Design of Wind-Powered Cold Storage Facility

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DESIGN OF A WIND-POWERED COLD STORAGE FACILITY

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Abstract

The design and construction of a cold storage facility for use with wind power is described. The facility includes a 10-kilowatt wind generator, a cold storage building, a vapor-compression refrigeration system, and a thermal storage unit. The building is designed for storage of 1000 bushels (18,000 kg) of apples and is insulated to minimize energy requirements. The refrigeration system has a three-horsepower d.c. motor-driven compressor with Freon 12 refrigerant. Thermal storage is accomplished with a total of 90, 2.13-m (7-ft) long, 152-mm (six-inch) diameter pipes filled with water and a small amount of ethylene glycol. When power from the wind is sufficient, heat is removed from the solution which then acts as a thermal storage for periods when wind energy is unavailable. The freezing point of the ethylene glycol/water mixture is adjusted to provide the latent heat of fusion at the temperature desired in the storage room. The design analysis of the complete system included a study of the storage requirements for apples, the cooling load calculations for the building, specifications of the system components, and thermal storage requirements. Operation of the system, with apples stored in the facility, began on March 7, 1978.

1. INTRODUCTION

By now, most Americans are aware of the energy crisis. The oil embargo, long lines at gasoline stations, natural gas shortages, and pending electrical power shortages all serve as examples to each of us. The rising costs of petroleum, coal, and other conventional energy sources, along with the threat of supply interruptions, have created a new awareness of alternative sources of energy to meet our future needs. One promising source is wind energy. Von Arx (1) estimates the available wind energy in the earth's atmosphere as 10^6 megawatts. This amount is approximately twice the total electric generating capacity of the U.S. power industry and about 10 times greater than the available hydroelectric power (2). In addition to its availability, though intermittent and relatively dilute compared to fossil fuels, wind is a clean, replenishable resource (3). As a result of the energy shortage and the renewed interest in wind power, the Federal government is funding research aimed at stimulating the development of wind energy conversion systems. It is possible that wind power could provide a significant portion of U.S. energy needs by the year 2000.

Wind machines were used for agricultural applications such as grinding grain as early as 200 B.C. (3,4). In the U.S., windmill technology began in the early 1800's. By

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about 1850, over 6 million small windmills, of less than 745 W (1 horsepower) each, were in use in the U.S., mostly for pumping water and generating electricity. Although many of the water pumping windmills are still in use today, the use of wind-driven electric generators was gradually discontinued as centralized electric power was brought to rural areas in the 1930's.

This paper discusses an investigation of the feasibility of using wind power for the refrigerated storage of apples. Although this research project involves several tasks, the design, construction, and operation of the cold storage facility are emphasized here. The facility includes a 10-kilowatt wind generator, a cold storage building, a vapor-compression refrigeration system, and a thermal storage unit.

2. SYSTEM DESIGN AND PROCEDURE

To size the model apple storage, the performance of each component in the overall system was analyzed and the selection of the optimum storage size was based on constraints such as cost, time, and research objectives. The analysis included the following factors: (1) the quantity of apples to be stored, (2) fruit storage practices, (3) available wind power and climatic conditions at the site, (4) building design and construction, (5) refrigeration equipment design and performance, (6) wind turbine selection, and (7) energy storage methods. Several possible schemes for converting the wind energy to a reliable and steady source of cooling energy were investigated.

2.2 APPLE STORAGE CHARACTERISTICS

Apples may be held in storage for several months after harvesting to provide fruit for the fresh market and for processing (2,5). Recommendations for cold storage environmental conditions for apple varieties range from -1 to 3°C (30-38°F) storage temperature, -1 to 0°C (30-32°F) fruit temperature, and 85-90% relative humidity. For most varieties, fruit temperatures above 0°C (32°F) decrease storage life significantly. Relative humidity levels below 85% result in excessive water loss from the apples and shriveling of the fruit.

The standard storage container for apples is the bushel box, having a capacity of approximately 18.1 kg (40 lb) and outside dimensions of 457 mm by 356 mm by 305 mm (18 in by 14 in by 12 in). In a typical fruit storage, the boxes are stacked onto pallets of 36 each (6 layers of 6 boxes each). The stacking arrangement exposes at least one surface of each box to the room air, thus providing a free cooling surface.

In Virginia, most varieties of apples are picked beginning in the middle of September and continuing through the latter part of October. The length of the storage period may vary from 3 to 8 months depending on the variety and intended use of the apples stored. During the storage period, wide variations in the ambient climatic conditions may occur. For example, records for 1955-64 for the mean monthly temperature between September and April in Blacksburg, Virginia, show a variation between -0.3°C (31.4°F) and 17.5°C (63.5 °F) (2).

2.3 SITING AND WIND GENERATOR CHARACTERISTICS

The amount of power available in a wind stream depends on the cross-sectional area of the stream (or that area subtended by the blades of the windmill) and the velocity of the wind (3). The theoretical power in a freely flowing windstream is defined as

POWER = (VOLUMETRIC FLOW RATE) X (KINETIC ENERGY PER UNIT VOLUME OF THE WINDSTREAM)

$$P = (AV) \times \left(\rho \frac{V^2}{2}\right)$$

$$P = \frac{1}{2} \rho A V^3$$

where A = cross-sectional area of the windstream,
ρ = density of air in the windstream and
V = velocity of the windstream.

Thus, wind velocity has a much greater effect on wind power than area (or blade length for a high speed propeller-type wind generator). A wind speed of about 11.3 km/h (7 miles per hour) is required to operate a typical propeller-type wind machine. While doubling the area will double the power output, doubling

the wind velocity will increase the power output by 8 times.

Unfortunately the power which can be extracted from the wind with the use of a wind machine is much less than the theoretical power available. An ideal wind machine operating at 100% efficiency can extract only about 59% of the theoretical power available. Real windmills have power coefficients much less than 59%, the actual value depending on the design of the windmill. The power coefficient of a wind machine is defined as the power delivered by the machine divided by the total power available in the cross-sectional area of the windstream subtended by the wind turbine. Typical power coefficients range from 10 - 45% depending on the type of rotor.

The available power is further reduced in the process of converting the shaft power to electrical power or to useful mechanical power. Gears, pulleys, and other conversion equipment reduce the overall efficiency. Also, since wind power is intermittent, a portion of the collected energy is often stored for use when wind power is available. Efficiencies of conversion for storage depend on the type of storage -- chemical (batteries), thermal (water, ice, rocks), pumped water, hydrogen, flywheels, compressed fluids, etc.

The site for a wind machine should be selected carefully since topography and surface roughness affect the wind speed. As a rule of thumb, wind speed increases as the one-seventh power of the height above the ground. Examples of good sites for the location of windmills include the top of a smooth well-rounded hill with no tall obstructions upwind, on an open plain or shoreline, or in a mountain gap which produces funneling. Maps are available which show average annual windspeeds, but not wind power. The Appalachian Region is an area where annual average wind speeds exceed 29 km/h (18 miles per hour) at 45.7 m (150 feet) elevation above ground level.

Based on design considerations, costs, and availability, a commercial highspeed windmill was purchased and installed at the site of the apple cold storage building. The wind turbine, an Electro 120VG rated to produce 10 kW at a windspeed of 48.3 km/h (30 mph), has a 3-bladed, 6.6 m (21.7 ft) diameter rotor (6,7). The angular velocity of the rotor is controlled by a governor that increases blade pitch as wind speed is increased. A downwind tail maintains orientation of the blades into the wind. The generator is 3-phase AC, and the windmill is mounted on a 27.4 m (90 ft) reinforced radio tower.

2.4 APPLE STORAGE FACILITY

Based on local climate surveys, predicted wind generator output, and other preliminary design data, the size of the model apple storage was selected to be nominally 1000 bushels, or approximately 18,000 kg of apples. Although commercial fruit storages may be much larger, this model storage serves as a test for the demonstration of the use of wind power for an agricultural application. Also, because of the intermittent nature of wind power and the uneven cooling requirements, a thermal energy storage using an ice tank energy exchanger was incorporated into the design. Figure 1 shows a schematic diagram of the cooling system with specifications for the wind generator, storage batteries, refrigeration system and storage room.

The detailed design of the apple cooling plant consisted of two parts. One part was the design of the cooling equipment including (1) the refrigeration system to convert electrical energy from the windmill to thermal energy stored in ice containers, (2) design of the ice storage, and (3) design of the system for cooling the apple storage building using the ice storage. The other part was the design of the building for storing the apples as well as for housing the cooling equipment.

2.4.1. Storage Building Design

Initially a state-of-the-art apple storage was proposed following design procedures such as those recommended by the U.S. Department of Agriculture and the state agricultural experiment stations (8,9). However, because of energy conservation considerations and since an ice storage unit was to be used,

some aspects of the conventional design had to be altered.

The refrigeration requirement, discussed later, consisted primarily of heat gains from conduction through the structure and from respiration from the apples. Incidental heat sources such as the operation of fans, pumps, and lights and air exchanges with the ambient were also included. Heat gains during the first 1-2 weeks after apples are loaded into the storage also include field heat from the apples and heat generated by men working in the facility. Field heat includes (1) the heat given off by the apples due to the temperature difference between the apples at field temperature and at storage temperature and (2) the increased heat of respiration during this 1-2 weeks. The specific heat of respiration for apples increases more than four times when the fruit temperature is increased from -1°C to 10°C(8).

Several types of building construction were investigated including wood frame, concrete block, metal buildings, foamed-in-place construction, and pole buildings. After considering factors such as the method of insulating, conventional wood frame construction was selected. There were definite advantages to keeping the design as close to "conventional" as possible (such as retrofitting of this type of wind energy system to existing apple storage buildings). Concrete block construction was ruled out for two reasons. First, studs would still be required in the building to accommodate insulation. Secondly, the building height needed for the ice tank would probably require some means of internal wall support. Additionally, a wood frame building is easier to insulate than a metal building.

At this stage in the design procedure, a 1000-bushel apple storage building with adjacent equipment room was designed complete with working drawings, a list of building specifications, and a bill of materials. Because cost estimates were greater than the budgeted funds, however, an existing building was sought for use with the project. Several possible alternatives were explored and, after comparison of wind speed data at the various sites, an existing "cannery" and storage building at the Horticultural Research Farm at VPI & SU was selected for renovation and use. This building was very similar in size and design to our original building design and also included an adjacent room for use in housing refrigeration equipment and instrumentation. This Horticulture Farm site also offered advantages of closeness to the campus, existence of fruit orchards at the site, close cooperation and participation by Horticulture personnel, and easy accessibility to groups visiting the campus.

2.4.2. Storage Building Construction

The same basic design of the original building plans were used in renovating this building. Before renovation, the building had a concrete slab floor, 51mm x 152mm (2 in x 6 in) stud wall construction with studs spaced 304mm (12 inches) on center, and some insulation. The apple storage room, which also houses the ice tank thermal storage, was originally 14.3m by 7.3m (47 ft by 24 ft) with a 3.1m (10 ft) ceiling height. An equipment/instrument room, which measures 3.1m (10 ft) by 7.3m (24 ft) and has an access door to the storage, is used to house the refrigeration equipment, storage batteries, and instrumentation.

In renovating the building, attempts were made to provide an energy-efficient building to be used as a test bed for the wind-powered apple cold storage demonstration. The interior walls and ceiling of the existing building were covered with 6.4mm (1/4 inch-thick) plywood sheathing and a plastic vapor barrier. The interior was then reframed with 51mm x 152mm(2 in x 6 in)boards 1.22m (4 ft) on center and 1.22m (4 ft) by 2.44m (8 ft) by 152mm (6 inches) thick Dylite expanded polystyrene insulation was installed in the floor and ceiling. The interior was then covered with exterior-grade plywood sheathing and painted. The concrete slab floor of the existing building was covered with 152mm (6 inch) thick Dylite insulation and another reinforced concrete slab was

poured over the insulation.

Insulated refrigerator doors were constructed and installed both to the outside (for loading the apples) and to the adjacent equipment room. A concrete loading ramp was poured on the front of the building for loading the apples into the building. Additional insulation was also placed on the walls of the equipment room. The equipment room is heated, has electric and telephone service, and provides work space for a technician and the investigators when they are located at the site.

2.5 COOLING SYSTEM DESIGN

2.5.1. System Requirements

The cooling requirements for the refrigeration system were based on approximate heat transfer calculations for the storage building and apples. As noted previously in the building design discussion, heat load estimates included (1) conduction through the building walls, floor, and ceiling; (2) the heat of respiration of the apples; (3) the initial field heat of the apples; and (4) incidental heat due to people and equipment in the building. The estimates used in the design of the cooling system are shown in Figure 2 for different months of the year. From these calculations, it was concluded that a standard vapor-compression refrigeration system with a cooling capacity of approximately 6.8 kW (2.0 tons) would be adequate.

2.5.2. Energy Storage

Because of the variation of available wind power, the variability in climatic conditions, and the need to maintain a constant apple storage temperature, some storage of energy was considered essential (10,11). Although there are many methods of energy storage, only electrical (batteries) and thermal were considered in detail.

Since the output power of most commercially available windmills is electric, storage batteries are convenient. In fact, if all of the energy storage was in the form of batteries, a conventional refrigeration system could be used with an inverter or DC motors on the equipment. A design of this type was considered with measures to reduce the energy required by conventional cooling systems. This design, however, resulted in a large number of batteries which are expensive and not highly efficient. Since much of the cooling and energy storage is required for the initial month of apple storage, a design that used auxiliary power for this period was also considered. Because of the advantages of thermal energy storage, however, this concept was not pursued.

Because thermal energy was required, and especially since the freezing point of water is near the desired temperature, thermal storage was included in the design. Water, with a small amount of ethylene glycol, was chosen as the storage medium. A design that depends entirely on thermal energy storage, thus eliminating the need for batteries, was considered first. In this design, the windmill could be connected directly to the refrigeration system, possibly with a synchronous motor or a hydraulic pump and motor. Attempts to match the load to the windmill output, however, resulted in complex systems or a large amount of wasted energy, or both, and some electrical power was needed to operate the circulating fans or pumps. Thus in the final design, it was decided to use thermal storage with batteries to allow the refrigeration system to operate periodically at rated power and the circulating fan to operate continuously.

A bank of nickel-cadmium storage batteries provides the electrical energy storage, which is necessary for operation of the electrical components, and for efficient loading of the wind generator. The battery bank provides 13 kWh of electrical energy storage.

2.5.3 Thermal Storage Design

Based on the available wind information for this area, it was concluded that approximately one week of storage would be sufficient. With the estimated heat load, the required storage was approximately 285 kWh (10^6 BTU). Making use of the latent heat of fusion, approximately 3140 kg or 3.5 m^3 of ice was required.

Major design considerations for the system included containers for the ice and the method of transferring heat (working mediums). Several alternatives were considered in arriving at the final design.

A single, large underground tank to contain the ice was considered first. Because of expansion problems, the ice would be frozen in smaller sections (possibly with a commercial-type ice maker) and stored in the tank. It was concluded, however, that it would be simpler to freeze and store the ice in smaller containers, such as small cans, shallow trays, or cylindrical cannisters. Although thermal storage in small cans (such as soft-drink cans) is feasible, they are not readily available for this purpose and rupture during freezing would likely be a problem. Shallow, open trays were considered in detail, but they would have to be constructed for this purpose and evaporation would probably be excessive. Thus it was concluded that cylindrical cannisters, such as commercially available pipe, would be best suited for this project. (However, less expensive containers for freezing liquids for thermal storage should be considered for future developments).

Several methods of transferring heat to and from the ice to the refrigerant and from the storage building were considered. The first method, which perhaps should be reconsidered for future projects, consisted of submersing the cannisters in a large tank filled with concentrated brine or ethylene glycol (Figure 3a). The refrigerant evaporator coils could then be submersed in either the freezing liquid or the concentrated solution or connected to the cannisters. Pumps would be used to move the concentrated solution through an overhead heat exchanger in the apple storage building. Either natural convection or circulating fans would be used to move air over the heat exchanger.

The second method, which was ultimately selected because of simplicity and low cost, uses air as the heat exchange medium between the evaporator and freezing water (Figure 3b). In this system, the evaporator coils are enclosed in an air duct with a circulating fan. When the refrigeration compressor is in operation, heat is removed from the air, which then cools the water in the cannisters. When the compressor is not in operation, heat is removed from the air by the ice stored in the cannisters.

The final design for the thermal storage unit, which was constructed in the apple storage building, is shown in Figures 4 and 5. It consists of 90, 2.13 meter (seven foot) long, 152 mm (six inch diameter steel pipes, arranged as a two-pass, shell-and-tube heat exchanger. The pipes are filled with approximately 1.83 m (six feet) of water and enough ethylene glycol to lower the freezing point to -3°C. Except under peak cooling loads, such as the initial period, this temperature should maintain the storage building at the desired temperature of approximately -1°C.

A simple control system was designed to provide for automatic operation of the system. During high wind-energy periods when electric energy is abundant, the cooling plant is allowed to operate. The chilled air from the evaporator is introduced into the thermal storage, where it flows over the tube bank in two passes. Heat is thus removed from the storage solution at its freezing point of -3°C and the air is subsequently introduced to the apple storage room at that temperature. During low wind-energy periods when the cooling plant is not operating, the warm return air from the apple storage room is circulated through the thermal storage, where it then gives up its heat to the solution and is introduced back to the storage room as before. The major advantages of this type of system are its simplicity and its inherent potential for temperature control.

2.5.4 Refrigeration Equipment

In addition to the thermal storage unit, the cooling system includes the circulating fan, the compressor and condenser unit, and the evaporator coil. The complete system, as installed in the storage building with associated duct-work, is shown in Figure 6. In the design of the system, commercially

available equipment was selected as far as possible.

The circulating fan is a centrifugal fan with airfoil blades for high efficiency. It has a rated flow rate of 2000 m^3/hr (1200 CFM) at a pressure rise of 2.5 cm (1.0 in) of water, which is slightly greater than the pressure loss estimated in the system design. The desired flow rate of 2000 m^3/hr was based on the recommended value for storage buildings (8) (The air flow rate through the system can be altered by changing the pulley size and speed of the fan). The fan is driven by a 0.19 kW (0.25 horsepower) DC motor.

The compressor and condenser unit is a heavy duty, air-cooled unit, which has a rated capacity of 6.5 kW (23,000 BTU per hour) at a suction temperature of -10°C (15°F). The compressor is driven by a 2.2 kW (3 horsepower) DC electric motor, which receives power directly from the wind generator-battery system.

The direct expansion evaporator coil has a frontal area of approximately 0.37 m^2 (4 ft^2) with minimum fin spacing specified as 2.5 mm (0.1 in). The coil has a rated capacity of 6.8 kW (24,000 BTU per hour) based on 2°C (35°F) entering air, -6°C (20°F) refrigerant temperature, and an air flow rate of 2000 m^3/hr (1200 CFM).

Ice formation on the evaporator coils was one of the major areas of concern in the design of the system. This is a problem in any system where heat must be removed from air at low temperatures (-1°C) and high relative humidity (85-90 percent), as required for apple storage. Conventional refrigeration systems often employ an active method of defrosting the coils. These methods, which were considered in the present design, include electrical resistance heating, circulating hot refrigerant in the coils, and spraying water or warm air over the coils. In some systems, however, where the capacity is sufficiently large to require operation less than 50 percent of the time and the surface area is sufficiently large, active defrosting is not necessary. Since this method is by far the simplest and least energy consuming, it was attempted in the present design after discussion with a number of coil manufacturers. (This problem is discussed further in the following section).

3. SYSTEM PERFORMANCE

The refrigeration system was placed in operation in the last week of February, 1978. Since the initial tests indicated that the system was adequate, apples were moved into the building on March 7, 1978. Typical performance data for the system are given in Table 1.

Although the refrigeration equipment cooled the building and apples to near the desired temperature, room temperatures were 2-3°C above the desired value of -1°C during the late spring and early summer, with the system operating as much as possible without excessive ice formation on the evaporator. Storage of this year's crop of apples began on September 7. By the end of September, the storage building temperature was down to the design value.

In addition to the cooling requirement being slightly greater than expected, ice formation on the evaporator coils is definitely part of the problem, which was not completely unexpected. It should be noted again that this problem is not unique to this particular design, and most conventional systems use heat to defrost the coils. The present design is an attempt to conserve energy, and might still be workable with some modifications. Possible modifications to the present system include higher air velocities, more coil surface area, parallel evaporators operating alternatively, or coils in the thermal storage medium. However, to increase the defrosting rate during periods when the refrigeration unit is in operation a large part of the time, a hot refrigerant line to the evaporator has recently been installed.

4. SUMMARY

An apple cold storage facility utilizing wind power as an energy source was designed, constructed, and performance tested during 1978. The facility uses a 10 kW wind turbine to provide power for a vapor-compression refrigeration system for a 1000-bushel storage building. The most unique design feature of the system is the dual energy storage, including

both nickel-cadnium batteries for electrical energy storage and an ice-tank/heat exchanger for thermal energy storage.

The wind-powered refrigeration system was used to cool a 1000-bushel apple storage building from March through July, 1978. Picking and storage of this year's apple crop began in late September. The cooling system, which is performing satisfactorily in achieving the desired storage temperature, will continue to be evaluated through the 1978-79 storage season.

5.0 REFERENCES

1. Von Arx, W. S. 1974. Energy: National Limits and Abundances. EOS Trans. Am. Geophys. Union 55: 828-832.
2. Blanton, J. C. 1977. Design of a Wind-Powered Cooling System for an Apple Storage Facility. M.S. Thesis, Mech. Engr. Dept., Va. Poly.Inst. & St. Univ., Blacksburg, Va., 50 p.
3. Eldridge, F. R. 1975. Wind Machines. NSF-RA-N-75-051. Supt. of Doc., U.S. Govt. Printing Office, Washington, D.C., 77p.
4. Vaughan, D. H. 1978. Agricultural Applications of Wind Energy. 4-H Energy-Environment Workshop and Handbook, Ext. Div., Va. Poly. Inst. & St. Univ., Blacksburg, 8p.
5. Schetz, J. A. et al. 1978. Application of Windmills to Apple Cooling and Storage. Progress Rpt., Nov. 1976-May 1978, VPI&SU, Nat. Tech. Inf. Ser., U.S. Dept. of Commerce, Springfield, Virginia.
6. Figard, R. L. and J. A. Schetz. 1978. Experimental and Analytical Studies of the Aerodynamic Performance of Windmills. Amer. Inst. of Aeronautics and Astronautics Paper No. 78-277, New York, N.Y., 7p.
7. Benim, T. E., 1977. Performance Testing of a 10 kW Horizontal Axis Windmill. M.S. Thesis, Mech. Engr. Dept., VPI&SU, Blacksburg.
8. Patchen, G. O. 1971. Storage for Apples and Pears. U.S. Dept. of Agri. Marketing Res. Rpt. 924, Washington, D.C., 51p.
9. Layer, J. W. 1971. Refrigerated Farm Storage. Inf. Bull. 16, Phys. Sci., Agr. Engr. 4, Ext. Pub., N.Y. State Coll. of Agr. and Life Sci., Cornell Univ., Ithaca, N.Y., 30 p.
10. Hewson, E. W. 1977. Electrical Energy from the Wind. Energy Technology Handbook, McGraw Hill, New York, N.Y.
11. Fisher, H. C. and E. A. Nephew. 1976. Application of the Ice-Maker Pump to an Annual Cycle Energy System. Amer. Soc. Mech. Engr. Paper No. 76-WA/Ener-4, New York, N.Y.

TABLE 1. TYPICAL TEST DATA FOR THE REFRIGERATION SYSTEM.

Date	Time	Temperatures - °C (°F)				
		T_5*	T_{13}	T_{14}	T_{15}	T_{16}
March 6 (without apples in building)	13:45	.6(33)	-2.2(28)	3.3(38)	0(32)	.6(33)
	15:25	.6(33)	-3.3(26)	2.8(37)	-.3(31.5)	.6(33)
	16:25	0(32)	-4.4(24)	1.7(35)	-.8(30.5)	0(32)
March 8 (with apples in building)	8:50	.6(33)	2.2(36)	3.1(37.5)	.6(33)	.6(33)
	9:34	.3(32.5)	-3.1(26.5)	2.5(36.5)	-1.1(30)	0(32)
	9:47-10:03 compressor off					
	10:02	.6(33)	1.7(35)	3.1(37.5)	.3(32.5)	.6(33)
	10:24	0(32)	-4.2(24.5)	2.2(36)	-1.1(30)	0(32)
	10:48 - 11:04 compressor off					
	11:00	0(32)	1.1(34)	2.5(36.5)	0(32)	0(32)
	11:47	-.3(31.5)	-5.6(22)	2.2(36)	-1.7(29)	-.3(31.5)
	11:57	0(32)	.8(33.5)	2.5(36.5)	-.3(31.5)	.3(32.5)
	13:35	-.3(31.5)	-5.8(21.5)	1.7(35)	-1.7(29)	-.3(31.5)
	14:48	-.3(31.5)	-8.9(16)	2.2(36)	-1.9(28.5)	-.3(31.5)
	14:51 - 15:07 compressor off					
	15:18	0(32)	-8.6(16.5)	2.2(36)	-1.7(29)	0(32)
March 10		1.1(34)	-2.8(27)	2.8(37)	-1.1(30)	1.1(34)
March 13		1.1(34)	-2.2(28)	2.8(37)	0(32)	1.7(35)
March 23		1.1(34)	-2.2(28)	1.7(35)	-1.1(30)	.6(33)

*T_5 = Storage room temperature
T_{13} = Temperature of air leaving evaporator
T_{14} = Temperature of air entering evaporator
T_{15} = Temperature of air leaving thermal storage tank
T_{16} = Temperature of air leaving apple storage building

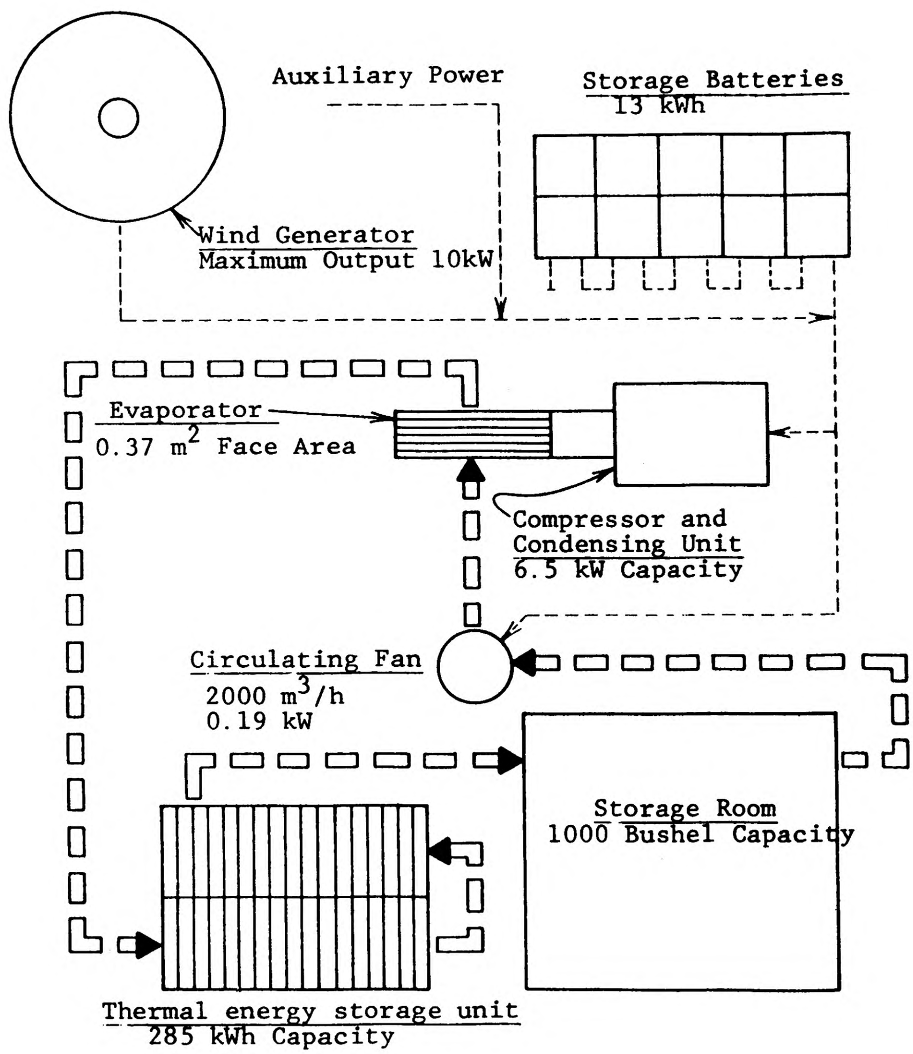


FIGURE 1. SCHEMATIC DIAGRAM OF THE COOLING SYSTEM WITH EQUIPMENT SPECIFICATIONS. (2)

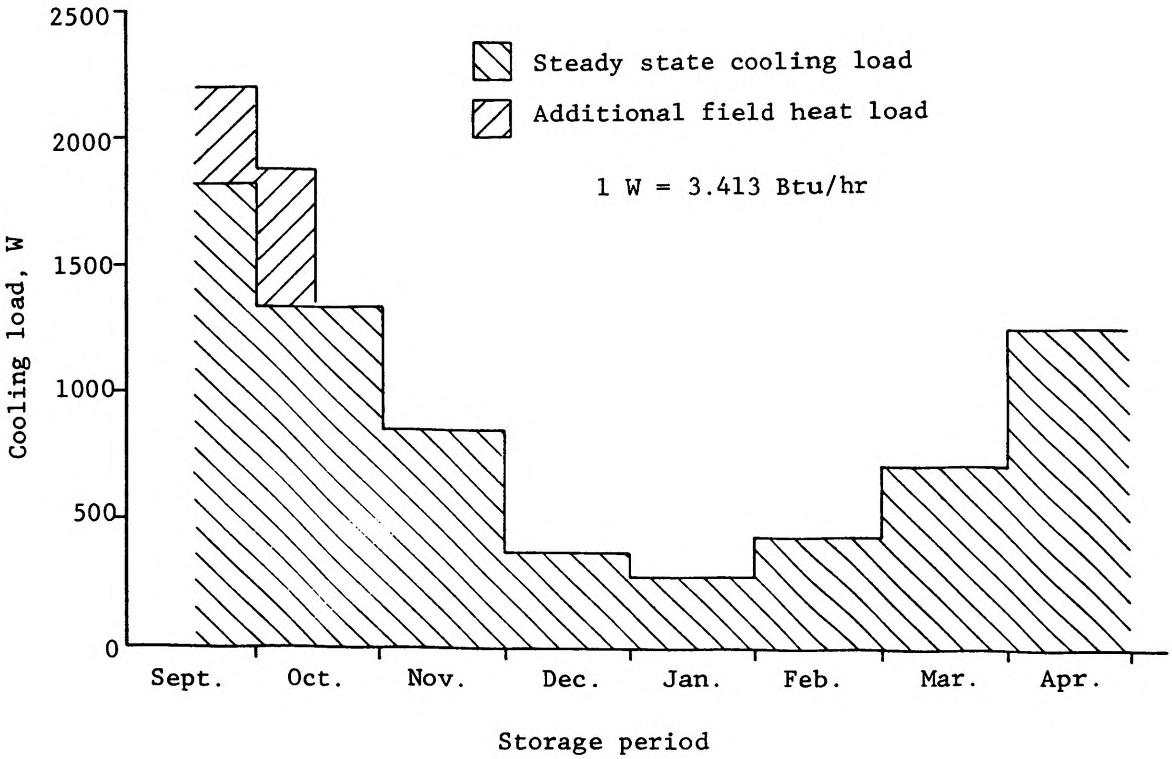
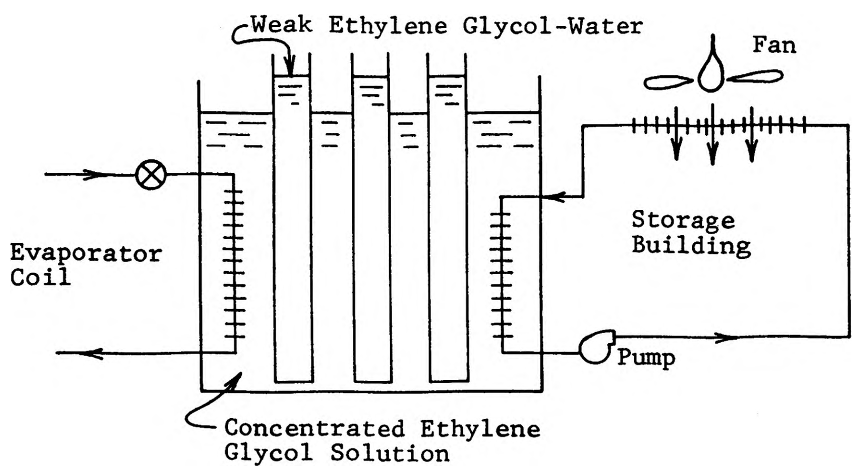
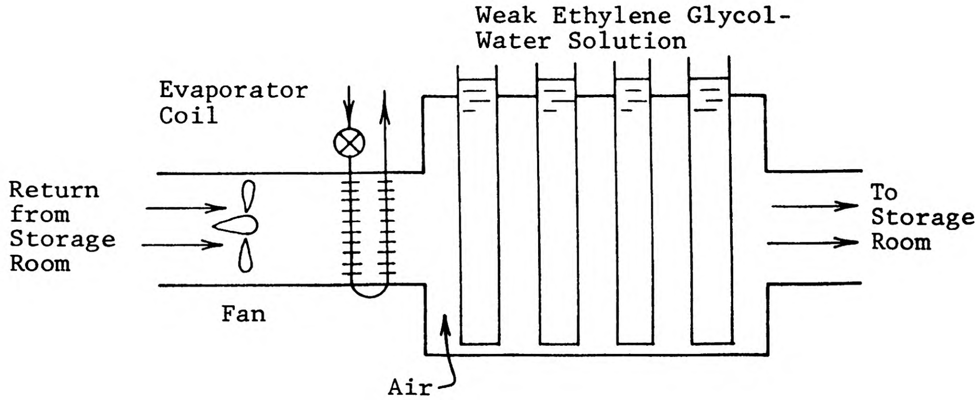


FIGURE 2. COOLING LOAD CALCULATION RESULTS.



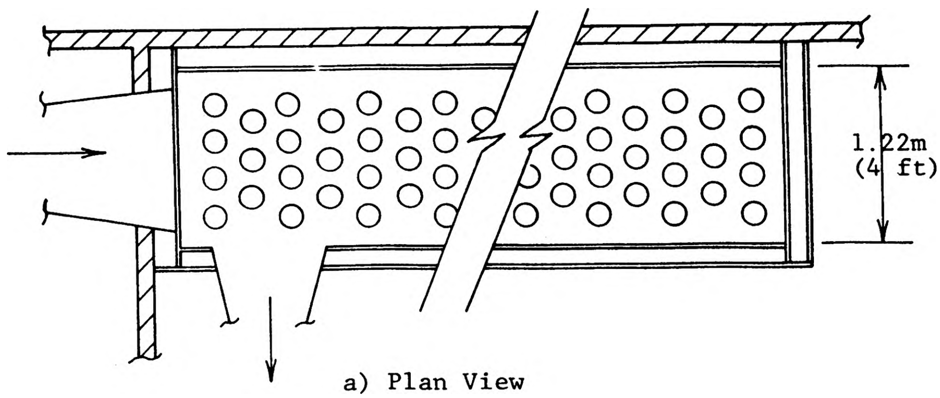
a) Liquid System

FIGURE 3. THERMAL STORAGE SYSTEM DESIGNS

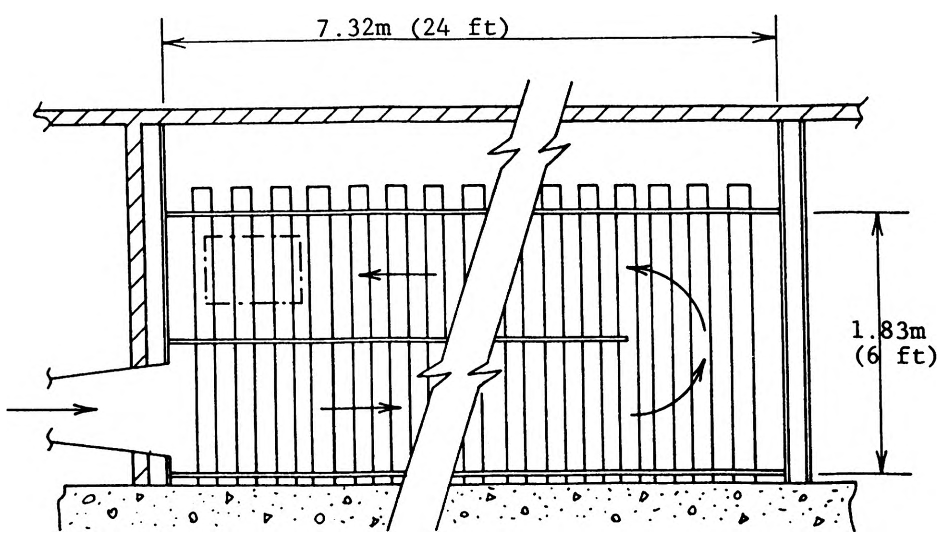


b) Air System

FIGURE 3. THERMAL STORAGE SYSTEM DESIGNS

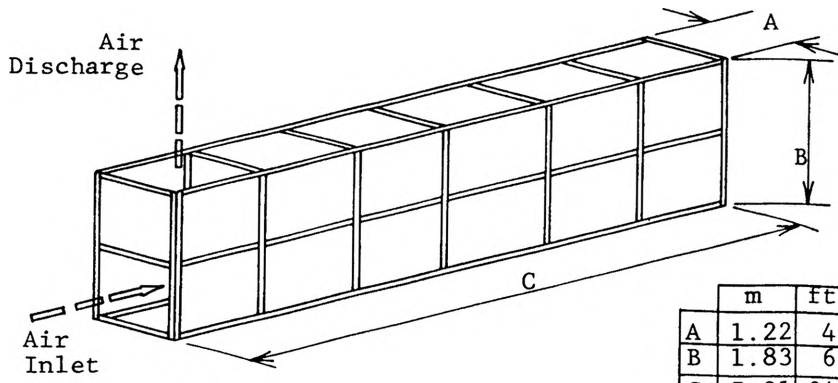


a) Plan View



b) Elevation

FIGURE 4. THERMAL STORAGE AND HEAT EXCHANGER UNIT.



	m	ft
A	1.22	4
B	1.83	6
C	7.31	24

FIGURE 5. THERMAL ENERGY STORAGE UNIT.

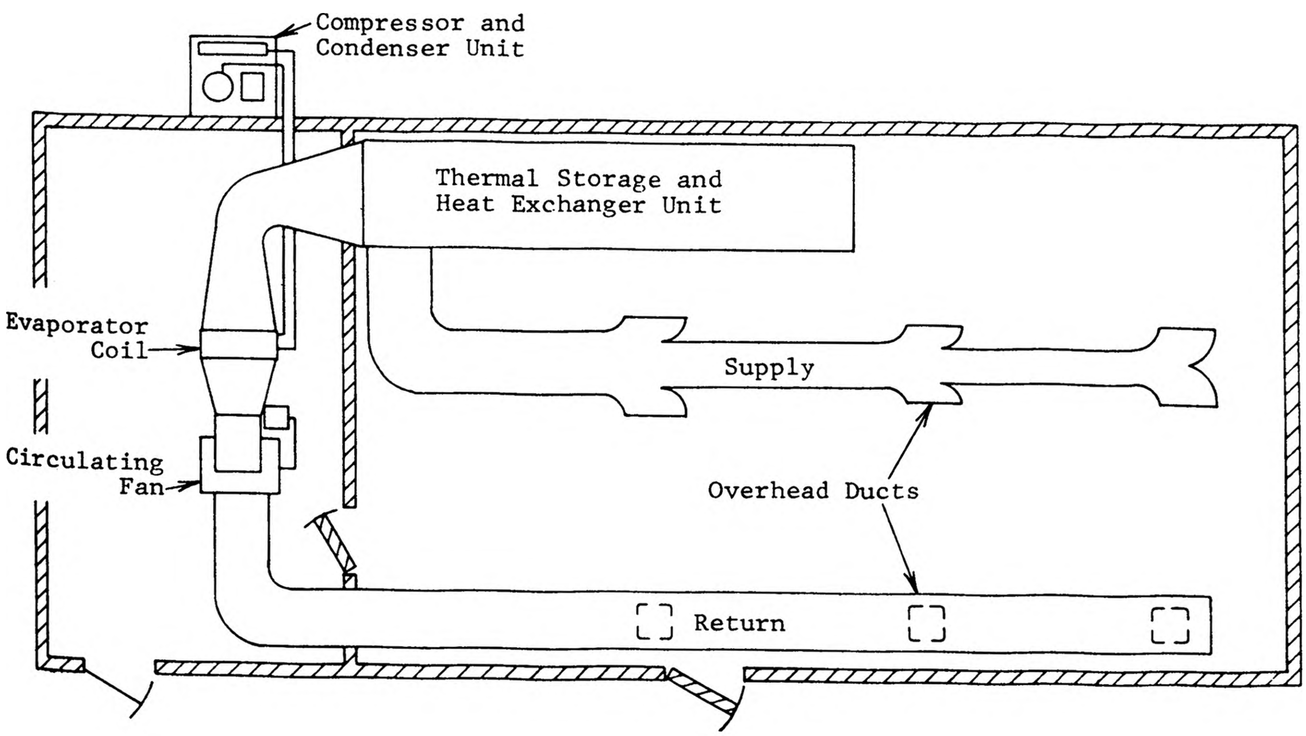


FIGURE 6. PLAN VIEW SKETCH OF THE APPLE STORAGE FACILITY AND COOLING SYSTEM. (5)