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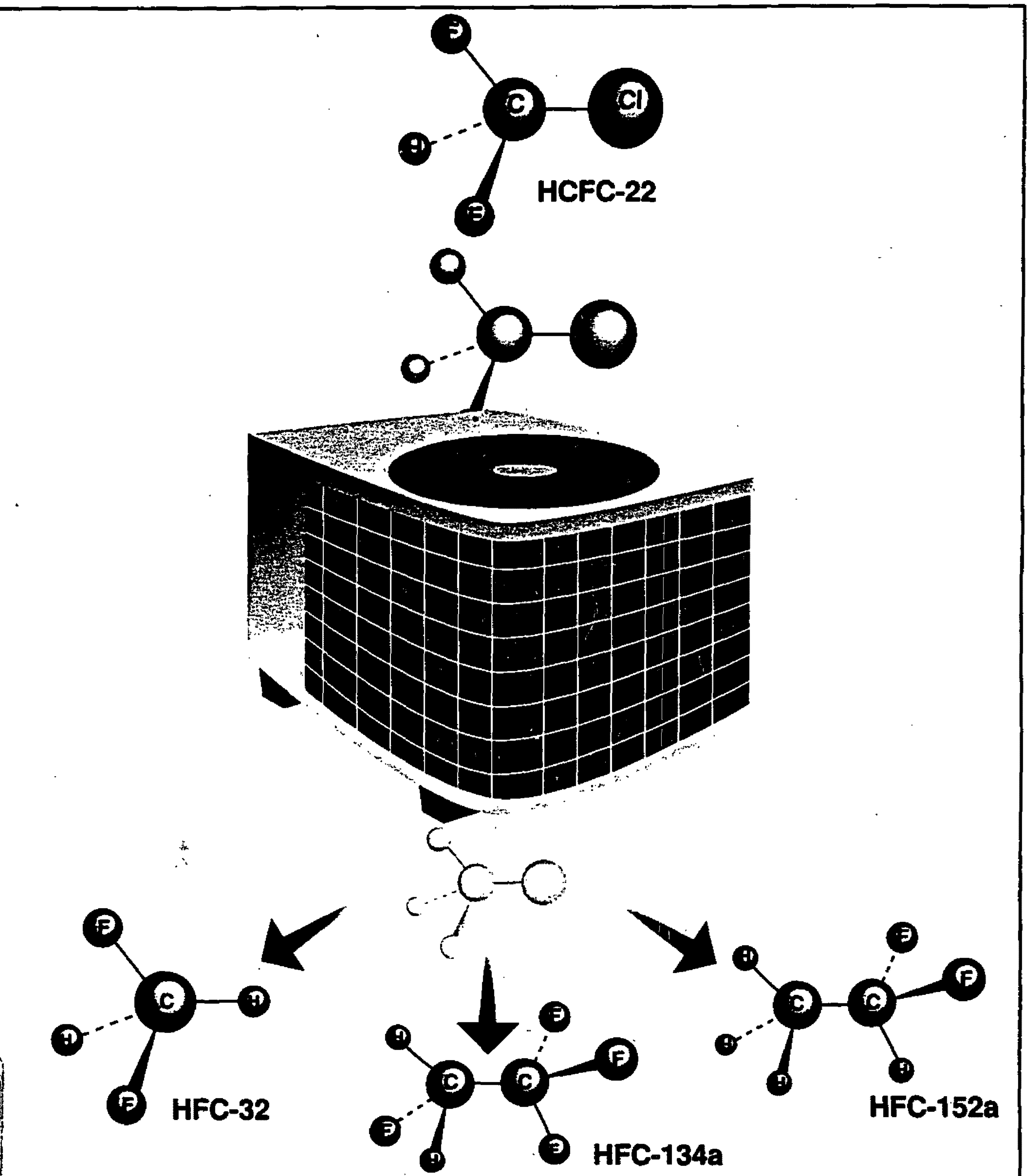
Experimental Investigation of R-22 Replacement Refrigerants in a Split-System Residential Air Conditioner



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Experimental Investigation of R-22 Replacement Refrigerants in a Split-System Residential Air Conditioner

Prepared for

U.S. Environmental Protection Agency
Technology & Substitutes Branch Global Change Division
Office of Atmospheric and Indoor Air Programs
Office of Air and Radiation
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by

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CONTENTS

MAJOR FINDINGS

- Experimental testing of five blends of R-32/R-134a and R-32/R-152a, potential R-22 replacements, was performed in a 2-ton split-system residential air conditioning system. The only change made to the original R-22 system was a non-production hand-operated expansion device and a different lubricant.
- The R-32 mixtures provided similar efficiency and capacities to R-22 with minimal hardware changes.
- The 40/60% mass fraction blend of R-32/R-134a had capacity and steady-state efficiency 1% greater than R-22.
- The 30/70% blend of R-32/R-134a had a 5% lower capacity and a steady-state efficiency within 1% of R-22 performance. The seasonal energy efficiency levels were within 2% of the R-22 values.
- Since capacity is a driving force for retrofit applications, the 40/60% of R-32/R-134a may be a good retrofit refrigerant for existing R-22 systems.
- All the blends of R-32/R-134a and R-32/R-152a had steady-state efficiency levels within 2% of R-22 performance levels but lower capacity levels.
- The R-32/R-152a blends (30/70% and 40/60%) had steady-state efficiency levels within 1.5% of R-22 but had a capacity reduction between 8 and 12%. Simulations have shown these blends to have the most promising energy performance potential, and with appropriate hardware modifications and optimization, it may be possible to improve efficiency and capacity levels considerably.

Table 1: Overview of Steady-State Results

(2 ton, 10.25 SEER Split System Air Conditioner)
(ARI Rating Condition 80-67/95)

Refrigerant	Capacity ("A" Test)	% CHANGE EER ("A" Test)	SEER
R-22	Base	Base	Base
R-32/R-134a (20/80 Mix)	-10%	-1%	-3%
R-32/R-134a (30/70 Mix)	-5%	0%	-2%
R-32/R-134a (40/60 Mix)	+1%	+1%	-1%
R-32/R-152a (30/70 Mix)	-12%	+1%	-5%
R-32/R-152a (40/60 Mix)	-8%	-1.5%	-2%

- Assumptions made in computer simulation, such as system optimization and counterflow heat exchangers, resulted in differences between the modeling and experimental results. The thermodynamic properties used in the simulations may have also contributed to the variation in the results.
- With appropriate hardware modifications and optimization, it is expected that systems using the R-32/R-134a and R-32/R-152a blends could achieve performance levels similar to that predicted by simulations.
- Independent tests conducted by Lennox Industries on similar equipment using the same refrigerant blends confirmed trends and results reported above.
- The present set of tests were for a cooling only, split-system air conditioner. The next immediate step should be a study of refrigerant blends in heat pumps operating in both heating and cooling modes.
- The results from these tests form the basis of preliminary "drop-in" tests of R-22 substitutes in operating residential air conditioning equipment. While the results are encour-

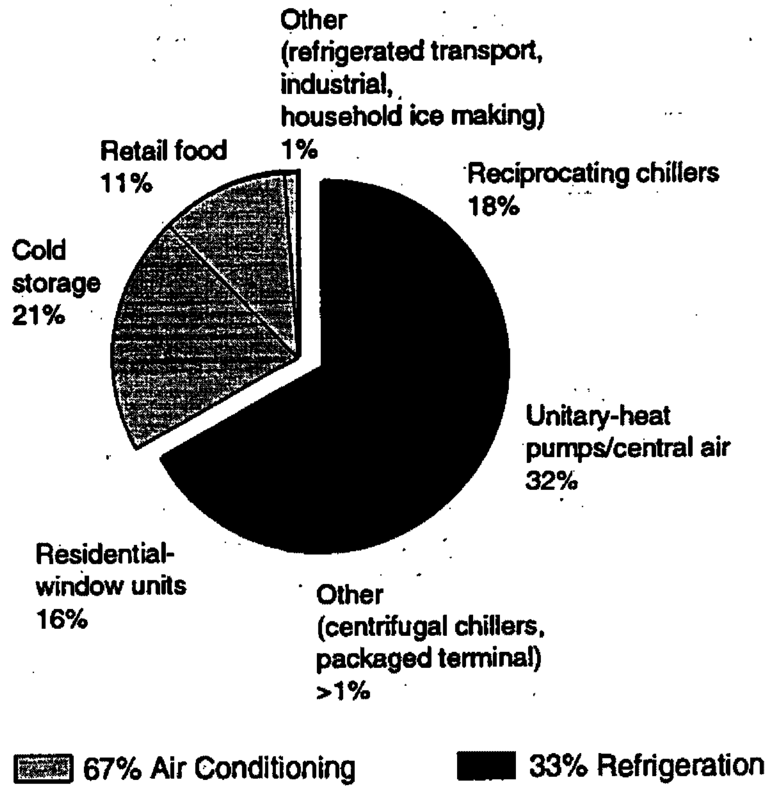
aging, a considerable amount of further work needs to be done prior to commercialization. Future work should include evaluation of:

- Counterflow Heat Exchangers for Air Systems
- Charge, Superheat, and Subcooling Optimization
- Expansion Devices
- Heat Pumps—Cooling and Heating Modes
- Composition Shifts of the Refrigerant Blends
- Accumulators and Reversing Valve Dynamics
- Compressor Life
- Materials Compatibility (long term)
- Flammability
- Servicing Issues

REFRIGERANTS AND THE ENVIRONMENT

- The environmental problems of ozone-depleting chlorofluorocarbons (CFCs) have been identified and are restricted worldwide by the Montreal Protocol. Fully halogenated CFCs, including the widely used refrigerants R-11, R-12, R-114 and R-502, are being phased out by the end of 1995 in the United States.
- A similar CFC phaseout, including restrictions on HCFC-22, will be negotiated under the Montreal Protocol in November 1992.
- R-22 is presently used in a wide variety of applications (Figure 1). The concern that continued use of HCFC-22 will lead to increased levels of stratospheric chlorine and to more significant ozone depletion, has lead to calls for an R-22 phaseout between the years 2000 and 2010.
- The Rio convention framework indicates that global warming is the next dominant environmental issue and that CFC and HCFC alternatives will be included in efforts to minimize global warming effects.
- Industry, government, and academia are concentrating efforts to develop alternatives for R-22.

Figure 1: Multiple Uses of HCFC-22



CHOOSING THE BEST ALTERNATIVES

- Several refrigerants and replacements are being evaluated as R-22 replacements.
- To achieve a significant net reduction in global warming effects when substituting R-22 with alternatives, it is important that the alternatives have both a low direct global warming potential and are at least as energy-efficient as R-22.
- Energy efficiency is especially significant domestically, since unitary air conditioners and heat pumps must meet the 1992 Department of Energy (DOE) minimum energy efficiency standard [1] of 10.00 Seasonal Energy Efficiency Ratio (SEER).
- Flammability, toxicity, and human health risks, as well as system performance, materials compatibility, and costs, must be carefully evaluated before the best alternatives can be determined.

- Computer simulations and breadboard tests have indicated that chlorine-free refrigerant blends of R-32/R-134a and R-32/R-152a can deliver capacities and energy efficiency levels greater than that of R-22.
- These simulations and breadboard type tests have only a limited value beyond which actual, "drop-in" tests must be performed to test actual viability.

PROJECT OBJECTIVES

- Evaluate the "drop-in" performance of potential R-22 alternatives blends in an actual full scale 2-ton residential split-system air conditioner.
- Measure the Capacity, Steady-State, and Seasonal Efficiency of the air conditioner.
- Demonstrate that comparable capacity and efficiency can be achieved with minimal hardware changes.
- Provide direction for evaluating engineering design changes in R-22 systems to achieve optimized energy performance.
- Test refrigerant blends of R-32/R-134a and R-32/R-152a based on results obtained by Radermacher and Jung [2] and Pannock and Didion [3] (Table 2).
- Measure differences in performance between different refrigerant compositions.

Table 2: List of Refrigerant Blends Tested

Refrigerant Blend	Composition Ratio (Mass)
R-32/R-134a	20/80%
R-32/R-134a	30/70%
R-32/R-134a	40/60%
R-32/R-152a	30/70%
R-32/R-152a	40/60%

PREVIOUS WORK

- Vineyard, Sands, and Statt [4] found that refrigerant mixtures with high potential for improved performance over R-22 included R-32/R-124, R-32/R-142b, R-143a/R-124, R-143a/R-142b, and R-143a/C-318.
- Radermacher and Jung [2] conducted a simulation study of potential R-22 replacements in residential equipment. They found that the most promising mixtures were R-32/R-152a mixture in a 40/60% blend by mass and R-32/R-134a in a 30/70% blend by mass.
- Sands, Vineyard, and Nowak [5] compared R-22, R-12, and R-114 with 11 single component non-CFC refrigerants to estimate heat pump performance potential. The study concluded that R-152a, R-143a, R-134a, and R-134 had the best performance of the 11 refrigerants evaluated.
- Other studies [6,7,8,9] suggest that when heat transfer fluids exchange heat with a refrigerant mixture in a counterflow mode, the thermodynamic irreversibilities could be reduced by matching the temperature glide on the refrigerant side against the drop in the air side. This will result in an improved efficiency or COP for heat pumps and air conditioners. Other advantages of NARMs include capacity control and increased capacity at lower ambient temperatures.
- Pannock and Didion [3] performed a set of simulations followed by tests using chlorine-free refrigerant mixtures on a mini-breadboard heat pump system. They found that two refrigerant mixtures, R-32/R-134a and R-32/R-152a, performed better than R-22 for certain composition ranges using counterflow heat exchangers.
- Shiflett, Yokozeki, and Bivens [10] conducted "drop-in" tests of a 32/68% mass ratio blend of R-32/R-134a in a room air conditioner. The test results showed comparable capacity and efficiency to R-22. They also concluded that R-32/R-134a mixtures with less than 25% R-32 by mass are non-flammable for almost all conditions.
- Treadwell [11] performed laboratory tests using Propane (R-290) and found that by increasing compressor displacement it was possible to attain capacities and efficiencies similar to that of R-22.
- The Air Conditioning and Refrigeration Institute (ARI) [12], in consultation with various equipment and refriger-

ant manufacturers, has identified a set of 10 refrigerants that the member companies will screen as potential R-22 replacements (Table 3).

Table 3: ARI Recommended List of Potential R-22 Replacements

Refrigerant	% Composition By Weight
R-32/R-125	60/40
R-32/R-134a	30/70
R-32/R-125/R-134a	10/70/20
R-290 (Propane)	--
R-134a	--
R-717 (Ammonia)	--
R-32/R-125/R-134a/R-290	20/55/20/5
R-32/R-125/R-134a	30/10/60
R-125/R-143a	45/55
R-125/R-143a/R-134a	40/45/15

TESTING DETAILS

- Tests were conducted for the U.S. EPA, at the facilities of ETL Testing Laboratories in Cortland, NY. To verify the tests conducted at ETL, similar tests were conducted at Lennox Industries in Dallas, TX.
- All tests were conducted in accordance with the ARI Standard 210/240 and ASHRAE Standards 37-1988 and 116-1989 for testing unitary equipment [13,14,15].
- A 2-ton split-system air conditioner manufactured by Lennox Industries with a rated Seasonal Energy Efficiency Ratio (SEER) of 10.25 was tested. Details of the condenser and evaporator section are given in Tables 4 and 5.

Table 4: Geometrical Specifications of Condenser Unit

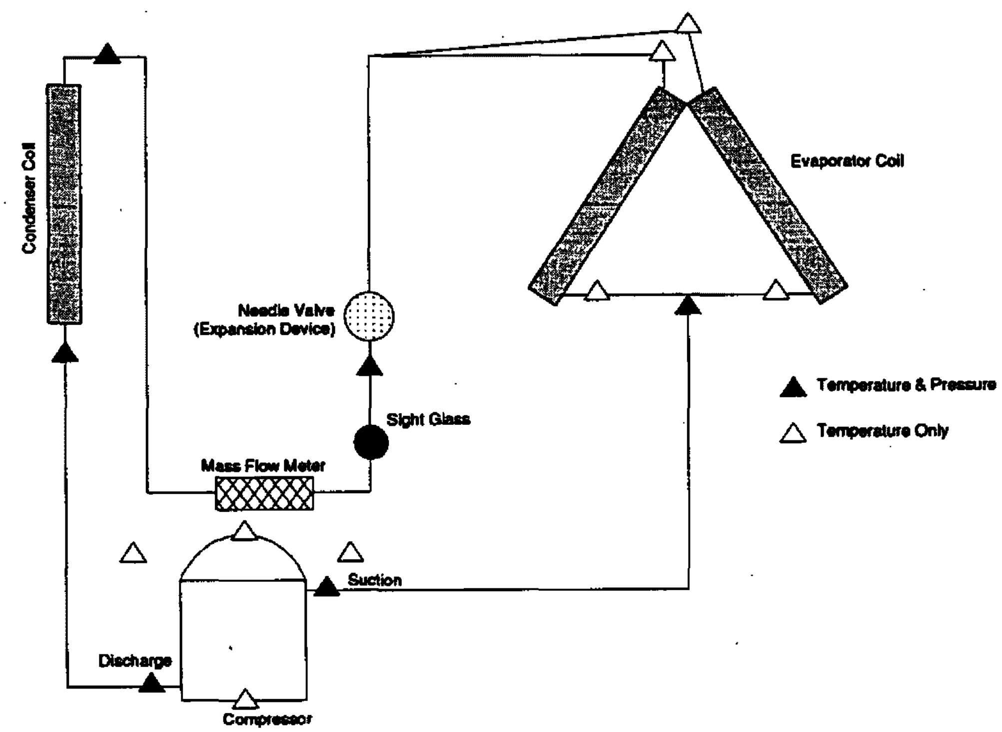
Manufacturer	Lennox Industries
Face Area	12.60 ft^2
Tube Diameter	0.375 inches
No. of Tube Rows	1
Tube Material	Copper
Fins Per Inch	20
Fin Type	Enhanced, rippled aluminum
Fan Specs	20 inch diameter, 3 Blades
Air Flow	2500 cfm
Fan RPM	850
Fan Power	200 watts
Fan Motor	1/6 HP
Compressor	Copeland CR22K6-PFV

Table 5: Geometric Specifications of Evaporator Coil

Manufacturer	Lennox Industries
Coil Type	A Coil (or V Coil) with 2 slabs
Face Area	3.44 ft^2 (1.72 ft^2 per slab)
Tube Diameter	0.375 inches
No. of Tube Rows	2
Tube Material	Copper
Fins Per Inch	15
Fin Type	Enhanced, rippled aluminum

- No hardware changes were made except for the use of a non-production hand-operated expansion device. This allowed for a "drop-in" comparison of the refrigerant blends.
- The following parameters were measured:
  1. System Capacity—as measured on the evaporator coil
  2. Power Consumption—Compressor and Fan
  3. System Efficiency—EER and SEER
  4. Refrigerant Pressures and Temperatures
  5. Refrigerant Mass Flow Rate
  6. Airside and Refrigerant Side Energy Balances
- Figure 2 is a test schematic showing the test setup and locations of thermocouple and pressure tap locations, along with other instrumentation such as mass flow meter and hand-operated expansion device.
- A hand-operated needle valve was used as the expansion device to allow for a continuous control over the level of refrigerant expansion.

Figure 2: Schematic of Test Configuration



- Thermodynamic properties for the refrigerant blends used were based on a modified version of REFPROP 3.0, which includes data on R-32 and R-32 mixtures.
- The original mineral oil lubricant used with R-22 is not compatible with R-134a. Therefore, a polyol ester-based lubricant developed for use with R-134a was used with the R-32/R-134a blends. Flushing of the system was performed to ensure that minimal traces of the original lubricant were present. The same polyester lubricant was used with the R-32/R-134a blends was used with the R-32/R-152a blends.
- The amount of refrigerant charge was based on a 15°F superheat setting at the compressor suction. The charge was adjusted to attain the best EER at the "80/67-95" test condition. In order to maintain consistency, the same superheat setting was used for all the blends.
- The same test facilities, instrumentation, and test personnel were used for all the tests. This minimized any uncertainty and inaccuracy in the measurements.

RESULTS AND DISCUSSIONS

PERFORMANCE RESULTS

- Capacity, power, EER, and SEER for each refrigerant tested are summarized in Tables 6 and 7.
- The results show that only the 40/60% R-32/R-134a blend had better performance than the R-22 baseline. In all other cases, the EER values were all within 2% of the R-22 baseline.
- The capacities of the other blends were less than the R-22 baseline and it is expected that with appropriate hardware changes and optimization, performance can be improved.
- The energy balance between the refrigerant side and the airside were typically within 5% of one another. All references to capacity are based on air side measurements.
- The results obtained from the ETL and Lennox tests are within 3 to 5% of each other. This range is well within expected range of experimental error considering that the tests were conducted on different test units in different test facilities.

Table 6: Summary of ETL Results

(All Percentage Compositions Are by Mass)

DOE "A" Test (80/67-95)	R-22	R-32/R-134a Mixture			R-32/R-152a Mixture	
	(Baseline)	20/80%	30/70%	40/60%	30/70%	40/60%
Airside Capacity (Btuh)	23690	20610	22390	23870	20630	21550
Total Power (W)	2489	2179	2345	2498	2152	2297
EER (Btuh/W)	9.52	9.46	9.55	9.56	9.59	9.38
Comp Disch Pressure (psig)	260.5	221	250	276	209	231.5
Comp Suct Pressure (psig)	81	62.5	71	79.5	60	66
Comp Disch Temperature (F)	185.5	169	175	181	186	190
Comp Suct Temperature (F)	63	65	64	63	68.5	66.5

DOE "B" Test (80/67-82)	R-22	R-32/R-134a Mixture			R-32/R-152a Mixture	
	(Baseline)	20/80%	30/70%	40/60%	30/70%	40/60%
Net Capacity (Btuh)	25320	22390	24210	25610	21250	23060
Total Power (W)	2319	2059	2195	2349	2009	2135
EER (Btuh/W)	10.92	10.87	11.03	10.90	10.58	10.80
Comp Disch Pressure (psig)	225	190.5	215	238	178.5	197
Comp Suct Pressure (psig)	77	60	68	75.5	57.5	63.5
Comp Disch Temperature (F)	170.5	156.5	162	167	171	174
Comp Suct Temperature (F)	59.5	62.5	62.5	60.5	66	64
SEER	10.10	9.80	9.90	10.00	9.58	9.89

Table 7: Summary of Lennox Results

(All Percentage Compositions Are by Mass)

DOE "A" Test (80/67-95)	R-22	R-32/R-134a Mixture			R-32/R-152a Mixture	
	(Baseline)	20/80%	30/70%	40/60%	30/70%	40/60%
Net Capacity (Btuh)	24134	21181	21996	23933	20522	22136
Total Power (W)	2468	2186	2342	2538	2174	2337.49
EER (Btuh/W)	9.78	9.69	9.39	9.43	9.44	9.47
Comp Disch Pressure (psig)	257	221.7	249	281	205.4	232
Comp Suct Pressure (psig)	76.6	60.8	70.3	79.6	58.9	66.3
Comp Disch Temperature (F)	183.6	167.3	174.5	181.8	182.5	189
Comp Suct Temperature (F)	60.5	62	63.5	62.8	66.8	66.8

DOE "B" Test (80/67-82)	R-22	R-32/R-134a Mixture			R-32/R-152a Mixture	
	(Baseline)	20/80%	30/70%	40/60%	30/70%	40/60%
Net Capacity (Btuh)	25543	22756	23795	26313	22231	23919
Total Power (W)	2319	2076	2230	2396	2049	2217
EER (Btuh/W)	11.01	10.96	10.67	10.98	10.85	10.79
Comp Disch Pressure (psig)	223	190	214	241.7	175.9	200.8
Comp Suct Pressure (psig)	74.4	59.6	676	76.3	56.9	64.8
Comp Disch Temperature (F)	155.1	160.7	160.7	168.6	169.1	174.4
Comp Suct Temperature (F)	59.5	62.7	61.6	61.1	65.7	66

SEER	10.16	10.08	9.68	10.24	10.00	9.94

NORMALIZED RESULTS

- Tables 8 and 9 present the data from ETL and Lennox normalized against the R-22 baseline. This allows for a more direct comparison of the results obtained in the different laboratories.
- The data shows that the capacities and power consumption decreased by the same percentage (except for the 40/60% R-32/R-134a blend). Hence, efficiencies remain effectively constant. This indicates that if a capacity boost could be achieved with an appropriate increase in power consumption, then results closer to the R-22 baseline could be achieved.

RETROFIT & NEW EQUIPMENT APPLICATIONS

- For the R-32/R-134a blends, 30/70 and 40/60% compositions appear to have good potential. Both capacities and efficiencies are within 5% of the R-22 system for both these blends. Since the seasonal efficiencies measured in the ETL tests are within 2% of one another (ETL results), it can be assumed that the use of these blends will have a minimal impact on SEER. This can be achieved with minimum hardware changes and forms the basis of a good retrofit refrigerant.
- Simulations indicate that the R-152a blends have a high performance potential and it is expected that with appropriate hardware changes in the compressor, heat exchanger, and expansion devices, and other system optimization, it may be possible to achieve higher capacity and efficiency levels than were measured in these tests.

Table 8: Performance Relative to R-22: ETL Results

(All Percentage Compositions Are by Mass)

	R-22	R-32/R-134a Mixture			R-32/R-152a Mixture	
DOE "A" Test (80/67-95)	(Baseline)	20/80%	30/70%	40/60%	30/70%	40/60%
Net Capacity (Btuh)	1.000	0.870	0.945	1.008	0.871	0.910
Total Power (W)	1.000	0.875	0.942	1.004	0.865	0.923
EER (Btuh/W)	1.000	0.994	1.003	1.004	1.007	0.986

	R-22	R-32/R-134a Mixture			R-32/R-152a Mixture	
DOE "B" Test (80/67-82)	(Baseline)	20/80%	30/70%	40/60%	30/70%	40/60%
Net Capacity (Btuh)	1.000	0.884	0.956	1.011	0.839	0.911
Total Power (W)	1.000	0.888	0.947	1.013	0.866	0.921
EER (Btuh/W)	1.000	0.996	1.010	0.999	0.969	0.989

SEER	1.000	0.970	0.980	0.990	0.949	0.979

Table 9: Performance Relative to R-22: Lennox Tests

(All Percentage Compositions Are by Mass)

DOE "A" Test (80/67-95)	R-22	R-32/R-134a Mixture			R-32/R-152a Mixture	
	(Baseline)	20/80%	30/70%	40/60%	30/70%	40/60%
Net Capacity (Btuh)	1.000	0.878	0.911	0.992	0.850	0.917
Total Power (W)	1.000	0.886	0.949	1.028	0.881	0.947
EER (Btuh/W)	1.000	0.991	0.960	0.964	0.965	0.968

DOE "B" Test (80/67-82)	R-22	R-32/R-134a Mixture			R-32/R-152a Mixture	
	(Baseline)	20/80%	30/70%	40/60%	30/70%	40/60%
Net Capacity (Btuh)	1.000	0.891	0.932	1.030	0.870	0.936
Total Power (W)	1.000	0.895	0.962	1.033	0.884	0.956
EER (Btuh/W)	1.000	0.995	0.969	0.997	0.985	0.980
SEER	1.000	0.992	0.953	1.008	0.984	0.978

REFRIGERANT CHARGE

- Tables 10 and 11 show the amount of refrigerant charge and mass flow rates measured in the tests.

Table 10: Amount of Refrigerant Charged/Reclaimed (ETL Tests)

Refrigerant	Ratio (% Mass)	Charge Amt (lbs-oz)	Reclaim Amt (lbs-oz)
R-22	—	4 - 05	4 - 05
R-32/R-134a	20/80	4 - 12	4 - 08
R-32/R-134a	30/70	4 - 05	4 - 02
R-32/R-134a	40/60	4 - 05	4 - 04
R-32/R-152a	30/70	3 - 05	3 - 03
R-32/R-152a	40/60	3 - 12	not measured

Table 11: Refrigerant Mass Flow Rates ("80/67-95 Condition")

Refrigerant Blend	Mass Ratio	Mass Flow Rate (Lb / Hr)	
		ETL	Lennox
R-22	—	375	352
R-32/R-134a	20/80%	291	295
R-32/R-134a	30/70%	302	300
R-32/R-134a	40/60%	305	305
R-32/R-152a	30/70%	196	206
R-32/R-152a	40/60%	212	219

COMPARISONS WITH SIMULATIONS AND BREADBOARD TESTS

- Table 12 and Figures 3 and 4 compare the simulation and breadboard testing conducted at the University of Maryland and the NIST to the "drop-in" results. The simulations predict that the refrigerant blends tested differently. There are several reasons for the difference in results.
- Counterflow heat exchangers were used in simulations and NIST test rig to better utilize temperature glide of the refrigerant mixture. The system tested at ETL was a standard production unit and had crossflow heat exchangers which could have impacted the performance.
- The breadboard test used water to refrigerant heat exchangers to obtain a constant capacity and the associated impact on the energy efficiency. In an actual operating system, the heat exchangers are air-to-refrigerant type and capacity is not easily controlled.
- Simulations assumed minimal subcooling and superheat since thermodynamically, these would be desirable. Practically, this could lead to incomplete condensation and evaporation. The EPA tests had 15°F superheat and 5-10°F subcooling, which could impact performance.
- Coefficients used for thermodynamic properties used in the University of Maryland simulations differed from the EPA tests.
- Better performance from the refrigerant blends tested is expected with further optimization such as optimum superheat settings, counterflow heat exchangers, and better transport and thermophysical properties of refrigerant blends.

Table 12: Comparison of Experimental and Simulation Results

(Simulation Data from Radermacher & Jung [4], Experimental Data from ETL)

ARI "A" Test Conditions

Refrigerant	% Change in Capacity		% Change in COP	
	Test	Simulation	Test	Simulation
R-22	Base	Base	Base	Base
R-32/R-134a (20/80 Mix)	-13	-10	-0.5	+5
R-32/R-134a (30/70 Mix)	-5	+2	+0.5	+6
R-32/R-134a (40/60 Mix)	+1	+13	+0.5	+6
R-32/R-152a (30/70 Mix)	-12	-9	+1	+12
R-32/R-152a (40/60 Mix)	-9	+2	-1.5	+12

Figure 3: Comparison of Capacity (ARI "A" Test Condition)

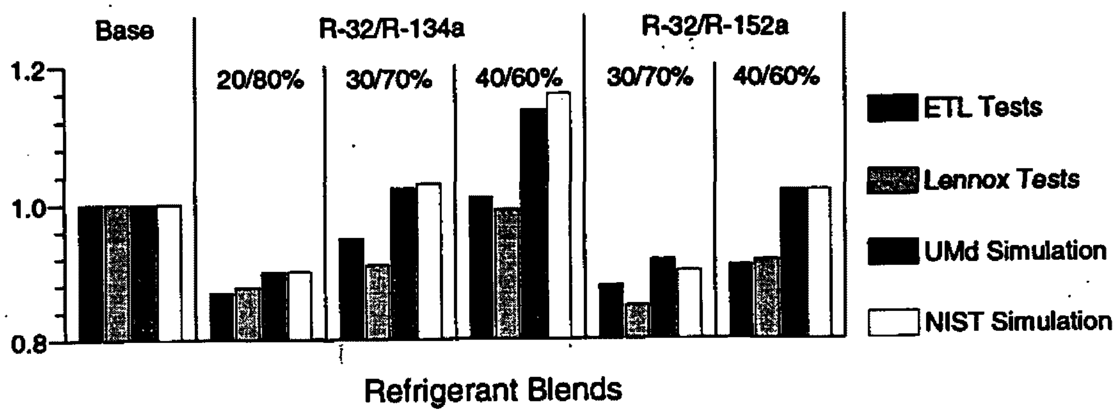
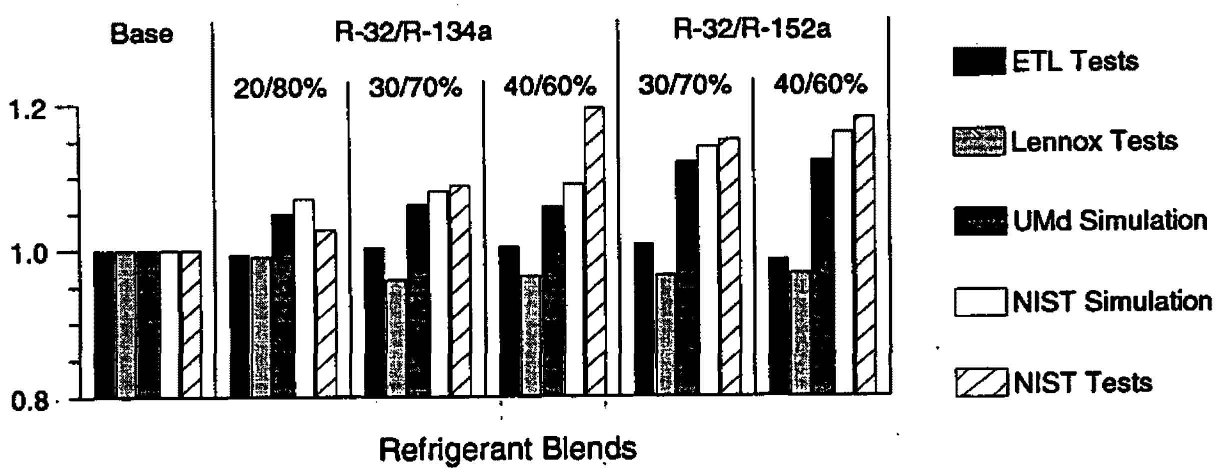


Figure 4: Comparison of COP (ARI "A" Test Condition)



CONCLUSIONS AND FURTHER WORK

- R-32 based refrigerant mixtures have been shown to be promising potential R-22 replacements in a split-system air conditioner. These tests were conducted in accordance with the ARI Rating Conditions and parameters measured included capacity, efficiency, and seasonal efficiency.
- The tests demonstrate that these refrigerants can achieve comparable performance levels to that of existing R-22 systems. With additional work and optimization, it should be possible to improve the performance levels beyond that of R-22.
- While the results of this test program are encouraging, considerable work is needed to better evaluate these alternatives. The following further work is recommended:
  - a. Use of Counter Flow Heat Exchangers to optimize performance of blends with temperature glide.
  - b. Optimize Charge, Superheat, and Sub Cooling levels
  - c. Use larger capacity compressors to make up capacity shortfall—experimental verification needs to be done.
  - d. Investigate the use of chemical additives to R-22 based lubricants for compatibility with new blends
  - e. Conduct Heating Tests on heat pumps
  - f. Conduct Composition Shifts Study for optimization in heating and cooling
  - g. Investigate Accumulators and Reversing Valve Dynamics
  - h. Study Compressor Life and Materials Compatibility
  - i. Study Flammability Aspects including Risk Analysis
  - j. Investigate Serviceability Issues

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