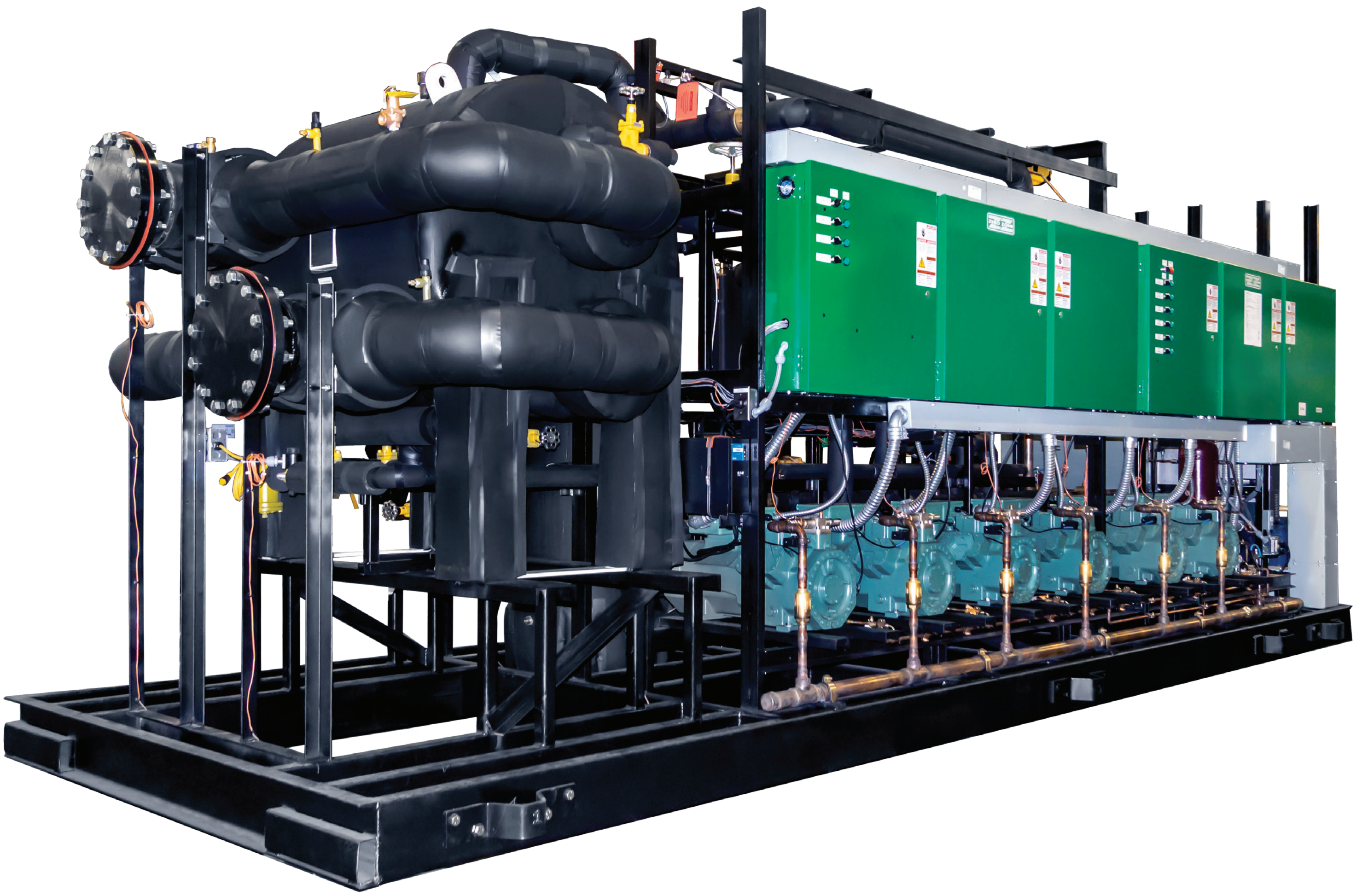


ANALYSIS OF PACKAGE CHILLER SYSTEMS:

Comparison of Natural (NH_3 and CO_2) and HFC/HFO Refrigerants

John D. Collins PE, Director of Industrial Sales, Zero Zone, Inc.

Table of Contents

- **Abstract** **3**
- **Introduction** **3**
- **Refrigerant Selection** **3**
  - **RELEVANT CRITERIA** **3**
    - **System 1** - Ammonia Packaged Chiller Machinery Room, Exterior 4
    - **System 1** - Ammonia Packaged Chiller Machinery Room, Interior 4
    - **System 2b** - HFC/HFO Packaged Chiller System 4
    - **System 3** - CO_2 Packaged Chiller System 5
  - **COMPARATIVE MATRIX** **5**
    - Matrix - Qualitative System Comparison 5
  - **EXAMPLES OF A QUALITATIVE COMPARISON OF REFRIGERANTS** **6**
    - Qualitative Comparison - **System 1**, NH_3 Preferred 6
    - Qualitative Comparison - **System 2**, HFC/HFO Preferred 6
    - Qualitative Comparison - **System 3**, CO_2 Preferred 6
- **Performance Analysis of 3 Refrigerants: CO_2, NH_3, and HFC/HFO** **7**
  - **SYSTEMS PERFORMANCE CRITERIA** **7**
  - **CALCULATED PERFORMANCE** **7**
    - Performance Data for **System 1** - NH_3 R-717 with Evaporative-Cooled Condenser 8
    - Performance Data for **System 2a** (Baseline), HFC/HFO R-448A with Evaporative-Cooled Condenser 9
    - Performance Data for **System 2b**, HFC/HFO R-448A with Air-Cooled Condenser 10
    - Performance Data for **System 3** - CO_2 R-744 with Adiabatic-Cooled Condenser 11
  - **COMPARISON OF SYSTEM PERFORMANCE** **12**
    - Comparison of Operating Costs Based on Performance Data, Minneapolis 12
    - Comparison of Operating Costs Based on Performance Data, Philadelphia 13
    - Comparison of Operating Costs Based on Performance Data, Atlanta 14
    - Comparison of Operating Costs Based on Performance Data, Los Angeles 14
- **Conclusion** **15**
- **Author Bio** **15**
- **Acknowledgments** **15**
- **References** **16**

ANALYSIS OF PACKAGE CHILLER SYSTEMS

John D. Collins PE, Director of Industrial Sales, Zero Zone, Inc.

Abstract

This technical paper evaluates criteria for selection of chiller systems in an ice rink application considering 3 refrigerants: ammonia (NH_3) R-717, carbon dioxide (CO_2) R-744, and hydrofluorocarbon/hydrofluoroolefin (HFC/HFO) blend R-448A. System performance based on calculated equipment operating data and analyzed with bin weather data is presented for similar systems using each refrigerant. Other factors involved in refrigerant selection are presented, including regulatory issues, safety, operations, and costs. A comparison of the performance with each refrigerant is presented.

Introduction

The decision process for refrigeration system design requires evaluation of many criteria. Design decisions have become more complicated in recent years as regulatory concerns, new technology, and economics have changed the factors that drive decisions. The choice of refrigerant is a primary criterion that has a fundamental impact on the entire system design. A comparison of systems using different refrigerants is a way to facilitate a good decision for a particular application.

For the purpose of this paper, a chiller system for an ice rink application is chosen. Ice rinks have a relatively consistent load profile, and operating conditions are similar between multiple facilities. This simplifies the comparison of systems utilizing different refrigerants and different types of components.

Good field data to compare different system options are often limited and difficult to obtain. A qualitative review, comparing key criteria for systems, is an effective means to select the right refrigerant for the application. A ranking of each system for criteria including cost, operation, safety, and environmental factors allows for a rational approach to compare multiple options.

Energy performance is a primary factor in system design and selection. For this paper, energy use for systems is compared using readily available manufacturer data on component performance over the range of operating conditions. Performance is then tabulated and annualized, relative to ambient conditions, with a bin weather analysis. Costs are estimated for energy and water use based on the performance of each system. These operating costs are annualized to allow a relative comparison of each system.

Calculated performance is important to establish a benchmark for comparison of systems options. By limiting the operational parameters of the analysis, a clear comparison of relative performance of different systems can be made. This information is useful to develop a baseline for operational expectations; however, this analysis is limited to relative comparison of the options presented.

Analysis of the data shows the effects of refrigerant selection on system performance. This can be used to guide decisions on component selection and optimization of design for a particular facility.

Refrigerant Selection

Numerous factors go into the selection of refrigerant for a system. For an ice rink chiller application, some of the primary concerns are efficiency, cost, ease of installation and operation, safety, environmental impacts, and availability of qualified support/service resources (Natural Resources Canada CanmetENERGY 2013).

RELEVANT CRITERIA

For the purposes of this paper, refrigeration systems with chillers circulating an indirect glycol coolant are the basis for comparison. 3 systems designed for different refrigerants are considered. The systems considered are actual installed chillers that have established design, cost, and performance data based on real equipment and experience across multiple installations. The options considered are **System 1** with R-717 (ammonia); **System 2** with R-448A (HFC/HFO blend), including options 2a with an evaporative-cooled condenser and 2b with an air-cooled condenser; and **System 3** with R-744 (carbon dioxide). For the comparative analysis of the system options, a baseline system is established as a benchmark. In this paper, **System 2a**, the R-448A system with the evaporative condenser, is selected as the benchmark/baseline that the other options are measured against.

System 1 utilizes ammonia (R-717). Ammonia has long been a common refrigerant selection for ice rink chiller applications. Chiller efficiency is the best of the options analyzed, but safety concerns have put increasing demands on the design of facilities and systems using ammonia, which increase installed costs by about 67% above the baseline **System 2a**.

System 2 utilizes HFC/HFO blend R-448A. The baseline **System 2a** uses R-448A with evaporative condensing. **System 2b** is the same as **2a** but with air-cooled condensing. HFC refrigerant systems are relatively simple to install and operate. Which HFC refrigerant to choose, however, has been in flux for several years. Regulatory changes have forced a move from hydrochlorofluorocarbon (HCFC) R-22 to HFCs R-404A/R-507A and now HFC/HFO blends R-448A/R-449A and other synthetic refrigerants. The trend is moving away from the use of higher global warming potential (GWP) refrigerants like R-404A/R-507A toward R-448A/R-449A and other lower GWP refrigerants (Nelson 2019). Installed costs are the lowest of the options analyzed, but the change in refrigerants has created new design challenges in maintaining efficiencies. The installed cost of **System 2b**, with air-cooled condensing, is less than the baseline by 10% or more, depending on the cost of water treatment equipment and local ambient design conditions.

System 3 utilizes carbon dioxide (R-744). Carbon dioxide has emerged as a viable alternative to ammonia or the synthetic refrigerants. Chiller efficiency with CO_2 outperforms the HFC/HFO systems, and initial cost is less than ammonia. As transcritical CO_2 systems become more commonplace, installation and service costs continue to come down. The installed cost for **System 3** is 47% higher than the baseline **System 2a**. The components and systems design for carbon dioxide refrigeration have developed rapidly over the last 15 years. This has expanded the range of applications and dramatically improved the efficiency of CO_2 refrigeration systems.

The systems evaluated for this paper are further described as follows:

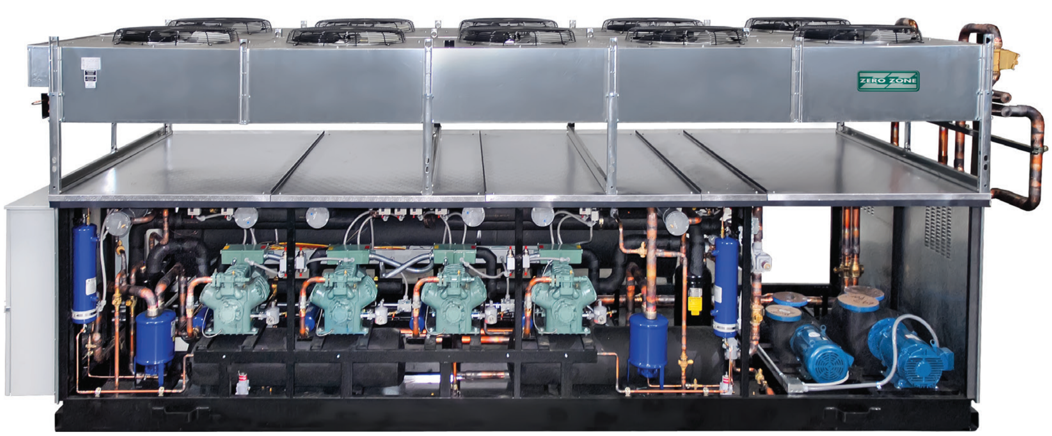
System 1: Ammonia system with flooded plate chiller and evaporative condensing (**FIGURE 1A** and **FIGURE 1B**).

FIGURE 1A: System 1 - Ammonia Packaged Chiller Machinery Room, Exterior

FIGURE 1B: System 1 - Ammonia Packaged Chiller Machinery Room, Interior

System 2: HFC/HFO system with direct expansion plate chiller (**FIGURE 2**).

FIGURE 2: System 2b - HFC/HFO Packaged Chiller System



System 3: CO_2 system with flooded plate chiller and adiabatic condensing/cooling (**FIGURE 3**).

FIGURE 3: System 3 - CO_2 Packaged Chiller System

COMPARATIVE MATRIX

The ideal refrigerant has the fundamental characteristics of being safe, effective, simple to use, and environmentally benign. A great variety of refrigerants are available to the industry. With the amount of change and development over the last 30 years, the options have increased. How to select the right refrigerant for your application is more complex than ever before. Those of us with experience designing, building, operating, and maintaining our refrigeration systems have a great amount of knowledge to share. The challenge is how to use all this information effectively to guide good decisions for refrigeration installations.

The use of a comparative matrix is a way to facilitate discussion and an effective means to guide refrigerant choice. It is easier to compare the refrigerant options when shown in a table. The numerical values (1 is worst, 5 is best) assigned to the criteria were determined through experience and knowledge of facilities, equipment, sites, construction, and personnel. **TABLE 1** demonstrates this method.

TABLE 1: Matrix - Qualitative System Comparison

Type of System	1st Cost	Safety	Efficiency - Electric	Efficiency - Water	GWP	Simple	Service	Reliable	Available	Total
System 1: NH_3 Evaporative-Cooled	1	1	5	2	5	2	3	5	5	**29**
System 2a: HFC/HFO Evaporative-Cooled	4	4	2	1	1	4	4	5	3	**28**
System 2b: HFC/HFO Air-Cooled	5	5	1	5	1	5	3	3	4	**32**
System 3: CO_2 Transcritical Adiabatic	2	5	3	4	5	2	2	3	3	**29**

EXAMPLES OF A QUALITATIVE COMPARISON OF REFRIGERANTS

By defining the priorities for a given facility, the key criteria can be highlighted to further the decision process. The factors that are most important to the operator/end user vary from facility to facility. An ice rink owner may give operating costs and efficiency the greatest weight. Another may be very sensitive to safety concerns. A third may want to be on the front edge of current technology, while another is focused on first cost. Still another facility may be most concerned with limitations of available support/service resources. These varying priorities will affect the outcome of a decision matrix exercise, and thus different facilities could have different outcomes regarding the best refrigerant for the job.

A prioritized ranking of each criterion yields a numerical factor to better define comparisons of each system option for a particular facility. **TABLES 2-4** exemplify how the priorities of the facility will change the preference for a particular system. The higher the number, the better the choice for that particular criterion.

TABLE 2: Qualitative Comparison - System 1, NH_3 Preferred

Facility Priorities	2	3	5	3	5	3	4	5	4	
Type of System	**1st Cost**	**Safety**	**Efficiency - Electric**	**Efficiency - Water**	**GWP**	**Simple**	**Service**	**Reliable**	**Available**	**Total**
System 1: NH_3 Evaporative-Cooled	2	3	25	6	25	6	12	25	20	**124**
System 2a: HFC/HFO Evaporative-Cooled	8	12	10	3	5	12	16	25	12	**103**
System 2b: HFC/HFO Air-Cooled	10	15	5	15	5	15	12	15	16	**108**
System 3: CO_2 Transcritical Adiabatic	4	15	15	12	25	6	8	15	12	**112**

TABLE 3: Qualitative Comparison - System 2, HFC/HFO Preferred

Facility Priorities	5	5	3	3	2	5	4	3	4	
Type of System	**1st Cost**	**Safety**	**Efficiency - Electric**	**Efficiency - Water**	**GWP**	**Simple**	**Service**	**Reliable**	**Available**	**Total**
System 1: NH_3 Evaporative-Cooled	5	5	15	6	10	10	12	15	20	**98**
System 2a: HFC/HFO Evaporative-Cooled	20	20	6	3	2	20	16	15	12	**114**
System 2b: HFC/HFO Air-Cooled	25	25	3	15	2	25	12	9	16	**132**
System 3: CO_2 Transcritical Adiabatic	10	25	9	12	10	10	8	9	12	**105**

TABLE 4: Qualitative Comparison - System 3, CO_2 Preferred

Facility Priorities	2	5	5	4	5	2	2	3	4	
Type of System	**1st Cost**	**Safety**	**Efficiency - Electric**	**Efficiency - Water**	**GWP**	**Simple**	**Service**	**Reliable**	**Available**	**Total**
System 1: NH_3 Evaporative-Cooled	2	5	25	8	25	4	6	15	20	**110**
System 2a: HFC/HFO Evaporative-Cooled	8	20	10	4	5	8	8	15	12	**90**
System 2b: HFC/HFO Air-Cooled	10	25	5	20	5	10	6	9	16	**106**
System 3: CO_2 Transcritical Adiabatic	4	25	15	16	25	4	4	9	12	**114**

The results of this qualitative analysis illustrate some of the differences in systems designed for the 3 refrigerants considered. The basis for this analysis is a combination of industry publications—including a comprehensive study of ice arenas by the Canadian government (Natural Resources Canada CanmetENERGY 2013)—and company and personal experience from dozens of system installations and end user feedback over 2 decades. The systems analyzed are actual installations of operating systems completed in the last 2 years.

System 1, the ammonia refrigerant chiller, has the best energy performance over the range of operating conditions. This translates to the highest ranking for electric efficiency. Ammonia is also a refrigerant proven by many decades of use in chillers, and the components are readily available and robust. At a facility where efficiency and long-term reliability are the top concerns, the refrigerant decision will tend toward ammonia. However, the first cost for ammonia refrigeration is the highest of the systems analyzed. The high cost is driven by factors including supplemental controls, components, materials, and design features required for systems using ammonia (classified as a B2L refrigerant) to address flammability and toxicity hazards.

System 2, the R-448A refrigerant chiller, has a relatively low installed cost and does not require special design for safety. The systems of this type are fairly simple to operate and maintain without highly specialized skills, materials, or tools. A facility where low first cost and simplicity of operation and servicing are top concerns will see R-448A refrigerant as a good option. However, the annual energy performance of this system is generally worse than that of the other options. Component and system design can address this to a degree, but as with any refrigeration system, a balance of first cost and operating cost drives construction decisions.

System 3, the carbon dioxide refrigerant system, shows good performance and beats the baseline (**System 2a**) energy efficiency for most of the year. Carbon dioxide is a natural, low-GWP refrigerant that is not at risk of regulatory phase out. These qualities, in addition to the fact that R-744 is an A1 refrigerant (safety classification for low toxicity and zero flammability), make it an attractive choice for a facility where safety and long-term viability are top priorities. The first cost is higher than the HFC/HFO option, but less than the ammonia option. With rapidly growing experience with CO_2 systems, concerns about a lack of qualified operators and service technicians to use R-744 properly are becoming a minor issue. The maintenance costs, from experience of end users, tend to be less than for ammonia systems and more on par with HFC systems. A qualified service technician can service a CO_2 system with commonly available "freon" tools and materials. The service gauges for CO_2 need to be a different range than for lower-pressure refrigerants, but most technicians use digital gauges, which have the capability to read CO_2 conditions.

Performance Analysis of 3 Refrigerants: CO_2, NH_3, and HFC/HFO

As noted previously, energy performance is a primary factor in system design, but may not be the deciding factor in refrigerant selection. Nevertheless, understanding how different systems compare on the basis of energy performance is important. Water use in refrigeration has become an increasingly critical factor in evaluating a system's performance and is considered here. Performance analysis of widely differing systems is a challenge because it can be difficult to get an effective and true "apples-to-apples" comparison.

SYSTEMS PERFORMANCE CRITERIA

Ice rink chiller systems are built to a very wide range of configurations and specifications. The operating conditions, however, are relatively consistent, at least for indoor arenas. The relatively consistent load profiles and process conditions allow a reasonable comparison of performance for refrigeration systems of significantly different types.

CALCULATED PERFORMANCE

The primary means of comparing relative cooling system efficiency is the coefficient of performance (COP). The COP is defined as useful work (refrigeration effect) achieved per unit of work input (ASHRAE 2019). For refrigeration systems, the inputs for COP are refrigeration capacity Q_c (kW) divided by input power W_{in} (kW).

$$COP = \frac{Q_c}{W_{in}}$$

For this analysis, the COP was calculated for each system with a nominal refrigeration capacity of 160 TR (562 kW), taking into account the rated compressor power and condenser power at the design capacity and ambient weather conditions (Bitzer 2019). Pump power for the glycol circulation loop is not considered. Each system compared utilizes a 40% solution of ethylene glycol with very similar loop design flow, pressure drop, and pump power. System performance was calculated for annual ambient conditions (bin analysis) at 100%, 55%, and 33% chiller capacity. System power was totaled for annual run hours to allow comparison of power cost. The resulting numbers for power consumption in kWh are tabulated (see **TABLES 5-8**) for the range of ambient operating conditions. The electric cost is estimated based on the total kWh at the local utility rate.

Water consumption and chemical treatment are considered for the systems that utilize evaporative or adiabatic condensers. Water consumption is based on nominal gallons/ton-hour basis. Chemical treatment cost is estimated based on a nominal dollars/ton-hour basis with quarterly service.

The weather conditions for this analysis are based on the location of Minneapolis, MN (ASHRAE 2009). The annual water and electric use and costs are calculated based on hourly bin data for Minneapolis in **TABLES 5-8** and summarized in **TABLE 9**. Additional bin analysis was completed for Philadelphia, Atlanta, and Los Angeles (**TABLES 10-12**) and is included here to show the effect of differing climates on performance. Annual power and water cost is calculated based on nominal local utility rates. System performance is evaluated on a full 12 months of operation per year. Note that many ice arenas only operate seasonally from September to April. A summary of seasonal performance is included to demonstrate how operation is quite different in the winter months and that results are significantly affected if seasonal operation is the basis.

TABLE 5: Performance Data for System 1 - NH_3 R-717 with Evaporative-Cooled Condenser

SYSTEM 1: R-717 Evaporative-Cooled Ice Rink Package - 160 Tons (562 kW) Design Capacity								
Weather Data		Performance				Power		
						Minneapolis, MN		
Ambient (°F)	MCWB (°F)	Operating Condition		EER (kBtu/h-W)	COP	Bin Hours	Total kW	kWh
		Load %	Capacity (kBtu/h)					
110	0.0		0		0.0	0		0.00
105	0.0		0		0.0	0		0.00
100	75.3	100%	1,920	9.0640	2.7	1	211.83	211.83
95	74.7	100%	1,920	9.1748	2.7	10	209.27	2,092.68
90	73.4	100%	1,920	9.3680	2.7	46	204.95	9,427.85
85	71.0	100%	1,920	9.7615	2.9	145	196.69	28,520.27
80	68.4	100%	1,920	10.2013	3.0	299	188.21	56,275.11
75	65.7	100%	1,920	10.6686	3.1	450	179.97	80,985.50
70	63.1	100%	1,920	11.1384	3.3	651	172.38	112,217.58
65	59.7	100%	1,920	11.7704	3.4	688	163.12	112,227.06
60	55.6	100%	1,920	12.5592	3.7	687	152.88	105,025.40
55	51.0	100%	1,920	13.4699	3.9	613	142.54	87,377.02
50	46.3	100%	1,920	14.4277	4.2	530	133.08	70,531.19
45	42.0	100%	1,920	15.3036	4.5	499	125.46	62,604.95
40	37.6	100%	1,920	15.7238	4.6	516	122.11	63,007.73
35	33.5	100%	1,920	16.0140	4.7	630	119.90	75,533.85
30	29.5	100%	1,920	16.3481	4.8	716	117.45	84,090.63
25	24.8	100%	1,920	16.5784	4.9	554	115.81	64,160.75
20	20.1	100%	1,920	16.7470	4.9	424	114.65	48,610.55
15	15.4	100%	1,920	16.8758	4.9	356	113.77	40,502.91
10	10.6	100%	1,920	16.9774	5.0	260	113.09	29,403.85
5	5.8	100%	1,920	17.0594	5.0	210	112.55	23,635.07
0	1.0	100%	1,920	17.1271	5.0	185	112.10	20,739.06
-5	-3.3	100%	1,920	17.1839	5.0	109	111.73	12,178.82
-10	-7.6	100%	1,920	17.3185	5.1	89	110.86	9,866.91
-15	-12.3	100%	1,920	17.3572	5.1	52	110.62	5,752.09
-20	-17.0	100%	1,920	17.3906	5.1	26	110.40	2,870.52
-25	-21.6	100%	1,920	17.4195	5.1	12	110.22	1,322.66
-30	-26.0	100%	1,920	17.4450	5.1	2	110.06	220.12
							Total Hours:	8,760
							Total kWh:	1,209,392
							Power Cost ($/kWh):	0.0900
							Electric Bill ($):	108,845
							Water & Sewer Cost ($/1000 gal):	9.02
							Cooling Tower System Water Evaporation (gal/ton-hour):	0.30
							Cooling Tower System Chemical Treatment Cost ($/ton-hour-treatment):	0.003
Dry Operation (hours/year)	**1,301**						**Water and Treatment ($/Year):**	23,679
							Total Operating Cost ($/Year):	132,493

Notes:

- Nominal rating condition: 1,920 kBtu/h unit at 14°F LWT
- Nominal design: 5.5°F Evap Approach, 20°F Condenser TD
- Analysis is calculated with refrigeration capacity at constant load at all times; condensing float down to 60°F
- Chilled water pump is not included
- Compressors, Evaporative Condenser Fan, and Pump included in power consumption
- 4 Treatments per year are assumed for Tower Maintenance
- Total Heat of Rejection (THR) includes heat of compression plus oil cooling

TABLE 6: Performance Data for System 2a (Baseline), HFC/HFO R-448A with Evaporative-Cooled Condenser

SYSTEM 2a (Baseline): R-448A Evaporative-Cooled Ice Rink Package - 160 Tons (562 kW) Design Capacity								
Weather Data		Performance				Power		
						Minneapolis, MN		
Ambient (°F)	MCWB (°F)	Operating Condition		EER (kBtu/h-W)	COP	Bin Hours	Total kW	kWh
		Load %	Capacity (kBtu/h)					
110	0.0		0		0.0	0		0.00
105	0.0		0		0.0	0		0.00
100	75.3	100%	1,920	8.2644	2.4	1	232.32	232.32
95	74.7	100%	1,920	8.3047	2.4	10	231.19	2,311.95
90	73.4	100%	1,920	8.4859	2.5	46	226.26	10,407.91
85	71.0	100%	1,920	8.7775	2.6	145	218.74	31,717.46
80	68.4	100%	1,920	9.0892	2.7	299	211.24	63,160.42
75	65.7	100%	1,920	9.4576	2.8	450	203.01	91,355.16
70	63.1	100%	1,920	9.7868	2.9	651	196.18	127,714.92
65	59.7	100%	1,920	10.2703	3.0	688	186.95	128,618.79
60	55.6	100%	1,920	10.8667	3.2	687	176.69	121,383.97
55	51.0	100%	1,920	11.6391	3.4	613	164.96	101,120.94
50	46.3	100%	1,920	12.4941	3.7	530	153.67	81,446.13
45	42.0	100%	1,920	12.9301	3.8	499	148.49	74,097.05
40	37.6	100%	1,920	13.1560	3.9	516	145.94	75,305.50
35	33.5	100%	1,920	13.3030	3.9	630	144.33	90,927.13
30	29.5	100%	1,920	13.4105	3.9	716	143.17	102,510.55
25	24.8	100%	1,920	13.5070	4.0	554	142.15	78,750.56
20	20.1	100%	1,920	13.5817	4.0	424	141.37	59,939.60
15	15.4	100%	1,920	13.6412	4.0	356	140.75	50,106.85
10	10.6	100%	1,920	13.6906	4.0	260	140.24	36,462.90
5	5.8	100%	1,920	13.7318	4.0	210	139.82	29,362.57
0	1.0	100%	1,920	13.7662	4.0	185	139.47	25,802.30
-5	-3.3	100%	1,920	13.7928	4.0	109	139.20	15,173.09
-10	-7.6	100%	1,920	13.8162	4.0	89	138.97	12,368.12
-15	-12.3	100%	1,920	13.8385	4.1	52	138.74	7,214.64
-20	-17.0	100%	1,920	13.8582	4.1	26	138.55	3,602.19
-25	-21.6	100%	1,920	13.8728	4.1	12	138.40	1,660.80
-30	-26.0	100%	1,920	13.8866	4.1	2	138.26	276.53
							Total Hours:	8,760
							Total kWh:	1,423,030
							Power Cost ($/kWh):	0.0900
							Electric Bill ($):	128,073
							Water & Sewer Cost ($/1000 gal):	9.02
							Cooling Tower System Water Evaporation (gal/ton-hour):	0.30
							Cooling Tower System Chemical Treatment Cost ($/ton-hour-treatment):	0.003
Dry Operation (hours/year) 1,301							Water and Treatment ($/Year):	25,293
							Total Operating Cost ($/Year):	153,366

Notes:

- Nominal rating condition: 1,920 kBtu/h unit at 14°F LWT
- Nominal design: 12°F Evap Approach, 15°F Condenser TD
- Analysis is calculated with refrigeration capacity at constant load at all times; condensing float down to 60°F
- Chilled water pump is not included
- Compressors, Evaporative Condenser Fan, and Pump included in power consumption
- 4 Treatments per year are assumed for Tower Maintenance
- Total Heat of Rejection (THR) includes heat of compression plus oil cooling

TABLE 7: Performance Data for System 2b, HFC/HFO R-448A with Air-Cooled Condenser

SYSTEM 2b: R-448A Air-Cooled Ice Rink Package - 160 Tons (562 kW) Design Capacity								
Weather Data		Performance				Power Minneapolis, MN		
Ambient (°F)	MCWB (°F)	Operating Condition		EER (kBtu/h-W)	COP	Bin Hours	Total kW	kWh
		Load %	Capacity (kBtu/h)					
110	0.0		0		0.0	0		0.00
105	0.0		0		0.0	0		0.00
100	75.3	100%	1,920	5.2549	1.5	1	365.38	365.38
95	74.7	100%	1,920	5.5932	1.6	10	343.27	3,432.73
90	73.4	100%	1,920	6.3313	1.9	46	303.25	13,949.72
85	71.0	100%	1,920	6.3373	1.9	145	302.97	43,930.34
80	68.4	100%	1,920	6.7090	2.0	299	286.18	85,568.13
75	65.7	100%	1,920	7.1337	2.1	450	269.14	121,115.19
70	63.1	100%	1,920	7.6151	2.2	651	252.13	164,137.91
65	59.7	100%	1,920	7.9987	2.3	688	240.04	165,145.97
60	55.6	100%	1,920	8.4919	2.5	687	226.10	155,329.85
55	51.0	100%	1,920	9.0068	2.6	613	213.17	130,675.17
50	46.3	100%	1,920	9.5427	2.8	530	201.20	106,636.14
45	42.0	100%	1,920	10.1068	3.0	499	189.97	94,795.91
40	37.6	100%	1,920	10.4474	3.1	516	183.78	94,829.36
35	33.5	100%	1,920	11.1636	3.3	630	171.99	108,352.11
30	29.5	100%	1,920	11.6421	3.4	716	164.92	118,081.72
25	24.8	100%	1,920	11.9848	3.5	554	160.20	88,752.16
20	20.1	100%	1,920	12.2425	3.6	424	156.83	66,496.23
15	15.4	100%	1,920	12.4427	3.6	356	154.31	54,933.39
10	10.6	100%	1,920	12.6035	3.7	260	152.34	39,608.05
5	5.8	100%	1,920	12.7346	3.7	210	150.77	31,661.74
0	1.0	100%	1,920	12.8441	3.8	185	149.48	27,654.62
-5	-3.3	100%	1,920	12.9369	3.8	109	148.41	16,176.92
-10	-7.6	100%	1,920	13.0165	3.8	89	147.51	13,127.96
-15	-12.3	100%	1,920	13.0856	3.8	52	146.73	7,629.77
-20	-17.0	100%	1,920	13.1458	3.9	26	146.05	3,797.41
-25	-21.6	100%	1,920	14.0534	4.1	12	136.62	1,639.46
-30	-26.0	100%	1,920	14.0534	4.1	2	136.62	273.24
							Total Hours:	8,760
							Total kWh:	1,758,097
							Power Cost ($/kWh):	0.0900
							Electric Bill ($):	158,229
							Water & Sewer Cost ($/1000 gal):	9.02
							Cooling Tower System Water Evaporation (gal/ton-hour):	0.00
							Cooling Tower System Chemical Treatment Cost ($/ton-hour-treatment):	0.000
							Water and Treatment ($/Year):	0
							Total Operating Cost ($/Year):	158,229
Notes:		▪ Nominal rating condition: 1,920 kBtu/h unit at 14°F LWT ▪ Nominal design: 12°F Evap Approach, 15°F Condenser TD ▪ Analysis is calculated with refrigeration capacity at constant load at all times; condensing float down to 60°F ▪ Chilled water pump is not included ▪ Compressor and Condenser Fans included in power consumption ▪ Total Heat of Rejection (THR) includes heat of compression plus oil cooling						

TABLE 8: Performance Data for System 3 - CO_2 R-744 with Adiabatic-Cooled Condenser

SYSTEM 3: R-744 Transcritical Adiabatic Gas Cooler Ice Rink Package - 160 Tons (562 kW) Design Capacity								
Weather Data		Performance				Power		
						Minneapolis, MN		
Ambient (°F)	MCWB (°F)	Operating Condition		EER (kBtu/h-W)	COP	Bin Hours	Total kW	kWh
		Load %	Capacity (kBtu/h)					
110	0.0		0		0.0	0		0.00
105	0.0		0		0.0	0		0.00
100	75.3	100%	1,920	7.1652	2.1	1	267.96	267.96
95	74.7	100%	1,920	7.2780	2.1	10	263.81	2,638.08
90	73.4	100%	1,920	7.5302	2.2	46	254.97	11,728.75
85	71.0	100%	1,920	8.0188	2.3	145	239.44	34,718.21
80	68.4	100%	1,920	8.5679	2.5	299	224.09	67,003.96
75	65.7	100%	1,920	9.1366	2.7	450	210.14	94,564.81
70	63.1	100%	1,920	9.6596	2.8	651	198.77	129,396.48
65	59.7	100%	1,920	10.2794	3.0	688	186.78	128,505.74
60	55.6	100%	1,920	10.9253	3.2	687	175.74	120,732.99
55	51.0	100%	1,920	11.6026	3.4	613	165.48	101,439.42
50	46.3	100%	1,920	12.4193	3.6	530	154.60	81,936.92
45	42.0	100%	1,920	13.3597	3.9	499	143.72	71,714.30
40	37.6	100%	1,920	14.1844	4.2	516	135.36	69,845.54
35	33.5	100%	1,920	14.9844	4.4	630	128.13	80,723.72
30	29.5	100%	1,920	15.5089	4.5	716	123.80	88,640.89
25	24.8	100%	1,920	15.8797	4.7	554	120.91	66,983.84
20	20.1	100%	1,920	16.1558	4.7	424	118.84	50,389.35
15	15.4	100%	1,920	16.3688	4.8	356	117.30	41,757.41
10	10.6	100%	1,920	16.5390	4.8	260	116.09	30,183.26
5	5.8	100%	1,920	16.6771	4.9	210	115.13	24,176.90
0	1.0	100%	1,920	16.7920	4.9	185	114.34	21,152.90
-5	-3.3	100%	1,920	16.8891	4.9	109	113.68	12,391.42
-10	-7.6	100%	1,920	16.9721	5.0	89	113.13	10,068.29
-15	-12.3	100%	1,920	17.0440	5.0	52	112.65	5,857.77
-20	-17.0	100%	1,920	17.1066	5.0	26	112.24	2,918.17
-25	-21.6	100%	1,920	17.1621	5.0	12	111.87	1,342.49
-30	-26.0	100%	1,920	17.2109	5.0	2	111.56	223.11
							Total Hours:	8,760
							Total kWh:	1,351,303
							Power Cost ($/kWh):	0.0900
							Electric Bill ($):	121,617
							Water & Sewer Cost ($/1000 gal):	9.02
							Cooling Tower System Water Evaporation (gal/ton-hour):	0.08
							Cooling Tower System Chemical Treatment Cost ($/ton-hour-treatment):	0.000
Dry Operation (hours/year)	4,141						Water and Treatment ($/Year):	500
							Total Operating Cost ($/Year):	122,117
Notes:		▪ Nominal rating condition: 1,920 kBtu/h unit at 14°F LWT ▪ Nominal design: 5.5°F Evap Approach, 10°F Condenser TD ▪ Analysis is calculated with refrigeration capacity at constant load at all times; condensing float down to 50°F ▪ Chilled water pump is not included ▪ Compressors, Condenser Fan, and Pump included in power consumption ▪ Considered water consumption for adiabatic gas cooler as 1/4 of evaporative-cooled condenser water consumption ▪ Total Heat of Rejection (THR) includes heat of compression plus oil cooling						

COMPARISON OF SYSTEM PERFORMANCE

Overall system performance is compared by establishing a baseline from the system options being considered. In this analysis, the R-448A option with evaporative condensing (**System 2a**) is selected as the baseline. System side variations in refrigeration load are not considered, and the data are based on a constant and equal chiller capacity output for each system option. This is useful for the purposes of evaluating relative performance. Important to note is that the energy and water consumption (and resulting costs) in actual operation will be lower since the load profiles drop below the design capacity much of the time. For this analysis, we focus on comparing costs between the systems options in relative percentage to the baseline versus actual dollar amounts. The local conditions and utility rates are equal for all system options, allowing a good comparison of relative performance.

The performance of each system option is evaluated based on the consumption of electric power and water. The annualized costs show that electric power is the primary operational expense. For the systems that use water, the proportional cost of water varies widely with system operating conditions and local water/sewer rates. **TABLES 9-12** show the results of the analysis for several operating conditions and locations. **TABLES 9A**, **9B**, and **9C** show the results for the Minneapolis location at 100% load, 55% load, and for seasonal operation in September-April. **TABLES 10-12** show the results for Philadelphia, Atlanta, and Los Angeles, respectively. Total operating costs are compared for each system. The use/cost numbers account for both water and electric power consumption at the local utility rates.

Comparing the air-cooled option (**System 2b**) with the evaporative-cooled option (**System 2a**) shows the following results. At 100% load conditions, the air-cooled R-448A **System 2b** has between 0% and 12% higher operating cost than the baseline evaporative-cooled R-448A **System 2a**. As the load reduces, this shifts dramatically. At 55% load, the air-cooled system operating costs are less than the evaporative-cooled system by 7-20%. The effect of local water/sewer rates on the operating costs is most apparent with the Atlanta analysis data (where rates are very high), which show that even at full load, the air-cooled option has the same operating cost as the evaporative-cooled option. The differential in electrical power use/cost for air-cooled systems shows 24-28% greater electric use over evaporative-cooled systems. This differential reduces to 16-20% as the load drops to 55% of design capacity. In the warmer and drier climate of Los Angeles, the increased electric use for the air-cooled system compared with the baseline evaporative system is more apparent than for the other locations that have colder and wetter climates.

Some notable differences come to light in comparing the summary data for system options with the 3 refrigerants at different operating conditions and locations (**TABLES 9-12**). The evaporative-cooled ammonia **System 1** operating cost is 11-15% lower than the baseline R-448A system across all operating conditions and locations. The ammonia electric power is 13-15% lower than the baseline. The adiabatic-cooled CO_2 **System 3** operating cost is 13-20% less than the baseline R-448A system at 100% capacity. The electric power for **System 3** ranges from 1% greater (in Atlanta) to 5% less (in Minneapolis). At 55% capacity, the CO_2 operating costs significantly reduce, in the range of 24-33%, below the baseline costs. The electric power required for CO_2 at this reduced load is below the baseline by 3-9%.

For the evaporative-cooled Systems 1 and 2a, the water cost is in the range of 12-15% of the total operating cost. This proportion increases to 25%-35% or more as the load reduces and compressor and fan power drops off while water keeps running. The water cost is minimal for the adiabatic-cooled **System 3** and eliminated with the air-cooled **System 2b**. At the Atlanta location, the water cost ratio increases to 1/4 of the total operating cost or more. This is due to the unusually high price of water/sewer in Atlanta.

TABLE 9A: Comparison of Operating Costs Based on Performance Data, Minneapolis, 100% Capacity

Relative Power & Water Use and Cost	System 2a Baseline	System 1	System 2b	System 3
	HFC/HFO Evap-Cooled	NH_3 Evap-Cooled	HFC/HFO Air-Cooled	CO_2 Adiabatic
Total Op Cost/Year	153,366	132,493	158,229	122,117
	0.0%	-13.6%	3.2%	-20.4%
Total Water Cost/Year	25,293	23,647	0	500
	0.0%	-6.5%	-100.0%	-98.0%
Total Power Cost/Year	128,073	108,845	15,8229	121,617
	0.0%	-15.0%	23.5%	-5.0%
Total kWh/Year	1,423,030	1,209,392	1,758,097	1,351,303
	0.0%	-15.0%	23.5%	-5.0%

TABLE 9B: Comparison of Operating Costs Based on Performance Data, Minneapolis, 55% Capacity

Relative Power & Water Use and Cost	System 2a Baseline	System 1	System 2b	System 3
	HFC/HFO Evap-Cooled	NH_3 Evap-Cooled	HFC/HFO Air-Cooled	CO_2 Adiabatic
Total Op Cost/Year	93,386	81,212	79,147	62,559
	0.0%	-13.0%	-15.2%-	-33.0%
Total Water Cost/Year	25,293	23,647	0	500
	0.0%	-6.5%	-100.0%	-98.0%
Total Power Cost/Year	68,092	57,564	79,147	62,059
	0.0%	-15.5%	16.2	-8.9%
Total kWh/Year	756,582	639,605	879,416	689,543
	0.0%	-15.5%	16.2%	-8.9%

TABLE 9C: Comparison of Operating Costs Based on Performance Data, Minneapolis, September-April

Relative Power & Water Use and Cost	System 2a Baseline	System 1	System 2b	System 3
	HFC/HFO Evap-Cooled	NH_3 Evap-Cooled	HFC/HFO Air-Cooled	CO_2 Adiabatic
Total Op Cost/Year	93,674	79,595	93,329	71,137
	0.0%	-15.0%	-0.4%	-24.1%
Total Water Cost/Year	15,284	14,289	0	186
	0.0%	-6.5	-100.0%	-98.8
Total Power Cost/Year	78,390	65,305	93,329	70,951
	0.0%	-16.7%	19.1%	-9.5%
Total kWh/Year	871,002	725,615	1,036,990	788,346
	0.0%	-16.7%	19.1%	-9.5%

OBSERVATIONS FROM THE ANALYSIS

Several interesting observations emerge from analyzing the performance of the systems under study. Some connections can be made on the observed differences in system performance related to the properties of the refrigerant used and system design. Additional observations can be connected to the performance effects related to component selection and local site conditions.

Facility geographic location has a big impact on system operation. This analysis evaluated sites in a cold northern climate (Minneapolis, **TABLE 9**), a mixed humid northern climate (Philadelphia, **TABLE 10**), a mixed humid southern climate (Atlanta, **TABLE 11**), and a dry warm climate (Los Angeles, **TABLE 12**). The most notable effects of facility location on the results of the analysis were on the relative performance of the CO_2 **System 3** and the benefit of evaporative condensing versus air-cooled condensing.

Looking at the performance data for evaporative condensing versus air-cooled options is helpful in making some decisions on component and system design. If the system is located in a hot climate, the increase in power consumption of the air-cooled system over the baseline is more significant. The cost of water and treatment programs varies widely on where a facility is located. In the northern United States, water is generally more plentiful and relatively good quality, but the cooler temperatures warrant serious consideration of air-cooled condensing. Even in warmer climates the local water conditions must be considered when evaluating relative performance and costs of the system options (Scott 2016).

For example, the data for the **System 2** R-448A chiller package in Atlanta and Minneapolis indicate that an air-cooled condenser would be a better choice than an evaporative condenser, from the standpoint of operating cost. The additional cost for the power to run the air-cooled system is more than offset by the added cost of water and treatment for the evaporative condenser. Furthermore, a premium of 10% installed cost goes with the baseline evaporative condenser (**System 2a**) over the air-cooled option (**System 2b**). In this case, air-cooled has clear advantages.

TABLE 10A: Comparison of Operating Costs Based on Performance Data, Philadelphia, 100% Capacity

Relative Power & Water Use and Cost	System 2a Baseline	System 1	System 2b	System 3
	HFC/HFO Evap-Cooled	NH_3 Evap-Cooled	HFC/HFO Air-Cooled	CO_2 Adiabatic
Total Op Cost/Year	240,306	208,875	263,995	209,144
	0.0%	-13.1%	9.9%	-13.0%
Total Water Cost/Year	28,626	26,812	0	558
	0.0%	-6.3%	-100.0%	-98.1%
Total Power Cost/Year	211,680	182,062	263,995	208,586
	0.0%	-14.0%	24.7%	-1.5%
Total kWh/Year	1,511,997	1,300,444	1,885,680	1,489,898
	0.0%	-14.0%	24.7%	-1.5%

TABLE 10B: Comparison of Operating Costs Based on Performance Data, Philadelphia, 55% Capacity

Relative Power & Water Use and Cost	System 2a Baseline	System 1	System 2b	System 3
	HFC/HFO Evap-Cooled	NH_3 Evap-Cooled	HFC/HFO Air-Cooled	CO_2 Adiabatic
Total Op Cost/Year	140,815	122,884	131,012	106,563
	0.0%	-12.7%	-7.0%	-24.3%
Total Water Cost/Year	28,626	26,812	0	558
	0.0%	-6.3%	-100.0%	-98.1%
Total Power Cost/Year	112,188	96,071	131,012	106,005
	0.0%	-14.4%	16.8%	-5.5%
Total kWh/Year	801,346	686,224	935,801	757,181
	0.0%	-14.4%	16.8%	-5.5%

TABLE 11A: Comparison of Operating Costs Based on Performance Data, Atlanta, 100% Capacity

Relative Power & Water Use and Cost	System 2a Baseline	System 1	System 2b	System 3
	HFC/HFO Evap-Cooled	NH_3 Evap-Cooled	HFC/HFO Air-Cooled	CO_2 Adiabatic
Total Op Cost/Year	201,366	177,754	201,469	163,800
	0.0%	-11.7%	0.1%	-18.7%
Total Water Cost/Year	41,768	39,048	0	2,523
	0.0%	-6.5%	-100.0%	-94.0%
Total Power Cost/Year	159,599	138,707	201,469	161,277
	0.0%	-13.1%	26.2%	1.1%
Total kWh/Year	1,595,987	1,387,066	2,014,688	1,612,775
	0.0%	-13.1%	26.2%	1.1%

TABLE 11B: Comparison of Operating Costs Based on Performance Data, Atlanta, 55% Capacity

Relative Power & Water Use and Cost	System 2a Baseline	System 1	System 2b	System 3
	HFC/HFO Evap-Cooled	NH_3 Evap-Cooled	HFC/HFO Air-Cooled	CO_2 Adiabatic
Total Op Cost/Year	126,213	112,287	99,900	84,536
	0.0%	-11.0%	-20.8%	-33.0%
Total Water Cost/Year	41,768	39,048	0	2,523
	0.0%	-6.5%	-100.0%	94.0%
Total Power Cost/Year	84,445	73,240	99,900	82,013
	0.0%	-13.3%	18.3%	-2.9%
Total kWh/Year	844,454	732,397	998,998	820,130
	0.0%	-13.3%	18.3%	-2.9

TABLE 12A: Comparison of Operating Costs Based on Performance Data, Los Angeles, 100% Capacity

Relative Power & Water Use and Cost	System 2a Baseline	System 1	System 2b	System 3
	HFC/HFO Evap-Cooled	NH_3 Evap-Cooled	HFC/HFO Air-Cooled	CO_2 Adiabatic
Total Op Cost/Year	232,728	202,369	259,803	202,051
	0.0%	-13.0%	11.6%	-13.2%
Total Water Cost/Year	30,340	28,210	0	1,263
	0.0%	-7.0%	-100.0%	-95.8%
Total Power Cost/Year	202,388	174,158	259,803	200,787
	0.0%	-13.9%	28.4%	-0.8%
Total kWh/Year	1,556,833	1,339,680	1,998,482	1,544,518
	0.0%	-13.9%	28.4%	-0.8%

TABLE 12B: Comparison of Operating Costs Based on Performance Data, Los Angeles, 55% Capacity

Relative Power & Water Use and Cost	System 2a Baseline	System 1	System 2b	System 3
	HFC/HFO Evap-Cooled	NH_3 Evap-Cooled	HFC/HFO Air-Cooled	CO_2 Adiabatic
Total Op Cost/Year	136,865	119,900	127,864	102,486
	0.0%	-12.4%	-6.6%	-25.1%
Total Water Cost/Year	30,340	28,210	0	1,263
	0.0%	-7.0%	-100.0%	-95.8%
Total Power Cost/Year	106,526	91,689	127,864	101,222
	0.0%	-13.9%	20.0%	-5.0%
Total kWh/Year	819,427	705,302	983,570	778,633
	0.0%	-13.9%	20.0%	-5.0%

System 1, the ammonia chiller package, clearly outperformed the baseline system across all locations and operating conditions. The operational cost savings for **System 1**, however, is less than the total savings for the **System 3** CO_2 option. The electric use/cost for ammonia is the least for all the options, but the added cost of water for evaporative condensing more than offsets the electric savings. This is more pronounced in cooler climates and where water costs are high. As the operating loads reduce below 100% capacity, the differential between **System 1** and **System 3** operating costs increases. The electrical cost savings for **System 1** are a significant benefit; however, the installed cost for the ammonia system is significantly higher. The premium of 67% in first cost for the ammonia system over the baseline system will take several years to make up.

System 3, the CO_2 chiller package, falls in between **System 1** and **System 2** in terms of first cost and electrical performance. The total operational cost savings over the baseline system are better than the ammonia option, yet the first cost premium is significantly less. Utilizing parallel compression and adiabatic condensing makes the CO_2 system perform effectively at all locations considered over the entire range of annual weather conditions. The CO_2 system electrical use outperforms the **System 2a** baseline evaporative-cooled system the majority of annual operating hours (62% of annual hours in Atlanta and 83% of annual hours in Minneapolis and Los Angeles). The added electric cost for the limited number of hours of peak hot weather operation is more than offset by the savings during off-peak operation. In reality, the systems operate at reduced capacity much of the year, which further improves the overall electric savings for CO_2 over the baseline system. The electrical savings for **System 3**, combined with much lower water use for the adiabatic gas cooler/condenser, results in total operating costs 13-33% below baseline across the range of locations and conditions. The CO_2 system outperforms the air-cooled **System 2a** over all annual operating conditions. The overall performance of the CO_2 chiller allows for payback of the 47% premium in first cost over the baseline in just a few years.

Conclusion

The decision of refrigerant selection has a significant impact on system design in chiller applications, and the technology suitable to a particular refrigerant significantly affects component selections and other system elements. There are many factors to consider in selecting the best refrigerant for a particular facility and application. A qualitative analysis using a decision matrix is an effective means to facilitate the decision of refrigerant selection.

System performance should be a primary factor in refrigerant selection. A bin weather analysis for comparable systems using different refrigerants highlights the difference in energy and water use.

Ammonia has clear advantages from an energy performance standpoint, but initial costs are relatively high and safety concerns must be addressed in the design, installation, and operation of an ammonia chiller system. HFC/HFO refrigerants have a lower first cost and have fewer safety concerns, but power costs will be higher and regulatory concerns continue to cause uncertainty on which synthetic refrigerant to use. Carbon dioxide chiller systems operate efficiently with fewer safety concerns compared with ammonia. CO_2 refrigerant is not at risk of being eliminated by environmental regulations like HFCs, but current installed costs are still relatively high. As carbon dioxide systems are now being more widely used, costs are coming down.

Author Bio

JOHN COLLINS, PE, DIRECTOR OF INDUSTRIAL SALES

Bio: John Collins joined Zero Zone in 2014 and is currently the Director of Industrial Sales. He leads business development and sales for industrial packaged refrigeration systems. John is a longtime IIAR member and has served in the code committee as chairman from 2006-2013, and currently the standards committee, where he is chairman of the IIAR CO_2 Task Group for the CO_2 Standard. He is a former IIAR Board of Directors member and 2013 member of the year.

Credentials: John Collins is a registered professional engineer with over 30 years of experience in refrigeration systems. He graduated from the University of Wisconsin - Madison with a Bachelor of Science in Mechanical Engineering.

Acknowledgments

The author would like to thank **Adam Ciesielski**, Zero Zone Systems Engineering Manager, and **Masood Ali**, Zero Zone Global Refrigeration Manager, for their invaluable assistance in developing the material presented here and reviewing this manuscript.

References

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). (2009). Climatic Design Information. *ASHRAE Handbook—Fundamentals*, Atlanta, GA: ASHRAE.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). (2019). Coefficient of Performance. ASHRAE Terminology, ASHRAE Technical Committee (TC) 1.6. 2019, ASHRAE, Atlanta, GA.

Bitzer. (2019). Bitzer Software ver 6.12.0, 2019. Bitzer Kühlmaschinenbau GmbH, Sindelfingen, Germany.

Natural Resources Canada CanmetENERGY. (2013). Comparative Study of Refrigeration Systems for Ice Rinks. Ottawa.

Nelson, C. (2019). The Catch 22 of R22 Replacements. *IIAR Condenser*, August 2019, pp. 30-38.

Scott, D. (2016). Comparing Evaporative and Air-Cooled Condensing in Ammonia and HFC-507 Refrigeration Systems. IIAR Conference, 2016. IIAR, Alexandria, VA.