THERMAL STORAGE APPLICATIONS OF THE ICE MAKER HEAT PUMP

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The high energy efficiency of the ice-maker heat pump makes it an attractive source of heating and cooling for buildings at current electric rates. When combined with heating storage and cooling storage which make it possible to take advantage of time-of-day or interruptable rates, no system on the current market can beat it. The designs of ice storage structures are discussed. The design of radiant/convector panels for use as a heat source and sink are examined from performance and cost standpoints.

INTRODUCTION

The dramatic increase in the price of energy since 1973 has revived interest in a number of old but still valid ideas of how to utilize energy in a more efficient manner. The ice-maker heat pump is a prime example of already-existing, energy efficient equipment that could be used to provide heat for space heating and water heating. The ice that is formed as a by-product during operation of the heat pump in the heating cycle can be discarded, sold, or stored for later use, as dictated by energy policy considerations or economics.

The greatest overall energy efficiency of the ice-maker heat pump system is realized when the harvested ice is stored and used to cool the building in the summer months. When the seasonal heating and cooling loads of a building are balanced in this manner, an Annual Cycle Energy System (ACES) results. In this paper, different modes of operation of an ice-maker heat pump system are examined with respect both to their energy savings and to their rate of return on investment. Particular attention is given to those systems which not only provide a reasonable rate of return based on current energy price levels, but which also offer flexibility in attaining even greater energy and cost savings as economic conditions and energy policies change. Applications of the ice-maker heat pump that are today only marginally economic may become much more attractive as higher energy costs and new utility rate structures come on the scene.

ICE-MAKER HEAT PUMP

The ice-maker heat pump is a unidirectional heat pump that extracts heat energy from water to form ice on the evaporator side. The heat that is extracted can be used for space heating or water heating, or it can be dissipated to the ambient air on the high side of the machine. If both the heating and cooling outputs of the heat pump are utilized, the combined coefficient of performance (COP) of a typical system, employing small hermetic compressors now on the market, can be as high as 5. The combined heating and cooling COP of such a system is defined as:

$$\text{Combined COP} = \frac{\text{heat of rejection + heat of absorption}}{\text{electrical input}}$$

Utilization of the ice to provide space cooling is especailly attractive because it not only saves energy, but also allows a portion of the building load to be deferred or stored. The

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*Research sponsored by the Energy Research and Development Administration and Department of Housing and Urban Development, under Union Carbide Corporation's Contract with the Energy Research and Development Administration.

ice can be made at night, on weekends, or on cool days, and used later on hot days when peak utility loads occur. Thus, the ice-maker heat pump system provides the potential for needed energy management.

In conceptualizing an ice-maker heat pump design, it should be realized that existing ice cube makers do not meet the special requirements of the ice-maker heat pump. Most ice cube makers on the market strive to produce "dry" shapes of ice that are of food quality. The objective is to obtain the greatest output of ice per dollar of investment and energy efficiency is not a primary goal. Furthermore, the need for producing food-grade, dry, shaped ice tends to make the evaporator design complicated and expensive. The ice-maker heat pump system should have the following characteristics:

1. Maximum heating output at the condenser with none of the high-side output used for harvesting the ice.
2. High evaporator temperature in order to improve the COP to the extent possible [typical evaporator temperature should average 20 F (-6.7 C) or higher].
3. Harvesting of the ice should be accomplished by means of the warm liquid that comes from the condenser.
4. The system should be simple, foolproof, and should utilize the compressor in its design range of temperatures in order to maximize its life and reduce maintenance.
5. The system should be capable of automatically converting from a water chilling function as the temperature of the water over the evaporator decreases.

There are two basic types of ice-maker heat pumps that have a potential market. The first is a small 2 — 5 hp (1.5 — 3.7 kw) ice-maker heat pump for residential and apartment use to replace the conventional gas furnace, air-to-air heat pump, or electric furnace. This unit must cycle in order to satisfy the room thermostat during the heating season and the hot water heater thermostat during the rest of the year. The second type is a 7-1/2 hp (5.6 kw) to 1,000 hp (746 kw) ice-maker heat pump for application in large commercial buildings. This unit will be tied into multiple fan coil units and other types of HVAC systems. In general, these units will run continuously with modulated output or will be used with storage of both heating and cooling outputs. Fig. 1 shows the schematic for the simple ice-maker heat pump. Fig. 2 is a photograph of an ice-maker heat pump on test at Oak Ridge.

Maintenance on ice-makers has traditionally been high largely because of water conditions. In the ice-maker heat pump, the same water will be used year after year. If necessary, the initial charge of water can be softened or even demineralized to eliminate liming and corrosion on evaporator surfaces. Aluminum evaporator coils tested for over a year in Oak Ridge water show no sign of corrosion or even dulling of the bright aluminum surface. Low temperature water is not a corrosive environment for most commonly used evaporator materials. With only one solenoid valve to operate, the cycling ice-maker heat pump should find widespread use in residential and small commercial applications such as ACES, load management, and in commercial applications where ice is the desired product. The schematic of such a complete system is shown in Fig. 3.

The large ice-maker heat pump must be efficient and reliable to meet the needs of commercial, industrial, and large residential applications where both the heating and cooling output of the equipment can be utilized. The most promising application is load management for commercial buildings. Load management will allow the use of off-peak electricity at time-of-day rates, to defer electrical loads to more desirable off-peak hours. The advantages of operation during off-peak hours are: lower electrical energy rate, lower demand charges, and improved operating conditions resulting from lower ambient temperatures. The lower ambient temperature results in a cooling COP of the ice-maker heat pump that is only slightly less than that of an on-peak air conditioner of conventional design.

A successful ice-maker heat pump of this larger size has been built by Turbo Refrigeration Company of Denton, Texas. It is a 30 hp (22.4 kw) machine operating 12 ice freezing plates, each having 19 ft^2 (1.77 m^2) of active surface. The 12 plates are divided into 6 groups, and ice is harvested from each group of 2 plates for 2 min out of 18. The plate groups are harvested in sequence so that the machine experiences a uniform and continuous load.

The warm liquid from the receiver which is diverted through the plates being harvested becomes subcooled as the ice is harvested. The refrigeration system uses R-22 in a pumped recirculating system with all the liquid refrigerant being supplied by the group of plates being harvested.

An experimental test procedure is currently being devised to obtain reliable performance data. Preliminary tests indicated that a COP of 3.4 was obtained. The schematic of this system is shown in Fig. 4.

The ice-maker heat pump in larger sizes can operate continuously by modulation, especially if connected to a screw compressor with its smooth unloading curve. The ice-maker heat pump as built is an excellent water chiller as long as water temperature over the plates exceeds 45 F (7.2 C). No ice is formed under these conditions and the COP is high because the evaporator temperature is above 32 F (0 C). This makes it possible to use the same piece of equipment to make ice on off-peak hours, weekends, and on cool periods of the day or week for storage cooling, while retaining the ability to operate as a high performance chiller during peak load periods.

The larger ice-maker heat pumps will be controlled by a repeat cycle timer once the evaporator temperature drops into the ice freezing range.

ICE STORAGE STRUCTURES

The ice storage bin must be considered to be an integral part of the ice-maker heat pump system because the heating and cooling outputs of the machine occur simultaneously whereas the heating and cooling demands of the building are separated in time. Furthermore, the ratio of the building's annual heating to cooling requirements varies with its geographical location while the heating and cooling supply from the machine remains at a constant ratio. Each cubic foot of an ice storage structure can accommodate a quantity of ice and water equivalent to about 1/2 ton-hr. [1 ton-hr = 12,000 Btu (12.66 MJ).] For a 36 ton-hr load, therefore, the required capacity of the storage bin is about 72 ft^3 (2.04 m^3).

Small ice storage bins can be constructed from plywood and blocks of foam insulation and can be provided with a vinyl liner for water tightness, much like an aboveground swimming pool. Larger bins can be constructed from lumber, concrete, steel, or prefabricated panels that have been insulated. All bins should be watertight so that when the ice is melted the water can be reused. The reuse of the water helps to reduce the water costs and eliminates problems of corrosion caused by the use of fresh water. Typical sidewall specifications for wooden tanks constructed from treated lumber and plywood are:

1. 4 ft deep (1.22 m) tank = 2 in. (50.8 mm) x 4 in. (101.6 mm) studs on 16 in. (406.4 mm) centers with 1/2 in. (12.7 mm) plywood,
2. 6 ft deep (1.83 m) tank = 2 in. (50.8 mm) x 6 in. (152.4 mm) studs on 16 in. (406.4 mm) centers with 5/8 in. (15.9 mm) plywood,
3. 8 ft deep (2.44 m) tank = 2 in. (50.8 mm) x 8 in. (203.2 mm) studs on 12 in. (304.8 mm) centers with 3/4 in. (19.1 mm) plywood liner.

The wooden tank should also be equipped with a vinyl liner and insulation should be applied between the studs.

Fig. 5 shows an artist's conception of a residence equipped with an ice-maker heat pump. The indoor unit contains the heating and cooling coil and blower, as well as the compressor and the hot water heating condenser coil which is connected to the domestic hot water storage tank. The outdoor units consists of an outdoor condenser and a ice freezing mechanism.

Fig. 6 shows a modular concrete tank that was developed to store liquid manure on dairy farms in order to meet EPA standards. It has 150 psf (735 kg/m^2) live load capability so that it could be located under a building parking lot or even under a lawn. The tank modules are 4 ft (1.22 m) wide, and the two depths available are 8 ft (2.44 m) and 10 ft (3.05 m). The larger tanks insulated and installed should cost from 65¢ — 95¢/ft^3 (\$22.9 — \$33.54/m^3).

Fig. 7 shows a basement type ice-storage bin. This can possibly be the least expensive system if the building can be designed with the ice bin as part of the original plan. The Richmond demonstration home now under construction will use an all-weather wood foundation which incorporates the insulation and vinyl liner to yield an ice bin occupying less than one-half of the basement space.

Other options include a tank made from prefabricated steel panel segments which can be bolted together to form a cylindrical shell. The insulation panels are laid against the inside of the tank before the vinyl liner is installed to make an inexpensive insulated ice bin.

The recently finished ACES demonstration house near Knoxville incorporated a foundation made with Foam Form which also serves as the insulated walls of the ice bin. A vinyl liner is provided to make the bin watertight. This system utilizes molded polystyrene blocks which are used as the forms into which the concrete is poured.

The amount of insulation required for the ice bin varies with the job. In Atlanta, good insulation is required to preserve as much as possible of the ice that is formed, but in Madison, Wisconsin weather conditions would allow less insulation because of the reduced air conditioning requirements.

The idea of building heat storage capacity in the basement of a building may be new in the U.S. but it is old hat in Japan where, according to Masanosuke Yanagimachi, President of Yanagimachi Laboratories Ltd. in Tokyo (speaking at ASHRAE conference in Atlantic City January 27, 1975), there are approximately 50,000,000 ft^2 (4,645,000 m^2) of buildings equipped with thermal storage systems. The storage volumes are as large as 1,300,000 gal (4,921 m^3). These tanks serve as a heat source and a heat sink for commercial buildings and have been in use for many years. They serve an additional purpose in Japan by adding seismic stability to the buildings.

ICE BIN HEAT LEAKAGE

There are two general statements that can be made about ice bins that are almost axiomatic. One is that as the size goes up, the cost per unit volume decreases; and second is that as size goes up, the heat leakage into the bin per unit volume goes down. Both of these assumptions are true because the surface-to-volume ratio is more favorable for large tanks.

In a detailed study of heat leakage, one needs to consider the top, sides, and bottom of the bin as separate problems since each obeys a different set of rules.

The heat leakage through the roof of the bin is the classic case of downward heat flow from still air through a slab where the upper surface is warm and the lower surface is cold. The heat leakage into the bin through the roof or top cover can be held to a low value by insulating the underside with a 2 in. urethane foam board that has reflective foil on the downside. The general practice would be to have at least 4 in. (10 cm) of air space between the roof of the bin and the surface of water or ice. The resulting conductance is so low that in mid summer, with an average air temperature of 75 F (24 C), the resulting heat leakage is 1.91 Btuh ft^2 (21,690 J/m^2 hr). This leakage would vary with the month and approach zero in the winter months. Heat leakage should be calculated on a monthly basis and should be subtracted from the ice storage so that a true picture of ice remaining for cooling can be obtained.

The problem of calculating heat leakage through the sides and bottom of the bin is more complicated because soil conductivities vary greatly with location and ground temperatures vary with the time of year.

HETRARZ — a computer program for calculating heat transfer in RZ geometry has been used to calculate the temperature pattern around a round ice bin 40 ft (12.2 m) in diameter and 10 ft (3.05 m) deep where surface temperatures varied between 40 F (4.4 C) and 70 F (21.1 C). The soil conductivity was conservatively taken to be 1.0 Btu/ft-hr F (1.73 w/m-K).

Fig. 8 shows how the size of the tank affects the average monthly heat leakage expressed as percent of the total heat storage capacity of the tank.

SOLAR ENERGY COLLECTOR PANEL

The ice-maker heat pump system may, in some applications, require a solar radiant/convector panel to act as a supplementary heat source and sink in order to compensate for imbalances in the heating and cooling seasons. In northern parts of the U.S., more ice would be produce by the heat pump than could be utilized for summer air conditioning. The excess ice could then either be discarded and allowed to melt naturally or it could be melted in the bin by energy collected by the radiant/convector panel. Discarding the ice could be difficult because of lack of available space and, in any case, it would deplete the inventory of water in the bin, thereby raising costs.

Unglazed panels, of the type manufactured by Fafco of Menlo Park in California for use as solar swimming pool heaters, could be used to collect the solar energy and transfer it to the ice bin. Collection efficiencies of 80 — 85% are probably obtainable even on cold [32 F (0 C)] winter days. The energy collected can exceed that from solar radiation alone because the panel is also heated by the ambient air. The cost of these panels is about $2.60/ft^2$ ($27.99/m^2$). During the summer, the radiant/convector panel can be used alternatively to dissipate heat from the compressor which is operated at night to take advantage of lower rates during off-peak hours.

The radiant/convector panels need not be located on the roof of the building, as is traditionally done. They may be formed into a solar fence with vertical panels. These panels can intercept the winter sun, even when it is at its lowest elevation, at reasonable efficiencies. A north-to-south running fence has active collecting surfaces on both its east and west sides and would collect about 85% as much energy as an east-to-west running fence. Fig. 9 shows an artist's conception of a solar fence used to screen a parking lot.

COMPARISON OF THE ALTERNATIVE HEAT PUMP SYSTEMS

Operating Characteristics

In comparing the air-to-air, water-to-air, and ice-maker heat pump systems for providing space heating of buildings, it should be noted that the energy used by the indoor blower is recoverable as useful heat in the indoor air circuit, whereas the energy expended to circulate air or pump water through the evaporator is lost as the kinetic energy of these fluids and as frictional losses of the fans and pumps. The mass flow rates of the heat source fluid that are required for three types of heat pumps are listed in Table 1 together with characteristics operating data for each system. The ice-maker heat pump is attractive because: (1) it has a low mass flow requirement; and (2) it produces solid ice, a valuable and storable commodity.

Economic Comparison

Ice-maker Heat Pump. The cost of operating the ice-maker heat pump to supply space heating requirements of a building is comprised of two components. These components are: the cost of the power needed to operate the compressor, fans, and pumps; and the cost of the water that must be supplied to the ice-maker. (For the present, the economic value of the ice that is formed during operation of the heat pump will be neglected.) For the ice-maker heat pump under consideration, the total power required for delivering 10^6 Btu (1.055 GJ) at the register is 105 kwh and the amount of water that must be frozen is 455 gal (1.72 m^3). Assuming electric power costs of 4¢/kWh and water costs of $1/1,000 gal ($0.26/m^3), the total operating cost of the ice-maker heat pump is seen to be $4.65 per million Btu ($4.41/GJ) of useful heat delivered to the building.

Oil-fired Furnace. The cost of delivering heat to a building by means of an oil-fired furnace having a seasonal efficiency of 50% is computed on the basis of assumed fuel costs of 40¢/gal ($88/$m^3$) and electrical power costs of 4¢/kwh. The energy consumption of the furnace per million Btu (1.055 GJ) of delivered heat is 18.7 kwh electrical energy for the burner and the blower and 13.87 gal (.063 m^3) of oil. This gives a total cost of heat delivery equal to $6.30/million Btu ($5.97/GJ).

Gas-fired Furnace. Typically, the price of natural gas is regulated at about $1.70/1,000 ft^3 ($0.06/m^3) while the unregulated price of LPG is about $4.29/1,000 ft^3 ($0.152/m^3). In this paper, the price of natural gas is taken to lie midway between these values, at $3/1,000 ft^3 ($0.11/m^3). At this price, natural gas would be approximately competitive with oil. The seasonal efficiency of the gas furnace is taken to be 50% (3). The energy consumption of the furnace per million Btu (1.055 GJ) of delivered heat is 13.3 kwh of electrical energy for the burner and blower and 954.5 ft^3 (27 m^3) of gas, which gives a total cost of $6.26/million Btu (5.93/GJ).

These considerations are summarized and shown in Table 2. From the table, it is evident that the ice-maker heat pump can deliver heat energy at lower operating costs than an air-to-air heat pump, and at a lower operating cost than an oil-fired furnace burning oil valued according to 1976 prices. The operating cost of the ice-maker heat pump is also competitive with gas-fired furnaces, where the price of natural gas is $3/1,000 ft^3 ($0.11/m^3). When the ice-maker heat pump is compared with electric resistance heating, the cost savings are even greater, as would be expected.

The operating costs listed in Table 2 do not take into account installed, first costs of equipment. However, it appears likely that the first costs of an ice-maker heat pump and a good air-to-air heat pump will be comparable because the weight and complexity of the two machines are about the same. Furthermore, the first costs of a complete, central system for providing heating, cooling, and domestic hot water to a residence is nearly independent of the type of heating system. Delene (4) reports first costs of $2,000 ± $200 for such systems, regardless of whether a heat pump, electric furnace, or an oil- or gas-fired furnace is employed. If the heat pump hot-water heating feature is added to the ice-maker heat pump, the cost increases. The cost also increases if the ice storage bin is added to provide the off-peak air conditioning feature together with solar heat exchangers.

DOMESTIC HOT WATER PRODUCTION

The domestic water heater is a major consumer of energy in the modern home. An average of about 2,000 Btuh (586 w) is used for this purpose, yielding a total daily energy consumption of 48,000 Btu (50.64 kJ), or about 14.1 kwh/day. On an annual basis, this amounts to 5,135 kwh which, at 4¢/kwh, costs $205.40. The ice-maker heat pump can be easily adapted to hot water production by adding a small pump, a thermostatic valve (not shown in Fig. 2) a desuperheater and a water-cooled condenser. These components add an incremental cost of approximately $125 to the ice-maker heat pump but make it possible for the system to deliver hot water [at 120 F (48.9 C)] at substantially lower energy costs.

The 120 F (48.9 C) temperature of the hot water produced is satisfactory for most modern appliances such as dishwashers which have resistance heaters to accomplish sterilization at the end of the washing cycle. The highest water temperature that can be tolerated in a tub or shower is 110 F (43.3 C). This temperature represents the actual, minimal, hot water temperature required in household use. When the heat pump is operated in the space heating mode, the hot water condenser acts as a desuperheater due to the fact that the thermostatic valve is set to open at 120 F (48.9 C) and the normal space heating condensing temperature is only 105 F (40.6 C).

For a typical 30,000 Btuh (8.8 kw) heat pump, about 6,000 Btuh (1.8 kw) would be transferred to the hot water heater storage tank when space heating is required. After the tank is completely charged with 120 F (48.9 C) hot water, the heat transfer to the tank drops sharply because only the highest temperature superheated gas could transfer heat to the circulating 120 F (48.9 C) water. During the normal space heating months of December, January, and February, the transfer of heat from superheated gas to the hot water would normally be sufficient to provide all domestic hot water needs. During the spring and fall months when neither heating nor cooling of the building is required, hot water is supplied by operating the compressor solely for this purpose. This would require raising the compressor condensing temperature from its normal 105 F (40.6 C) value to 120 F (48.9 C).

The increase in head pressure will reduce the COP of the heat pump, but during hot water heating the indoor fan motor is not running and the resulting COP for water heating is approximately the same as for space heating, as shown in Table 1. The energy required to heat water using the ice-maker heat pump system is 5.05 kwh/day, as compared to the 14.1 kwh/day rate of consumption using electric resistance heating. On an annual basis this amounts to 1,840 kwh which costs $73.60 at 4¢/kwh. Thus, the ice-maker heat pump effects an annual savings of $132/yr over the electric resistance water heater. This amount is about equal to the incremental cost of adapting the ice-maker heat pump for hot water production and yields a payback period of about 1 yr. Thus, the water heating function is justified both economically and as a means of conserving energy.

SUMMARY

In summary, the ice-maker heat pump has been shown to be a simple and practical application of refrigeration technology for extracting not only the sensible heat, but also the latent heat of fusion from water. Harvesting the ice is accomplished without thermodynamic penalty by using the enthalpy of liquid from the condenser to provide the heat for harvesting. The COP of the heat pump is good and the performance of the heat pump is unaffected by drops in ambient temperature.

The ice-maker heat pump compares favorably with the oil-fired furnace, the gas-fired furnace, and the air-to-air heat pump at oil and electricity prices currently prevailing on the Eastern Coast of the U.S. as well as at de-regulated gas prices, where they exist.

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3. E. C. Hise and A. S. Holman, "Heat Balance Efficiency Measurements of Central, Forced-Air, Residential Gas Furnaces," *ORNL/NSF/EP-88* (October 1975).
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Table 1. Comparison of Typical Heat Pump Operating Parameters

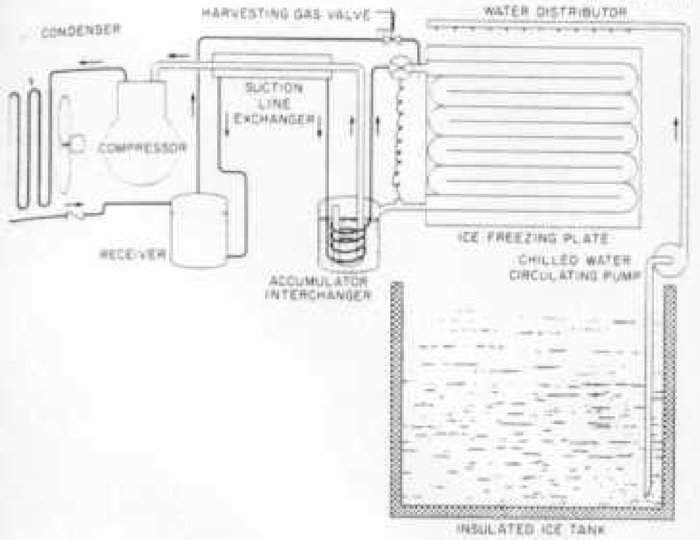
	Air-to-Air[a]	Water-to-Air[b]	Ice-Maker
Heating capacity, Btuh (kw)	30,000 (8.8)	30,000 (8.8)	30,000 (8.8)
Total power, w	3,900	3,800	3,160
Instantaneous COP with indoor fan	2.25	2.31	2.78
Indoor-fan power, w	400	400	400
Outdoor fan or pump power, w	400	400	160
Heat from evaporator, Btuh (kw)	16,693 (4.9)	18,264 (5.4)	19,636 (5.8)
Mass flow outdoor coil, lb/h (kg/h)	11,316 (5133)	2,199 (997)	136 (62)
Energy removal, Btu/lb (J/g)	1.58 (3.7)	8.30 (19.3)	144 (335)
Inlet temperature, F (C)	47 (8.3)	60 (15.6)	32 (0)
Fluid temperature drop, F (C)	6.6 (3.7)	8.3 (4.6)	0 (0)

[a] From Ellison, Ref 1

[b] From *Climate Master Products*, Ref 2

Table 2. Operating Cost Per Unit of Heat Delivered at the Register

Assumed cost of electricity, ¢/kwh	4.00
Assumed cost of oil, ¢/gal ($/m^3$)	40.00 (88.00)
Assumed cost of gas, $/1,000 ft^3 ($/m^3$)	3.00 (0.105)
Assumed cost of water, $/1,000 gal at 60 F ($/m^3$)	1.00 (0.26)
Operating cost for heat delivery: $/10^6 Btu ($/GJ)	
Ice-maker heat pump, (COP = 2.78)	4.65 (4.41)
Air-to-air heat pump, (Seasonal COP = 2.0)	5.86 (5.55)
Oil-fired furnace	6.30 (5.97)
Gas-fired furnace	6.36 (5.93)
Resistance electric heat	11.72 (11.11)



ig. 1 Schematic drawing f the ice-maker heat pump

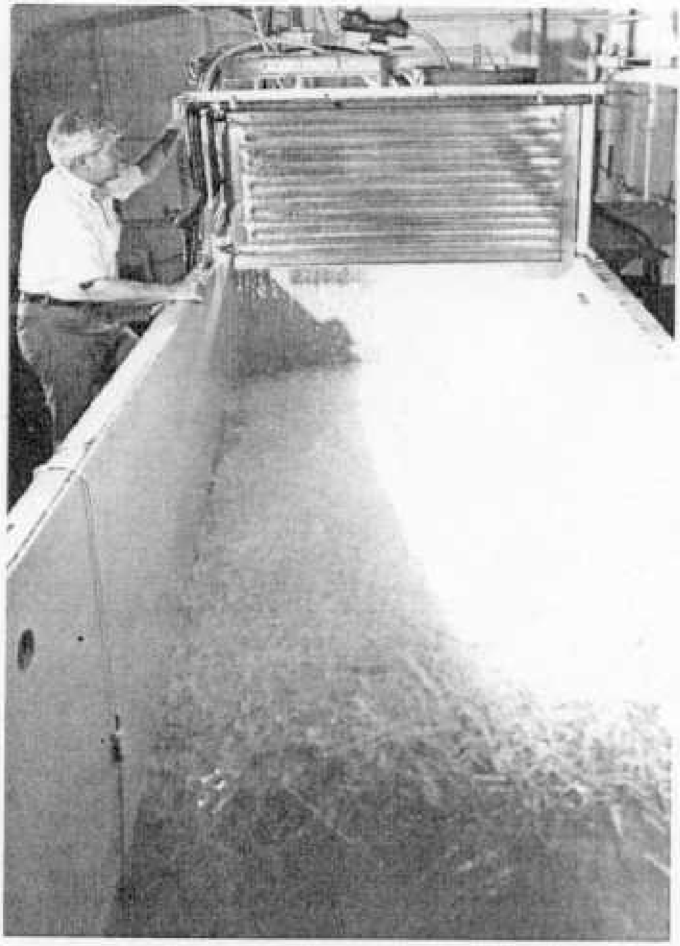


Fig. 2 Ice-maker heat pump test at the Oak Ridge National Laboratory

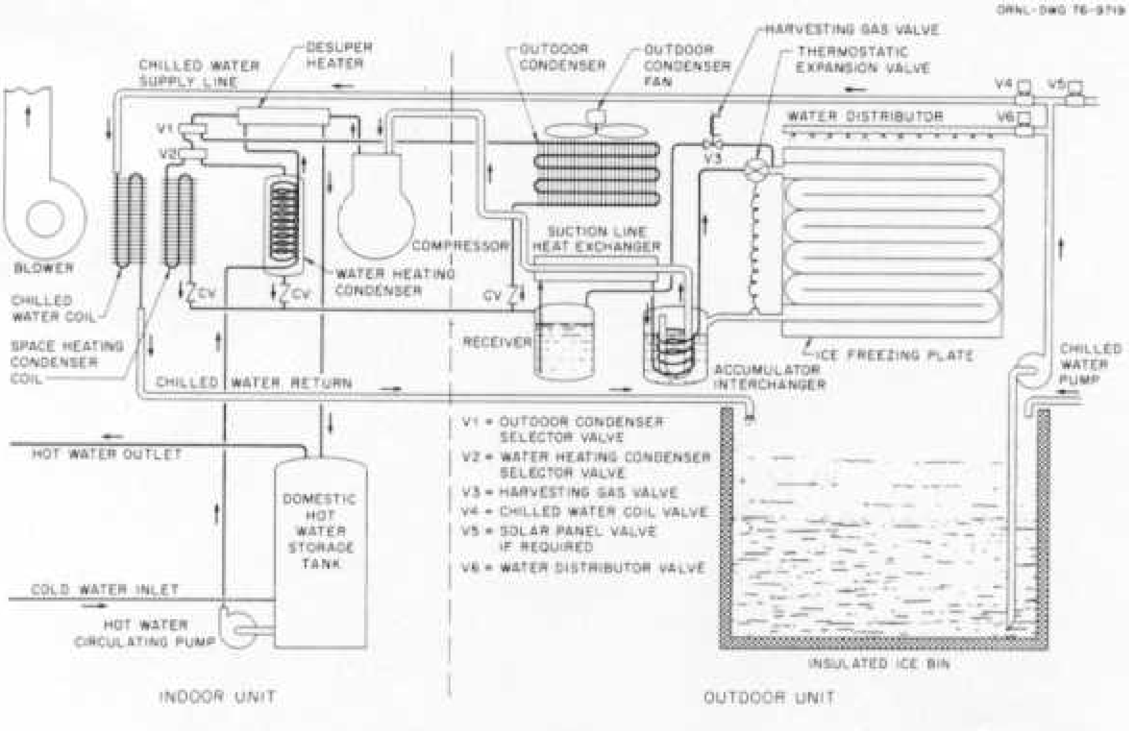


Fig. 3 Schematic drawing of the ACES ice-maker heat pump

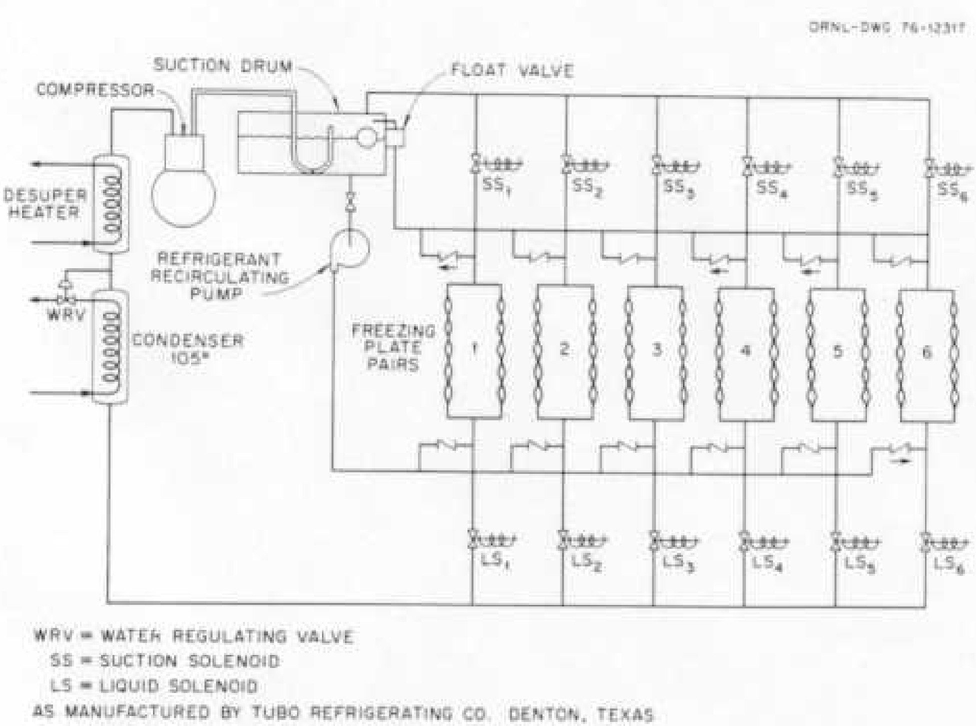


Fig. 4 Piping schematic for 12 plate ice-maker heat pump

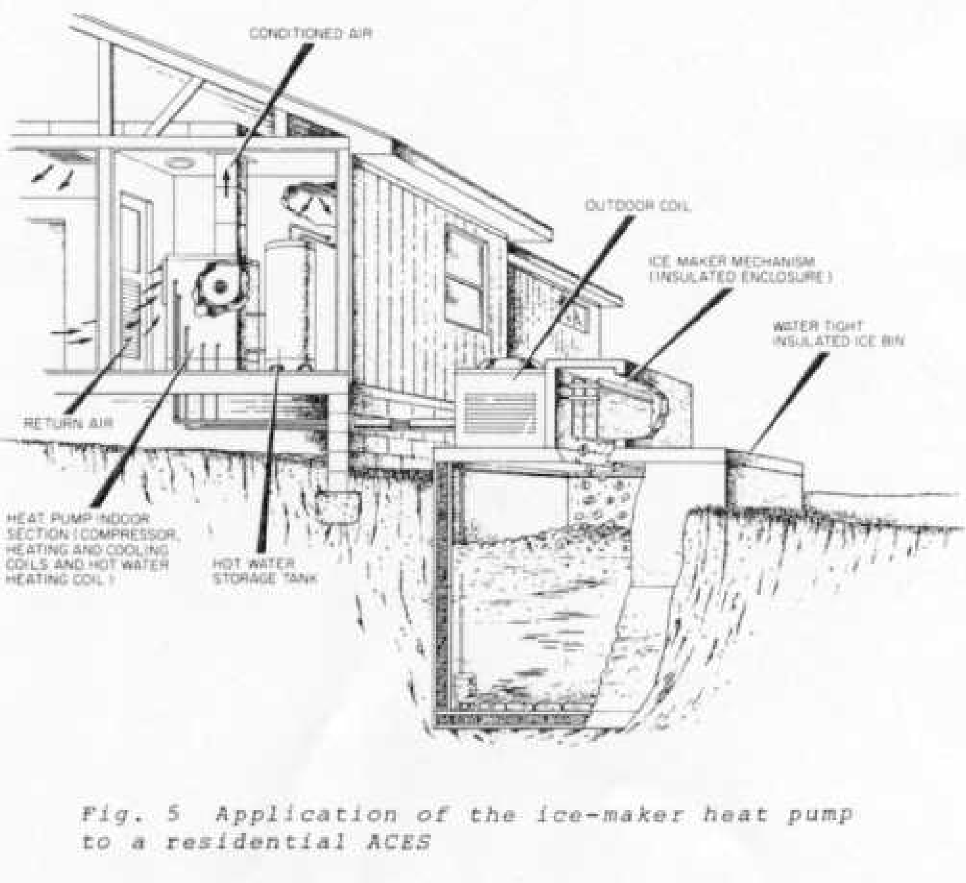
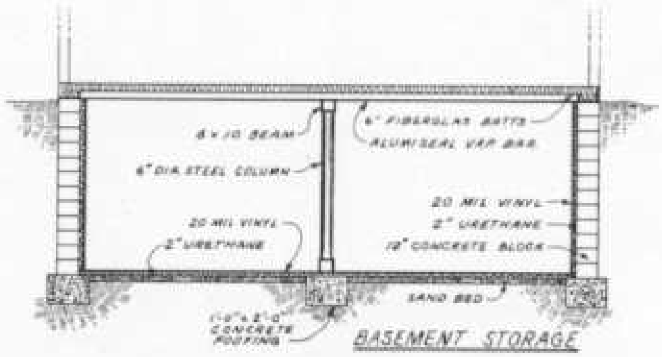


Fig. 5 Application of the ice-maker heat pump to a residential ACES

Fig. 6 Photo of modular water tank under construction

Fig. 7 ACES ice bin incorporated into basement structure of building



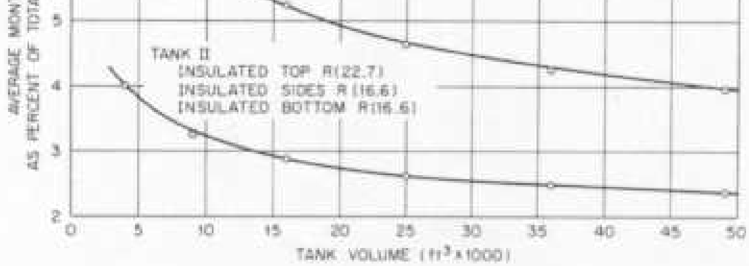
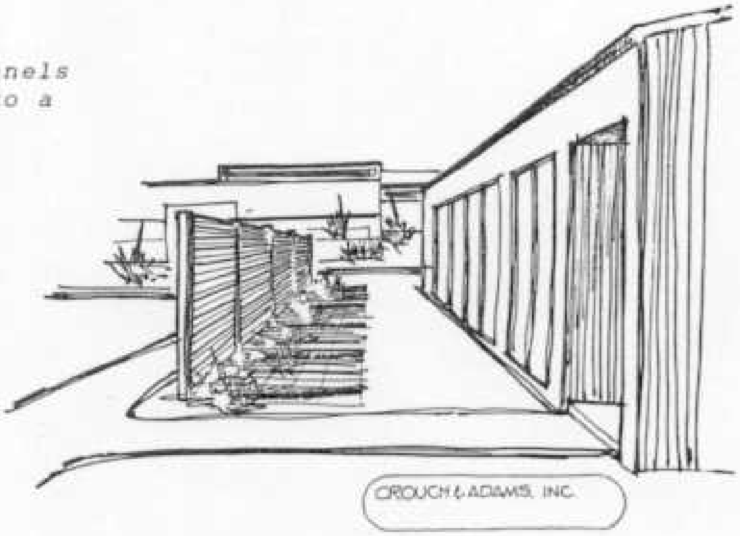


Fig. 8 Average monthly heat leakage as percent of total Btu storage capacity vs tank volume for square tanks 10 ft (3.05 m) deep buried in wet soil in a climate where average annual temperature is 55-59^{0}F (12.8-18.3^{0}C)

Fig. 9 Solar panels incorporated into a fence



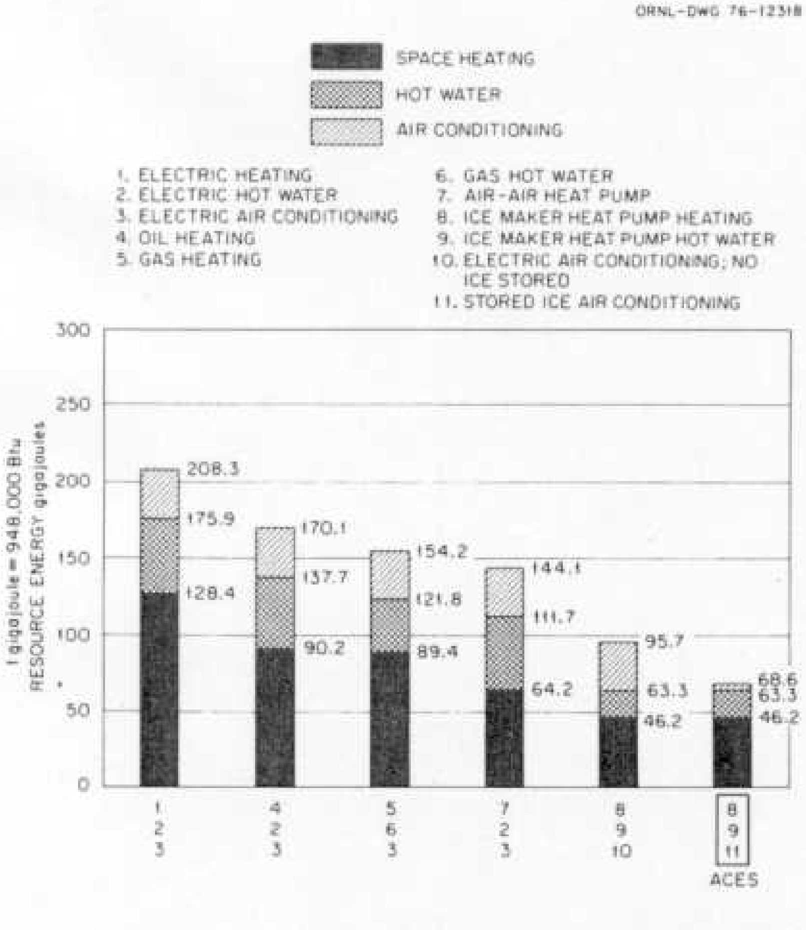


Fig. 10 Resource energy requirements for different space-heating, domestic water-heating, and air-conditioning systems