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A Four-Way Comparison of a 100-Ton Industrial Refrigeration System Using Two Common Refrigerants

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Author's note: For many years, we have seen comparisons between different refrigerants. Most of these examinations have focused on the refrigerant itself and not its actual usage in a complete system. To achieve a more comprehensive understanding of the costs involved, I decided to completely design and price four separate central refrigeration systems to handle an identical load. These four designs gave me a basis for a total system energy comparison, and the conclusions of this article.

In order to achieve accurate initial construction costing, all the physical characteristics of the refrigeration systems must be taken into account, not just the refrigeration load. I selected a 100-ton –20° F storage freezer as the basis of design. A reverse load calculation was performed, allowing the size and shape of the cold storage facility to be determined. The building was chosen to be 200 feet long, 200 feet wide, and 30 feet high. All walls and ceilings were to have 6-inch urethane insulated panels, while the floor was to have 4 inches of insulation under an 8-inch concrete finished floor. No allowance was made for any refrigerated docks, cooler space, or adjacent rooms. The entire perimeter of the building was designed to experience +95° F ambient temperature. The result was a storage freezer with approximately 398 square feet per ton of refrigeration.

Because the facility is a perfect square, I elected to place the compressor room at one of the corners of the building and install four ceiling-hung evaporators blowing down isles. This allowed for the shortest and straightest pipe run between the evaporators and the remaining equipment. For simplicity and practicality, four identical 25-ton evaporators were selected for each system.

The compressor room was chosen to be 30 feet long by 20 feet wide and 18 feet high. It was assumed that this structure would be strong enough to act as the primary support for the evaporative condenser in each case.

Figure 1. Facility Floor Plan

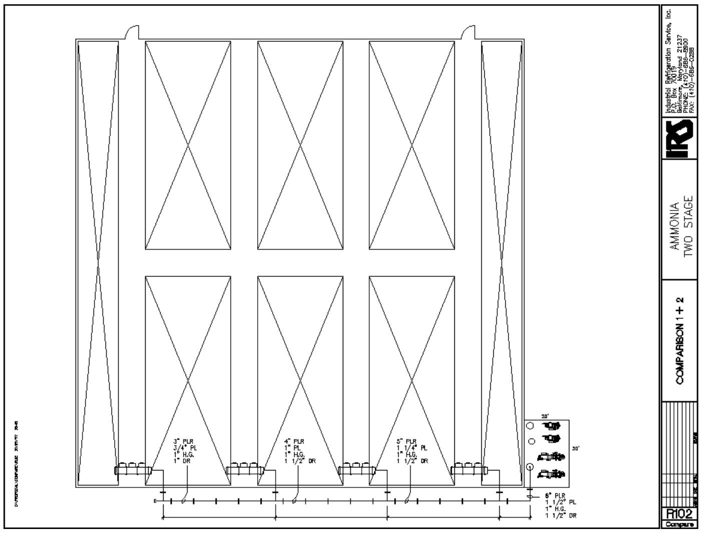


Table 1. Comparative Cost for 100 Tons Refrigeration @ –20° F Storage Temperature

Item	Ammonia Two-stage		Ammonia Single-stage		R-22 Two-stage		R-22 Single-stage	
	Price	%	Price	%	Price	%	Price	%
General Conditions	$3,611.00	0.70%	$3,611.00	0.85%	$3,611.00	0.69%	$3,611.00	0.85%
Equipment Rentals	$12,236.00	2.37%	$12,236.00	2.89%	$12,236.00	2.33%	$12,236.00	2.87%
Evaporators	$44,606.20	8.66%	$44,606.20	10.53%	$37,798.20	7.18%	$37,798.20	8.87%
Major Equipment	$221,655.60	43.02%	$158,363.05	37.38%	$204,741.40	38.92%	$137,403.15	32.23%
Evaporative Condenser	$15,366.30	2.98%	$15,366.30	3.63%	$18,411.50	3.50%	$18,411.50	4.32%
Purger/Ventilation/Detection	$14,860.30	2.88%	$14,860.30	3.51%	$18,664.50	3.55%	$18,664.50	4.38%
Pipe, Valves, & Fittings	$34,636.16	6.72%	$28,881.79	6.82%	$43,510.71	8.27%	$34,973.80	8.20%
Hangers, Hardware, & Consumables	$8,133.95	1.58%	$7,788.95	1.84%	$8,133.95	1.55%	$7,512.95	1.76%
Refrigerant Charge	$1,371.81	0.27%	$1,133.96	0.27%	$9,528.10	1.81%	$7,967.32	1.87%
Specialties & Controls	$4,757.55	0.92%	$4,757.55	1.12%	$4,757.55	0.90%	$4,795.50	1.12%
Cutting, Patching, & Identification	$1,911.30	0.37%	$1,726.15	0.41%	$1,911.30	0.36%	$1,766.40	0.41%
Insulation: Pipe, Valve, & Vessel	$42,298.15	8.21%	$34,482.75	8.14%	$37,875.25	7.20%	$33,336.20	7.82%
Control Wiring (Base System)	$15,870.00	3.08%	$15,236.35	3.60%	$15,352.50	2.92%	$13,685.00	3.21%
Freight To Jobsite	$3,530.50	0.69%	$2,771.50	0.65%	$3,565.00	0.68%	$2,725.50	0.64%
Maryland Sales Tax	$17,345.64	3.37%	$13,854.89	3.27%	$17,353.54	3.30%	$13,445.35	3.15%
Labor To Install	$73,084.80	14.18%	$63,949.20	15.10%	$88,642.00	16.85%	$77,983.80	18.29%
Totals	$515,275.26	100.00%	$423,625.94	100.00%	$526,092.50	100.00%	$426,316.16	100.00%
Price Per Square Foot (40,000)	**$12.88**		**$10.59**		**$13.15**		**$10.66**	
Price Per Cubic Foot (1,200,000)	**$0.43**		**$0.35**		**$0.44**		**$0.36**	
Price Per Ton Refrigeration (100)	**$5,152.75**		**$4,236.26**		**$5,260.92**		**$4,263.16**	

Table 2. Comparative Operating Cost for 100-Ton System @ –20 F*

Ammonia Two-Stage Pumped Liquid Recirc				**Ammonia Single-Stage Pumped Liquid Recirc**			
Item	Qty	H.P.	TOTAL	Item	Qty	H.P.	TOTAL
Evaporator	2	5.0	10.0	Evaporator	2	5.0	10.0
Evaporator	2	5.0	10.0	Evaporator	2	5.0	10.0
Evaporator	2	5.0	10.0	Evaporator	2	5.0	10.0
Evaporator	2	5.0	10.0	Evaporator	2	5.0	10.0
Refrig. Pump	1	2.0	2.0	Refrig. Pump	1	2.0	2.0
Full Oil Pump	2	1.5	3.0	Full Oil Pump	0	0	0.0
Booster Screw	2 52.	9	105.8	Booster Screw	0	0	0.0
High Stage Screw	2	74.8	149.6	High Stage Screw	2	137.7	275.4
Condenser Fan	2	5.0	10.0	Condenser Fan	2	5.0	10.0
Condenser Pump	1	2.0	2.0	Condenser Pump	1	2.0	2.0
Pan Heaters	1	5K W	N/A	Pan Heaters	1	5K W	N/A
Total			312.4	Total			329.4
Additional H.P.			0.0	Additional			H.P. 17.0
@ 5658 Hr.S/Year				@ 5658 Hr.S/Year			
= H.P. Hr.S			0.0	= H.P. Hr.S			96,186.00
@ .7457 Kw/Hp-Hr.S				@ .7457 KW/HP-HR.S			
= Kwh			0.0	= Kwh			71,725.90
@ $0.10/Kwh				@ $0.10/Kwh			
= Annual Add Cost			$0.00	= Annual Add Cost			$7,172.59

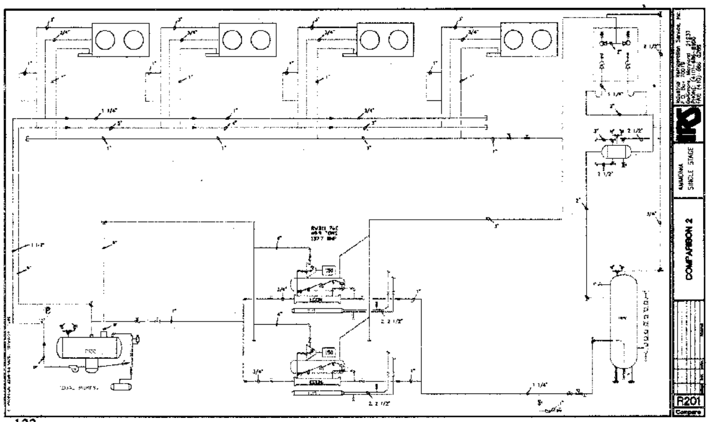
*continues on page 5

The conclusions of this research experiment were in part a surprise. Since any two-stage refrigeration system requires more equipment than its single-stage counterpart, it was probable that the initial cost of single-stage would be less. As you can see, Ammonia single-stage had a comparative installed cost of $10.59 per square foot, while the Ammonia two-stage system was $12.88. Likewise, The R-22 single-stage had a comparative installed cost of $10.66 per square foot vs. the $13.15 for two-stage. However, in each design category ammonia achieved a lower initial

System B, Ammonia Single-Stage (–31° F s.s.t./ +95° F)

- Four 25-ton hot gas defrost evaporators
- Individual defrost valve stations
- Largest "wet" suction pipe 6-inch (3,576 ft/min)
- One pumped recirculation unit (2 h.p. pumps)
- Two single-stage screw compressors (thermosyphon)
- Two 150 h.p. motors and starters (137.7 bhp each)
- One evaporative condenser
- One thermosyphon vessel
- One high-pressure receiver
- All interconnecting piping
- All pipe and vessel insulation
- All electro-mechanical controls
- All refrigeration control wiring
- 2,665 lb. ammonia charge

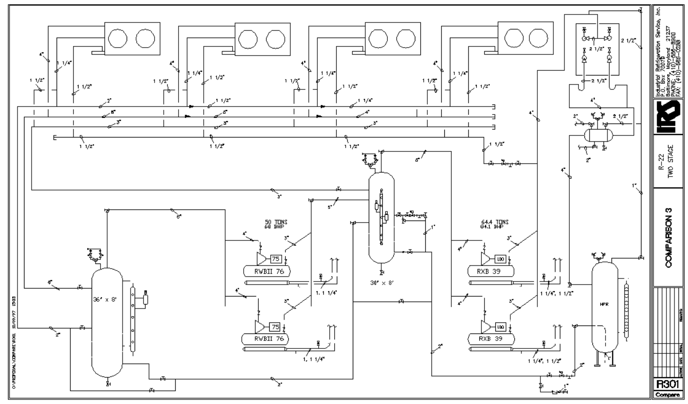
Figure 3. System B, Ammonia Single-Stage



System C, R-22 Two-Stage (–36° F s.s.t./ +95° F)

- Four 25-ton hot gas defrost evaporators
- Individual defrost valve stations
- Largest "dry" suction pipe 6-inch (3,839 ft/min)
- One suction trap
- Two booster screw compressors (thermosyphon)
- Two 75 h.p. motors and starters (68.0 bhp each)
- One gas and liquid intercooler
- Two high-stage screw compressors (thermosyphon)
- Two 100 h.p. motors and starters (84.1 bhp each)
- One evaporative condenser
- One thermosyphon vessel
- One high-pressure receiver
- All interconnecting piping
- All pipe and vessel insulation
- All electro-mechanical controls
- All refrigeration control wiring
- 5,714 lb. R-22 charge

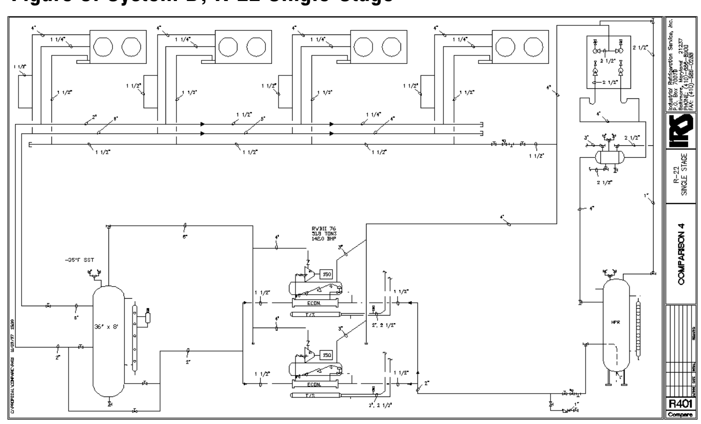
Figure 4. System C, R-22 Two-Stage



System D, R-22 Single-Stage (–36° F s.s.t./ +95° F)

- Four 25-ton hot gas defrost evaporators
- Individual defrost valve stations
- Largest "dry" suction pipe 6-inch (3,839 ft/min)
- One suction trap
- Two single-stage screw compressors (thermosyphon)
- Two 150 h.p. motors and starters (142.1 bhp each)
- One evaporative condenser
- One thermosyphon vessel
- One high-pressure receiver
- All interconnecting piping
- All pipe and vessel insulation
- All electro-mechanical controls
- All refrigeration control wiring
- 4,778 lb. R-22 charge

Figure 5. System D, R-22 Single-Stage



The comparative analysis is demonstrated best by the following spreadsheets. The first shows the percentage of cost for various items within each system and tabulates the cost per system, the cost per square foot and the cost per ton installed.

With the physical layout complete, I selected the installation criteria. It is not unusual to install a variety of refrigerants in a large central system using steel pipe. Ammonia requires it, and as the pipe size increases it becomes practical to use for other CFC and HFC refrigerants. Therefore, all the field-installed piping was to be steel. The installation would follow ANSI/ASHRAE 15 Safety Code, and conform to the B31.5 Piping Code.

To complete the basic design criteria, screw compressors were selected using thermosyphon oil cooling. From my experience, the vast majority of cold-storage warehouses do not have sufficient numbers of maintenance personnel to handle the annual tear downs and increased attention required for most reciprocating compressors. The screw compressors appear to be the ideal choice for a high-compression-ratio, low-maintenance application.

For years I have been telling people that any time the saturated suction temperature drops below –20° F, a two-stage system should be considered. So I decided to compare single-stage refrigeration with two-stage under this controlled environment.

The choice of the refrigerants to compare was easy. Ammonia is still the most efficient refrigerant for most of the industrial applications, with R-22 as runner-up. Even though R-22 will be phased out, none of the replacement refrigerants, as yet, seem as efficient or practical for large central systems.

The four comparisons were set: Ammonia single-stage, Ammonia two-stage, R-22 single-stage, and R-22 two-stage. However, since this article was to compare initial cost as well as operating cost, I added one wrinkle to the design. By necessity, ammonia at low temperatures requires a refrigerant feed of either flooded or pumped recirculated. R-22 can and often does use direct expansion (thermal expansion) as a liquid supply method. This would have a tendency to drive down the initial cost and favor R-22. Nevertheless, it is not unusual for industrial refrigeration contractors to compete against packaged equipment using TXVs, so I elected to keep these parameters. The ammonia-recirculated systems would use a 10° F T.D., while the R-22 DX systems would use a 15° F T.D. Both values are common in the industry but are often adjusted to suit. For this comparison I would not adjust either value up or down.

The initial construction costs were all compiled using the same estimating methodology. Suppliers submitted their pricing on individual pieces of equipment and alternates, not knowing the purpose of their proposals. Each system was completely designed with accurate line sizes, best-match compressor equipment, proper pipe and vessel insulation, correctly sized vessels, and best-match condenser and evaporator equipment. The piping circuit was then analyzed and a complete system refrigerant charge calculated. The labor total was generated by proven methods using the prevailing wage scale.

All estimates were arrived at in 1995 and therefore reflect 5-year-old pricing. The values presented here should not be used for estimating, but the percentages and conclusions are still accurate. It is important to note the following are not included:

- general construction
- under-floor warming
- power wiring
- computer control

These prices are for the refrigeration system only. They do include a basic electro-mechanical control system and control wiring. The term "computer control" encompasses too wide a variety of options and services for inclusion in this article.

System A, Ammonia Two-Stage (–31° F s.s.t./+95° F)

- Four 25-ton hot gas defrost evaporators
- Individual defrost valve stations
- Largest "wet" suction pipe 6-inch (3,576 ft/min)
- One pumped recirculation unit (2 h.p. pumps)
- Two booster screw compressors (thermosyphon)
- Two 60 h.p. motors and starters (52.9 bhp each)
- One gas and liquid intercooler
- Two high-stage screw compressors (thermosyphon)
- Two 75 h.p. motors and starters (74.8 bhp each)
- One evaporative condenser
- One thermosyphon vessel
- One high-pressure receiver
- All interconnecting piping
- All pipe and vessel insulation
- All electro-mechanical controls
- All refrigeration control wiring
- 3,223 lb. ammonia charge

Figure 2. System A, Ammonia Two-Stage

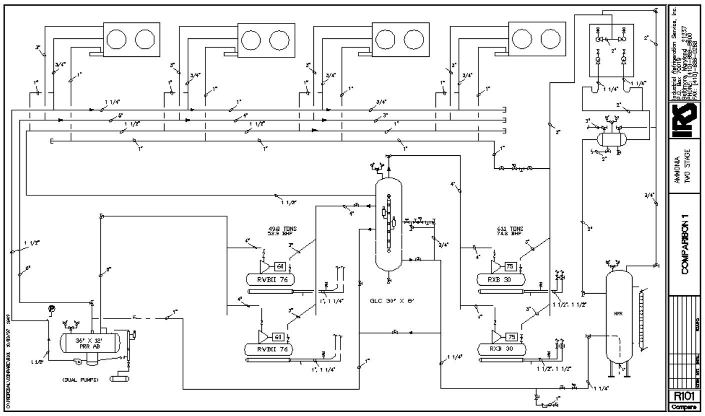


Table 2. continued

R-22 Two-Stage Thermal Expansion				**R-22 Single-Stage Thermal Expansion**			
Item	Qty	H.P.	TOTAL	Item	Qty	H.P.	TOTAL
Evaporator	2	5.0	10.0	Evaporator	2	5.0	10.0
Evaporator	2	5.0	10.0	Evaporator	2	5.0	10.0
Evaporator	2	5.0	10.0	Evaporator	2	5.0	10.0
Evaporator	2	5.0	10.0	Evaporator	2	5.0	10.0
Refrig. Pump	0	0.0	0.0	Refrig. Pump	0	0.0	0.0
Full Oil Pump	2	1.5	3.0	Full Oil Pump	0	0	0.0
Booster Screw	2	68.0	136.0	Booster Screw	0	0	0.0
High Stage Screw	2	84.1	168.2	High Stage Screw	2	142.1	284.2
Condenser Fan	1	15.0	15.0	Condenser Fan	1	15.0	15.0
Condenser Pump	1	2.0	2.0	Condenser Pump	1	2.0	2.0
Pan Heaters	1	5KW	N/A	Pan Heaters	1	5KW	N/A
Total			364.2	Total			341.2
Additional H.P.			51.8	Additional H.P.			28.8
@ 5658 Hr.S/Year				@ 5658 Hr.S/Year			
= H.P. Hr.S			293,084.40	= H.P. Hr.S			162,950.40
@ .7457 Kw/Hp-Hr.S				@ .7457 Kw/Hp-Hr.S			
= Kwh			218,553.04	= Kwh			121,512.11
@ $0.10/Kwh				@ $0.10/Kwh			
= Annual Add Cost			$21,855.30	= Annual Add Cost			$12,151.21

cost. Due to the requirement of a pumped recirculation package for ammonia it was assumed R-22 would achieve a lower construction cost, but this was not the case. I attribute this to the cost of the refrigerant charge and relatively minor changes in equipment. The actual system h.p. was 17% greater for R-22 Two-stage than Ammonia Two-stage, and 4% more for R-22 Single-stage vs. Ammonia Single-stage.

Any critical review of this comparison should point out the lower saturated suction temperature used in the R-22 models. This would, of course, bring the cost of the R-22 systems closer to their ammonia counterparts. It would not, however, make the R-22 systems any less expensive than ammonia. There would still be higher pricing for: piping, pipe insulation, valves, refrigerant charge, and labor to install. In this case, the compressor model numbers would be identical to the ammonia system, but the evaporators would have to increase to compensate for lowering the T.D. from 15° to 10° F. The R-22 systems would remain a more expensive option from a pure initial cost standpoint. The final standings listed from least cost to most are as follows: Ammonia single-stage $4,236.26 per ton, R-22 single-stage $4,263.16 per ton, Ammonia two-stage $5,152.75 per ton, and R-22 two-stage at $5,260.92 per ton.

For an accurate energy cost evaluation of the four systems, I used the system with the least bhp as the base and compared it to the remaining three models. Ammonia two-stage achieved the lowest comparative system operating bhp of 312.4. Ammonia single-stage was second with 329.4 bhp, followed by R-22 Single-stage with 341.2 and R-22 Two-stage with 364.2 bhp. I attribute the last place standing of the R-22 two-stage system to the finite number of compressor selections. Most of the compressor selections were running between 97%–100% of full load, whereas the 364.2 bhp system's high-stage equipment was operating at only 90% of full load.

I then calculated the additional annual energy cost for each system over the base. I used a very conservative 5,658 hours of 100% operation per year (65% of 8,760) at a combined electrical rate of $0.10 per kwh. The comparative results show Ammonia single-stage will cost an additional $7,172.59 per year in electric cost over the base line Ammonia two-stage system. R-22 single-stage will cost an additional $12,151.21 per year, and R-22 two-stage will cost an additional $21,855.30 per year.

The actual payback of any system compared to another due to energy savings will depend upon: the actual hours of operation, the refrigeration loads imposed upon it, the weather, the actual cost of electric power, methods of operation (lead/lag, sequencing, defrost on demand, defrost termination, etc.), and the end user's commitment to maintain an efficient operation, (strict door policing polices, preventive maintenance, cleanliness, and common sense). If the ammonia two-stage system is selected for its lowest energy cost, the initial construction cost difference will be paid back as follows: Ammonia single-stage, 8.25 years; R-22 two-stage, immediate; and, R-22 single-stage,

Table 3. Summary of Four-way Comparison in 1995 Dollars

Refrigerant	System	Liquid Feed	S.S.T.	Bhp	Bhp/Ton	$/Sq. Ft.	$/Ton
Ammonia	Two-stage	Pump Recirc	–30	255.4	2.55	$12.88	$5,152.75
Ammonia	Single-stage	Pump Recirc	–30	275.4	2.75	$10.59	$4,236.26
R-22	Two-stage	Direct Expansion	–35	304.2	3.04	$13.15	$5,260.92
R-22	Single-stage	Direct Expansion	–35	284.2	2.84	$10.66	$4,263.16

Refrigerant	System	Liquid Feed	S.S.T.	C.R.	Lbs./Min	Charge	$/Lb.
Ammonia	Two-stage	Pump Recirc	–30	14:1	44.24	3,224	$0.42
Ammonia	Single-stage	Pump Recirc	–30	14:1	44.24	2,665	$0.42
R-22	Two-stage	Direct Expansion	–35	11.4:1	316.96	5,714	$1.67
R-22	Single-stage	Direct Expansion	–35	11.4:1	316.96	4,778	$1.67

4.73 years. Note that as the system size increases, the duration of the payback will drop.

In summary, ammonia is still the most efficient refrigerant for this industrial application. The refrigeration system will cost less to install and provide continuing economy of operation. The lower mass flow experienced with ammonia, combined with the lower bhp/ton more than compensate for the smaller compression ratio of R-22. Any new construction or refrigeration addition involving a –30° F or below saturated suction temperature should consider a two-stage system for economy. With the high compression ratios available in today's screw compressor packages, it can be tempting to install a single-stage system for a low temperature application. The consumer should be made aware of the options available and make a decision based on the continuing cost of operation, not just the initial installation price.

Mark Broomer welcomes comments on the above material. He can be reached at Industrial Refrigeration Service, Inc., P.O. Box 70019, Baltimore, MD 21237, or by e-mail at irsmd@aol.com.

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