A Combined Refrigerator-Electric Water Heater

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After space conditioning, water heaters and refrigerators are the typical American home's second and third largest energy users, respectively. Efficiency improvements for individual refrigerators and water heating systems offer substantial energy conservation opportunities. However, combining the two functions in a single appliance offers potential "source energy" savings even without efficiency improvements. Evaluations completed in 1991 indicated that a combined refrigerator-electric water heater (CREWH) could substantially reduce total source energy consumption vs. a natural gas heating base case.

A prototype CREWH model was designed, built, shop-tested, and installed at the first new construction home for the Pacific Gas and Electric Company (PG&E) Advanced Customer Technology Test (ACT^2). The prototype was installed in a domestic water preheating configuration working in conjunction with a condensing natural gas water heater.

The CREWH prototype was developed and tested using a new high efficiency refrigerator with a custom membrane-lined water storage tank located atop the appliance. The tank membrane was configured to surround the condenser coil and the compressor so as to maximize heat delivery to the storage water.

Initial shop test results show that the CREWH can achieve water temperatures warmer than 120°F in its integral preheat tank. Field data indicate successful CREWH operation in the occupied home.

Introduction

Energy Use

Refrigerators and water heaters are significant residential energy users. After space conditioning, refrigerators and freezers are the highest electrical energy users in typical residences, with average annual energy consumption of greater than 1,000 kWh per household. (A large California utility estimates approximately 1450 kWh of annual refrigerator energy use per household.) In many mild climates, water heating is the largest residential thermal energy use; the California Energy Commission (CEC) projects that by the year 2000 statewide residential natural gas use will be higher for water heating than for space heating *(Energy Efficiency Report* 1990).

In a typical single family home, the total annual heat discharge from the refrigerator condenser is approximately half the annual domestic water heating "recovery load" which includes end uses and pipe losses, based on new refrigerators with 750 kWh/year consumption and 60 gallons (227 liters) per day water use with 70°F (39°C) temperature rise. For apartments and mobile homes, where the number of occupants per dwelling are typically lower, average annual refrigerator condenser output more nearly equals average recovery load. The conventional refrigerator heat output increases building cooling loads, and decreases heating loads.

Hot Water Distribution

"Sunbelt" climates where significant U.S. growth is occurring, slab-on-grade construction is common and residential water heaters are typically located in garages or outdoor closets, with extended hot water piping and relatively large standby losses. A water heating study prepared for the CEC (Water *Heating Project Technical Report* 1990) indicates that the kitchen sink normally has the largest number of hot water draws. For a typical home studied, locating the water heater near the kitchen sink would reduce piping heat losses by 46%, reducing annual water heating energy use by 5.8%. A preheating CREWH configuration will not realize these distribution loss reductions; instead it usually will increase losses. While the preheating configuration is not ideal, the ACT[2] project provided an opportunity to apply CREWH technology to a new construction home and monitor performance. Future efforts will be made to test CREWH as a stand-alone water heater.

Combined Appliance Advantages

The prototype CREWH model installed in the ACT[2] home in Davis, California, was installed as a preheater for the hot water heater, because a high efficiency water heater was already specified for the radiant floor heating in the house. The preheater application actually increases distribution losses compared to the base case, since additional hot water piping is necessary. However, the water heater and refrigerator are only 12 feet (3.66 m) apart in the ACT[2] house. In an application where the CREWH could eliminate the auxiliary water heater, the economics would be more favorable than for the installed ACT[2] prototype model (see section on Energy Savings). Although condensing temperatures would be higher with this configuration, eliminating gas storage heater cost and standby losses adds significantly to CREWH value.

Energy Savings

Potential CREWH energy savings depend on climate, CREWH configuration, and occupant energy use patterns. A typical California "base case" configuration is shown in Figure 1, with water heater in a "buffer space" (garage or outdoor closet). Figure 2 shows the proposed CREWH, in a preferred configuration without auxiliary heater, located in the kitchen. Water heating loads exceeding refrigerator condenser output are assumed to be satisfied by adding an indoor air path through the refrigerator evaporator.

Approximate energy use quantities for an energy-efficient California home are provided, based on specific examples from prior studies for a typical single family home.

Refrigerator performance values are based on identical compressors for base case and CREWH systems. Standard refrigerator energy use and efficiency are based on refrigerator efficiency studies at Lawrence Berkeley Laboratory *(ACEEE Proceedings* 1990).

A CREWH can affect base case energy consumption as follows:

1) CREWH can reduce hot water system losses. Based on detailed modeling from the CEC study (Water Heating Project Technical Report 1990), a kitchen water heater location would reduce example hot water piping system heat loss by 1.13 MBtu/yr (1,192 MJ/yr) and tank standby heat loss by 1.37 MBtu/yr (1,145 MJ/yr) annually for a standard sample house.

2) CREWH can change the refrigerator space conditioning role. The standard refrigerator affects indoor space as a resistance heater, which decreases heating loads and increases cooling loads. The CREWH is a space cooler, allowing a more efficient heat pump or natural gas heating system to satisfy the increased heating load. These analyses assumed that the CREWH reduces cooling load during 30% of its operating hours, increases heating load for 30% of its operating hours, and operates 40% of the time during mild conditions when it does not affect heating or cooling system operation.

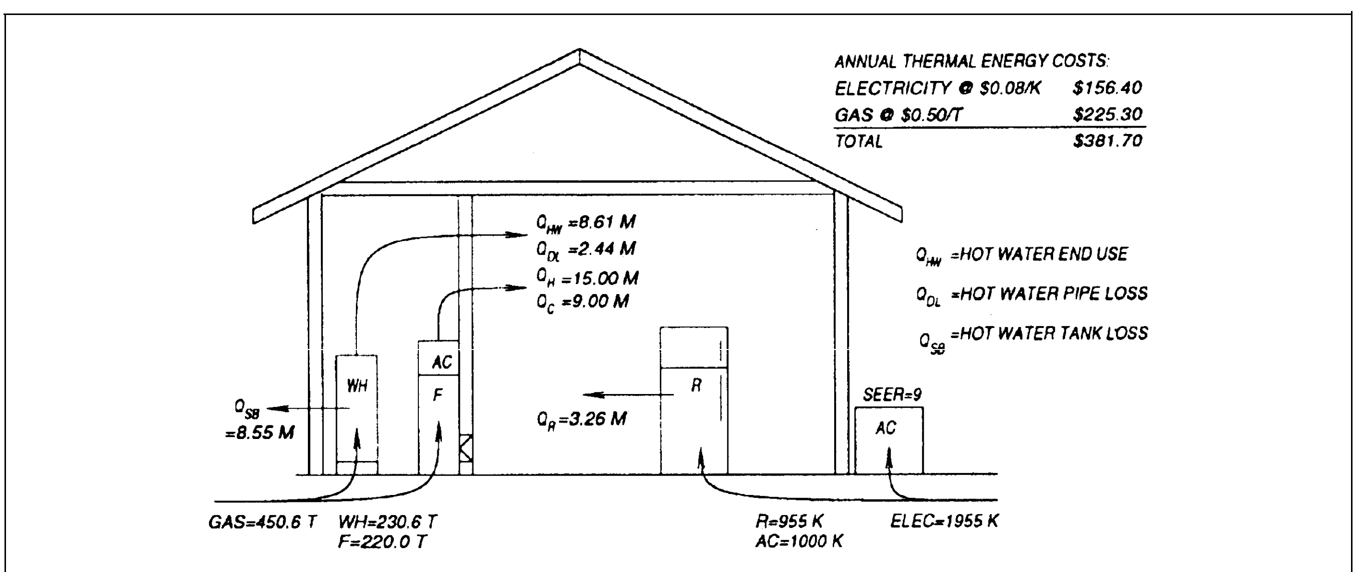


Figure 1. Base Case (M = million Btu's/yr; K = kWh/yr; T = therms/yr)

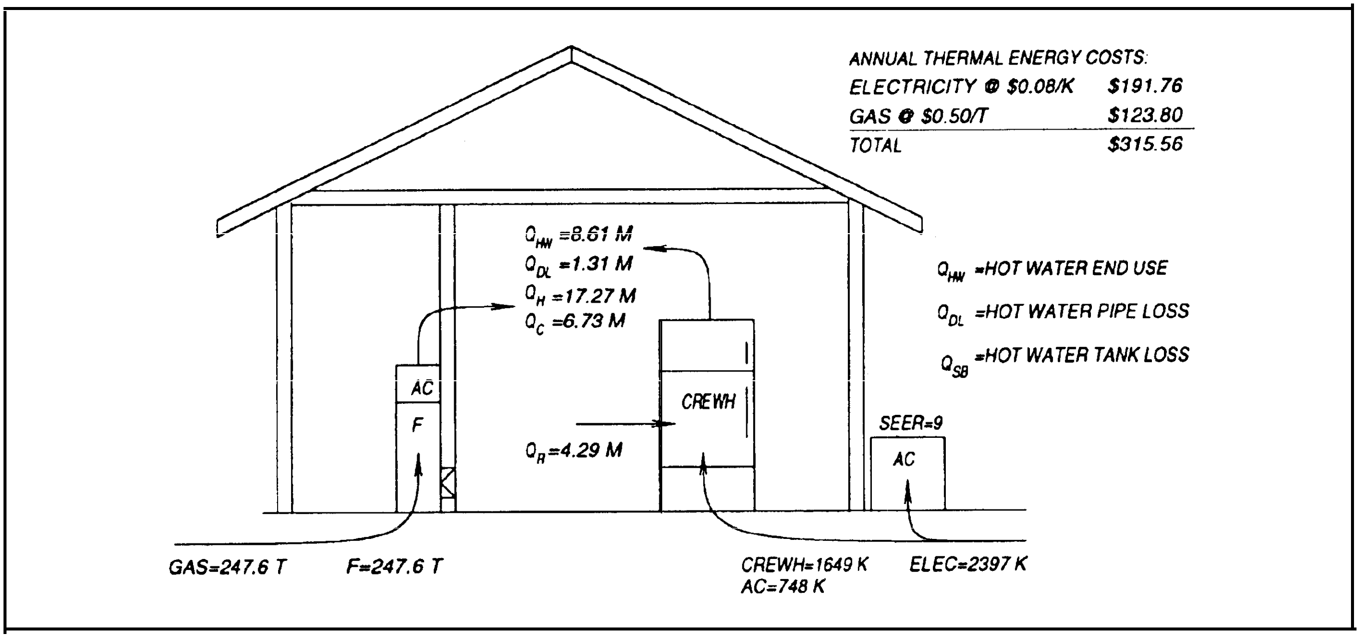


Figure 2. Basic CREWH (M = million Btu's/yr; K = kWh/yr; T = therms/yr)

3) CREWH can recover hot water tank standby losses. While standard gas water heater jacket losses occur in the outdoor buffer space, CREWH tank losses are much lower (no center flue) and occur indoors, partially countering refrigerator space cooling.

In summary, the CREWH can save energy by curtailing the refrigerator's role as an uncontrolled resistance space heater, and by eliminating outdoor standby losses and distribution piping losses experienced by the conventional water heater. Based on the standard CEC source energy conversion (1 kWh = 10,239 Btu's), the example "stand alone" CREWH with indoor air auxiliary heat source would reduce combined (refrigerator + water heater) source energy use by 53% using a standard compressor when space conditioning impacts are consistent (see Figures 1 and 2 and Table 1).

Development Status

In a 1991-92 project funded by Southern California Edison (SCE), Davis Energy Group modified a new side-by-side refrigerator to become a prototype CREWH. That project was generally successful but made clear that effective CREWH performance requires delivery of compressor jacket heat into the storage water.

In 1993, DEG designed and installed a second prototype model at the first new construction home in the Pacific Gas and Electric Company's Advanced Customer Technology Test (ACT[2]). The design responded to earlier SCE project results, incorporating the compressor and the condenser coil as heat sources for the storage tank. Performance tests were first completed for the base case, commercially available refrigerator. The CREWH was then assembled, and tested without hot water draws. The CREWH was subsequently installed in the house. General house monitoring has begun and will continue through 1995.

Design

For the ACT[2] project, a high efficiency refrigerator (rated at 612 kWh/yr for the 19.8-cubic-ft bottom freezer unit) was modified by removing the condenser coil and fan, and relocating the compressor. The 23-gallon (87-liter) water storage container was located atop the refrigerator to facilitate water removal, if necessary, by draining into the kitchen sink. Figure 3 shows side and front views of the modified unit with water storage box on top.

A sealed PVC liner was used for water containment inside a 16-in. (40.6-cm) tall vertical extension of the refrigerator walls. Figure 4 shows plan and vertical section views of the CREWH storage container. The compressor was placed in the center of the water containment area, surrounded at its base by the spiral condenser coil. A 14-in. (35.6-cm) width of copper solar absorber fin/tube was wrapped horizontally around the interior side of the vertical wall extensions, to serve as the domestic water preheater. The vinyl liner was placed inside the heat exchanger wrap, and atop the compressor and condenser, contouring to all surfaces when the liner is filled with water. In this configuration, the compressor and condenser coil surfaces heat storage water through the liner bottom, and the storage water heats the cold inlet water flowing through the heat exchanger via the liner walls.

Table 1. "Stand-Alone" CREWH Energy Use Projection

Compressor Operating Modes:

Mode 1 = Water Heating from Refrigerator
Mode 2 = Water Heating from Indoor Air through Evaporator

	Base Case	CREWH Mode 1	CREWH Mode 2	CREWH Mode 3
Evap. Temperature	-15 F	-15 F	45 F	
Condens. Temperature	105 F	125 F	125 F	
Refrigerator Effic.				
Heating COP	2.42	2.13	3.05	
Cooling COP	1.42	1.13	2.05	
Water Heating				
Recovery Load	11.05 M			9.92 M
Standby Loss	8.55 M			7.18 M
Total Output	19.60 M			17.10 M
Refrigeration Cooling	4.62 M	4.62 M	5.65 M	10.27 M
Compressor	3.26 M	4.08 M	2.75 M	6.83 M

F = Degrees Fahrenheit; M = Million Btu's\year

	Base Case	CREWH Mode 1	CREWH Mode 2	CREWH Mode 3
Evap. Temperature	-26 C	-26 C	7.2 C	
Condens. Temperature	40.6 C	51.7 C	51.7 C	
Refrigerator Effic.				
Heating COP	2.42	2.13	3.05	
Cooling COP	1.42	1.13	2.05	
Water Heating				
Recovery Load	11,686 MJ			10,467 MJ
Standby Loss	9,021 MJ			7,576 MJ
Total Output	20,680 MJ			18,042 MJ
Refrigeration Cooling	4,875 MJ	4,875 MJ	5,961 MJ	10,836 MJ
Compressor	3,440 MJ	4,305 MJ	2,902 MJ	7,206 MJ

C = Degrees Celsius; MJ = Million Joules/year

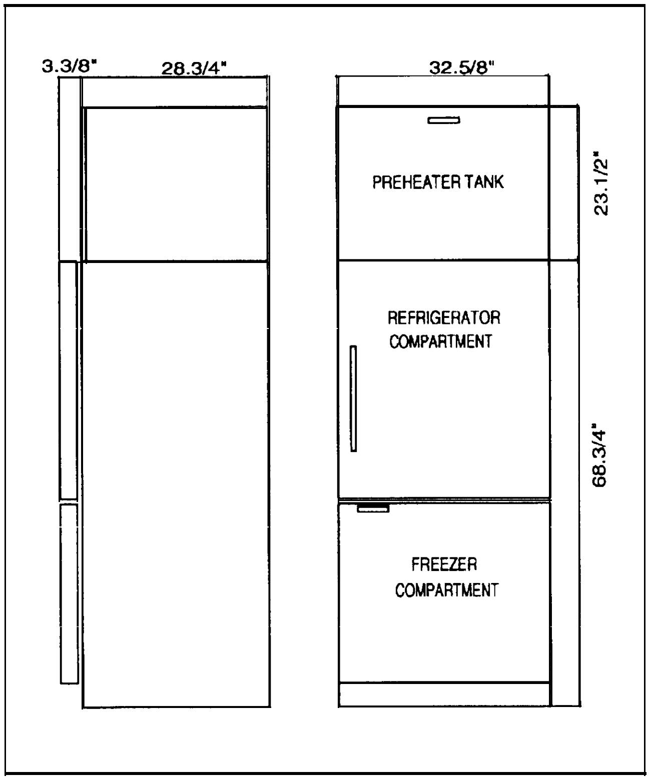


Figure 3. CREWH Front and Side Views

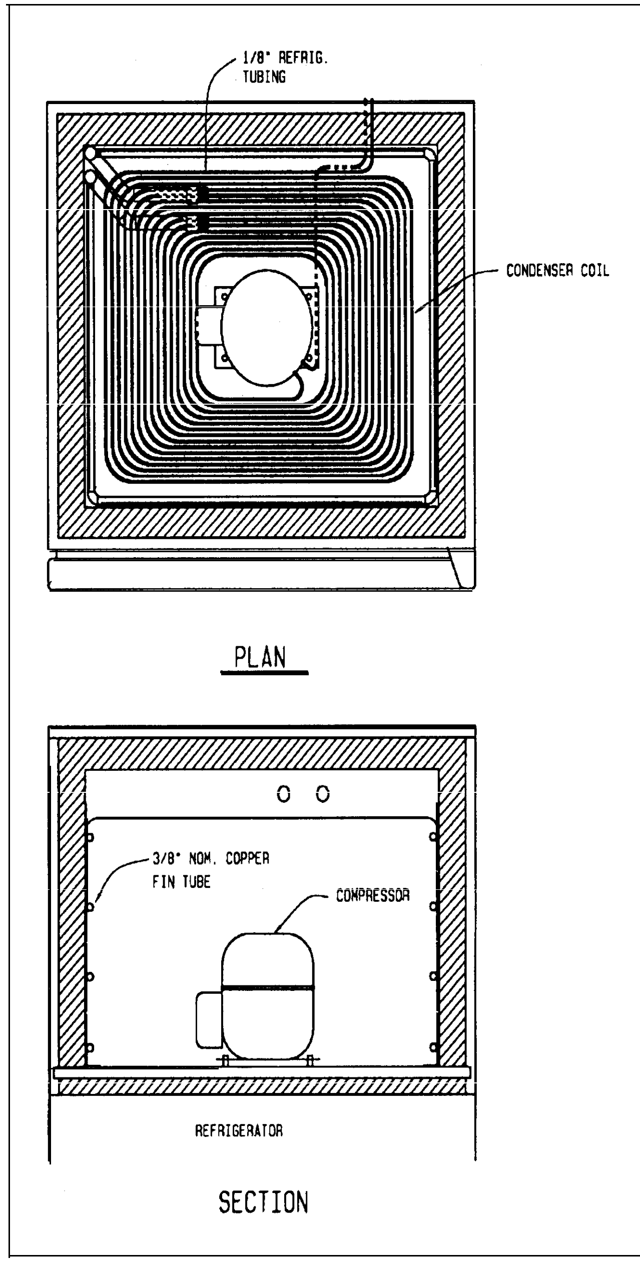


Figure 4. CREWH Components

Manual protection was incorporated to prevent compressor overheating (and potential failure) during extended periods (more than two days) without hot water draws. Before departing on vacation, the occupants must open the front insulating panel of the CREWH tank to allow heat to discharge into the kitchen. In an alternate design, automatic overheat protection could discharge preheated water to a drain, or operate a vent fan.

Testing

The refrigerator was shop-tested without internal loads or hot water draws before and after CREWH modifications. Testing was completed in an unconditioned shop facility. Indoor temperature averaged almost 70°F (21°C) for the base case test and 54°F (12°C) during the CREWH test. Thermocouples were linked to an electronic data logger to record indoor, freezer, fresh food box, condenser, evaporator, and water (CREWH configuration only) temperatures. Power transducers connected to the same data logger measured individual power consumption by compressor, evaporator fan, defrost heater, controls, and condenser fan (before modification only) components. In the six-day base case test, condensing temperature varied with indoor temperature. The CREWH test was begun with cool storage tank water which was continuously heated to 119°F (48°C) during the nine day test. Since the shop test of CREWH occurred at 54°F (12°C) ambient temperatures, and because there was no internal load on the refrigerator, test operation cannot be easily compared to earlier estimates. The main purpose of the shop test was to verify proper operation of the unit before site installation.)

Installed Unit

The CREWH was installed at the ACT[2] house in mid-December, 1993, and the owner-occupants moved in on December 27. Figure 5 shows a block diagram of the combined hydronic loop in which the CREWH was installed. The CREWH is used as a preheater for the high efficiency condensing water heater, with the boiler as the primary heat source for both domestic hot water and

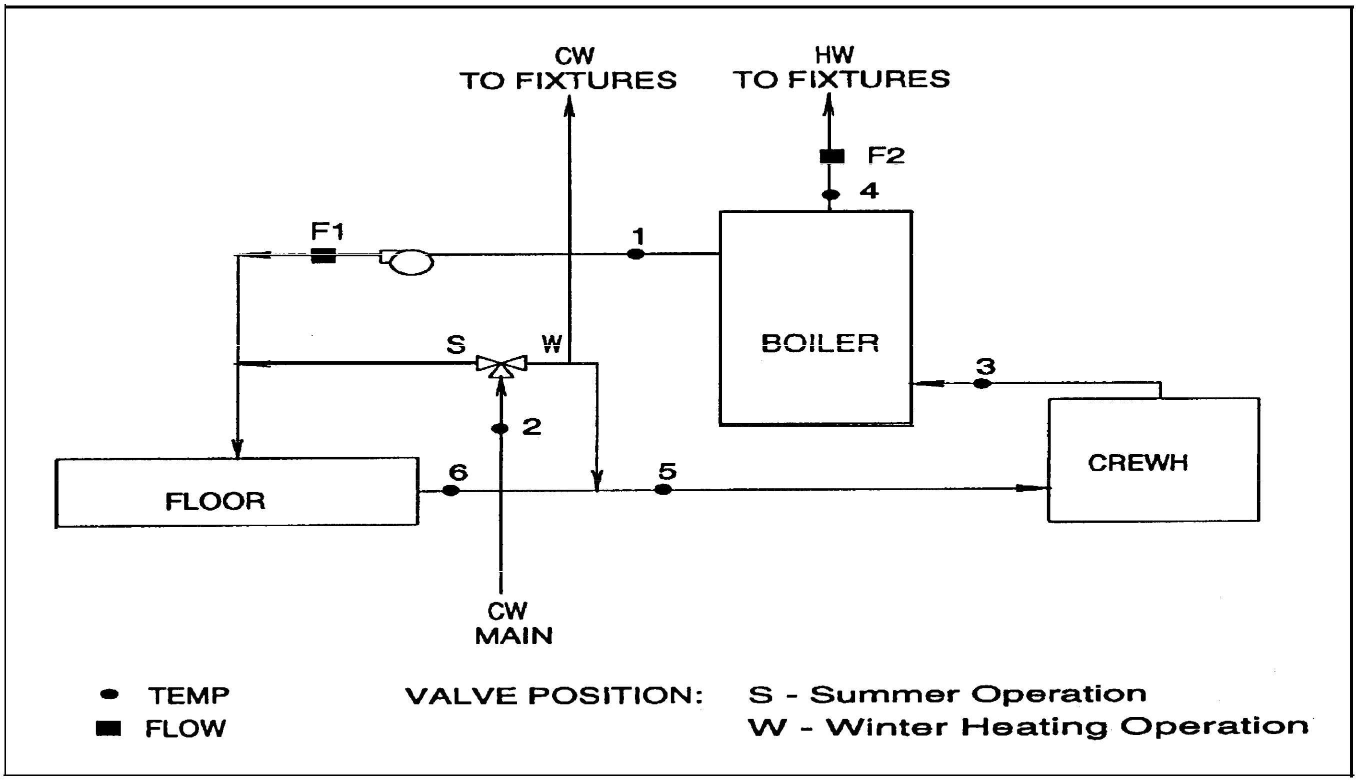


Figure 5. Hydronic System Schematic

radiant floor heating. When hot water is drawn, cold water is preheated in the CREWH heat exchanger before entering the water heater. When space heating is required, water pulled through the radiant floor from the heater passes through the CREWH heat exchanger before returning to the boiler. During the cooling season, all cold water passes through the floor to cool the slab.

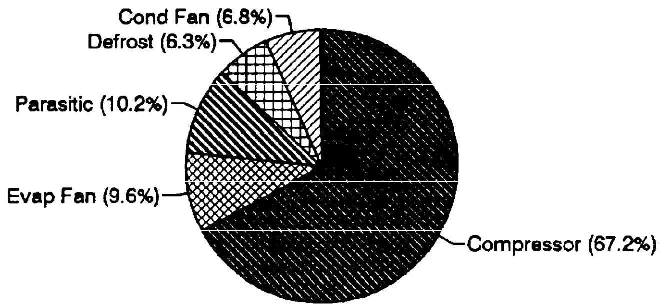
Figure 5 also shows locations of the flow and temperature sensors used to monitor the combined hydronic heating system. Temperatures are read with immersed thermocouples and flow is measured using impeller-type flow meters. Electronic data loggers record CREWH temperatures, flows, and power consumption every fifteen minutes, with sensor sampling every 5 seconds.

Preliminary Results

Figure 6 shows monitored energy use for the base case refrigerator, with freezer and fresh food box temperatures maintained at approximately 2°F (-17°C) and 42°F (6°C), respectively. The compressor consumed over 67% of total energy during the seven day test period. The evaporator fan and controls consumed approximately 10% each; the condenser fan and defrost heater approximately split the remaining 13% of total energy. During compressor operation, condensing temperature averaged approximately 36°F (20°C) above indoor temperature. The 0.26 run fraction indicates that the compressor ran approximately one-quarter of the time, as might be expected without food and door opening loads.

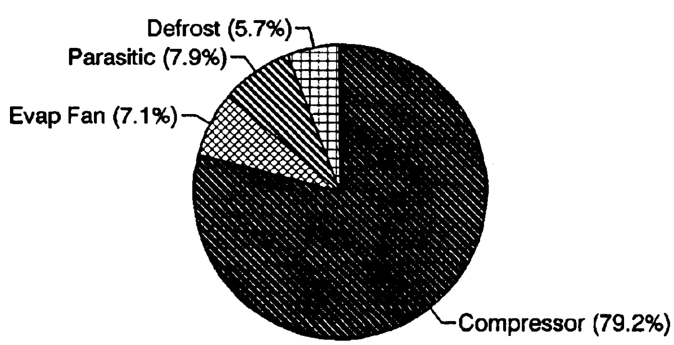
Figure 7 shows post-modification data comparable to Figure 6. The 54°F (12°C) average room temperature affected results by reducing refrigerator and freezer loads and increasing CREWH water storage tank heat losses. Average freezer temperatures were almost identical during the base case and CREWH tests. The fresh food box temperature averaged 4.5°F (2.5°C) cooler at the same control setting in the CREWH test, probably due to the cooler room. With addition of R7.2 insulation in the water container floor, warm water probably did not increase fresh food box cooling loads.

At 79%, the compressor consumed a larger piece of the total energy pie, mostly because the condenser fan was eliminated and both evaporator fan and parasitic control energy percentages were reduced because of higher compressor energy consumption. Compressor energy consumption increased at higher water temperatures. At 0.29, the compressor run fraction was slightly longer than in the base case, probably due to slightly lower cooling capacities during the last half of the test, when water and condensing temperatures were relatively high.



Temperatures	deg F	deg C	Defrost Power	83.0	Wh/cy	Component	Wh/day
Indoor	69.9	21.1	Avg Parasitic	4.7	watts	Compressor	744
Refrigerator	42.1	5.6	Cond Fan	12	watts	Evap Fan	106
Freezer	2.4	-16.4	Comp Frac	0.74		Parasitic	113
Avg. Condenser	105.9	41.1	Run Fraction	0.26		Defrost	69
			Defrost Timer	7.5	hours	Cond Fan	75
			Defrost Cycle	28.7	hours	Total	1,107

Figure 6. Base Case Refrigerator (Power Consumption Breakdown)



Temperatures	deg F	deg C	Defrost Energy	81.0	Wh/cy	Component	Wh/day
Indoor	54.0	12.2	Avg Parasitic	4.6	watts	Compressor	1,098
Refrigerator	37.5	3.1	Comp Frac	0.79		Evap Fan	99
Freezer	1.7	-16.9	Run Fraction	0.29		Parasitic	110
Avg. Condenser	104.3	40.2	Defrost Timer	7.1	hours	Defrost	80
Max Water	118.8	48.3	Defrost Cycle	24.4	hours	Total	1,387

Figure 7. CREWH Test Operation (Power Consumption Breakdown)

Figures 8 and 9 show room, condensing, and water (CREWH only) temperatures during the base case and CREWH test periods, respectively. In the base case test, the unit operated for approximately 12 cycles per day, with an average cycle length of approximately 30 minutes. Measured condensing temperature varied with room temperature, increased continuously through each cycle, and averaged 106°F (41°C) during the test period. In the CREWH test, condensing temperatures were, as expected, related to water temperature rather than room temperature. Condensing temperatures were warmer than the water during the first three days of the test, as water was heated from 61.5°F (16°C) to approximately 100°F (38°C); approximately equal to water temperature from 100°F (38°C) to 110°F (43°C); and cooler than the water beyond that point, apparently due to superheated refrigerant at the compressor discharge.

CREWH test data were further analyzed to evaluate the relationship between daily energy consumption and water temperature. Since unit operation responds to the refrigerator's interior thermostat, daily energy consumption is dependent on both room temperature and water temperature. However, daily average room temperature remained relatively consistent over the nine-day test period, as seen in Figure 9. Therefore, any change in daily energy consumption was expected to result largely from compressor efficiency variance with condensing temperature. Figure 10 shows daily CREWH energy consumption plotted versus the temperature difference between CREWH storage water and freezer temperature. This temperature range is closely related to the refrigerant evaporating and condensing temperatures. Figure 10 shows daily energy consumption remaining relatively constant at 800 to 850 watt-hours/day until it begins to rise noticeably when the temperature difference reaches about 100°F (38°C). While data are limited, daily energy use appears to rise more than 25% as temperature difference increases from 100°F (38°C) to 115°F (46°C). Since freezer temperature was near 0°F (-18°C), the water-freezer temperature difference has the same value as water temperature. Based on the data shown in Figure 6, the CREWH at 819 Wh/day compressor energy would have equal consumption with the base case compressor and condenser fan at 744 and 75 Wh/day, respectively (since CREWH eliminates the condenser fan). These results suggest that the preheat mode CREWH would incur no efficiency penalty when water temperatures stay below about 95°F (35°C).

Data from the field installation had not been fully analyzed at the time of paper publication. The unit had operated successfully since installation. Noise levels were noticeably lower than an identical unmodified refrigerator in a nearby house, due probably to a combination of condenser fan removal and addition of water mass around the compressor.

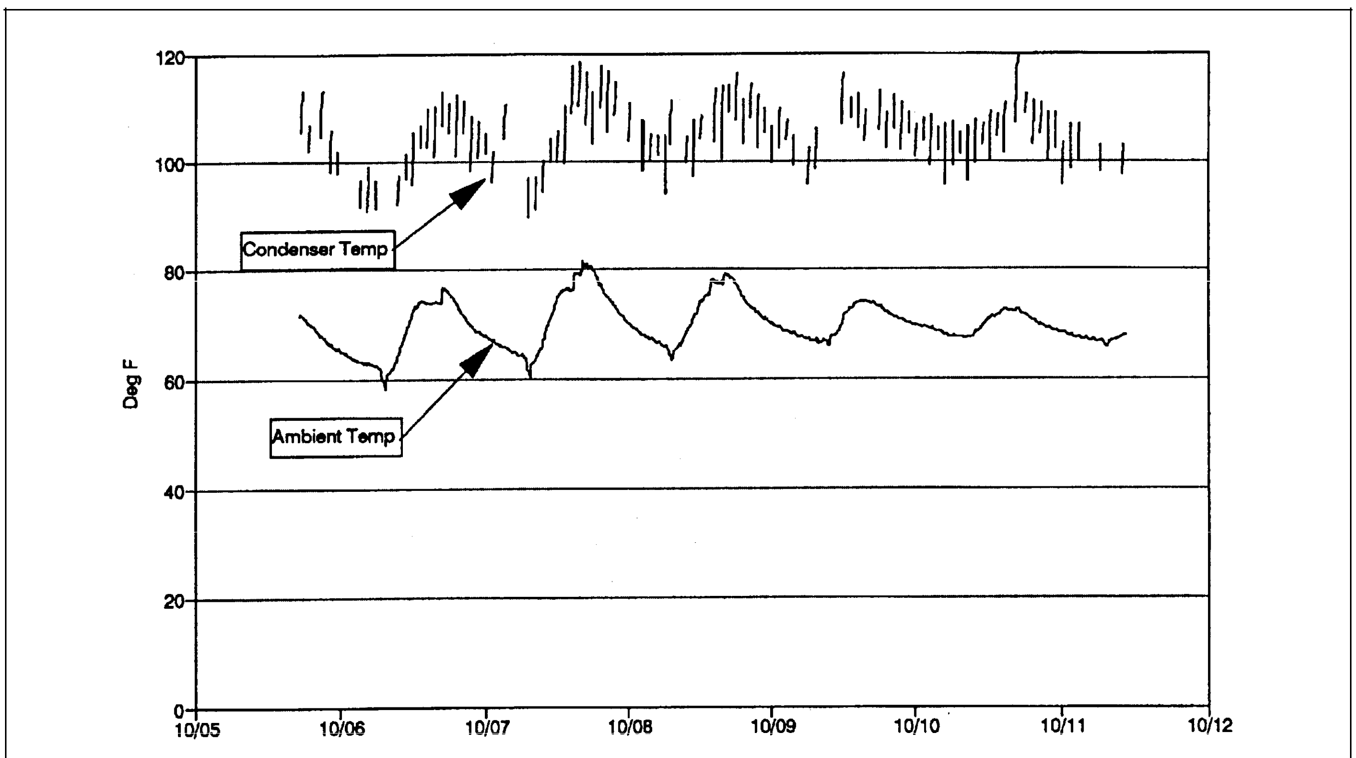


Figure 8. Base Case Refrigerator (Condenser Temperature Profile)

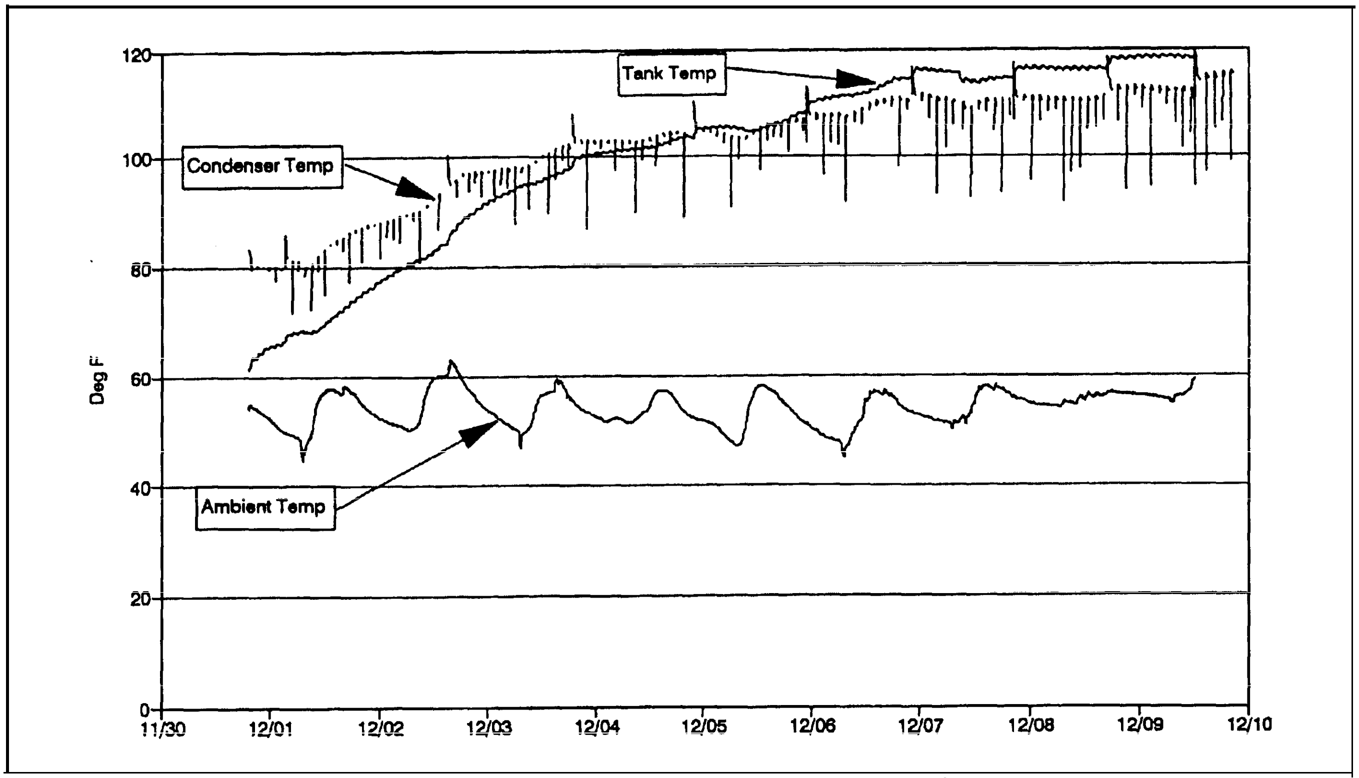


Figure 9. CREWH Test Operation (Temperature Trends of CREWH)

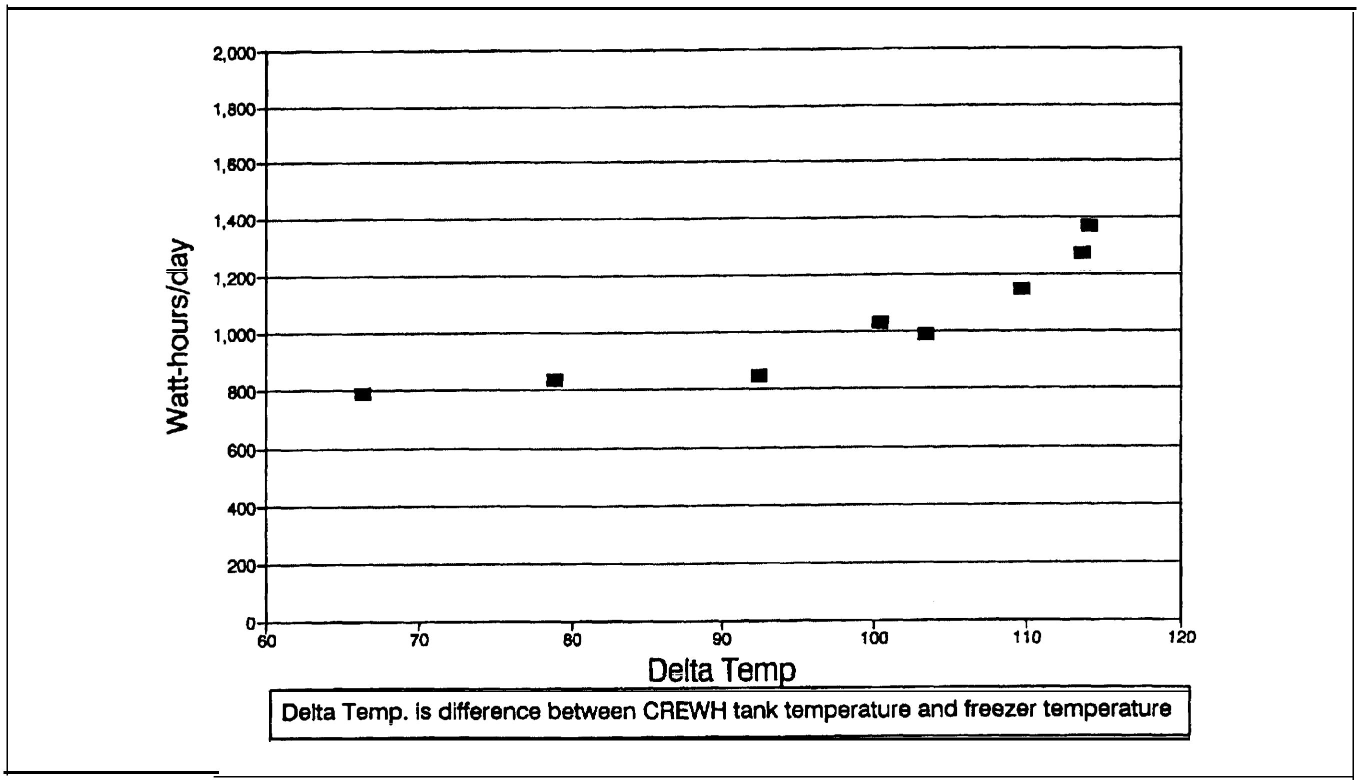


Figure 10. CREWH Test Operation (Avg. Daily Compressor Energy vs. Delta T

Initial field data show the preheater maintaining tank temperatures between about 110°F (43°C) and 120°F (49°C) (see Figure 11). With inlet water averaging about 67°F (19°C), preheater outlet temperatures varied with flow rate, but typically averaged almost 20°F (11°C) lower than tank temperature.

Conclusions

Preliminary analyses and tests indicate that a combined-refrigerator water heater can be a valuable energy-efficiency measure offering significant source energy savings, particularly when used as a stand-alone water heater. In the ACT^2 project, the CREWH was projected to be cost effective when "mature" as a preheater for an efficient gas water heater. In this application, CREWH economic value derived partially from displacing gas consumption and partly from reducing cooling loads and capacity by converting the refrigerator from a space heater to a space cooler. One key assumption of the value assumptions was that average CREWH condensing temperature would be unchanged from the base case refrigerator. Shop test data indicated that the tank temperature should average approximately 95°F (35°C) to equal base case performance.

Preliminary field data show tank temperatures averaging about 115°F (46°C). Lower-than-projected hot water use is causing warmer tank water, suggesting potential for full water heating output in future CREWH projects. For the current project, additional heat exchange surface should be added to improve performance, reducing tank temperature and increasing the temperature of preheated water leaving the unit. Field data will facilitate additional conclusions on efficiency and cost-effectiveness in the near future.

Acknowledgments

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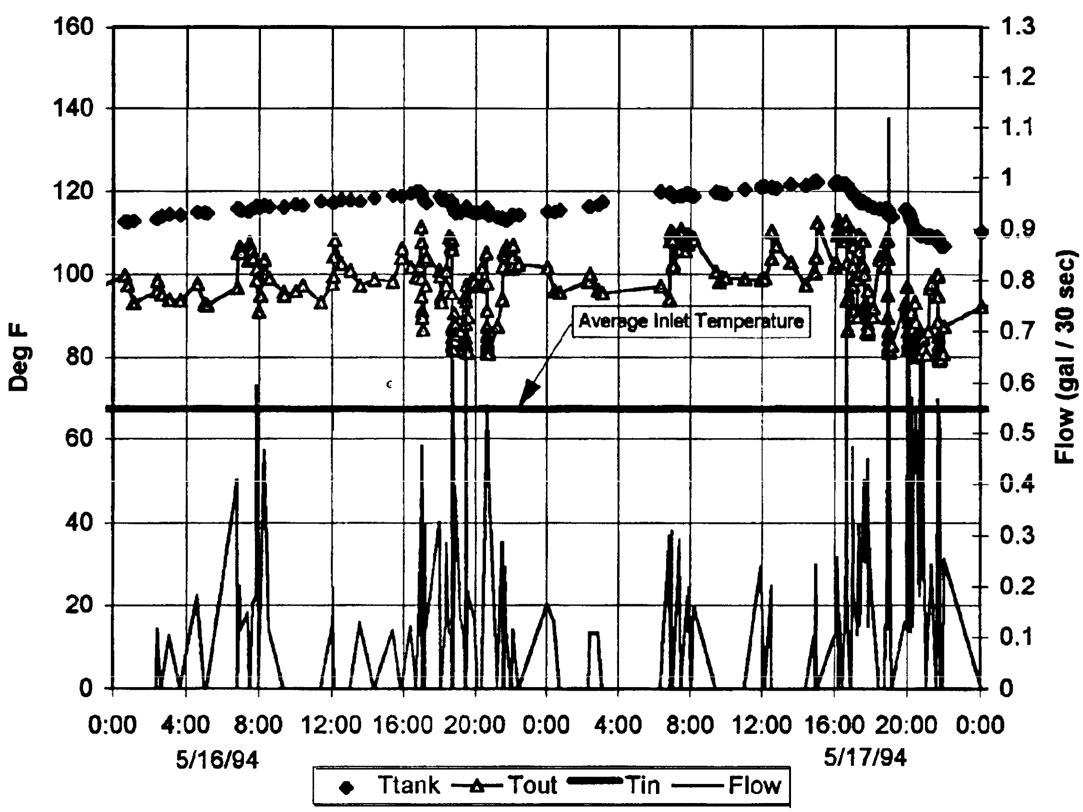

Figure 11. ACT^2 Davis Site (CREWH Field Operation)