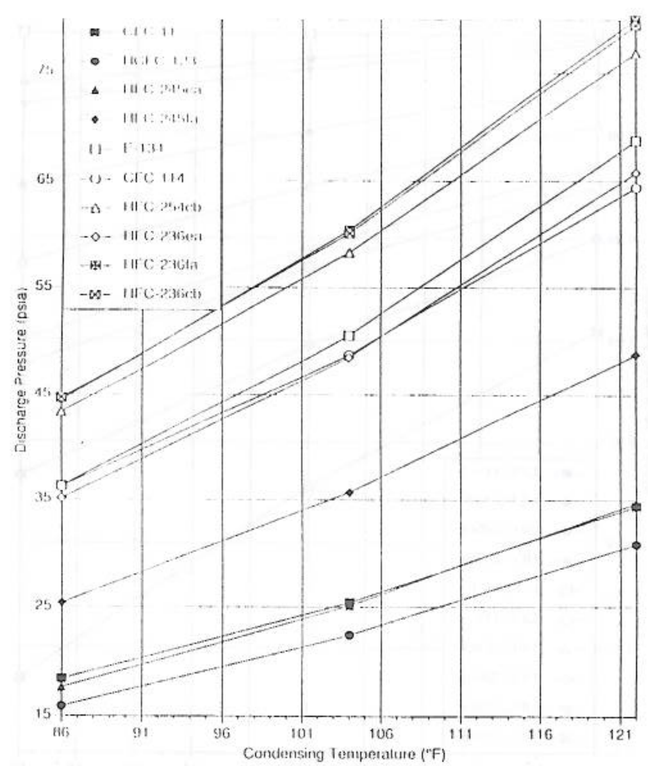

Figure 4b *Discharge pressure for R-11, R-114, and replacements at various condensing temperatures, 40°F evaporating temperature, and isentropic compression.*

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