SAE Alternate Refrigerant Cooperative Research Project Phase I

March 2004

Project Objective

Provide a directly comparative engineering evaluation of the existing HFC-134a systems and other refrigerant technologies.

Organization

Three core groups interfaced with vehicle and A/C system manufacturers

- USA Core-USA manufacturers
- JAMA-Asian manufacturers
- VDA-European manufacturers

Project Overview

- SAE Alternate Refrigerant Cooperative Research Program
- Independent Laboratory Evaluation of four alternatives
    - R134a Baseline System representative of that used in a current production mid-sized passenger car
    - R744 System representative of the current state of development for R744 systems in 2001
    - R134a Enhanced System representative of next generation R134a system components
    - R290 Hydrocarbon Secondary Cooling Loop
    - R744 System representative of the current state of development for R744 systems in mid-2002
- Test schedule developed with industry input
- Detail test administration by representatives of four of the major OEM's
    - Two from USA, two from Europe
- Final System configurations were also chosen by this group from components submitted by suppliers

Introduction

The SAE Interior Climate Control Standards Committee established the Alternate Refrigerant Cooperative Research Program (ARCRP) in 2001. This is a part of the international automotive air conditioning industry's response to HFC-134a (R134a) being listed as a global warming gas in the Kyoto Protocol. Through the auspices of the SAE Strategic Alliance (SSA), the SAE Interior Climate Control Standards Committee selected the Air Conditioning and Refrigeration Center at the University of Illinois at Urbana-Champaign to conduct a series of mobile air conditioning system performance tests.

The purpose of the ARCRP was to investigate the performance and efficiency of automotive refrigeration systems with alternate refrigerant cycles. The program provides a directly comparative engineering evaluation of the existing R134a system and other refrigerant system technologies as described in this report.

Project Sponsors

The Alternate Refrigerant Cooperative Research Program was funded by a consortium of 25 industry stakeholders, including vehicle manufacturers, air conditioning suppliers, and governmental agencies. The program established a test procedure for evaluation of different mobile air conditioning refrigerant system technologies.

Background

Under the guidance of the SAE Cooperative Research Program industry shared the cost to provide a comparable technical evaluation of alternate refrigerant systems at a minimum cost. Testing new technologies in a cooperative effort of this nature affords the opportunity for all vehicle makers and system suppliers to learn more about potential future systems in a focused effort supported by industry stakeholders.

When installed in a vehicle, the A/C system consumes energy over the life of the vehicle resulting in carbon dioxide tail pipe emissions. These emissions are caused by the impact of the total mass of the A/C system as carried on the vehicle, the system electrical requirements for controls and airflow, and energy to drive the compressor. This study only addresses the indirect emissions caused by the energy to drive the compressor and refrigerant system. Direct emissions caused by refrigerant leakage and/or release of the refrigerant to the atmosphere also occur and are not included in this study. Some of the alternate refrigerants evaluated in this report will nearly eliminate the direct emissions impact to the environment.

Since alternative refrigerant options for mobile air conditioning systems have shown suitable occupant comfort (SAE Phoenix Forums), this test program focuses on the comparative performance and energy use of these systems. This development test program and comparable results are expected to provide data to aid the industry decision-making process for future mobile air conditioning systems.

Project History

The original test program was submitted for consideration during the July 2000 Phoenix Alternate Refrigerant Symposium. A revised test matrix was submitted after the November 2000 Interior Climate Control Standards Committee Washington meeting. After input from industry representatives, the test matrix was agreed upon in April 2001. A specific set of test parameters were run for comparison and the results identified system performance and energy requirements on a common engineering basis. This is the first global industry directed system comparison done by an objective and independent laboratory.

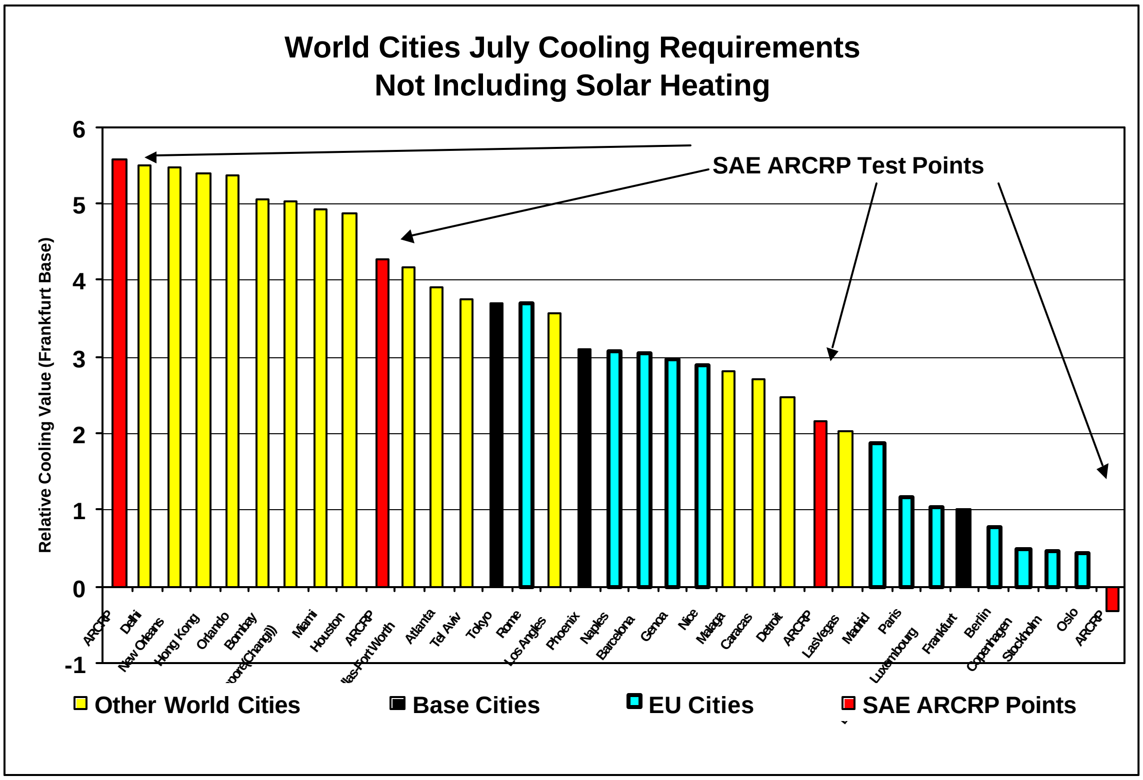
The test cycles reflect vehicle users demands for hot climate conditions as well as middle and low ambient load conditions. The test conditions cover an estimated average load profile on these systems might allow comparison of the system COP for estimated annual supplemental power consumption for a typical vehicle air conditioning system on a typical driving cycle and typical climate conditions.

The four test load conditions were selected to represent expected cooling requirements for mobile air conditioning systems in various parts of the world.

Since vehicle manufacturers export vehicles throughout the world, so it is important that the cooling system provide the performance expected by the consumer under a wide range of conditions. Vehicles that can be driven over a wide range of climatic conditions must meet consumer's needs.

Relative Cooling Value

Relative Cooling Value (RCV) is a comparative measure and, simply stated, is the relative difference in the enthalpy of ambient air and the enthalpy of the passenger cabin air at comfort (75F - 24C / 33% RH). This is the imposed cooling workload on the A/C system required to provide comfort, excluding solar load, within the vehicle passenger compartment. The information found in the following graph compares the "Relative Cooling Value" (no solar load) for the month of July for many world cities and ARCRP test points. The four ARCRP test points reflect the worldwide system loads that mobile air conditioning systems will encounter.



RCV - ARCRP Test Points - World Cities

Overall comments/conclusions from Expert Team:

- This first independent lab cooperative test program has produced results for a valid comparison of alternative refrigerant systems. Automotive components tested were constructed for use with each refrigerant.
- The test facilities/methods used should become a standard for future evaluations of this nature.
- The components evaluated were the best that were offered to the Expert Team for evaluation prior to the beginning of each test sequence. The components may not be fully optimized as a refrigerant system in a vehicle.
- Vehicle system controls will not always be optimized for both COP and capacity. This may result in compromises in both COP and capacity values. Systems utilizing electronic controls give the ability to better optimize COP and capacity values. Capacity may be more important than COP at high ambient conditions. Optimization for only COP or capacity affects vehicle emissions of grams of CO_2 per km.
- The face area of the heat exchangers tested was above the average size in current production vehicles. The condenser/gas cooler was 25% and the evaporator/cooling core was 10% above the average. This was less beneficial to the R744 system when operating at high loads and more beneficial for the other systems evaluated.
- The five systems were compared under identical, but idealized conditions. Real world vehicle results will be different, but significant trends should be similar.
- Based upon this available information from this data and extrapolated projections, the expert team has reached consensus on a calculation to analyze energy consumption of each system over various drive cycles.
- Compressor RPM's, based upon engines and drive ratios, have a major affect on system efficiency. Compressors may run at higher speed as compared the test program in vehicle usage. The compressor RPM may affect the comparison of system efficiencies.
- Many of these factors have been adjusted in Phase II of the ARCRP.

Overview of Project

After the completion of the Phase I ARCRP it was determined that a Phase II project should be conducted to address certain issues that were identified in this program.

- Phase I activity used a condenser size having a greater surface than currently used on the average vehicle. Phase II activity will utilize condenser and evaporator surfaces typical of an average vehicle in 2002-2003 production. [Graph I and II]

- It was also determined that during high load operation, after initial soak and cooldown, that typical system loads did not recognize the system would be operated on recirculated air conditions rather than the outside air ambient load for thermal comfort. Phase II conditions were modified to address this issue.

- Calculations for energy consumption over various drive cycles had to be established with extrapolated data due to the limited compressor speed data points. The Phase II ARCRP has included a fourth, higher compressor speed to allow additional data for calculation of energy consumption for the different drive cycles. This new data may reflect a change in actual air conditioning energy consumption.

Summary Results

Stabilized Efficiency and Capacity tests:

[Note: the expert team chose different load conditions to compare each]

For system capacity higher ambient conditions are most important for occupant comfort. The systems are compared at maximum capacity at 45, 35 and 25ºC.

Summary of System Capacity (kW) at MAXIMUM capacity

Evaporator	**45°C x 27%**	**45°C x 27%**	**35°C x 45%**	**35°C x 45%**	**25°C x 80% +**	**25°C x 80% +**
Condenser	60ºC	45ºC	50ºC	35ºC	40ºC	25ºC
Speed	900	2500	900	2500	900	2500
Baseline R134a	4.3	7.6	4.2	7.0	4.0	5.6
Enhanced R134a	4.6	8.5	4.7	8.1	4.5	5.8
2001 CO2	4.6	8.5*	4.7	9.4	4.7	6.0
Secondary Loop R290	4.5	8.3	4.5	8.1	4.6	5.6
2002 CO2	4.6	8.7	4.8	9.6	5.1	5.9

*Controlled capacity

+10ºC control setting

For annual energy analysis the moderate and lower ambient temperatures are more important because they have higher weighting factors. COP is presented at equal capacity for comparison at 35, 25 and 15°C.

Summary of COP at EQUAL capacity

Evaporator	**35°C x 45%**	**35°C x 45%**	**25°C x 80% +**	**25°C x 80% +**	**15°C x 80%**	**15°C x 80%**
Condenser	35°C	35°C	25°C	25°C	15°C	15°C
Speed	900	2500	900	2500	900	2500
Baseline R134a	3.4	1.9	3.8	2.8	4.4	3.8
Enhanced R134a	3.9	2.7	4.2	3.8	5.7	4.5
2001 CO2	3.1	2.6	3.5	3.6	5.6	4.5
Secondary Loop R290	2.5	2.0	2.7	2.8	4.0	3.5
2002 CO2	3.4	2.7	4.1	4.1	6.0	5.4

*Controlled capacity
+10°C control setting

Pilot 2002 CO_2 (R744) program

During the 2003 SAE Phoenix Alternate Refrigerant Symposium Pega Hrnjak made a presentation on the Design and Performance of Improved R-744 System Based on 2002 Technology. The Pilot 2002 working group undertook this project at the University of Illinois, outside of the ARCRP, to demonstrate next generation R744 system performance.

The sponsors of this activity requested that the results of the Pilot 2002 program be included in the SAE ARCRP report.

After the Expert Advisors reviewed the test results from the Pilot 2002 working group it was determined that not all of the test conditions specified in the ARCRP testing were run. Additional tests were funded by the working group and run to provide comparable data to the other ARCRP results.

The Pilot 2002 working group selected the CO_2 components. The evaporator face area was similar but depth was thinner as compared to that used in the previous ARCRP. The gas cooler face area was larger but depth was slightly thinner as compared to that used in the previous ARCRP.

Energy Analysis of Cycles

Air Conditioning is or is becoming a standard feature of cars. It improves driving alertness and climate comfort, but it also places a burden on the environment. While the transport related energy consumption of a car depends on mileage and driving style, the non-transport consumption, associated with the AC system, mainly depends on external climate conditions, individual preferences, and on the selected refrigerant cycle.

The purpose of ARCRP was, to investigate performance data of a production HFC-134a automotive refrigeration system with an enhanced HFC-134a refrigeration cycle and other alternate refrigerant systems. This comparison was also defined with the aim, to compare at the same capacity COP behavior, on hot climate, middle and low ambient load conditions at three compressor speeds.

Fuel consumption of the AC system is influenced by numerous parameters. Some of the main parameters are as follows:

- HVAC component efficiencies
- HVAC component masses
- Refrigeration circuit
- Vehicle type and vehicle use
- Powertrain type and efficiency

Further, most parameters have an impact on each other, which has not been fully studied here. For this reason, a reliable fuel consumption calculation model could not be provided. In order to evaluate the energy consumption for the use of a refrigerant circuit in vehicles, other parameters and assumptions have to be taken into account.

Based upon the available data the expert team has reached consensus on a calculation to analyze compressor energy consumption of each system over various drive cycles. The results are listed in the table.

Simulation results for energy [kJ] and mean compressor power [kW]

Vehicle Class	Mid-size		Full-size	
Drive cycle	NEDC [EU Combined]		US FTP 75	
Cycle Duration [s]	1180		2138	
System demand	Energy/ cycle [kJ]	mean compressor Power [kW]	Energy/ cycle [kJ]	mean compressor Power [kW]
Baseline R134a	699	0.59	1965	0.92
R744 2001	539	0.46	1530	0.72
Enhanced R134a	540	0.46	1517	0.71
R290 Secondary Loop	605	0.51	1808	0.84
R744_2002	487	0.41	1405	0.66

Climate and User model is from Visteon

Comparing to the Baseline R134a, Enhanced R134a and R744 (2001) show 23% less compressor power consumption. The R744 2002 shows a reduction of approx. 30% as compared to the baseline R134a system. The R290 secondary loop system's energy demand is influenced by the coolant pump energy consumption. For Europe climate conditions, having lower climate load, a mid-size vehicle, and higher compressor RPM's, the analysis provides a minor advantage for the R744. For the US, a small advantage occurs for enhanced R134a in the full size vehicle with lower engine RPM under higher thermal loads that are typical of Southern Europe and Asian countries.

The European and USA drive cycle temperatures for fuel consumption testing are performed at 24 - 26 degrees C but with AC turned off.

Below is a chart [from NREL presentation] that illustrates the differences in several drive cycles, including those used in the analysis above.

Drive Cycle	Time sec	Distance km	Max Spd km/h	Avg Spd km/h	Idle Time sec	Max Accel m/s^2
US06	600	13	129	77	45	3.8
SC03	600	6	88	35	117	2.3
FTP	2477	17.8	91	26	360	1.5
NEDC (Urban + ExtraUrban)	1184	11	120	33	298	1.1
J-1015	660	4	70	23	215	0.8

Comparison System Technologies Used in ARCRP

Component	R134a Baseline	2001 R744	R134a Enhanced	R290 Secondary Loop	2002 R744
Evaporator	Plate/fin	Micro-channel	Micro-channel	Brazed Plate	Micro-channel
Cooling Core	None	None	None	Plate fin	None
Condenser/gas cooler	Micro-channel	Micro-channel	Micro-channel Integrated Receiver/drier, Subcooling type	Micro-channel	Counter Cross flow micro-channel
Compressor	Variable swash plate	Variable swash plate	Variable swash plate	Variable swash plate	Variable swash plate
Compressor Control	External PW/M	External PW/M	External PW/M	External PW/M Cycling	External PW/M
Refrigerant Storage	Separate High Pressure Receiver	Separate low Pressure {accumulator}	See Condenser	Separate low Pressure {accumulator}	Special Laboratory Test Component
Internal Heat Exchanger	None	Co axial in line	None	Co axial heat exchanger	Micro channel
Oil Separation	None	Built In Compressor	None	None	External separator [Special Laboratory]
Head Pressure Control	Not Applicable	Attempt to maximize COP	Not Applicable	Not Applicable	Attempt to maximize COP
Expansion Controls	Block Expansion Valve	Electronic stepper motor valve adapted for test stand control	Electronic stepper motor valve adapted for test stand control	Electronic stepper motor valve adapted for test stand control	Electronic stepper motor valve adapted for test stand control
Component Technology Level	2002 Production	2001 Prototype	2003/4 Production	2002 R134a and commercial water/glycol loop components	2002 Prototype

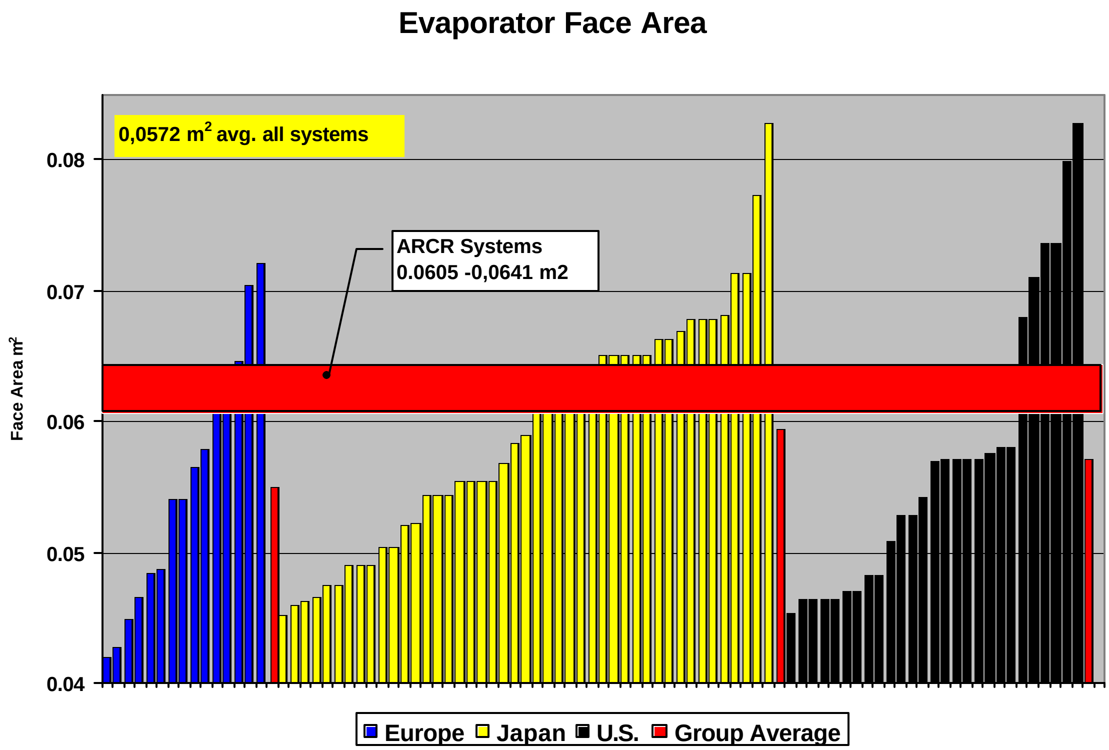
Component	Feature	R134a Baseline	R744 year 2001	R134a Enhanced	R290 secondary loop	R744 year2002
Condenser	Core effective face [mm]	W768xH400xD20	W689xH464xD16	W679xH465xD16	W768xH400xD20	Micro-channel W686xH476xD16
	Face area [mm^2]	307,200	319,696	315,735	307,200	326,536
	Core volume [mm^3]	6,144,000	5,115,136	5,051,760	6,144,000	5,224,576
	Aspect ratio [-]	0.52	0.67	0.68	0.52	0.69
	Mass [kg]	2.8	2.4	2.9*	2.8	3.6
Evaporator	Core effective face [mm]	W280xH216xD73	W306xH214xD58	W294xH216xD50	W283xH216xD73	Micro-channel W285xH230xD38
	Face area [mm^2]	60,480	65,484	63,504	61,128	65,550
	Core volume [mm^3]	4,415,040	3,798,072	3,175,200	4,462,344	2,490,900
	Aspect ratio [-]	0.77	0.70	0.73	0.76	0.81
	Mass [kg]	2.0	2.7	1.6	1.7	1.6
Compressor	Type	Variable swash-plate	Variable swash-plate	Variable swash-plate	Variable swash-plate	Variable swash-plate
	Displacement [cc]	~165	~33	~165	~165	~31
	Mass (including pulley) [kg]	6.4	7.0	6.4	6.7	7.0
SLHX	Length [mm]	Not applicable	2100	Not applicable	320	Micro-channel 750
	Mass [kg]		1.1		1.0	1.4
Receiver/Drier	Volume [cc]					Special laboratory test high pressure vessel with integrated glass side walls, oil/refrigerant return with manual valve[LV]
	Mass [kg]	0.4	1.4	IRD, see condenser	2.1	over 10kg
Oil Separator	Volume [cc]	Not applicable		Not applicable	Not applicable	
	Mass [kg]		0.1			1.2
Water pump (R290)	[kg]	Not applicable	Not applicable	Not applicable	2.2 (two pumps)	Not applicable
Chiller (R290)	[kg]	Not applicable	Not applicable	Not applicable	2.2	Not applicable
Total Mass	[kg]	**11.6**	**14.7**	**10.9***	**18.7**	**16.2****
Note:				*R134a enhanced condenser mass Includes IRD (Integrated Receiver/Drier)		**Receeiver/Drier Mass 1.4 kg [2001 year system] is included in Total mass

System Technologies Notes:

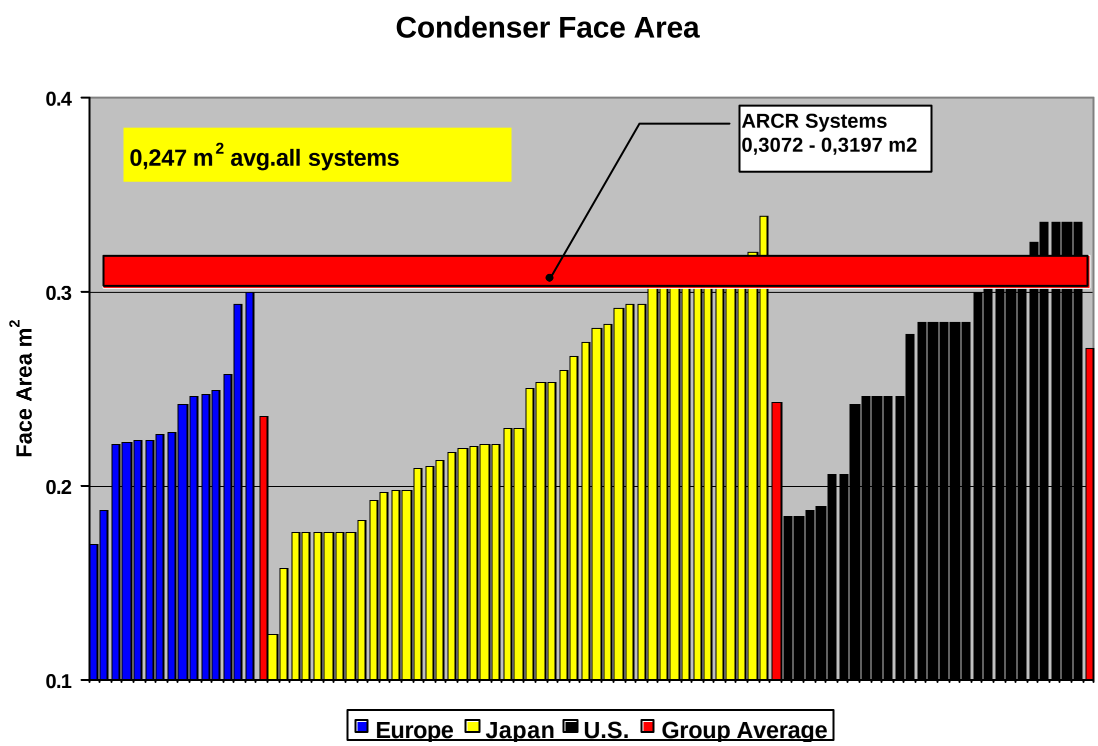
Note 1: The Enhanced R134a evaporator core was over sized and was partially covered to better match the other core face areas. The 2.9 kg mass would be less with the correct face area.

Note 2: Mass includes heat exchangers, compressor and refrigerant storage. Does not include refrigerant lines, fittings, valves or system controls or secondary loop coolant.

Note 3: Receiver/Drier mass. The R744 year 2002 system testing was conducted with a special laboratory high-pressure vessel that is not included in the Total Mass value. The R744 year 2002 system Total Mass value includes the receiver/drier mass of 1.4 kg identified in the R744 year 2001 system.



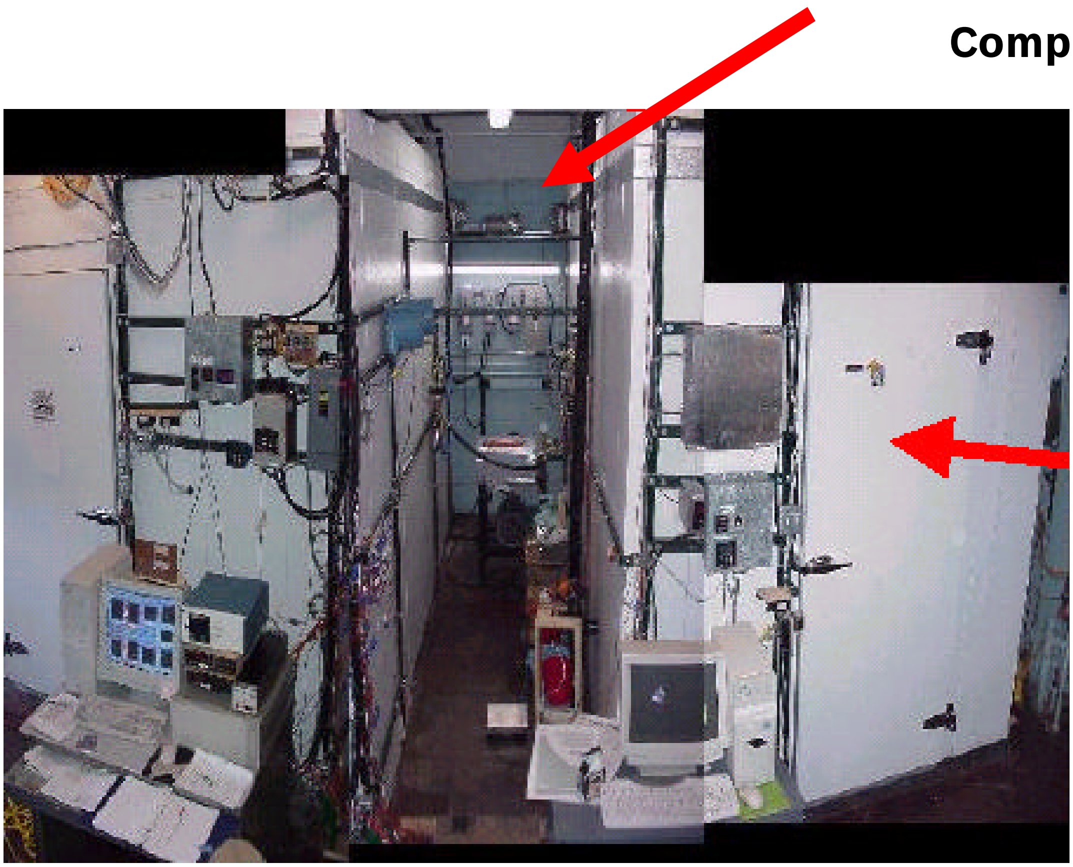
Comparison Evaporators Graph I



Comparison Condensers Graph II

SAE ARCRP
University of Illinois
Test Facility

Compressor Chamber



Condenser Chamber

Evaporator Chamber

Typical System Schematic