DRAFT REPORT

EVALUATION OF THE COOLBOT™ LOW-COST WALK-IN COOLER CONCEPT

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NOTICE

EXECUTIVE SUMMARY

Store it Cold, LLC has developed the COOLbot™ controller to allow a conventional room air conditioner to maintain a refrigerated cooler at temperatures approaching 32°F. The controller includes sensors and well as a small heating element that connects to the AC's space temperature sensor and "fools" the unit into running at these unusual conditions. The controller maintains the cooler at a specified set point and also determines when the unit needs to cycle off to defrost the evaporator coil.

Room AC units are highly-engineered products that typically use a rotary compressor with a built in suction line accumulator. Unlike larger air conditioners, room AC units include few safeties to shut down the unit at abnormal conditions. Instead, the units are designed to operate safely over a wide range of space and ambient conditions. We used the Heat Pump Design Model (HPDM) from Oak Ridge National Labs to simulate air conditioner performance over a wide range of conditions. The Simulation results confirmed that a room AC can in theory operate over the range of conditions expected in a COOLbot™ application.

The HPDM results were also used predict the energy use of a room AC in the Coolbot™ application and compare it to a conventional refrigeration system. The room AC was typically 16-22% less efficient than a conventional system. However, since the COOLbot™ approach with a room AC offers the potential for cycling fan control, its seasonal energy use is 200 to 500 kWh lower for a typical 100 square foot walk-in cooler.

The analysis showed that the quality of construction for the walk-in cooler significantly impacts seasonal energy use. A 100 square foot cooler at 35°F with leaky construction and R16 walls uses about 1500 kWh per season. The same cooler with more air-tight construction and R-30 insulation in the walls uses 25% less energy.

An analysis of greenhouse gas (GHG) emissions associated with food transportation and on-farm refrigeration showed that impact of on-farm produce refrigeration is likely to reduce net GHG emissions. A 100 square foot cooler, can hold 2 tons of produce that turns over 16 to 32 times per season; this can eliminate the need to transport 32 to 64 tons of produce from the farm to consumer. Assuming the truck must travel 200 or 400 miles, the CO_2 emissions impact of transporting this produce ranges from 3,500 to 14,000 lbs per season.

The COOLbot™ approach costs about $750 to install compared to $4,400 for a conventional refrigeration system. Therefore, the COOLbot™ approach not only offers energy savings but is also cheaper to install!

The COOLbot™ approach makes on-site refrigeration more accessible to farmers, resulting in more income and productivity. GHG emissions are decreased overall because less produce must be transported from farm to consumer. A single 100 square foot cooler displaces more than 600 gallons of diesel fuel per season that would otherwise be required for transporting food.

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1 Introduction

NYSERDA is currently working with Store It Cold, LLC to understand the technical, economic, and environmental potential of the COOLbot™ controller that enables farmers to build a low-cost walk-in cooler for storing produce and other food products (www.storeitcold.com). The controller allows a conventional room air conditioner (Room AC) to be used to maintain a walk-in cooler at temperatures as cold as 32°F. The controller manufacturer also provides extensive application guidance to enable a "do-it-yourself" customer to select the proper air conditioner and build a walk-in cooler from common materials.

The controller connects to the air conditioner without wiring modifications and includes built in defrost cycles to prevent the unit from freezing/frosting up.

This report evaluates the performance of this low cost walk-in cooler concept to determine its energy efficiency, durability, and lifecycle cost relative to conventional walk-in cooler/refrigeration system designs. It also evaluates the overall energy and environmental impacts (i.e., CO_2 emissions) of this technology by considering the potential for reduced transportation impacts by providing locally-grown and marketed produce.

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2 COOLbot™ System

2.1 Concept

The COOLbot™ controller essentially "fools" an air conditioner into operating at much lower indoor temperatures. The controller also tracks the amount of frost buildup on the coil and periodically stops AC operation allowing the coil to defrost. The concept provides a low-cost way to provide on-farm refrigeration down to 32°F. While Room AC units were not designed to operate at these conditions, the characteristics of these highly-engineered products allow them to successfully operate at these off-design conditions.

2.2 The Controller

The COOLbot™ controller is installed inside the cooler near the Room AC. The microprocessor-based controller unit includes three remote probes/sensors:

1. a room temperature sensor,
2. a defrost sensor that is placed next to the evaporator coil fins (on the outlet side),
3. a small heater element that attaches to the sensor bulb from the air conditioner that normally senses space conditions. This small heater is activated to make the AC run, and deactivated to stop cooling operation.

The controller maintains the cooler set point and controls the defrost initiation and termination settings. The human interface includes three buttons and LCD display.

Figure 1. Photo of COOLbot™ Controller

2.3 Walk-in Coolers at Khosla Farm

Two site-constructed coolers at the Khosla Farm were blower door tested to determine leakage and air infiltration rates. The test data are given in Appendix A. The thermal and leakage performance characteristics of the two coolers are summarized in the table below.

Table 1. Construction of Walk-in Coolers at Khosla Farm in New Paltz, NY

	Green Standalone	**Metal-Skinned Pole barn**
Dimensions (ft)	10 x 16 x 8	11 x 7 x 7.66
Floor Area (ft^2)	166	74
Volume (ft^3)	1330	565
ACH @ 50 Pa	10.5	18.3
Equivalent Leakage Area (in^2)	15	10
ELA per 100 ft^2 Surface Area	1.9	2.7
Foam Thickness (in)	9.5 Expanded Polystyrene	4 Polyisocyanate
Estimated R-value	R-40	R-24

Figure 2. Photos of Green Standalone Cooler

Figure 3. Photos of Metal-skinned Cooler Built Inside Pole Barn

2.4 Room Air Conditioner Performance at Off-Design

The COOLbot™ controller has been applied in hundred's of applications with a conventional room air conditioner. Practical experiences have demonstrated that most Room AC units work well in this application, though some work better than others (see Appendix B and the www.storeitcold.com web site).

In order to understand at the performance of a room air conditioner at these conditions, we used the Heat Pump Design Model (HPDM) from Oak Ridge National Laboratory. This web-based air conditioner model explicitly models the performance of an air conditioner at any operating condition. The results of this theoretical analysis are given in Appendix C. We used the default data for a 2.5 ton air conditioner with a reciprocating compressor and capillary expansion device. A full performance map was developed to understand the relative performance variations at off-design conditions compared to the nominal performance (80°F DB / 67°F WB indoors; 95°F outdoors). The results showed that the unit is capable of operating over a range of low temperature and low ambient conditions. The model does predict some degree of liquid flooding back to the compressor, though the built in accumulator (see Appendix B) appears to mitigate any compressor damage or other problems. The rotary compressor – which is used on virtually all Room AC units under 18,000 Btu/h – is also apparently able to operate at a low pressure difference (and high volume flow) conditions.

Generally room AC units have few safeties built in into the unit (such as low pressure, high pressure, and high temperature limits). The main safety function that most units typically have is over-current protection. Store it Cold LLC reports that some compressors have trouble tripping out at low ambient conditions – i.e. when the high-to-low pressure difference is small and the refrigerant volume flow rate is high. This is exactly the operating condition that leads to a high compressor current. The LG AC units apparently have more tolerant settings for the over-current which allows the units to operate over a wider range conditions. The rotary compressor with built in accumulator is able to reliably operate with some refrigerant flood back and at low lift conditions.

3 Energy Use Analysis

3.1 Overall Approach

A simple hour-by-hour model of a walk-in cooler was developed to compare the energy performance of the COOLbot™ concept to a conventional refrigeration system. The loads on the cooler were modeled with a simple conduction model and an infiltration model (based on the Sherman and Grimsrud method) that calculates the infiltration rate for each hour using the ambient temperature and wind speed from a TMY file.

3.2 Assumed Loads

Table 2 summarizes the range of load conditions that were used in the analysis. The cooler loads are calculated using the "UA" for the cooler (including the floor area) based on the R-value. The infiltration is calculated from the Equivalent Leakage Area (ELA). Figure 1 shows the range of infiltration rates (air changes per hour) that result based on the hourly temperatures and wind speed for Albany with two different levels of leakage. We also added two different door openings for each day into the ventilation calculations (30-minutes and 4 hours at 2 ACH). Three different cooler temperatures were considered. The latent (or moisture) portion of the infiltration load is determined for the each hour assuming and indoor humidity is 90% RH. The cooler is periodically stocked with new produce. We assumed 1400 lbs of product is added each day and must cooled from ambient conditions down to the cooler temperature. The product is assumed a have a specific heat corresponding to 75% water content (0.8 Btu/lb-°F). The analysis only looked at summer operation.

Table 2. Cooler Load Assumptions

Floor Area (ft^2)	100 & 250
R-value	16, 24 & 30
ELA per Surface Area (in^2 per 100 ft^2)	2 & 4
Climates	Albany, New York, Atlanta, Washington (June through October only)
Operating Temperature (°F)	35, 41 & 50

Other assumptions:
Space RH at 90% RH; doorway is open 0.5 or 4 hours each day (ACH=2.0 when open)
Infiltration calculations assumes terrain with heavy shielding

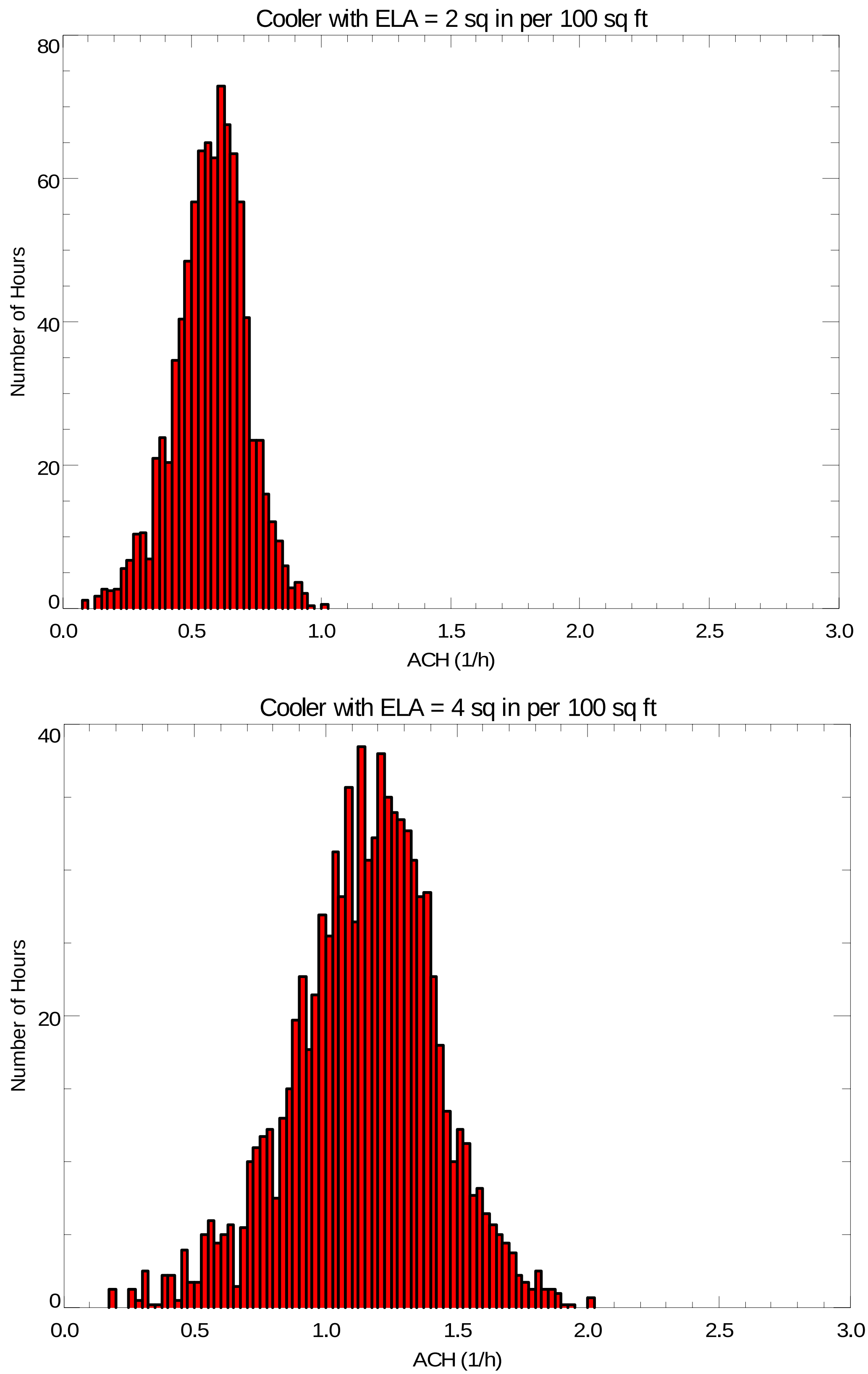


Figure 4. Air Change Rate During Cooling Season in Albany, Two Different Leakage Rates (100 sq ft cooler)

3.3 Assumed Equipment Performance

The loads on the cooler were met with two different systems:

1. A conventional refrigeration system with performance characteristics similar to a Carlyle 06D compressor (see Table 3),
2. An LG room AC unit with a nominal EER of 9.8 Btu/Wh (see Table 4)

The model for the conventional system is based on the compressor curves (i.e., ARI 10-coefficient curves for power and capacity). Saturated condenser and evaporator temperatures were determined using the rules in Table 3. Fan power was also added in the calculations to determine overall efficiency.

Table 3. Conventional Refrigeration Unit

Compressor	Carlyle 06DR820 (reciprocating)
EER	8.7 Btu/Wh (at 15°F suction and 110°F condensing)
Fan Power	0.200 kW/ton, condenser fans 0.144 kW/ton, evap fans
Saturated Suction	20°F lower than space temperature
Saturated Discharge	15°F higher than ambient (never below 80°F)

The performance of the room AC at different operating conditions was determined by curve-fitting the simulation results from the Heat Pump Design Model (HPDM) from Oak Ridge National Laboratory (see Appendix C). Generic, dimensionless curves were developed to predict off-design efficiency and capacity based on the nominal performance at 80°F/67°F indoors and 95°F outdoors. Table 4 summarizes the nominal performance for the LG room Air conditioner (i.e., the unit recommended for use with the COOLbot™ controller).

Table 4. Room Air Conditioner Nominal Performance

Manufacturer	LG
EER	Nominal = 9.8 Btu/Wh (at 80°F/67°F and 95°F ambient)
Capacity	10 MBtu/h (at 80°F/67°F and 95°F ambient)

Figure 5 compare the load calculated for 100 sq ft cooler at 35°F to the capacity curve for the LG air unit. The results show the LG 10 MBtu/h unit can meet maintain the cooler at 35°F for all but the warmest ambient temperatures (e.g., above 85°F). In reality it is likely that the 10 MBtu/h unit could maintain conditions close to 35°F even on the hottest days due to the thermal mass of produce stored in the cooler.

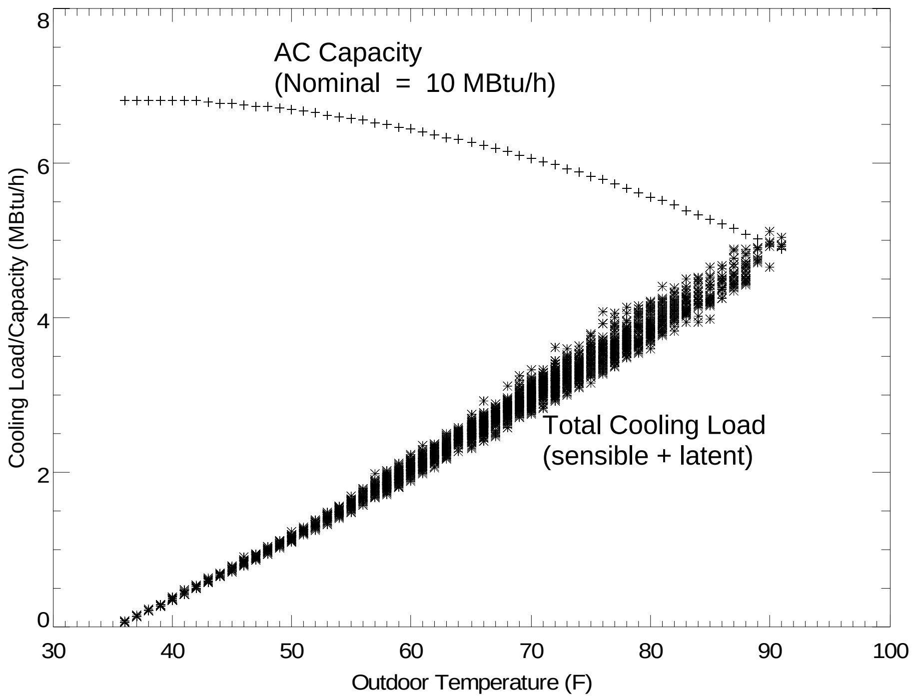


Figure 5. Comparing Load and AC Capacity (100 sq ft cooler, 35°F, ELA = 2 in^2 per 100 sq ft, R24)

Figure 6 compares the resulting EER (Btu/Wh) for the conventional refrigeration system and room AC over the range of outdoor temperatures. The conventional refrigeration system has constant efficiency below 65°F because the condenser fan controls maintain a minimum condensing pressure of 80°F. Over most conditions the conventional system is predicted to be more efficient than the room AC.

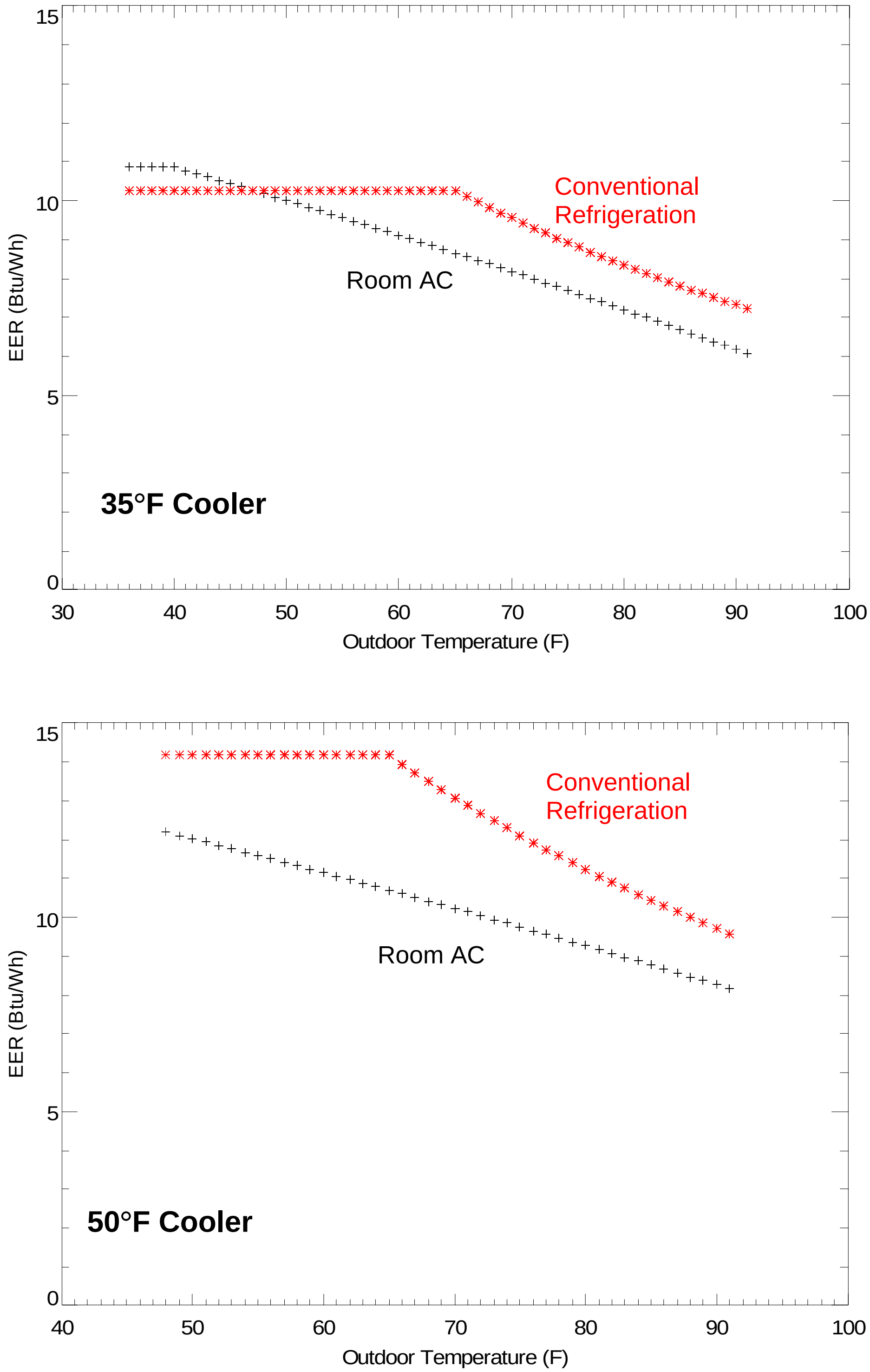


Figure 6. Comparing Efficiency of Room AC and Conventional Refrigeration (35°F and 50°F Cooler)

3.4 Predicted Energy Use

The results from the seasonal simulations are summarized in the tables and graphs below. Table 5 summarizes the results in each city for the two extremes:

- Small, efficient cooler (100 sq ft, ELA = 2, R-value = 30) at 50°F
- Large, leaky cooler (250 sq ft, ELA = 4, R-value = 16) at 35°F

The annual energy use increases by a factor of five between these extremes. The impact of lowering cooler temperature from 50°F to 35°F changes the energy use by a factor of two. The seasonal energy use in Atlanta is 50% bigger than in Albany. The efficiency penalty of the Room AC approach is 12-14% compared to the conventional refrigeration system at 35°F. The penalty increases to increases to 15-16% with a 50°F cooler temperature (see Figure 7). Over the range of conditions the Room AC approach increases energy use by 100-500 kWh over the season.

Table 5. Results for Cooler in Variation Cities at 35°F and 50°F – Cycling Evaporator Fans

					Energy Use (kWh)			Avg EER (Btu/Wh)		
City	Temperature (F)	Floor Area (ft^2)	R-Value	Leakage ELA	Conventional Refrig	Room AC	Energy Difference	Conventional Refrig	Room AC	EER Ratio
Albany.txt	50	100	30	2	399	474	(74)	11.75	9.9	84%
Albany.txt	35	250	16	4	2,123	2,419	(296)	9.19	8.07	88%
NewYork.txt	50	100	30	2	525	621	(96)	11.54	9.75	84%
NewYork.txt	35	250	16	4	2,614	3,003	(388)	8.99	7.83	87%
Atlanta.txt	50	100	30	2	660	777	(117)	11.21	9.52	85%
Atlanta.txt	35	250	16	4	3,078	3,556	(478)	8.73	7.56	87%
Sterling.txt	50	100	30	2	539	636	(96)	11.32	9.61	85%
Sterling.txt	35	250	16	4	2,628	3,024	(396)	8.87	7.71	87%

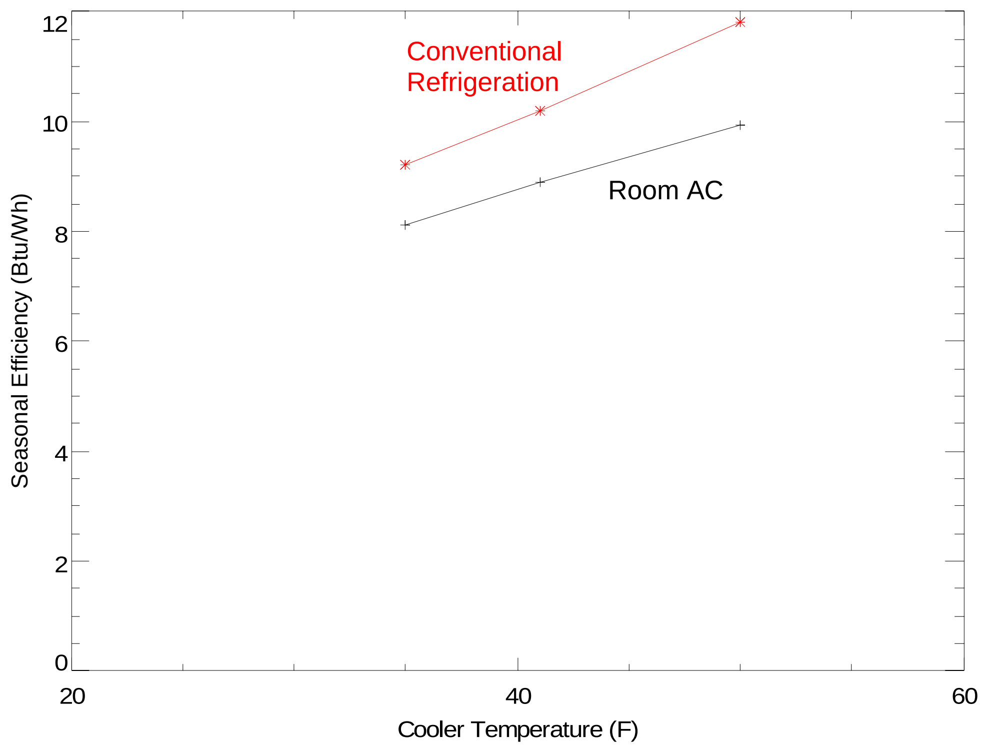


Figure 7. Comparing Overall Seasonal Efficiency for Refrigeration and Room AC (Albany, NY)

Table 5 above summarizes the results for the case of the evaporator fans cycling on an off with the refrigeration system. In most cases conventional refrigeration systems keep the evaporator fans running continuously whenever the cooler is in use to ensure the space is well mixed. The room AC approach lends itself more to cycling the fans. Table 6 shows that if the conventional system is assumed to have continuous evaporator fan operation and the Room AC has cycling fans, then the Room AC approach has lower energy use. The savings of the Room AC approach under this scenario are 200 to 500 kWh per season.

Table 6. Results for Cooler in Variation Cities at 35°F and 50°F – Constant Running Evaporator Fans

					Energy Use (kWh)			Avg EER (Btu/Wh)		
City	Temperature (F)	Floor Area (ft^2)	R-Value	Leakage ELA	Conventional Refrig	Room AC	Energy Difference	Conventional Refrig	Room AC	EER Ratio
Albany.txt	50	100	30	2	703	474	230	6.67	9.9	148%
Albany.txt	35	250	16	4	2,917	2,419	498	6.69	8.07	121%
NewYork.txt	50	100	30	2	859	621	238	7.06	9.75	138%
NewYork.txt	35	250	16	4	3,390	3,003	387	6.94	7.83	113%
Atlanta.txt	50	100	30	2	983	777	206	7.53	9.52	126%
Atlanta.txt	35	250	16	4	3,813	3,556	257	7.05	7.56	107%
Sterling.txt	50	100	30	2	853	636	218	7.16	9.61	134%
Sterling.txt	35	250	16	4	3,394	3,024	371	6.87	7.71	112%

The energy use of the system depends on how well the cooler is insulated and air-sealed as well and how often the cooler door is open. Figure 8 compares the seasonal energy use for standard and energy efficient cooler. The higher R-value and lower air leakage cooler design can cut the energy use by nearly a third

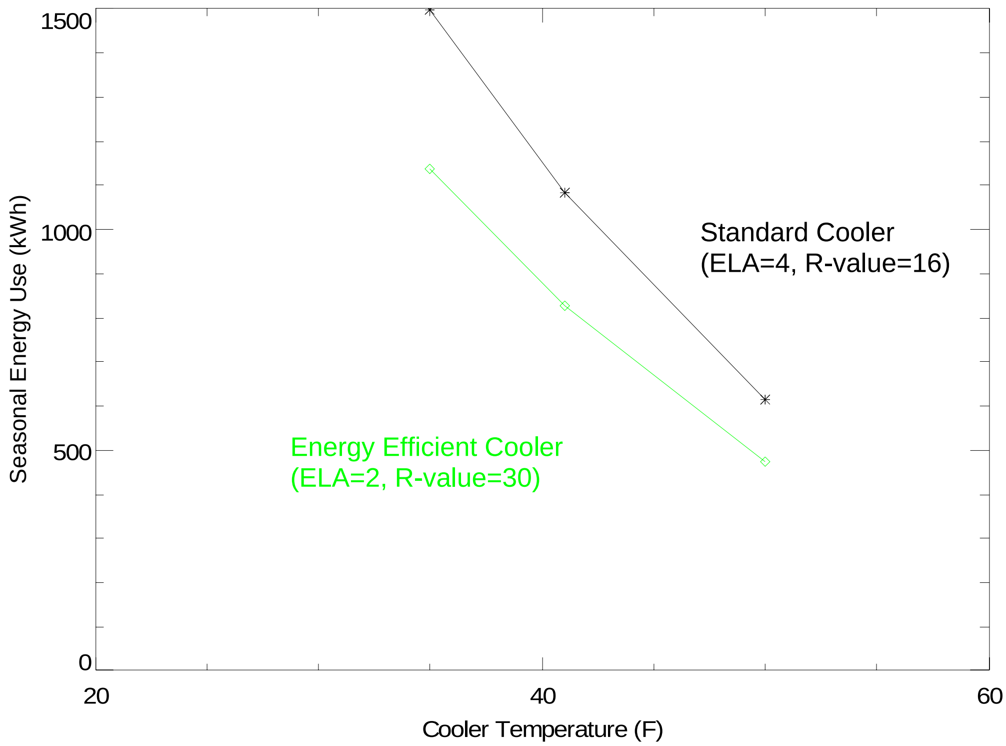


Figure 8. Comparing Standard and Energy Efficient Coolers for Room AC (100 sq ft cooler, Albany, NY)

The impact of different cooler construction and operating details are shown by the different runs in Table 7. The results correspond to the case with the evaporator fans on continuously for the conventional system and cycling for the Room AC.

Table 7. All Simulation Results for Cooler in Albany with Different Operating Conditions

City	Infiltration Rate	Temperature (F)	Floor Area (ft^2)	R-Value	Leakage ELA	Energy Use (kWh) Conventional Refrig	Room AC	Energy Difference	Avg EER (Btu/Wh) Conventional Refrig	Room AC	EER Ratio
Albany.txt	Door Open for 4 hrs	35	100	30	2	1,300	1,138	162	7.07	8.08	114%
Albany.txt		41	100	30	2	1,030	827	204	7.12	8.87	125%
Albany.txt		50	100	30	2	703	474	230	6.67	9.9	148%
Albany.txt		35	100	16	4	**1,583**	**1,499**	83	7.67	8.1	106%
Albany.txt		41	100	16	4	1,227	1,083	143	7.85	8.89	113%
Albany.txt		50	100	16	4	**804**	**614**	190	7.57	9.92	131%
Albany.txt		35	250	30	2	2,371	1,720	651	5.82	8.03	138%
Albany.txt		41	250	30	2	1,951	1,250	700	5.66	8.83	156%
Albany.txt		50	250	30	2	1,421	717	704	4.98	9.86	198%
Albany.txt		35	250	16	4	2,917	2,419	498	6.69	8.07	121%
Albany.txt		41	250	16	4	2,330	1,747	583	6.64	8.86	133%
Albany.txt		50	250	16	4	1,617	989	628	6.05	9.89	163%
Albany.txt	Door Open for 0.5 hrs	35	100	30	2	1,225	1,042	184	6.9	8.12	118%
Albany.txt		41	100	30	2	973	752	221	6.89	8.92	129%
Albany.txt		50	100	30	2	668	426	242	6.34	9.94	157%
Albany.txt		35	100	16	4	1,546	1,452	94	7.62	8.11	106%
Albany.txt		41	100	16	4	1,196	1,044	152	7.77	8.91	115%
Albany.txt		50	100	16	4	784	587	198	7.43	9.94	134%
Albany.txt		35	250	30	2	2,162	1,451	711	5.45	8.11	149%
Albany.txt		41	250	30	2	1,791	1,044	747	5.19	8.91	172%
Albany.txt		50	250	30	2	1,325	587	738	4.4	9.94	226%
Albany.txt		35	250	16	4	2,781	2,245	537	6.54	8.1	124%
Albany.txt		41	250	16	4	2,223	1,608	615	6.44	8.9	138%
Albany.txt		50	250	16	4	1,550	898	652	5.75	9.93	173%

4 Greenhouse Gas Impacts of On-Farm Storage

The COOLbot™ concept of low-cost storage allows local farmers to retain locally-grown produce for a longer period of time, thereby effectively serving more local customers. The approach provides greater income for the local farmer and offsets the need to transport food long distances. The ability to produce, store and consume food locally is expected to reduce the greenhouse gas (GHG) emissions associated with food transport.

4.1 GHG Emissions for Food Transportation

The transportation of produce from far away fields results in greenhouse gas emissions because of fuel consumption for hauling and transport refrigeration. Appendix D provides a full discussion and evaluation of fuel consumption for both of these activities. Table 8 (also Table D-2) summarizes the range of emissions levels predicted by various studies. Transport refrigeration is estimated to increase these estimates by approximately 100 gr per ton-mile in small trucks and 40 to 50 gr per ton-mile for medium and heavy trucks.

Table 8. GHG Emission Reductions for Various Production Levels and Travel Distances

	GHG Emissions (gr per ton-mile)			
	Light Truck	Mid-size Truck	Tractor Trailer (Heavy)	Fleet or Average
Our Calculations (Table D-1)	3,195	834	421	
USPS best est.	1,363	1,134	278	555
USPS range	1340-1432	1115-1192	273-292	545-583
Grier (2002)				828
Wal-Mart			174	
NREL (from USPS)			250	

For purposes of this analysis, we assume that the produce transport displaced by on-farm storage primarily occurs in the summer/spring/fall. This produce would normally come from 200 to 400 miles away in a medium-sized refrigerated truck. Therefore the displaced emissions due to transport are:

Medium-sized truck	1,150 gr/ton-mile
Increment from refrigeration	50 gr/ton-mile
Net Impact	1,200 gr/ton-mile

4.2 Determining GHG Reductions from Local Agriculture

A 100 sq ft cooler is capable of holding approximately 2 tons of produce[1]. If cooler capacity turns over 16-32 times[2] during the cooling season, then 32-64 tons of produce will be supplied to

[1] Assuming a density of 10 lb per ft^3 for general produce and that 50% of the cooler volume is effectively utilized.
[2] Khosla Farms reported a seasonal throughput of 42 tons for a 77 sq ft cooler on their farm. This scales to 55 tons per season for a 100 sq ft cooler.

the local market. Table 9 lists the greenhouse gas emissions associated with transporting 32 and 64 tons of produce a distance of 200 or 400 miles from farm to consumer. The CO_2 emissions associated with transporting this produce ranges from 3,491 to13,964 lbs per season, depending on production level and transport distance.

Table 9. GHG Emission Impacts for Various Production Levels and Travel Distances

lbs CO_2/season	Turnovers/season:	16	32
	Production:	32 tons	64 tons
Displaced Transportation	200 miles	3,491	6,982
	400 miles	6,982	13,964

Notes: Assuming a medium-sized, refrigerated truck with emissions of 1200 gr of CO_2 per ton-mile

The use of on-farm refrigerated storage with the COOLbot™ concept decreases power plant emissions by reduced on-site electricity use relative to a conventional refrigeration system. In addition, the reductions in GHG impacts for transportation are substantial. Table 10 summarizes the net impacts of on-farm refrigeration and storage with the COOLbot™ concept (i.e., Room AC). Even with the most pessimistic assumptions for production and transport distances, the on-farm refrigeration results in a net reduction in GHG emissions. The emissions reductions range as high as 14,000 lb of CO_2 per season. The reductions are greater for refrigeration provided at 50°F than at 35°F. The ratio of transportation reductions to power plant increases (i.e., the R/I ratio) ranges to over 20.

Table 10. Net GHG Emission Impacts of On-Site Refrigeration and Storage

	Power Plant Emissions[1] (lbs)		**Reduced Transportation Emissions[2] (lbs)**		**NET Emission Reductions (for Room AC)**	
Cooler Temperature (°F)	Conv Refrig	Room AC	32 tons, 200 miles	64 tons, 400 miles	**Net Reduction (lbs)**	**Impact Ratio (R/I)**
35	1,729	1,637	3,491	13,964	1,854 – 12,326	2.1 – 8.5
50	878	671			2,820– 13,293	5.2 – 20.8

Notes: 1 – Energy use corresponds to red values from Table 7. Emissions calculated assuming 1.09 lb of CO_2 per kWh for NY State (developed by Karl Michaels, NYSERDA)
2 – highest and lowest values from Table 9 above.

This analysis assumes that produce remains refrigerated during transport and distribution.

The COOLbot™ approach of using a room AC slightly decreases on-farm electricity use compared to a conventional refrigeration system, which decreases GHG emissions; however, the impact is modest compared to the transport impacts. Since the COOLbot™ approach has a much lower installed cost than conventional refrigeration, it is expected to significantly increase the use of on-farm refrigeration and storage. Wide-spread adoption of the COOLbot™ concept will result in a net reduction in GHG emissions by reducing the need for food transport.

5 COOLbot™ Economics

The COOLbot™ concept offers farmers a low cost means of providing on-farm refrigerated storage. The tables below estimate the costs for a conventional refrigeration system (from R.S. Means) as well as costs for the COOLbot™ system. The conventional system is more than $4,400 installed compared to $750 for the COOLbot™ system. The cooler construction costs are assumed to be a separate construction item that is similar for both approaches. Therefore, the cost of the cooler is not included in the analysis.

Table 11. Installed Cost of Conventional Refrigeration System

Item	Installed Cost
1.5 ton Air-Cooled Condensing Unit (Means Line # 156703000050)	$1,585
15 MBtu/h Evaporator, Celing Mount, Air Defrost (Means Line # 156803002750)	$2,830
Total	$4,415

Notes: Costs from R.S. Means including material, labor, overhead and profit

Table 12. Installed Cost of COOLbot™ Room AC System

Item	Installed Cost
LG Air Conditioner, 15,000 Btu/h	$350
COOLbot™ Controller	$299
Installation (2 hrs)	$100
Total	$749

Notes: Installation labor is assumed to be 2 hours at $50/hr

As a result, the COOLbot™ approach not generates energy savings of 200-500 kWh (or $30-$60) relative to conventional refrigeration system, but is also cheaper to install.

Appendix A
Blower Door Leakage Test Results from Coolers at Khosla Farm

Leakage Data for Standalone SIP (Structurally Insulated Panel) Cooler

Flow Coefficient (K)	22.3	166	sq ft, floor area
Exponent (n)	0.599		
Leakage area (LBL ELA @ 4 Pa)	15 sq in	1.92	ELA / 100 sq ft
Airflow @ 50 Pa	232.6 cfm	10.5	ACH @ 50

Test Data:

	Nominal Building Pressure (Pa)	Nominal Flow (cfm)
1	63.9	266
2	65.5	271
3	64.6	269
4	90.4	335
5	91.1	335
6	90.0	333
7	90.3	337
8	59.0	251
9	58.4	254
10	58.2	254
11	58.5	250
12	43.8	230
13	44.8	215
14	45.1	214
15	45.0	221

Leakage Data for Metal-Skinned Cooler

Flow Coefficient (K)	14.7	73.7 sq ft, floor area
Exponent (n)	0.629	
Leakage area (LBL ELA @ 4 Pa)	10 sq in	2.71 ELA / 100 sq ft
Airflow @ 50 Pa	171.9 cfm	18.3 ACH @ 50

	Nominal Building Pressure (Pa)	Nominal Flow (cfm)
1	89.6	244
2	90.5	252
3	91.3	253
4	72.2	216
5	72.9	217
6	73.1	217
7	63.2	198
8	60.9	195
9	61.0	192
10	53.7	186
11	54.1	181
12	54.2	186
13	44.8	158
14	44.4	157
15	44.2	159

Appendix B
Practical Experiences with Room Air Conditioners in COOLbot™ Application

Practical experiences with room air conditioners shows that most units work fairly well at the lower temperatures required for CoolBot™ application (i.e., indoor temperatures 35 to 50°F) as long as they have a plastic temperature sensor (see Table B-1 for recommendations). Experience has demonstrated that the LG room AC units work the best. Fridgidaire and Kenmore units seem to "trip out" when the ambient temperature is low AND/OR when the cooler temperature is low.

All room air conditioners under 18,000 Btu/h use a rotary compressor with an accumulator. The components in the LG unit from Khosla house are shown in Figure B-1 below. The LG unit appears to use a QK series compressor with a built in suction accumulator. The Accumulator prevents liquid refrigerant from entering the compressor (see Figure B-2) when liquid floods back from the evaporator at off-design conditions. This appears to be an important feature which allows the unit to run at low ambient conditions.

LG LWHD Series Room Air Conditioner

LG QK series compressor
(R22, 8-16 MBtu/h)

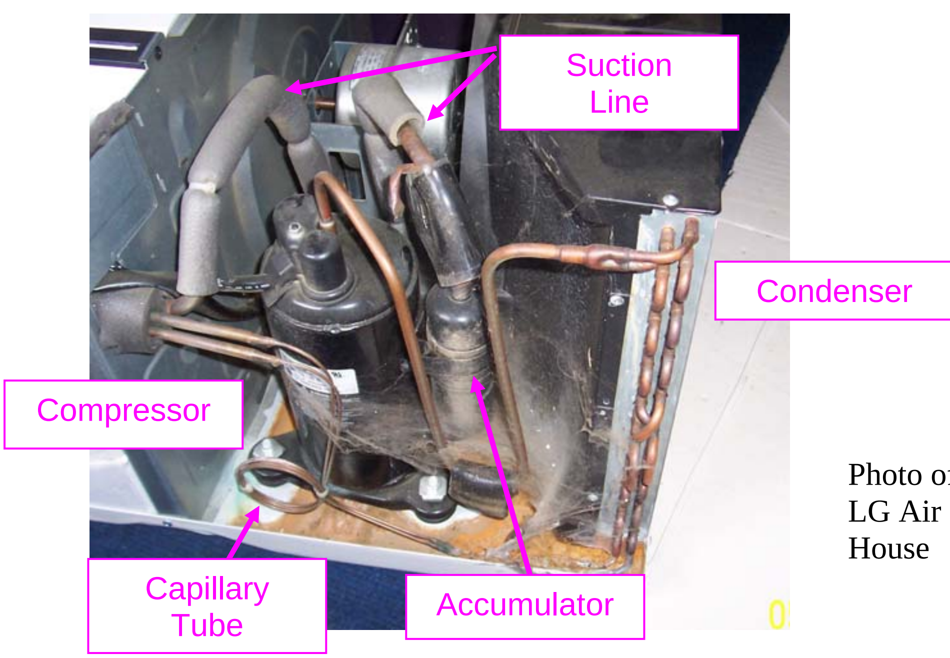
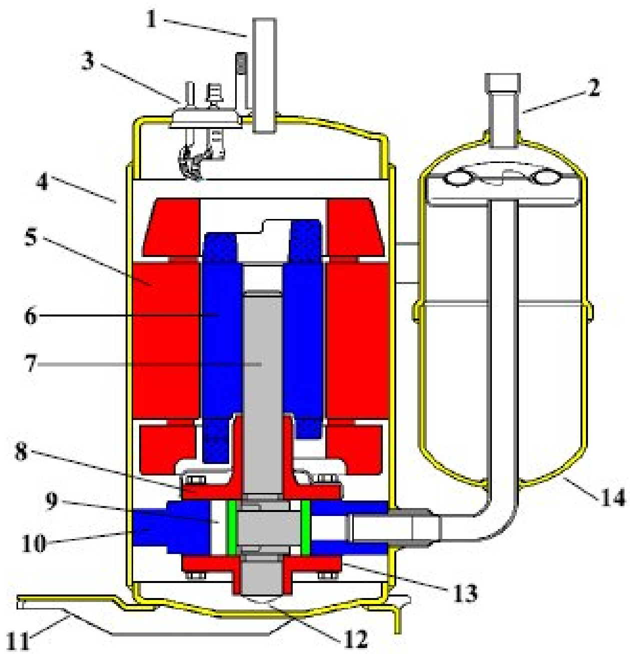


Photo of Main Components in an LG Air Conditioner from Khosla House

Figure B-1. LG Room AC unit

The LG unit has simple 2-circuit refrigerant piping design with a capillary tube serving as the expansion device for each circuit. The LG design also includes an extra “dip” in the suction line (see photo in Figure B-1) before the accumulator that affords addition protection from refrigerant flood-back. The LG AC units have no high pressure or low pressure safety switches.

Panasonic Industrial Company



1	Discharge Tube	8	Upper Bearing
2	Suction Tube	9	Piston
3	Glass Terminal	10	Cylinder
4	Shell	11	Base
5	Stator	12	Oil Pump
6	Rotor	13	Lower Bearing
7	Shaft	14	Accumulator

Figure B-2. Schematic of Typical Rotary Compressor Used in Room AC Applications (from Panasonic)

The LG room air conditioner (model LWHD1006) has an Energy Efficiency Ratio (EER) of 9.8 Btu/Wh for a 10,000 Btu/h unit (the federal minimum requirement). EnergyStar AC units can have EERs as high as 11 Btu/Wh.

Table B-1. Recommendations for Which AC to Use from Storeitcold.com

What BRAND of Air Conditioner should I buy?

By now it seems one customer or another has tried the CoolBot on every brand of A/C unit that's our there. It works on *ALL* brands of air conditioners that have a plastic temperature sensor. That being said, there are some brands that perform exceptionally well with the CoolBot.

LG Brand - Sold on the internet and at Home Depot stores across the country (they are cheapest at Home Depot). All models above 8,000btu work flawlessly with the CoolBot and have plastic temperature sensors. If you have a choice of a/c unit to buy, this is our FIRST CHOICE! They also seem to be very solidly built. Of hundreds of customers with LG units, only two have reported a problem and Home Depot immediately replaced them. They run even during the fall and winter when outside temperatures fall (this is not true of all brands!). Many hundreds of people are using these with CoolBots and are happy. We've bought an LG for our new larger cooler here on our farm and we've had it for three years with no problems.

Samsung - Sold on the internet and at most of the Lowes stores across the country. Also a good choice. We have a few hundred customers using these and they are happy as well.

Frigidaire/Kenmore -sold at about 1/2 the Lowe's stores in the country. In Sears, they sold under the brand name of KENMORE, but they are made by Frigidaire. These are not a great choice unless you live in a southern state because they stop working when the OUTSIDE temperature goes below even 50 degrees. As soon as the outside temperature warms up, if you unplug and plug them in again they will again start working and cooling your room to whatever you set it at. The original cooler on our farm has been running with a Frigidaire and one of the prototype CoolBots for many, many years now, but we only use it consistently from May through September here in NY. In October and November it invariably konks off at night when outside temps get cold. It doesn't seem to effect the a/c unit at all, but we have to manually reset it in the morning. I think they are well built and certainly they are efficient cooling machines, but... annoying for that reason.

GE Brand - Some work, some don't. The ones that have plastic temperature sensors seem fine from all reports we've had so far. The ones with metal do NOT work.

Sharp - sold in a number of stores. All seem to work okay. All brands above 6500 btu's that we've seen have plastic temperature sensors.

Brands of Air Conditioner that we know DO NOT WORK with the CoolBot are:

Emerson (all the models tested so far have metal temperature sensors)
Whirlpool (all models tested so far have metal temp sensors)
Goldstar (all models have metal temperature sensors)
Any and all brands of "portable" A/C units. They all actually "work" but because they constantly suck (hot) fresh air into the room they are extremely inefficient and you won't be able to get the room very cold. People making cheese caves are the only people that seem happy enough with them, but even if you are doing a cheese cave, for efficiency sake we don't recommend these.

Appendix C
Theoretical Evaluation of Air Conditioner Performance with HPDM

The Heat Pump Design Model (HPDM) Mark V from Oak Ridge National Laboratory[1] was used to simulate air conditioner performance at low temperature conditions. We used the default input file for a 2.5 ton split system air conditioner with a reciprocating compressor and capillary tube that was available in HPDM to predict the performance of a room air conditioner. The nominal performance of the simulated air conditioner was typical of conventional room air conditioners, as shown in the table below. The LG room air conditioner has similar (but not identical) characteristics and performance.

Table C-1. Nominal Air Conditioner Performance for HPDM compared to LG Room AC

	HPDM Defaults	**LG Model LWHD1006**
Compressor	Reciprocating	Rotary
Expansion Device	Capillary tube	Capillary tube
Energy Efficiency Ratio (EER)	9.3 Btu/Wh	9.8 Btu/Wh
Sensible Heat Ratio	0.69	0.669 (3 pints/h)
Airflow	410 cfm/ton	288 cfm/ton
Saturated Suction / Condensing Temperature	46°F / 123°F	
Compressor Superheat / Subcooling	25°F / 13°F	
Refrigerant Charge (R22)	2.7 lbs/ton	1.15 lbs/ton (15.3 oz)

Conditions: 80°F db / 67°F wb indoors, 95°F outdoors

The HPDM model was then used to subject the AC unit to lower operating temperatures in order to quantify its efficiency and capacity at these conditions. The plots on the next pages show the impact of operating the air conditioner with indoor temperatures between 35°F and 55°F along with humidities between 75% to 95% RH (or wet bulbs from 32°F to 54°F).

The results are normalized using the nominal or rated performance data. The results show that the AC unit should generally be able to operate at the low temperature conditions. At 40°F and 95% RH with an ambient of 75°F, the modeled system operates at:

- 86% of the nominal efficiency
- 66% of the nominal cooling capacity
- 76% of the nominal power draw

At this operating condition, the subcooling drops to 5°F and the system operates with no superheat (i.e., saturated vapor and perhaps liquid coming back to compressor). The saturated suction and discharge conditions at the compressor are 21°F and 93°F. At some conditions the EER can reach has high as the nominal efficiency, though the compressor power draw never exceeds the rating (so the built in breaker should not trip).

[1] http://www.ornl.gov/sci/btc/apps/hpdm.html

The system has more risk of the compressor flooding at higher ambient temperatures combined with lower cooling temperatures.

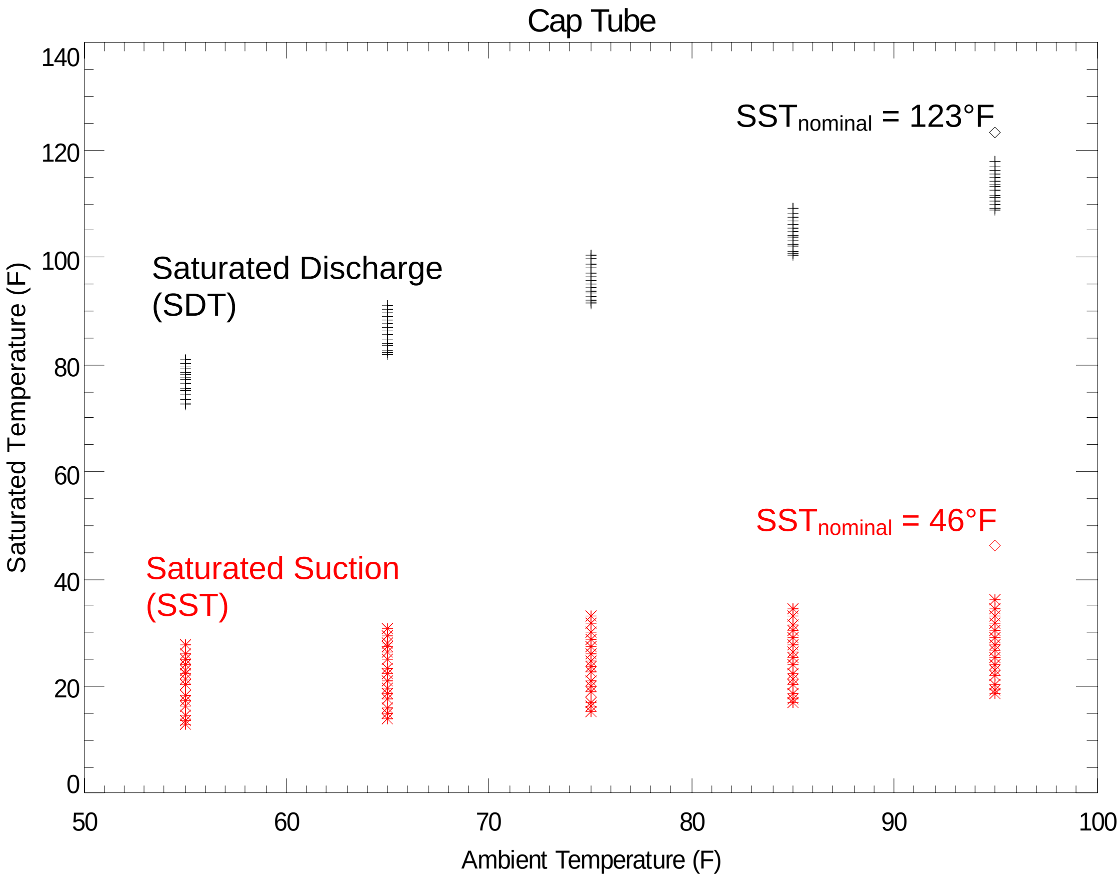


Figure C-1. Variation of Saturated Suction and Discharge Temperatures with Ambient Temperature

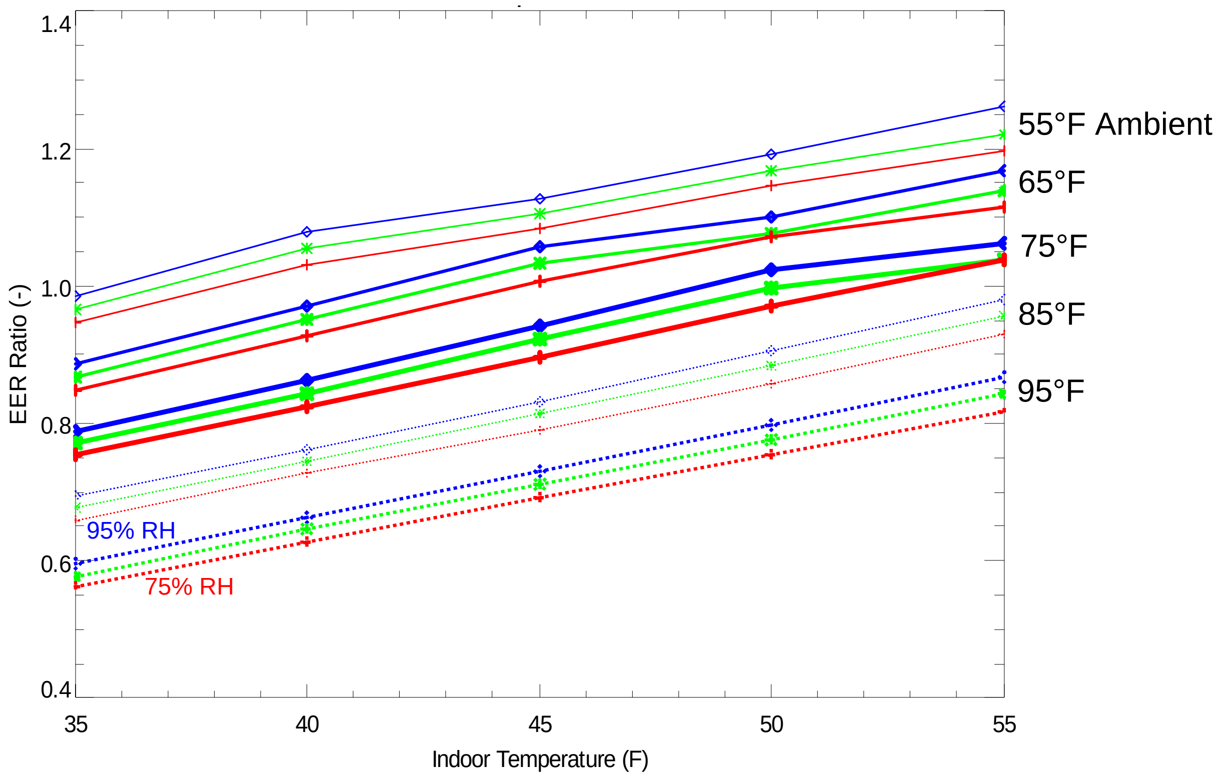


Figure C-2. EER Ratio at COOLBOT Operating Conditions (DB, RH)

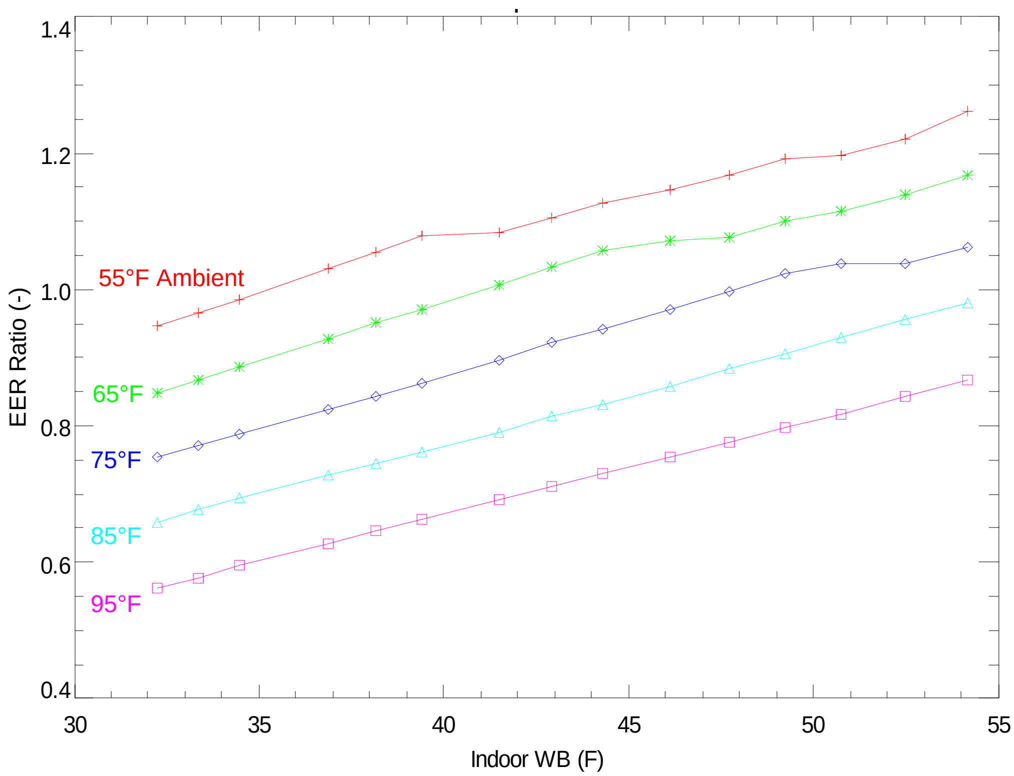


Figure C-3. EER Ratio at COOLBOT Operating Conditions (WB)

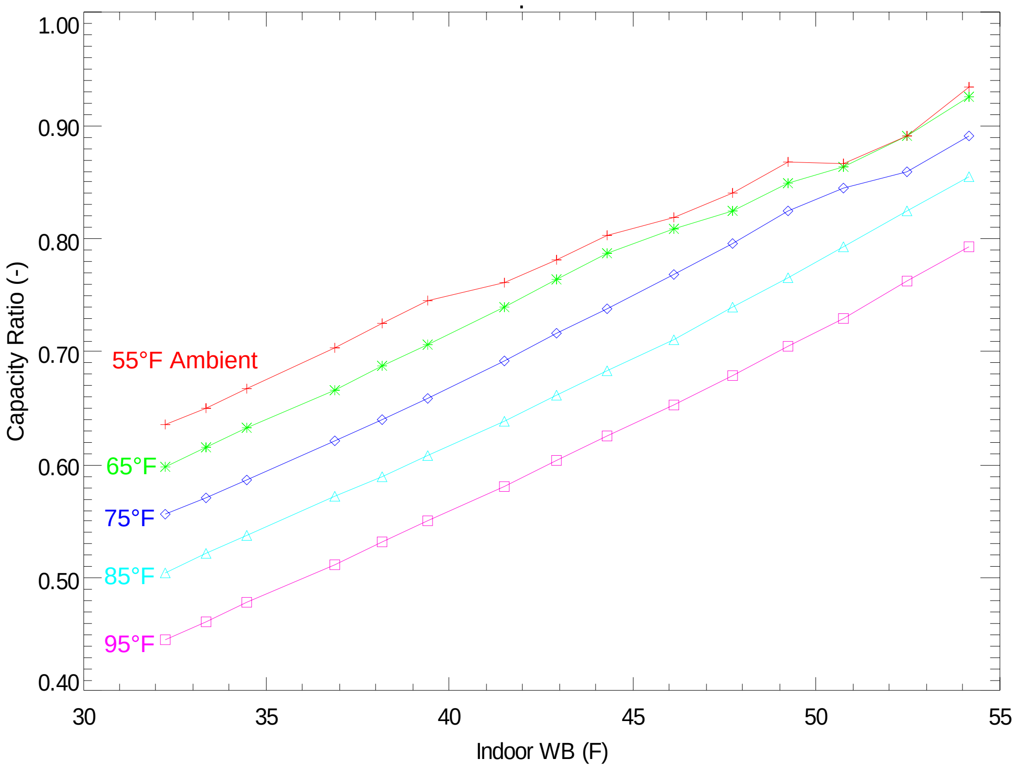


Figure C-4. Capacity Ratio at COOLBOT Operating Conditions (WB)

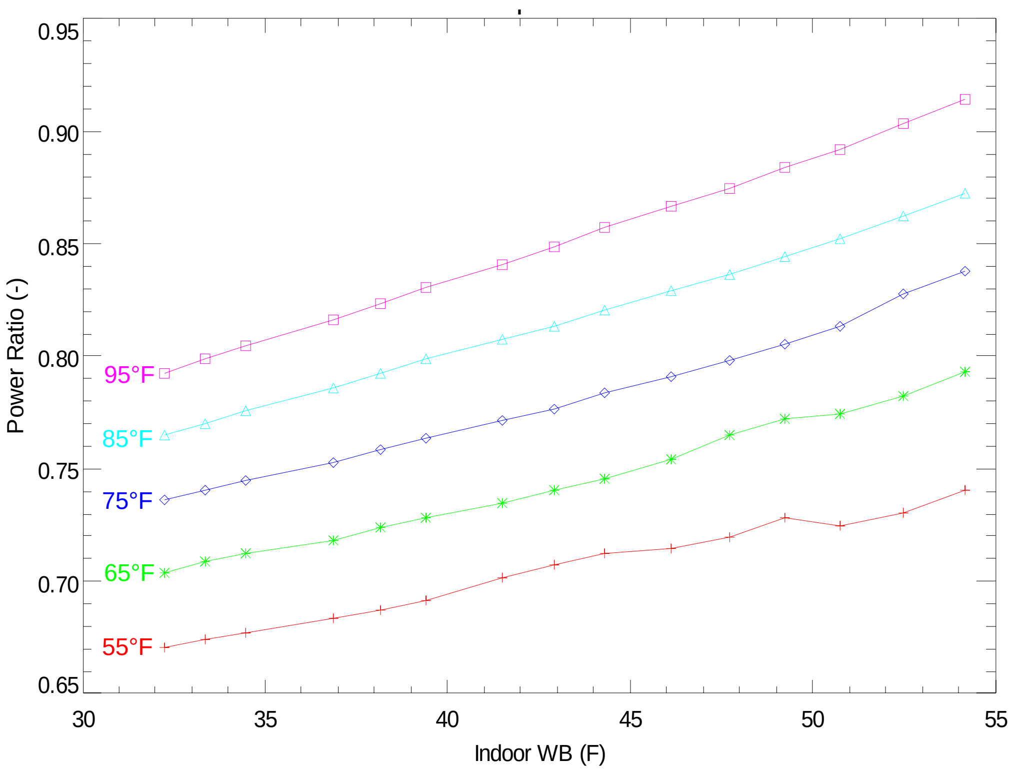


Figure C-5. Power Ratio at COOLBOT Operating Conditions (WB)

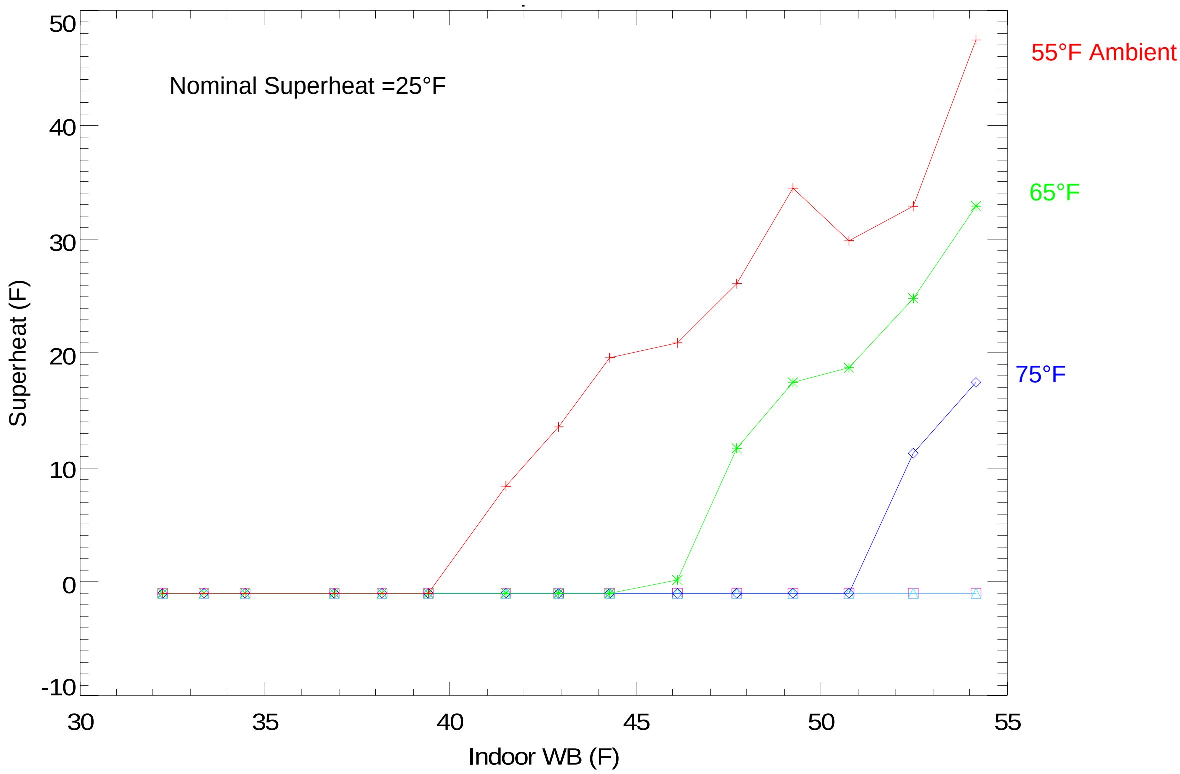


Figure C-6. Compressor Superheat at COOLBOT Operating Conditions (WB)

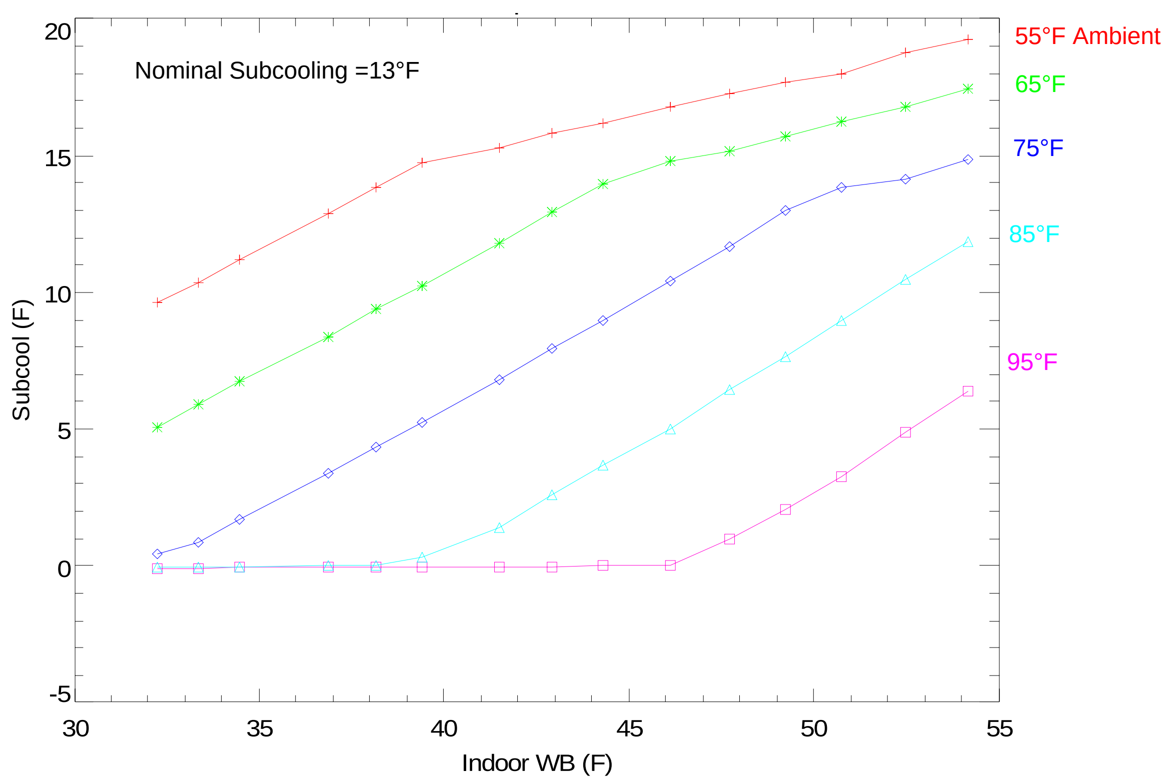


Figure C-7. System Subcooling at COOLBOT Operating Conditions (WB)

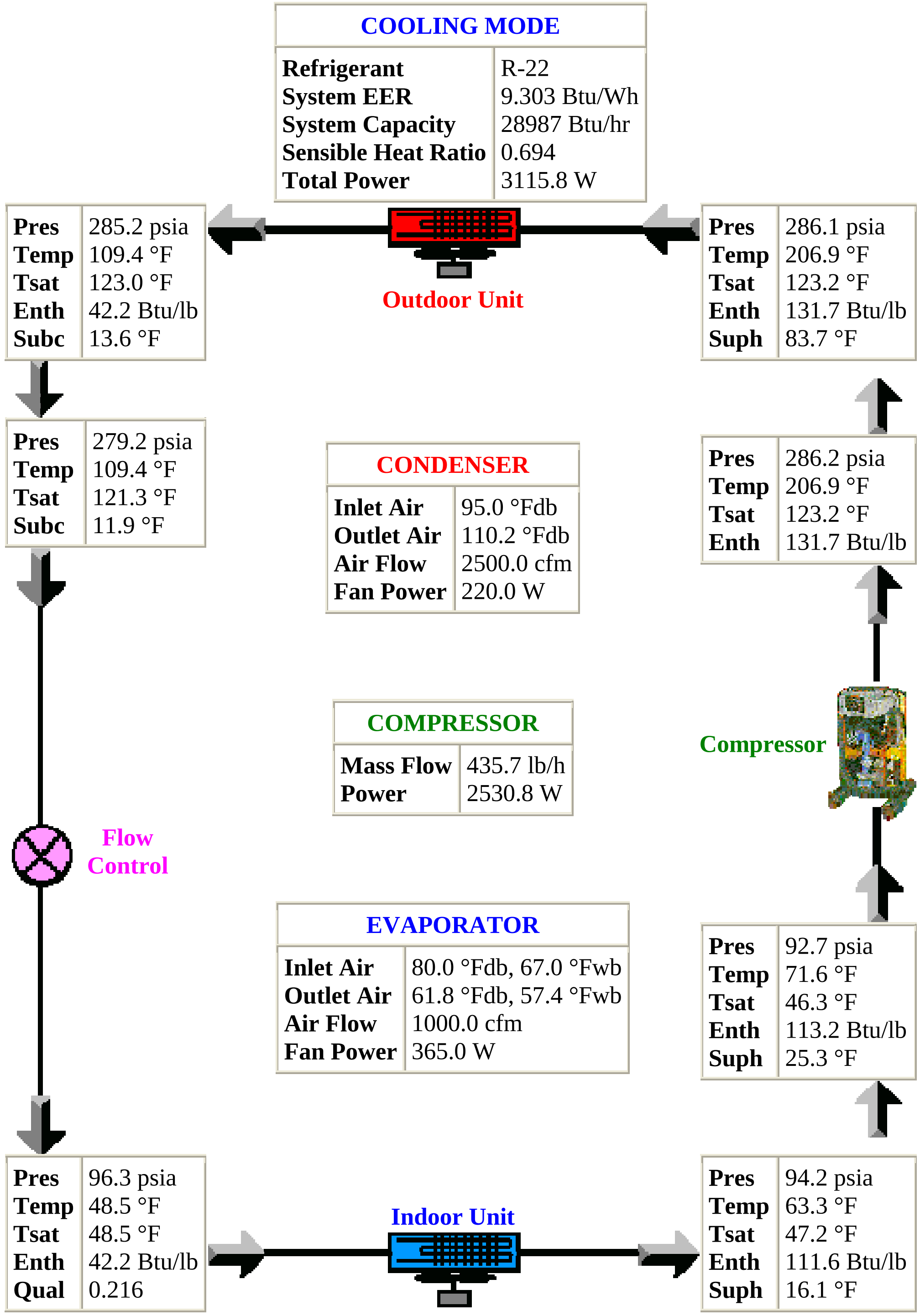
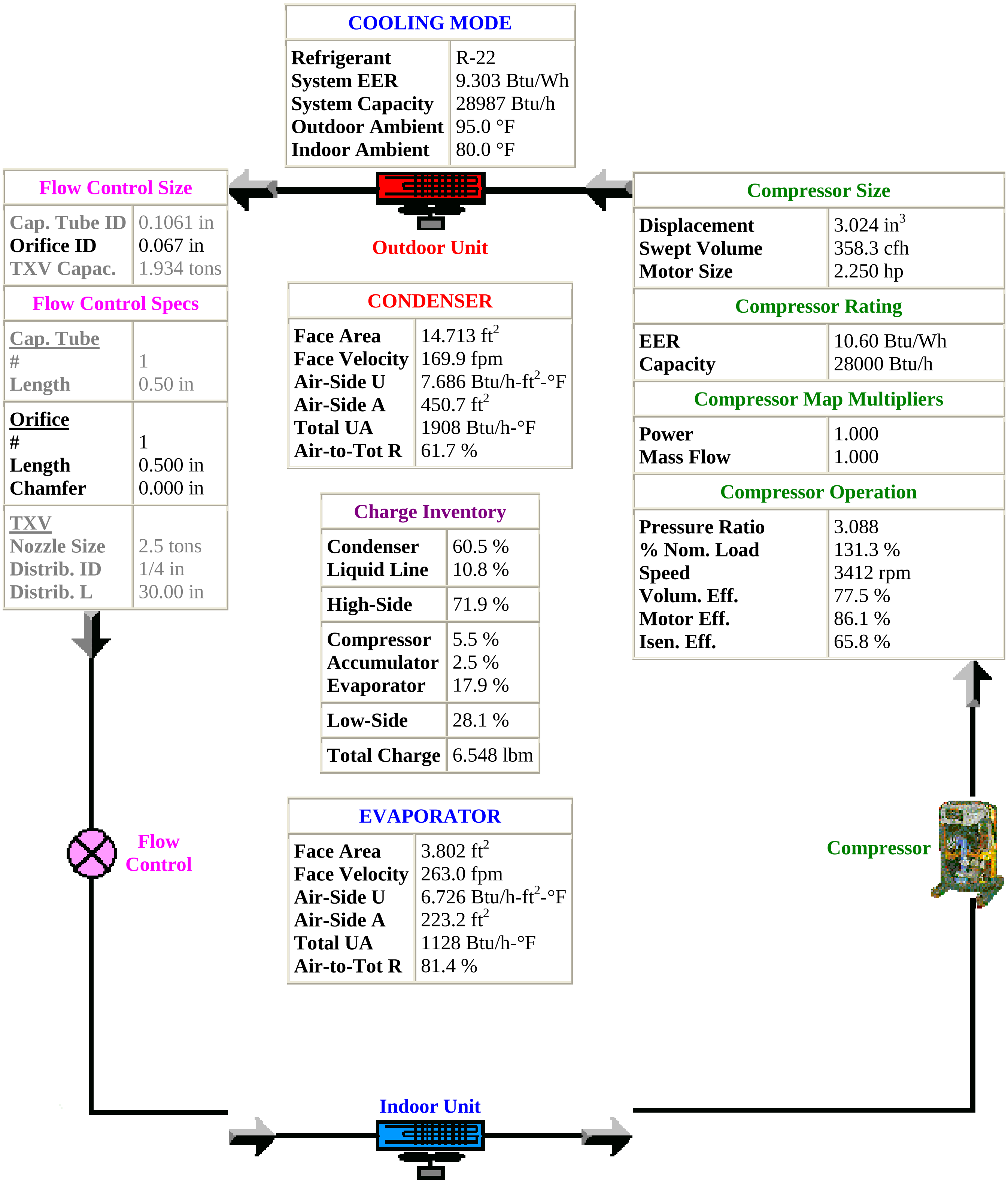


Figure C-8. Summary Screen from HPDM Showing Performance of Air Conditioner at Nominal Conditions



COOLING MODE	
Refrigerant	R-22
System EER	9.303 Btu/Wh
System Capacity	28987 Btu/h
Outdoor Ambient	95.0 °F
Indoor Ambient	80.0 °F

Flow Control Size	
Cap. Tube ID	0.1061 in
Orifice ID	0.067 in
TXV Capac.	1.934 tons

Flow Control Specs	
Cap. Tube	
#	1
Length	0.50 in
Orifice	
#	1
Length	0.500 in
Chamfer	0.000 in
TXV	
Nozzle Size	2.5 tons
Distrib. ID	1/4 in
Distrib. L	30.00 in

CONDENSER	
Face Area	14.713 ft^2
Face Velocity	169.9 fpm
Air-Side U	7.686 Btu/h-ft^2-°F
Air-Side A	450.7 ft^2
Total UA	1908 Btu/h-°F
Air-to-Tot R	61.7 %

Charge Inventory	
Condenser	60.5 %
Liquid Line	10.8 %
High-Side	71.9 %
Compressor	5.5 %
Accumulator	2.5 %
Evaporator	17.9 %
Low-Side	28.1 %
Total Charge	6.548 lbm

EVAPORATOR	
Face Area	3.802 ft^2
Face Velocity	263.0 fpm
Air-Side U	6.726 Btu/h-ft^2-°F
Air-Side A	223.2 ft^2
Total UA	1128 Btu/h-°F
Air-to-Tot R	81.4 %

Compressor Size	
Displacement	3.024 in^3
Swept Volume	358.3 cfh
Motor Size	2.250 hp

Compressor Rating	
EER	10.60 Btu/Wh
Capacity	28000 Btu/h

Compressor Map Multipliers	
Power	1.000
Mass Flow	1.000

Compressor Operation	
Pressure Ratio	3.088
% Nom. Load	131.3 %
Speed	3412 rpm
Volum. Eff.	77.5 %
Motor Eff.	86.1 %
Isen. Eff.	65.8 %

Figure C-9. Summary Screen from HPDM Showing Details of AC Design and Performance at Nominal Conditions

Appendix D
GHG Emissions for Food Transportation

Several reports and documents were reviewed to determine the Greenhouse Gas (GHG) emissions that are normally associated with produce transport in the US. This calculation was important because the locally-grown and stored produce displaces some of the need to transport food.

The EPA estimates that the CO_2 emissions associated with gasoline and diesel fuel are 19.4 and 22.2 lbs per gallon[1]. A food transportation study[2] by the Leopold Center for Sustainable Agriculture in Ames, Iowa predicted transport costs for food based on small, medium and large trucks. The assumptions from the study are summarized in the table below. In the US, food is typically transported approximately 1,500 miles to reach a supermarket shelf.

Table D-1. GHG Emissions for Food Transportation

	Light Truck	**Mid-size Truck**	**Tractor Trailer**
Fuel	Gasoline	Diesel	Diesel
Truck Capacity (lbs)	1,553	13,775	38,000
Fuel Consumption (miles/gal)	17.2	8.5	6.1
Emissions (lb of CO_2 per mile)	1.13	2.61	3.64
Emissions (lb CO_2 per ton-mile)	1.45	0.38	0.19
(gr CO_2 per ton-mile)	3,195	835	421

Notes: Assuming 19.4 and 22.2 lb of CO_2 per gallon of gasoline and diesel.
Capacity assumes shipping containers are 5% of total load weight

A recent study for US Postal Service[3] showed that the gr of CO_2 per ton-mile in 2005 was for light, medium, and heavy trucks were 1,363, 1,134 and 278, respectively. The weighted average for fleet was 555 gr CO_2 per ton-mile.

Grier (2002) reported that typical trucks achieve 59 ton-miles per gallon[4] when transporting freight. Assuming diesel fuel is used, this translate to 828 gr CO_2 per ton-mile

An article about Wal-Mart's freight operations[5] reports that their heavy trucks get 7 mpg hauling about 80,000 lbs of refrigerated products per load (they are aiming for 13 mpg for future

[1] From http://www.epa.gov/otaq/climate/420f05001.htm
[2] Page 17 of: Priog, R. et al. 2001. "Food, Fuel, and Freeways: An Iowa perspective on how far food travels, fuel usage, and greenhouse gas emissions". Leopold Center for Sustainable Agriculture, Iowa State University, Ames. June.
[3] Slides from Green Design presentation at International Life Cycle Assessment and Management Conference in 2007. http://www.lcacenter.org/InLCA2007/program.html
[4] Reference from page 50 of: 2008. Boies, A., David Kittelson, Winthrop Watts, Jan Lucke, Laurie McGinnis, Julian Marshall, Tyler Patterson, Peter Nussbaum, Elizabeth Wilson. "Reducing Greenhouse Gas Emissions from Transportation Sources in Minnesota." Report CTS-08-10. June. Center for Transportation Studies, University of Minnesota.

vehicles). Assuming Diesel fuel is 22.2 lb CO_2 per gallon, the emission rate for their tractor trailers is 174 gr CO_2 per ton-mile.

All this data is summarized and compared in Table D-2 below.

Table D-2. Comparing GHG Emissions for Freight Transportation from Several Sources

	GHG Emissions (gr per ton-mile)			
	Light Truck	Mid-size Truck	Tractor Trailer (Heavy)	Fleet or Average
Our Calculations (Table D-1)	3,195	834	421	
USPS best est.	1,363	1,134	278	555
USPS range	1340-1432	1115-1192	273-292	545-583
Grier (2002)				828
Wal-Mart			174	
NREL (from USPS)			250	

The GHG emission values listed above include the impact of freight transport but not the impact of refrigerated transport. To estimate the incremental impact of transport refrigeration, we used data from Gaines et al (2006)[6] which implies that refrigerated transport (Class 8C trucks) typically achieves 5.6 to 6.7 mile per gallon (mpg). While other types non-refrigerated trucks have slightly higher mileage: "enclosed van" 6.1 to 7.3 mpg and "flatbed" 5.6 to 7.4 mpg. This implies that the refrigerated storage function lowers the mpg by approximately 0.4 to 0.5, or 7-8%.

So we will assume ghg emissions per ton-mile are 7% higher for heavy trucks. Across all truck types (light to heavy) the incremental impact of refrigeration is estimated to be 0.5 miles per gallon. Therefore, the incremental emissions for adding refrigeration for light to heavy trucks range from 96 to 38 gr CO_2 per ton-mile, respectively.

[5] from http://refrigeratedtrans.com/news/Wal-Mart-wants-more-fuel-efficient-trucks/
[6] From Table 2 of paper from Argonne Natial Laboratory "Estimation of Fuel Use by Idling Commercial Trucks", Linda Gaines. Presented at 85th Annual Meeting of Transportation Research Board, Washington, DC.