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DEVELOPMENT OF A HIGH EFFICIENCY, AUTOMATIC DEFROSTING REFRIGERATOR-FREEZER*

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Abstract

This paper describes the development of an energy-efficient refrigerator-freezer prototype involving the Department of Energy's Oak Ridge National Laboratory, Arthur D. Little, Inc., and Amana Refrigeration, Inc. The project was initiated in 1977 by Oak Ridge National Laboratory and the Department of Energy to accelerate the commercialization of residential, high efficiency refrigerator-freezers. The resulting 16 cubic foot prototype uses significantly less energy than the most energy-efficient automatic defrost product designs of comparable size on the market today.

Early in the design phase, a computer model was developed by Arthur D. Little, Inc. to simulate the cabinet and refrigeration unit performance. It was used to evaluate alternative designs and optimize the cabinet insulation as well as the refrigeration component integration. Computer-optimized placement of polyurethane foam insulation in the cabinet and thicker insulation in the doors were used to reduce the closed-door heat load of the prototype.

Modifications to the evaporator system provide fully automatic frost-free operation with a significantly reduced defrost energy requirement compared to a typical automatic defrost refrigerator-freezer. Resulting higher moisture levels in the refrigerator compartment enhance fresh food storage. In addition, a dual control system, different from most models which use only one active control, provides precise temperature regulation in both the freezer and refrigerator compartments.

I. INTRODUCTION

The purpose of the project* described in this paper was to accelerate the design, development, and commercialization of a highly energy efficient residential refrigerator-freezer. Early in the project, it was realized that nationwide energy savings resulting from the development of a new high efficiency refrigerator design would only be realized through successful marketing of the product.

To prepare for anticipated market constraints, a preliminary market assessment was undertaken to identify the sector of the marketplace to which the refrigerator-freezer design should be addressed. The factors examined were:

- defrost features;
- size (cubic foot capacity);
- freezer to fresh food compartment volume ratio;
- cabinet style: top mount: side-by-side, bottom mount;

Recent sales data clearly showed that the top mount freezer unit with automatic defrost holds the major share of sales, and typically, these units have a freezer to fresh food volume ratio of approximately 1/3.

A survey of food consumption and food storage trends, family size, and consumer buying habits suggested a decrease in the historically high annual growth rate of the average refrigerator-freezer size sold. The 16-18 cubic foot, top-mount, frost-free refrigerator-freezer class was identified as the target market for high efficiency having the highest expected sales in 1985.

Eighteen energy-saving options were considered for the target market. An evaluation of the likely acceptance of the design options was undertaken using a rating system combining the impact of energy savings, noise, change in unit size and life.

Seven options were selected in the development phase of the program to undergo comprehensive computer analysis and prototype testing in facilities at Amana Refrigeration, Inc., and Arthur D. Little, Inc. In combination, these seven design options were estimated to reduce the baseline unit (16 cubic foot) energy consumption from 3.1 kwh per day to 2.0 kwh per day, which was set as the target energy consumption level for the development. A prototype was developed and tested which exceeded the target by achieving a 1.8 kwh per day energy consumption level.

II. TARGET MARKET

The average size of a refrigerator purchased for the typical U.S. household depends in a large measure on the following factors:

- The amount of food consumed by each individual in the household and the number of people per household.

* This work was sponsored by the U.S. Department of Energy, Division of Buildings and Community Systems and performed for Oak Ridge National Laboratory operated by Union Carbide Corp. The work was performed by Arthur D. Little, Inc. and its subcontractor, Amana Refrigeration, Inc. under UCC-ND Subcontract No. 7255.

- The portion of the food consumed requiring refrigeration or freezing versus the amount of canned or otherwise shelf-stable processed food.

- The timing of food purchases and the duration of storage.

- Trends in the selection of cabinet design: i.e., side-by-side versus top-mount freezer.

Per Capita Food Consumption and Household Size

An analysis of historical food consumption patterns (Table 1) shows increasing per capita levels with a large increase in soft drink and beer consumption offset by a decline in milk consumption. The decline in the consumption of milk has continued through the early 1970's and appears to be continuing, which may be tied to the declining birthrate.

Although the per capita consumption rates and the types of food consumed are increasing, the average size of the household is declining as shown in Table 2. The projected decline in the number of persons per household is a result of two factors: the increasing number of older people who are living alone, and more singles who postpone marriage. The average household is expected to consist of two to three persons in 1985, which represents the target market for the 1985 high efficiency refrigrator-freezer.

Combining this information, projected household food consumption is shown in Table 3, indicating a modest 3.5% increase in household refrigerated food consumption between 1975 and 1985. Included in this table is an estimate of the portion of the food eaten at home.

Food Storage Trends

In the future, it is anticipated that more families will have both husband and wife in the work force, and this is expected to affect the household's food buying habits and their food storage needs. In 1976, the average number of food trips made per week was three.* There is reason to believe that this number will be lower in the future. A study by the Bureau of Advertising** revealed that working women are more likely than non-working women to shop for food only once a week, increasing the storage volume requirements. Increasing use of microwave ovens, which would appeal to the same group of customers (i.e., families with two wage earners and working mothers) will facilitate the use of frozen foods, and probably further increase demand for larger freezers in refrigerators--or separate freezers. Furthermore, projected

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* Frankel, M., What Do We Know About Consumer Behavior?, National Science Foundation, 1976.

** Working Women's Food Buying Habits Revealed, EDITOR AND PUBLISHER, September 30, 1972.

TABLE 1

PER CAPITA CONSUMPTION (In Pounds)
FRESH, FROZEN, AND CANNED FOODS

	MEAT, POULTRY AND FISH		DAIRY PRODUCTS				VEGETABLES			FRUIT AND JUICE				
Year	Fresh and Frozen	Canned	Milk and Cream (Fresh)	Butter and Cheese	Sherbert Ice Cream Ice Milk	Canned and Dry Milk	Fresh (Refrigerated)	Frozen	Canned	Fresh (Refrigerated)*	Frozen	Canned	Soft Drinks***	Be
1960	179.7	14.8	322	20.6	24.3	25.5	138.5	9.7	44.7	100.4	12.6	35.5	(122)	(1
1965	187.8	15.6	302	20.7	26.6	22.7	130.1	13.8	48.7	88.8	12.2	34.4	169	1
1970	209.7	18.6	264	22.6	27.1	17.3	129.3	20.8	52.9	91.8	13.2	38.0	225	1
1975	206.3	16.2	248	24.0	27.8	14.6	131.1	23.7	55.5	89.7	16.2	33.7	262	1
1985	(205.0)	No est.	(275)**	25.0	(28.0)	No est.	(132.0)	(24.0)	No est.	(90.0)	(16.0)	No est.	(380)	(

*Includes chilled juices

**Reflects a 20% increase in 1-5 year olds in population representing about 1/2 of the milk consumption

Source: U.S. Department of Agriculture, 1976 Food Consumption Data and ADL estimates

***Source: Beverage Industry Annual Manual 1975-76, 1976-77
Straight Line Projection to 1985 see Appendix A

TABLE 2

FORECASTS OF AVERAGE HOUSEHOLD SIZE

Year	Average Number of Persons per Household	
1955	3.33	
1960	3.33	
1965	3.29	
1970	3.14	
1975	2.92	
1980	2.73	Target Household Size
1985	2.60	

Source: ADL estimates and U.S. Bureau of Census Current Population Reports, Series P-25

TABLE 3

TREND IN REFRIGERATED FOOD CONSUMPTION*
AND STORAGE VOLUME

	Year	Average Number of Persons per Household**	% of Food Eaten at Home***	Refrigerated and Frozen		Sales Weighted Average Cubic Feet
				Lbs./Yr.-Person	Lbs./Yr.-Household	
	1960	3.33	86.5	1049	3018.8	12.2
	1965	3.29	85.3	1085	3045	13.6
	1970	3.14	84	1158	3049	15.3
	1975	2.92	83	1209	2929	15.7
Projected	1985	(2.60)	(82)	(1408)	(3001)	(16-18)

*Perishable food only--canned and dry foods not included.

**Source: U.S. Bureau of Census, Current Population Reports Series P-25

***Source; "National Food Situation," Nov. 1976.

gasoline shortages and price increases will probably tend to reduce the number of weekly shopping trips. All these factors will tend to increase refrigerator size.

Refrigerator Size Trends

The average capacity of purchased refrigerators has mirrored trends in annual household refrigerated food consumption as shown in Figure 1. Factors in addition to increased average refrigerated food consumption which may have accounted for the steep rise in average refrigerator sizes in the 1960-1970 period were:

1) Reduced number of shopping trips arising from the increasing number of working married women.

2) The growing share of the market captured by side-by-side units which are not offered in sizes below 18 cubic feet. The side-by-side is promoted by portraying it as two separate units (a freezer and a refrigerator) conveniently located near one another.

Factors Affecting Future Refrigerator Size Selection

It is anticipated that there will be a slower growth rate in the average refrigerator size purchased in the future because of the following factors:

1) The rate of increase of working married women may start to level off.

2) The market share of side-by-side, bottom-mount, and large top-mount units should not increase markedly as consumers consciously consider energy consumption and operating cost in their purchase decisions. Federal labelling and consumer education programs may intensify this trend.

3) Average house (and kitchen) size may decrease as building and energy costs rise and household size decreases.

Based on these expectations, a 1985 sales weighted mean capacity of 16-18 cubic feet was forecast and a top-mount, auto-defrost refrigerator-freezer in this size range was anticipated as the sales leader. To meet this expected demand, a 16 cubic foot unit was selected as the baseline for the design and development phase of the program.

III. DESIGN OPTION ANALYSIS

Numerous energy saving designs were conceptualized, evaluated and rated* as the first step in selecting the best features for development, and

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* For a complete description of the design options and the rating method see W. David Lee, "Development of a High Efficiency Automated Defrosting Refrigerator/Freezer, Phase I - Design and Development, Final Report, Volume II - R&D Task Reports", ORNL/Sub-7255/2, U. S. Department of Energy, Washington, D. C., February, 1980.

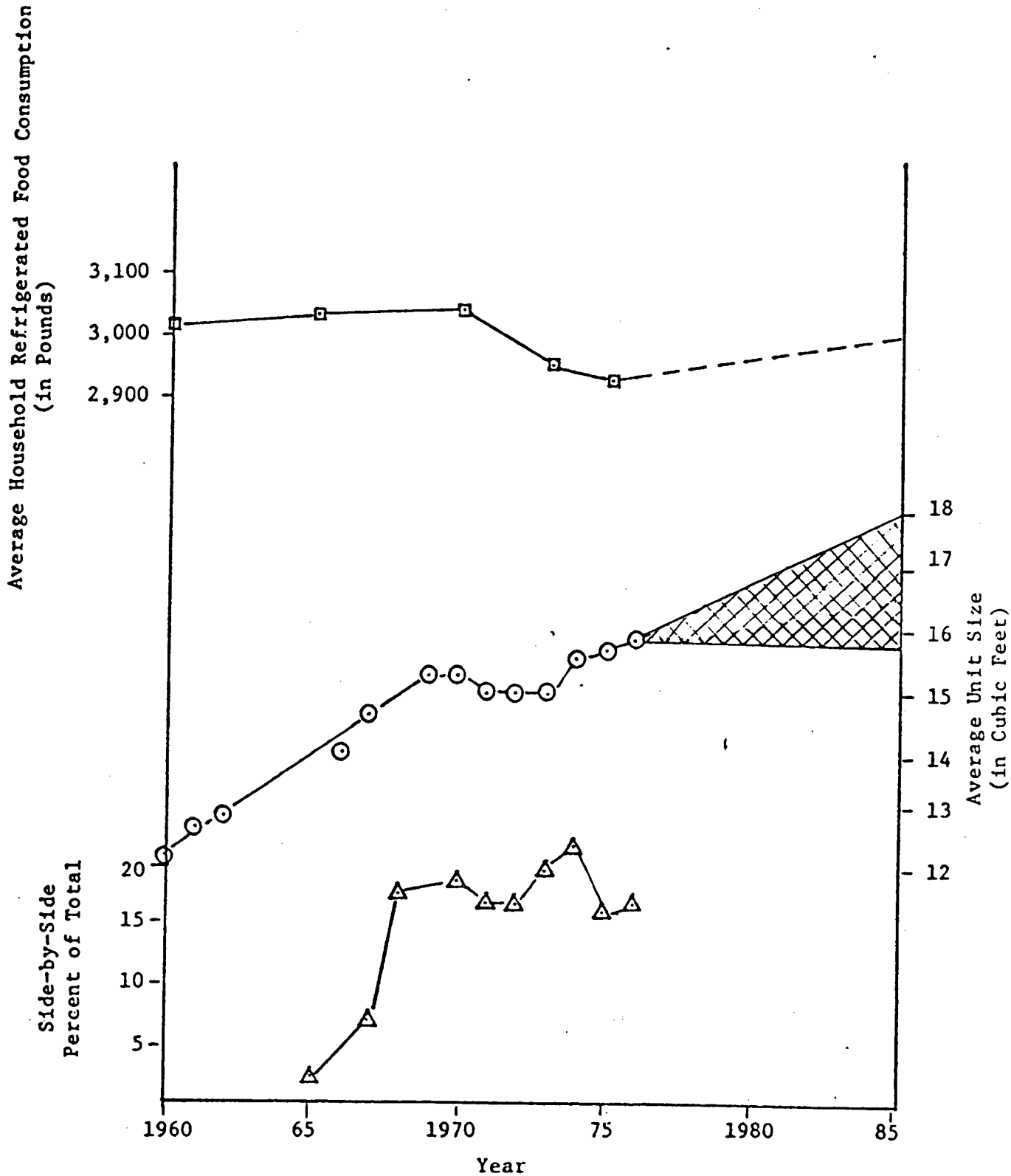


FIGURE 1 COMPOSITE FACTORS AFFECTING REFRIGERATOR-FREEZER SIZE

demonstration. The rating system utilized consumer perception indices to quantify the following factors:

- Annual Energy Savings
- Added First Cost
- Effect on Noise
- Effect on Storage Volume
- Effect on Unit Life

Table 4 is a listing of the eighteen design options that were examined for technical feasibility, energy savings and likely consumer acceptance. Seven options showed considerable promise:

1) optimized cabinet insulation
2) alternative condenser design
3) improved door seal gaskets
4) improved evaporator fan system
5) new evaporator system
6) thermostatic expansion valve
7) improved defrost control

Eight individual design studies involving both computer simulation and laboratory pre-prototype testing were undertaken to better understand the benefits and design trade-offs for the design concepts under examination. For example, a design guidance pre-prototype unit combining the major refrigeration unit changes was designed and built to test the synergistic effects of the computer changes. A fan test rig was constructed to optimze airflow over the freezer evaporator and provide maximum airflow at minimum power consumption. A computer program was developed to assist in cabinet design by distributing insulation and varying wall thickness to minimize heat leak given fixed exterior dimensional constraints, capacity, and freezer/fresh food volume ratio. This model was then combined with a previously developed refrigeration system component performance routine to provide a comprehensive analytical design model which was used to specify the final prototype design.

IV. PROTOTYPE DESIGN AND TESTING

With the completion of the individual design option tasks and analyses, a clear path was indicated for the development of an energy saving refrigerator/freezer prototype incorporating the following features:

- optimized insulation design
- static back-mounted condenser
- standard forced convection freezer evaporator
- free convection fresh food evaporator in series with the freezer evaporator
- new fan/air flow path design
- reduced defrost frequency
- double door gasket in freezer

TABLE 4

ENERGY-SAVING OPTIONS

Options	Comments
Most Promising Prospect	
1. Optimized Insulation Thickness	
2. Alternative Condenser Design	
3. Door Seal Improvement	
4. Improved Evaporator Fan System	
5. New Evaporator	
6. Expansion Valve	
7. Improved Defrost Control	
Good Prospect	
8. Improved Static Condenser Design	Significant design uncertainties
9. Hot Water Feature	Significant design uncertainties
10. Sequential Control	Significant design uncertainties
Distant Prospect	
11. Evacuated Powder Insulation	Development beyond the time frame of 1985 production
Not Promising Prospect	
12. Multiple Evaporator-Compressor	Poor payback period
13. Thermal Storage	Small energy savings, uncertain peak electric cost
14. Mechanical Expander	Too many uncertainties
15. Other Thermodynamic Cycles	No energy savings with known componer
16. Hot Gas Defrost	Poor payback periods
17. Inner Doors	Option #3 makes this obsolete based on present test procedures
18. Two-Speed Compressor	Poor payback period

NOTES ON CLASSIFICATIONS

- The classification of "Most Promising Prospects" are options which appear to have payback periods less than 3 years and are regarded as being most promising.
- "Good Prospects" are options which offer good payback periods but at a perceived higher risk.
- "Distant Prospect" means that development is beyond the scope of this work.
- "Less Promising," see specific note.

The two evaporator concept is the key to significantly reducing the energy needed to defrost the unit and therefore to lowering the overall energy consumption. In a conventional automatic defrost refrigerator-freezer, moisture is collected as frost on the evaporator heat exchanger. About every eight hours of compressor operation, a large electric heater (300-500 watts) is activated in the vicinity of the evaporator to melt the frost. The power used by this heater can account for over 30% of the total daily energy use.

The prototype uses a standard frost-free evaporator, heater, and fan system in the freezer as described above, but also has a natural convection evaporator, or "cold plate" in the fresh food compartment. The cold plate concept is taken from conventional partial automatic defrost units and offers the advantage of self-defrosting after every refrigeration cycle when the plate returns to the fresh food compartment temperature which is above freezing. The frost therefore melts off the plate without the need of an electric heater. Since the primary source of moisture is the fresh food compartment, the freezer evaporator accumulates much less frost and the electric defrost cycle can be extended to once every 38 hours of compressor operation. Therefore, the energy required to defrost the prototype is reduced by over 80%. An added advantage of the design is that the normal dehydration of foods stored in the fresh food compartment of standard automatic defrost units is eliminated.

The cabinet specifications and a picture of the prototype are shown in Figure 2. The insulation thickness schedule reflects a computer-optimized minimum heat leak configuration. A significant departure from conventional cabinet designs is the 2.5 inch door insulation resulting in quite thick doors. There has been no indication, however, that consumers will react unfavorably to the different door appearance; and the benefit of uniform temperatures throughout the cabinet and door area should be a welcome feature.

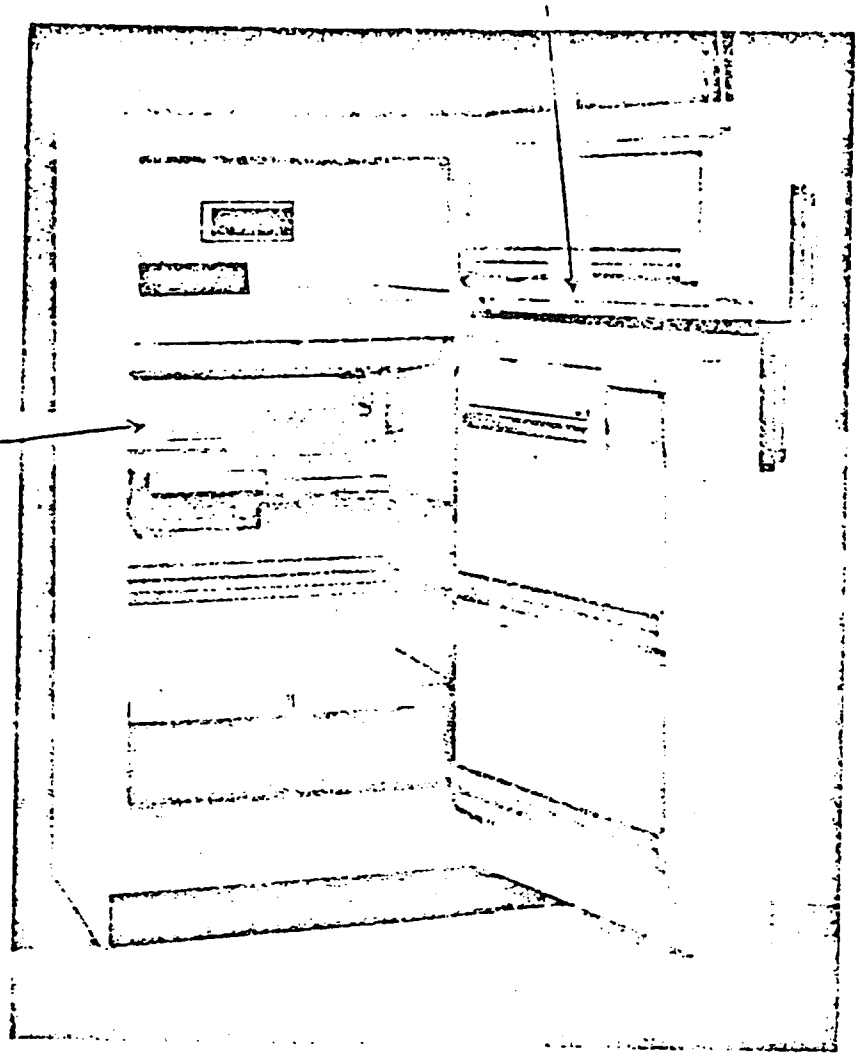
Test Program and Results

The 16 cubic foot prototype was fabricated by Amana Refrigeration, Inc. in accordance with design specifications developed jointly with Arthur D. Little, Inc. and subjected to the following performance tests:

1) 107°F ambient performance tests
2) High energy usage Gulf States test
3) Low ambient 65°F test
4) AHAM energy consumption test

These tests were performed at Amana Refrigeration, Inc. The high ambient (107°F) tests are designed to evaluate the pull-down (cabinet cool-down from ambient) characteristics, the steady-state operating conditions at 107°F, and the performance with the freezer door open. The results of the test indicated acceptable unit performance.

Double Gasket Around
Freezer Door



Refrigerator cold surface evaporator which is in series with the conventional forced air evaporator

INSULATION THICKNESS (INCHES)							HEAT FLOW (BTU/HR)					
Freezer				Fresh Food								
Side	Front	Back	Top	Side	Front	Back	Freezer	Mullion	Fresh Food	Gasket	Wedge	Total
3.00	2.50	3.00	3.00	2.25	2.50	2.25	43.08	13.28	68.39	41.9	10.0	176.7

FIGURE 2 PROTOTYPE CABINET SPECIFICATIONS

The Gulf States test consists of a series of door opening conditions at 90°F and 65% relative humidity, and is used to evaluate the thermal and frosting characteristics of the unit under heavy usage. The unit is expected to maintain a freezer temperature below 10°F and a fresh food temperature below 50°F. Two design factors are critically examined by this test:

- the defrost interval and defrosting control necessary to maintain appropriate operation under the high ambient, high humidity door opening tests

- the proper refrigeration capacities to maintain a desired balanced unit operation.

The unit performance in the Gulf States test was good by Amana standards. The freezer compartment never exceeded 5°F, the refrigerator compartment was over 50°F for a very limited period of time, and the average percent run-time was approximately 55%. This indicates that the unit has sufficient refrigeration capacity to perform acceptably and efficiently in virtually any normal kitchen environment.

A 65°F ambient test is performed primarily to evaluate the control ability of the unit. Often times difficulty in maintaining cabinet temperatures occurs at low ambient and low percent run-time. The prototype maintained the desired 5°F freezer and 38°F fresh food compartment temperatures, a necessary condition for reliable field performance.

The AHAM test is a 90°F ambient closed door test designed to measure energy consumption. The high ambient temperature is assumed to simulate actual home usage. The performance in the AHAM test resulted in a test energy consumption level of 1.72 kilowatt hours per day and 33.7% run-time. The prototype design, therefore, exceeded the target efficiency level.

Arthur D. Little manufacturing staff analyzed the major design changes from a manufacturing cost viewpoint. Unit costs are extremely difficult to estimate as costs depend on the existing capital equipment and tooling. Certain manufacturers may fabricate all of the major components and require only added materials, while other manufacturers may have to purchase some of the major parts. It was decided to develop costs using purchased components because this may better reflect the initial product introduction process. It was assumed that the manufacturer has cabinet foaming facilities machines and plastic liner equipment, and that only tooling for the new cabinet would be required. Using these criteria, a manufacturing cost increase of $20 to $40 was estimated, leading to a price increase at the retail level of $50 to $100 over a conventional auto defrost unit with comparable features. At 5¢ per kilowatt-hour, the expected energy savings is approximately $25 per year, resulting in a simple year-to-payback estimate of 2-4 years.

V. CONCLUSION

The prototype testing confirmed the feasibility of the high-efficiency automatic defrosting refrigerator/freezer design incorporating many innovative energy saving features. The promising results of this program led the Department of Energy to sponsor a field test program using pre-production units in actual home usage situations. An 18 cubic foot top-mount test unit was designed and built, nearly identical in design to the 16 cubic foot prototype. These units are currently in the field and results should be available in mid-1982. It is also expected that two-evaporator designs of the type presented in this paper will be commercially available in one to three years.