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IFAS EXTENSION

CIR1166

A Portable Demonstration Forced- Air Cooler [1]

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During the past five years, there has been a significant increase in the production of fruit and vegetable crops in the twelve-county region north of Gainesville, Florida. The principle crops being grown or considered in the region are squash, peppers, cucumbers, tomatoes, sweet corn, and eggplant. Most of these crops are produced for the fresh market. Estimates indicate the acreage will increase more during the next 5 years. The State Farmers' Market in White Springs, provides an excellent marketing opportunity and incentive for vegetable and fruit producers in the region [2].

Produce which is not cooled quickly after harvest degrades in quality [5]. It has been estimated that 10 percent of crops which are harvested never make it to market due to improper or the absence of cooling of the commodity. This translates into a large economic loss. The energy loss after harvest but before market, due to the large amount of energy sequestered in the produce, is also substantial. Sequestered energy is that energy which is invested in a crop during land preparation, planting, fertilization, irrigation, pest control and harvest. The sequester energy, lost cost of production, or lost sales value can be used to estimate the impact of a 10% loss due to spoilage. The direct and total primary energy requirements to produce various Florida vegetables have been reported [4]. For pepper, cucumbers, eggplant, greenhouse vegetables, squash, and tomato, the total primary energy requirements are $8.2x10^4$, $3.3x10^4$, $7.3x10^4$, $295.5x10^4$, $2.3x10^4$, and $7.6x10^4$ kWh/ha ($113.3x10^6$, $45.1x10^6$, $101.0x10^6$, $4080.0x10^6$, $31.8x10^6$, and $104.3x10^6$ BTU/acre), respectively. Therefore, a 10% spoilage loss would equate to a sequestered energy loss of $0.8x10^4$, $0.3x10^4$, $0.7x10^4$, $29.5x10^4$, $0.2x10^4$, and $0.8x10^4$ kWh/ha ($11.3x10^6$, $4.5x10^6$, $10.1x10^6$, $408.0x10^6$, $3.2x10^6$, and $10.4x10^6$ BTU/acre), respectively. Postharvest losses diminish proportionately the productivity of energy inputs for agricultural systems [3]. The quantity of commodity produced per ha (acre) and the cost of production per ha (acre) are available for most crops and the postharvest loss can be accessed in terms of monetary value. The value received for the product also indicates the impact of postharvest loss. Preventing postharvest loss is an important factor in preventing energy loss as well as maintaining quality.

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There are several methods of cooling produce: hydrocooling, forced-air cooling, room cooling, vacuum cooling, slush icing [5]. All of these processes use electrical energy extensively, but the amounts or time-of-use of energy being consumed depends on the scale of the operations. While it is difficult to make a side-by-side comparison of the various cooling methods, forced-air cooling is the most energy efficient followed by package ice (including slush icing), hydrocooling, and vacuum cooling [9]. There are many considerations in the selection of a precooling method and one is thecompatibility of the method with the commodities to be cooled. Some crops can be cooled with more than one method while others are limited to one method [5].

Many produce types grown in North Florida cannot be exposed to water or ice (water-borne decay organisms, chilling injury) [5]. Maintenance of the hydrocooling water quality and disposal of the this water after use are both potential problems. Vacuum cooling is best for high surface area to volume ratio commodities like leafy crops. The slush ice method has advantages and disadvantages. However, like vacuum cooling, requires more specialized equipment and operator skills than forced-air cooling and the investment cost would be too high for most growers in North Florida. The use of thermal storage (ice making) systems may have potential but the value has not been demonstrated. Room cooling can be used for most crops but is generally too slow for precooling.

Although a few large farmers in the North Florida region have installed precooling systems at packinghouses, there are many small, low-volume growers who are unable to justify the large capital investment. The initial equipment cost for many types of cooling systems can be substantial. In the past, the added investment required and operational costs of precooling systems have been a major barrier to the adoption of this technology. Presently, their only alternatives are to not cool, which severely limits their markets, or to construct homemade precoolers that can be energy inefficient and potentially hazardous from a food safety standpoint.

Of the crops listed above, forced-air cooling is applicable for all except sweet corn. In addition, forced-air cooling is well suited for peaches, blueberries, and other deciduous fruits grown in North Florida. The ability to retrofit existing cold rooms for use as forced-air coolers is also an economic advantage. Therefore, forced-air cooling is a preferred precooling method for most of the commodities are grown in North Florida.

A need was recognized to demonstrate the principles of forced-air cooling and illustrate the investment and operational costs required. This publication discusses the design considerations, construction, system cooling performance and system costs of the small, portable, extension demonstration forced-air cooling unit which essentially uses off-the-shelf technology. The forced-air cooler is intended for extension demonstrations to demonstrate the principles of forced-air cooling. This cooling unit illustrates how to cool, stressingmanagement practices, as well as, provides a model for adoption by growers. It is not intended to be the final design for which a particular grower would cool all his produce harvested in one day. Most commercial precooling systems are custom designed to meet the requirements at each location. Part of the extension program objective is to assist the grower in the design of a system which would satisfy the needs of his operation.

The trailer-mounted cooling unit consists of two air conditioner units (mobile home type) and ducting, a high pressure fan, controls, and a cooling chamber for cooling a pallet of approximately 454 kg (1000 lb) of containerized product [7]. The unit is energy efficient and affordable to a grower in the range of 2 to 20 ha (5 to 50 acres), and will be demonstrated in North Florida and various locations around the state with various commodities. The results of these demonstrations will continue to have a positive impact as additional demonstrations and educational programs are presented. Requests for demonstrations should be coordinated with the county cooperative extension agent.

How Forced-air Cooling Works

In forced-air cooling, produce is air-cooled rapidly by a difference in air pressure on opposite faces of stacks of vented containers (pallet boxes, corrugated cartons, flats, etc.) [1, 5, 6, 7, 8]. Fan(s) create the pressure difference, which is called static-pressure difference or pressure drop. This pressure difference forces air through the containers and product, removing produce field and respiration heat. The product is most efficiently cooled when the cooling air flows around the individual fruits or vegetables in the containers, rather than by flowing around the outside of the containers (as in room cooling). In other words, the cooling medium (cold air) comes into intimate contact with the product to be cooled. Forced-air cooling cools the product several times more rapidly than room cooling [5, 9].

Forced-air precoolers can be made more efficient by several minimal cost methods and by increased management [6, 8]. These methods include sealing air-leak areas to force additional air through products, improving carton stacking configurations or orientation, modifying pallet-tunnel length and width, and proper temperature monitoring. Methods requiring more time and cost include improvement in carton design, increased fan and cooling capacity.

Description of Portable Demonstration Forced-air Cooler

The trailer-mounted portable forced-air cooling unit shown in Figures 1 and 2 can be demonstrated at any location which provides 100 amp, 230 VAC, single phase service. This self-contained unit consists of two 10.5 kW (3-ton or 35,600 Btuh) packaged refrigeration units with associated ducting and controls, a high-pressure 1.1 kW (1.5 hp) fan, and a self-constructed 2.4 m (8 ft) cubic cooling chamber.

Figures 1 .

2 .

The unit is set up to illustrate tunnel-type forced-air cooling. The interior can be modified to illustrate other types of forced-air cooling. The design criteria for the forced-air cooling system required forced-air cooling of a pallets of containerized vegetables in less than an hour. The air conditioner units provide the energy required for cooling the produce, as well as, the transmission, infiltration, and miscellaneous cooling loads.

Cooling Chamber

Figure 3 shows the plan and side views of the cooling chamber. The basic design was based on USDA Plan 6380 [10]. The length of the chamber was reduced from 3.7 m to 2.4 m (12 ft to 8 ft) in order to fit the chamber onto the trailer. The false wall and 1.1 kW (1.5 hp) high pressure fan were added to provide the pressure difference across the pallet of containerized produce. The construction requirements are simple and materials are available from local building construction stores. Table 1 lists the materials and costs for the cooling chamber construction ($1,313) and other system components. Florida Plan Service plan number SP-5179 provides additional construction details [11].

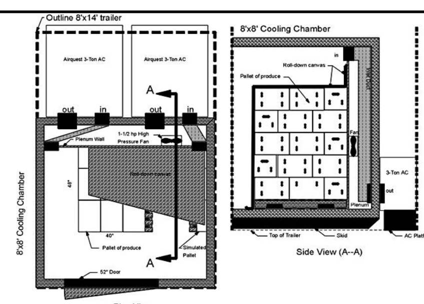


Figure 3 .

High Pressure Fan

The canvas was rolled down over the space between the pallet of containerized produce and the simulated pallet. The pressure produced by the high pressure fan pulled cool air from inside the cooling chamber through the openings in containers of produce and returned the warmer air to the air conditioner units. The fan produces an airflow of about 0.94 m^3/sec (2,000 cfm) depending on the static pressure and was selected to match the combined air flow of the two air conditioner units over a range of static pressures.

Cooling Units and Controls

The cooling was accomplished with two 10.5 kW (3-ton) packaged (mobile home type) air conditioner units. The rated air flow of the evaporator fan for each air conditioner unit is about 0.47 m^3/sec (1,000 cfm) depending on the static pressure. Each air conditionercost $690 and was purchased along with flexible ducts from a local air conditioner company.

The cooling units were controlled using both a programmable controller and a timer relay. A schematic of the control wiring is shown in Figure 4 . The microprocessor based temperature/process controller was used instead of two thermostats. A single thermocouple was used to sense the return air temperature and two set points (cut off) were programmed so that each air conditioner was controlled independently. For all tests reported, one air conditioner was set to cut off at a sensed temperature of 4 ^oC (40 ^oF) and the other was set to cut off at 10 ^oC (50 ^oF). The controller cost $194, but for a farm system, two bulb type thermostats could be installed for around $40 each. Since the air conditioners had no defrost capabilities, the variable timer relay was used to control the compressor motor to provide for defrosting. The two switch timer, timing gear, relay and switches cost $169. The power control wiring was arranged to allow the compressor to cycle on and off at a predetermined rate while the evaporator coil fan operated continuously. The timer gear operated on a 10 minute cycle and the typical relay settings allowed the compressor of each air conditioner unit to operate at a 80 percent duty cycle (on eight minutes and off two minutes). The two timer switches were off set 180 degrees to prevent both air conditioner units from cycling off at the same time. Any evaporator coil icing that occurred during the time the compressor was operating was melted by the relatively warm air from the cooling container during the compressor off time.

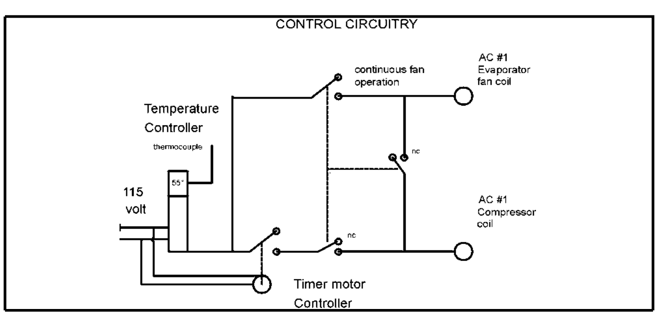


Figure 4 .

Electrical Wiring and Connectors

An (Figure 1) electrical cable (extension cord) connected to a local power source provides electric energy to the forced-air cooler (for fan and air conditioner power). The electrical wiring cost was high ($738) due to the design for flexibility and portability. A breaker service panel was installed on the trailer. Each air conditioner unit and the high pressure fan were wired to an individual circuit breaker. A master circuit breaker was also installed. A 47.2 m (100 ft) long size #2/3 600 V electrical cable ($310) was connected to the on-trailer service panel. The other end of this large cable was connected to a 100 amp circuit breaker and this circuit breaker was installed in the on-site electrical service panel. Several 100 amp circuit breakers of common brands were purchased to allow for differing service panels. The actual wiring cost for a permanent system would be much less since 30 amp circuit breakers and size #10 wire with shorter length could be used to wire each air conditioner unit, and even smaller components could be used for the high pressure fan.

PERFORMANCE OF PORTABLE DEMONSTRATION FORCED-AIR COOLER

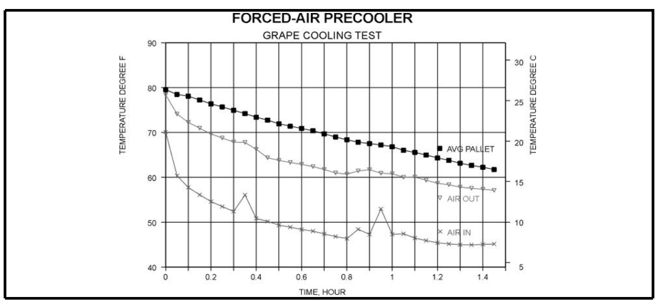
Operational Testing

After completion, the system was operated without a cooling load for several days to insure the proper operation of the fan, air conditioner units, and control circuitry. The inlet (cooling) air, outlet air, evaporator coil, condenser coil, and ambient temperatures were measured using thermocouples.

The power requirements were measured using a clamp-type AC ammeter. A digital manometer was used to measure the static pressure loss (drop) across the air conditioner units. The system performed well in various operational modes during testing without a cooling load. The control circuitry functioned as desired. The air conditioner units required 18 amps each, while the high-pressure fan required 6 amps.

Cooling Experiments

The system was used to cool grapes and to compare room cooling to forced-air cooling at a farm near Ft. White, FL [7]. A major difference between large commercial force-air coolers and the portable forced-air cooler is magnitude of scale. Normally, commercial systems are of such large volume that a near constant cooling air temperature is maintained. As evident in Figures 5 , 6 , and 7 , the initial cooling air temperature was not constant. To insure a constant initial grape temperature, the portable forced-air cooling unit was not precooled. If the unit was operated prior to initiation of product cooling, the heat load from walls of cooling chamber would be reduced and the evaporator coils would reach a lower initial operating temperature.



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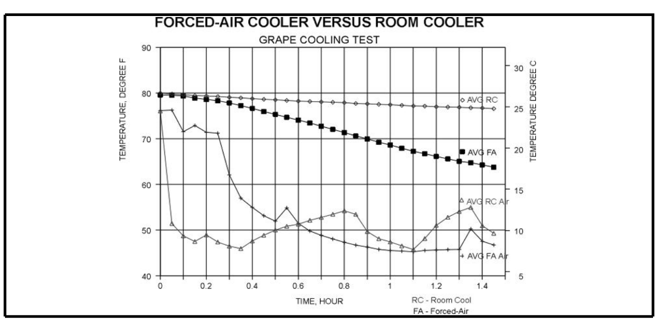

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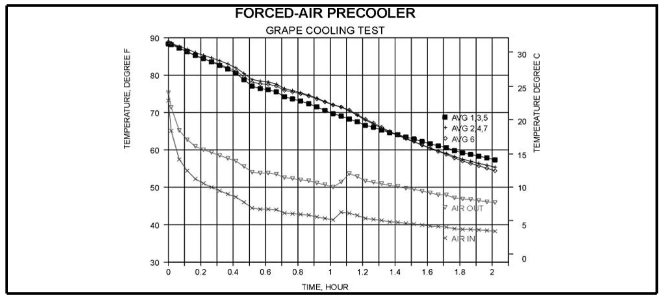
The corrugated grape container were filled with 10 kg (22 lb) of 1.9 cm (0.75 inch) diameter muscadine grapes stacked seven containers per layer



7 .

on a pallet. Several grapes on one layer were instrumented with thermocouples to measure the temperature at the center of the grapes. Figure 5 shows the average pallet grape temperature, the average inlet and outlet air temperatures. The 698 kg (1,540 lb) of grapes (10 layers) were cooled approximately 8.3 ^{o}C (15 ^{o}F) in one hour. This product load exceeded the design load by 30%, which caused a longer cooling time. The spike increases of the average inlet temperature shown in Figure 5 were caused by opening of the cooling chamber door during the test. A plastic curtain will be added tohelp reduce this significant energy loss. During the 1.5 hour cooling test, the electric meter on the power pole indicated 19 kWh were consumed. However, this included the power for the room cooling system, a trailer camper, and the electricity used in the packing shed.

During the later stages of one cooling test, the timer was disengaged and one of the evaporator coils iced. When the evaporator coils freeze up, the air flow resistance increases and the cooling capacity decreases. Using the timer and controller, evaporator coil icing was not a problem. In order to quickly detect evaporator coil icing in the future, a sight window will be installed in the side of the each air conditioner unit.

Room Cooling Tests

The cooperator was using the cooling body from an old 907 kg (2,000 lb) meat delivery truck for room cooling. This walk-in cooler was cooled with an old refrigeration unit of less than 3.5 kW (1-ton). A room cooling test was conducted simultaneously with a forced-air cooling test [7]. Figure 6 shows the average pallet grape temperature for forced-air cooling, the average temperature for two containers of room cooled grapes, the average forced-air inlet and average room cooling air temperatures. The 698 kg (1,540 lb) of grapes were cooled approximately 6.7 ^{o}C (12 ^{o}F) in one hour, but again, the cooling load was 30% greater than the design load and the cooler was not precooled and the containers provided less than 2% vent opening area. The room cooled grapes were cooled only 2 ^{o}C (4 ^{o}F) in one hour, indicating the superior cooling of forced-air cooling. The cooling test data were recorded for nearly three hours. After 2.5 hours, the forced-air cooled grapes were cooled approximately 14.6 ^{o}C (26.2 ^{o}F), while the room-cooled grapes were cooledapproximately 3.5 ^{o}C (6.2 ^{o}F). Interestingly, the cooperator requested the performance comparison of the forced-air unit and his room cooler before he was informed of this planned test. When the grower was shown the increased cooling by the forced-air cooler, he indicated that many growers would be interested in forced-air cooling.

During the 2.5 hour cooling test, the electric meter on the power pole indicated 16 kWh were consumed, but this included the power for the room cooling system, a trailer camper, and the electricity used in the packing shed. In the future, the power consumed by the cooling unit will be isolated from the local power consumption.

Increased Vent Opening Area and Air Stacking

The grape containers used were not designed for forced-air cooling and provided (2%) much less than the recommended vent opening area and causing a high pressure drop. The recommended vent opening is 5% for containers used for forced-air cooling [1, 6, 8]. In order to increase the vent opening area, additional vent openings were added using a 1.9 cm (0.75 inch) diameter metal center punch. A cooling test was conducted with the containers modified to provide 3.3% vent openings (not illustrated). The 698 kg (1,540 lb) of grapes were cooled approximately 5.6 ^{o}C (10 ^{o}F) in one hour, with less cooling than anticipated. Again, this product load exceeded the design load by 30% and the cooler was not precooled, which caused a longer cooling time. Despite the increased vent opening area, the containers continued to produce a large pressure drop. A slight increase in flow through the product was not sufficient to appreciably increase the cooling rate. The increased vent openings were less than the recommended 5%. In addition, the newly added 1.9 cm(0.75 inch) diameter vents were in many cases blocked by the grapes. The importance of properly sized and located container venting was confirmed.

A cooling test was conducted where the containers were stacked allowing a space between each container to permit air flow between containers [7]. Figure 7 presents the average container grape temperature for three containers on the inlet air side of the pallet (1,3,5), the center container (6), the three containers on the outlet air side of the pallet (2,4,7), the average inlet and outlet air temperatures. This illustrates that the cooling air first passed through containers 1, 3, and 5, then passed through container 6, and finally passed through containers 2, 4, and 7. The cooling air is warmed as it passes through each subsequent container and this is frequently called "bed effect". Therefore grapes in the containers closest to the entrance of the cooling air (containers 1, 3, and 5) cooled slightly faster than the containers near the air outlet (containers 2, 4, and 7). This factor is important when selecting a temperature monitoring or sampling location [8]. For this test, only seven layers of containers were used, rather than ten layers. The 489 kg (1,078 lb) of grapes were cooled approximately 10 ^{o}C (18 ^{o}F) in one hour, which approximated the design load. The cooler was not precooled and the containers provided less than 2% vent opening area, but the containers were stacked (air stacked) with 1.9 cm (0.75 inch) wide spaces between each container. With the reduced cooling load, the average entering cooling air temperature was lower than the tests with larger cooling loads. Although air stacking did allow a lower static pressure and slightly increased flow rate, the slow grape cooling rate indicates that insufficient cooling air flowed through the containers. In future tests, the proper cooling load and containers with 5% vent openings will be cooled and the cooling response should be much improved.

ENERGY ANALYSIS

This unit requires energy input to produce the desired results (precooled product with less spoilage and higher quality and value). For example, if two pallets of pepper (approximately 1000 pounds per pallet) were cooled from 29.4 ^{o}C (85 ^{o}F) to 18.3 ^{o}C (65 ^{o}F) with 7.2 ^{o}C (45 ^{o}F) cooling air the product load would be 10.3 kW (37,600 BTU/hr) to cool the pepper in one hour. This would require 3.1 tons of refrigeration. It is unlike some systems which provide an alternative energy or reduce the energy requirements of an operation. In addition to providing a higher quality product to the consumer and increased profit to the producer, the reduction of postharvest loss as a result of cooling provides an energy savings in terms of the sequestered energy which was discussed above. The following example illustrates the potential energy savings in terms of sequestered energy. Reliable estimates indicate there are 50 growers with 20 ha (50 acres) and 575 growers with 2 ha (5 acres) for a total of 2175 ha (5,375 acres) in the twelve county region north of Gainesville. The average total primary energy requirements for pepper, cucumbers, eggplant and squash is 5.3×10^{4} kWh/ha (73×10^{6} BTU/acre). If the acreage in region were all planted in pepper, cucumbers, eggplant and squash, the total primary energy requirements for 2175 ha (5,375 acres) would be 1.1×10^{8} kWh (3.9×10^{11} BTU). Assuming all this production is cooled and as a result the loss due to spoilage is reduced by only 5%, the energy savings as a result of cooling in this twelve county area would be $5.8 \times 10_{6}$ kWh (20×10^{9} BTU) or a per ha (acre) savings of 2.6×10^{3} kWh/ha (3.7×10^{6} BTU/acre).

ECONOMIC ANALYSIS

The cost for the demonstration forced-air cooler is listed in Table 1 as $4,612.97. This does not include construction labor costs since many growers who will adopt this design will use in-house labor. The demonstration forced-air cooler incorporates additional electrical component and controls which required added expense. Also, the additional cost to make the system portable would not be required for a stationary unit. Table 2 presents a simplified economic analysis for the system and indicates a five-year payback based on a precooling charge of $0.55 per kg ($0.25 per lb) for 93 pallets per year.

SUMMARY

The portable forced-air cooler is a good demonstration unit that addresses the advantages of energy efficient techniques for postharvest cooling and handling of Florida fresh fruits and vegetables. In addition to demonstrating proper cooling techniques, the demonstration unit has several important management guidelines incorporated [8]. These management factors include the following: how to precool with forced-air cooling, block air bypasses, proper container vent opening area (5%), proper temperature monitoring and management, proper cooling time determination, and how to measure and use pressure drop readings. The cooling techniques and management factors will be illustrated at future on-farm demonstrations. Besides the hands-on educational experience, the unit provides producers with an example of a precooling system they could economically adopt for their operations.

Energy-use efficiency and grower profitability will be improved because proper postharvest handling helps maintain the quality and shelf-life of the produce, allowing for a surer market. The energy invested in the production of the crops will be more fully utilized because of reduced spoilage and longer transit and storage life. As growers of horticultural crops in North Florida start considering building postharvest cooling and handling equipment and facilities, this demonstration forced-air cooling unit will provide a unique opportunity to influence this process to insure the most appropriate, energy efficient, and economical selections are made. The goal of this demonstration project is to contribute to the long-term viability of this growing segment of Florida's agriculture.

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Table 1.

Table 1. Material and price list (forced-air cooler).	
Description of Component	**Total**
Cooling Chamber	
Lumber, plywood, roofing, plastic, fasteners, paint	$1,020.79
Styrofoam insulation	$ 151.20
Latch handle door and 20 cm (8 inch) T Hinges	• $ 74.30
Canvas pallet cover	• $ 66.68
Subtotal	• **$1, 312.9 7**
High Pressure Fan (Dayton model 7H128)	
26.7 cm (10.5 in) backward inclined 1.1 kW (1.5 HP)	$ 502.00
Subtotal	**$ 502.00**
Air Conditioner Units (Airquest Model NA2P036A2N)	
10.5 kW (3-Ton) Package Air Conditioner (2 @ $690.00)	$1,390.00
Ducting, 30.5 & 35.6 cm (12 & 14 inch) (diameter, flexible & metal)	$ 134.00
Subtotal	**$1,524.00**
Electrical Components	
Wiring, connectors, panel, junction boxes	$ 738.00

Table 1.

Controller (Love Model 16011)	$ 194.00
Timer, two terminal, relay and gear (Newark Electronics Model 62F2006)	$ 169.00
Subtotal	**$1,101.00**
Trailer	
Used, 1.8 x 4.3 m (6 x 14 ft), 2,721 kg (3-ton) tandem trailer	• $ 200.00
Retrofit and repairs	$ 73.00
Subtotal	**$ 273.00**
Total	**$4,612.97**

Table 2.

Table 1. Material and price list for a portable forced-air cooler.								
Fixed Costs:								
Depreciation 2 AC units, 1 fan and electrical components (cost $3,127; salvage value $300; 10-year life)								$282.70
Cooling Room (cost $1,312.97; 25-year life)								$52.52
Interest (1/2 combined cost of equipment, $4,612.97/2 x 14%)								$322.91
Repairs, maintenance, taxes and insurance (estimated at 3% of new cost)								$138.39
Fixed Cost								$796.52
Variable Cost:								
Electricity, 10 kWh per 680 kg (1,500 lb) at $0.10/kWh				$0.67/454 kg (1,000 lb)				
Labor, 1 hr per 680 kg (1,500 lb) at $5.00 per hr				$3.33/454 kg (1,000 lb)				
Variable Cost for cooling 454 kg (1,000 lb)				$4.00/454 kg (1,000 lb) or $0.009 kg ($0.004/lb)				
Total Cooling Cost at Various Volumes:								
	454 kg (1,000 lb) per year							
	30	40	50	60	70	80	90	100
Variable Cost	$ 4.00	$ 4.00	$ 4.00	$ 4.00	$ 4.00	$ 4.00	$ 4.00	$ 4.00
Fixed Cost	$26.55	$19.91	$15.93	$13.28	$11.38	$ 9.96	$ 8.85	$ 7.96

Table 2.

Total Cost	$30.55	$23.91	$19.93	$17.28	$15.38	$13.96	$12.85	$11.96

Payback Method. How many 454 kg (1,000 lb) pallets must be processed per year to pay off the system in 5 years? Assume a precooling charge of $0.02/kg ($0.01/lb) is applicable [for a 11.3 kg (25 lb) container this amounts to $0.25 or $10 per pallet]. Total system cost $4,612.97/$10/pallet/5 years = 93 pallet per year for 5 years. If only 5 pallets are cooled per day, the system would need to be operated (93/5) 19 days per year. The payback period should also be based on the increased profit from higher quality product and reduced spoilage versus the capital investment for the forced-air cooling system.