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THE ENGINEERING AND MANUFACTURE OF A HIGH-EFFICIENCY, AUTOMATIC DEFROSTING REFRIGERATOR-FREEZER*

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1. INTRODUCTION

This paper describes the engineering effort and method of manufacture used to build thirty-six high efficiency, automatic defrosting, refrigerator-freezers. This work was undertaken as Phase II of a Department of Energy sponsored project to develop and test market a refrigerator-freezer of the automatic defrosting type that represented current "state-of-the-art" capability for energy efficiency. Arthur D. Little, Inc. was the prime contractor for the project, with Amana serving as a sub-contractor for the design engineering and manufacturing phases of the task.

Phase I of this project, optimizing the design and proving it feasible, has previously been reported.[1] While the prototype model developed was a $16ft^3$ refrigerator-freezer, there was agreement by all parties involved in the project that an $18ft^3$ model would be better suited for the market test. Early in 1979 the engineering team involved in this project began the design work to produce this model.

2. SPECIFICATIONS

Having settled on the internal volume of the refrigerator-freezer, calculations were made to establish its physical size. Insulation thickenesses that had been determined for the Phase I prototype were specified for this model also. The resulting dimensional characteristics are listed in Table 2-1.

(Table 2-1)

Cabinet Specifications

Cabinet Wall Thickenss (inches)

Freezer Compartment		Fresh Food Compartment	
Side	3.00	Side	2.25
Front	2.50	Front	2.50
Back	3.00	Back	2.25
Top	3.00	Top	2.25

Exterior Dimensions (inches)

Height: 66

Width: 32

Depth: 29.75 (excluding condenser & door hardware)

Overall Depth: 33(including " " " ")

Adjusted Volume (ft^3)

Freezer	4.39
Fresh Food	13.80
Total	18.19

Freezer/Fresh Food Volume Ratio - 0.32

Calculated Heat Flow (BTU/Hr)

Freezer	49.37
Mullion	10.47
Fresh Food	85.33
Gasket	39.17
Wedge	19.10
Total	203.44

The heat leaks were calculated using a computer program developed by Arthur D. Little, Inc. for Phase I of this project.[2] The calculation established the expected heat flow when operated in a 90°F ambient with a 5°F freezer and a 38°F fresh food compartment. The program was also used to determine expected performance when various refrigeration system components and configurations were considered.

During the course of the prototype development process, some two hundred computer simulations were run to determine the optimal combination of refrigeration system components. Evaporator and condenser coil configurations and airflow parameters, compressor performance characteristics and cabinet insulation schedules were varied over a wide range of values. The net effects of all parameter levels on the final energy performance of the product were computed and tabulated. The simulation process was used extensively first as a preliminary design guidance tool in the early stages of the project and then again later in the development cycle as actual prototype units became available. Once actual thermal performance test data became available, the simulation program was able to be calibrated with minor changes to the parametric inputs so that theprogram's output was more highly correlated with the test data. With this "calibration" accomplished, the thermal performance of the subsequent rounds of product modifications could be fine tuned with a minimum of actual test effort.

3. ENGINEERING DESIGN

The specifications listed above had grown out of the testing of the Phase I prototype and the general consensus of all involved in the project. To complete a design, however, other design parameters needed to be established, so that engineering design, layout and detail drafting could proceed. Three general design criteria were established for the task:

1. Make maximun use of existing parts and tooling.

2. Retain product styling and convenience features associated with similar Amana products.
3. Meet the performance targets established by extrapolation of the Phase I results.

In order to design this unit so that existing tools could be most advantageously used, it was essential to involve Manufacturing Engineering in the project from the very beginning. This was done on a routine basis with informal problem solving sessions conducted as needed to resolve design issues while the total design was still in the layout stage. Where part or tool modification was needed, the design team sought direction from Manufacturing Engineering for the optimum design.

Product styling and convenience features were established based on comparison with other Amana models of the same general type (Automatic defrosting, top mounted freezer section) and size. Features specified for this model were these:

1. Reversible doors
2. Fast freeze shelf in freezer section
3. Two ice trays and ice storage container.
4. Suitable for field installed icemaker
5. Meat storage pan
6. Twin crispers
7. Egg storage tray
8. Door shelving
9. Butter compartment in door
10. "Glide-out" shelving for general storage

To meet the performance targets, the design closely adhered to the criteria established in the Phase I testing. Insulation schedules, air system duct sizing, door gasket design, door "wedge" configuration, condenser and evaporator designs and fan motor placement were among the parameters established during Phase I. By use of computer simulation, the effect of changes in design of these components was examined and a "sensitivity analysis" made. This tool was very helpful in establishing optimal solutions to the many little design problems that arose during the layout stage.

4. COMPONENT SELECTION

Once the optimum levels of refrigeration system component parameters were determined by simulation and performance testing, several different methods of achieving those specified levels were evaluated. For example, it was determined that the overall heat transfer coefficient area product (UA) of the evaporator coil should be approximately 54.5 BTU/hr ^{o}F for the best performance of the product, and several alternative ways to achieve that UA level were evaluated. The field of feasible candidates was narrowed down to two evaporator coil designs - one having a 4.0" x 19.5" face area and a 4.0" coil depth, and the other identical except with a 6.0" coil depth (both coils were fin-and-tube configurations with 3/8" diameter aluminum tubing spaced on one inch centers and having fin pitches of 5 fins per inch). The 6.0" deep coil had a higher frost tolerance and thermal capacity than the 4.0" deep coil due to the higher fin surface, but the airflow resistance of the deeper coil was also greater due to the longer wetted perimeter of the airflow channels. An analysis of the air handling system's capabilities vs. the two different coils' air flow resistances yielded a comparison of the expected airflow attainable with each coil installed. Further tests were run to determine the effects of a frost load on the system performance, and these results are summarized in figure 4-1.

5. PROTOTYPE TESTING

The first series of prototype testing undertaken was airflow testing. Early in the development program an adequate airflow level was judged to be one of the critical design tasks and the evaluation of various air handling system efficiencies was given a high priority in the test program. Based on simulation results, an overall air handling system efficiency of 4 cfm/WaH was targeted and improvements in both the duct system resistance and fan motor and blade performance were pursued in an attempt to achieve the target efficiency level. With the evaporator configuration fixed and the airflow requirements bracketed at this point in the development process, nearly a dozen combinations of fan motors and blades were evaluated. After several unsucessful attempts to reach the specified efficiency, both the inlet and outlet ducts were redesigned to reduce the duct system resistance and the evaluation of the fan motor/blade assembly resumed. With a special high efficiency fan motor and the improved duct system, an efficiency of 4 cfm/watt was reached at an airflow level of 47.4 cfm and an input of 11.8 W.

After the airflow system design was established, the prototype refrigerators were subjected to a series of thermal performance tests ranging over a variety of ambient and load conditions. The units were first allowed to cycle normally in 55, 65, 90 and 104°F ambients without door openings or compartment loading. Thermal loads were then introduced into the units by using pans of water and simulated frozen foods and the 65 and 90°F test series were repeated. Analysis of compartment temperatures, energy consumption, duty cycle, and strategic system temperatures led to the conclusion that the product performed satisfactorily over this range of operating conditions.

Table 5-1

AMBIENT	FREEZER RANGE	MID	REFRIGERATOR RANGE	MID	ENERGY	MID
55	4.0/20.5	8.0	31.2/37.3	36.0	0.837	
65	0/18.5	6.2	29.7/38.8	35.7	1.22	
90	-3.0/18.5	4.5	24.5/39.7	35.3	2.10	
104	-9.0/15.5	2.0	23.7/40.3	32.8	3.68	

Following these performance tests, selected units were placed in a 110°F ambient and disconnected from the power supply. When these units reached ambient temperature they were energized and forced to operate until compartment temperatures stabilized. By measuring final temperatures and peak values of input wattage, amperage, and various system temperatures the products performance under heavy load conditions was evaluated and judged to be acceptable.

Several test units were then installed in a warm humid room and subjected to a dynamic usage test involving a schedule of timed door openings designed to simulate Gulf state conditions. This dynamic usage test was allowed to run for twenty-one days and gauged the product's capacity to recover from periodic infusions of warm, humid air into both compartments. The defrost system was also thoroughly tested and the amount of water collected and discharged through the defrost drain was periodically measured. All results from this series were also satisfactory.

During an earlier part of the test program the noise level of the evaporator fan in the product became a concern. This particular system design utilizes a fairly high level of airflow in the freezer compartment to achieve a rather infrequent defrost interval, and the high airflow rate was thought to contribute to the overall product noise level. Six units were chosen as noise test units and four alternate methods of mounting the evaporator fan motor were evaluated. The noise attenuating attributes of the quietest motor

mounting system were incorporated into the balance of the production run with favorable results.

Energy certification was begun when the design was finalized and five units were chosen as a representative product population. The results from the certification testing were very satisfactory and the project goal of an energy factor of 10 was met with an average energy consumption of 2.053 Kwh/day (the adjusted volume for this product was 20.6 cubic feet which yielded an energy factor of 10.03).

6. MANUFACTURING APPROACH

Amana Engineering and Manufacturing chose to treat the Phase II refrigerator-freezer as it would any new model for production. In this way, all of the normal procedures for procurement, inspection and inventory control could be used, thus making the manufacture of this model less disruptive to the normal flow of manufacturing processes than otherwise might be expected.

In December of 1979, production drawings and a complete bill of material were released. In reviewing the parts list, it became apparent that all component parts for this model could be grouped into six categories:

1. Extended use items. This category included those parts that were common to other models in Amana's line. In addition to fasteners and hardware, such items as door handles and handle pads, crispers pans, meat pan, control escutcheons, egg tray, ice trays and dairy door were included in this group. These parts were immediately available at any time, and presented no procurement problems.
2. "Off-the-shelf" purchased parts. Parts in this category were unique to this model, but were readily available as off-the-shelf items that required little or no modification to meet the requirements of the model. Examples were the compressor, fan motor, defrost timer, refrigerator control, freezer control, and defrost terminator. These parts were available with only moderate lead time.
3. Purchased parts produced by special set-up or minor modification of standard tooling. The parts grouped into this category were unique to this model, but could be produced from tooling that made similar items for other Amana models. Minor tool

modifications or special set-ups generally were all that was required to enable the vendor to produce the unique part. Examples of parts in this category included the evaporator, cold plate, wire and tube static condenser, shelving, defrost heater, anti-sweat heaters, exterior door trim, door shelf retainers, door gaskets, wire harnesses and shipping carton. Moderate lead times and tooling or set-up changes were required, but easily met the time restraints of the project.

4. Parts manufactured from Amana tooling and modified to the models requirements. The basic tooling for parts in this category existed, but additional rework or modification was needed to make the part acceptable for this model. Normally, tools would be modified to produce the new part, but in this project it was more economical to rework the part since only 40 to 50 sets were needed. Parts in this category included the cabinet bottom, compressor support rails, crisper pan cover, ice tray tunnel and toe grille. Procurement of the basic parts in this category was fairly easy; however, adequate model shop time for rework was a matter of concern to Amana Engineering.

5. Parts fabricated using a special set-up on Amana tooling. Here again the basic tooling to produce the parts existed, but a special set-up was required to produce exactly what was required. Examples of parts in this category included the cabinet wrapper, cabinet back panel and the cabinet door panels. In the case of the last item, the door panels were notched and pierced using templates and "Whistler" tooling, then formed and welded by special set-up of production tooling and equipment.

6. Parts requiring new tooling to produce. Parts fitting into this category could not be produced by any of the above methods. New temporary tooling was needed. The objective here was to produce the needed number of usable parts with minimum investment in tools.

Temporary or experimental tooling methods were used to create the necessary tooling to produce this group of parts. There were fourteen items which fell into this category. These parts were grouped as follows:

Sheet Aluminum Stamping

Drip tray, evaporator

Top panel, refrigerator

Drain cover

Mounting plate, fan motor

Sheet Steel Stamping

Center mullion

Lower mullion

Mounting bracket, fan motor

Vacuum Formed ABS Plastic

Food liner

Door liner, freezer

Door liner, refrigerator

Freezer compartment floor

Injection Molded ABS Plastic

Fan shroud, evaporator

Breaker molding, mullion

Expanded Polystyrene (EPS) Molding

Insulation block, mullion

Each of the above parts was produced on short-run tooling typical for that group. In some cases, the run of 40 to 50 parts literally "used up" the tooling. Tool procurement and parts delivery were on schedule for all parts except the injection molded group and the EPS molding. With those items, several technical and contractural difficulties delayed delivery beyond the mid-1980 production date planned. When delivery was made, the pilot production was rescheduled and ultimately completed in late October, 1980.

The pilot production run was accomplished using techniques that have long been used at Amana for pilot runs of new models. For this model, identified as ESTR-18D, 25 units were designated for the performance test. Then additional units were planned for program back-up, local field test, engineering tests, in-house display, etc. Manufactured parts and sub-assemblies were prepared as a group. Cabinet weldments were then infiltrated into the assembly line at key points for assembly operations that required the use of capital equipment located at that point. Such operations included foaming, electrical harness testing, refrigeration system hook-up and brazing, evacuation, charging and final testing. Other assembly operations were generally conducted off-line in repair areas by a small staff of skilled technicians and assembly line personnel. All products received the standard Quality Control checking and qualification testing. Using these techniques, the assembly operations were completed in approximately one week. By utilizing all available sets of parts, a total 36 units were finally completed.

7. ENGINEERING AUDIT TESTING

The normal test procedures used for performance qualifications of other Amana refrigerator/freezers were also used for the ESTR-18D. Each unit was operated for 25 minutes on an electrified conveyor prior to reaching the test station. At the test station, the unit's input in watts was measured and air temperature in the freezer compartment recorded. Additional control function checks, defrost system checks, and electrical system integrity checks were also made.

Normally, 10 to 15% of each day's production are also given a 5 hour (minimum) thermal performance test where temperatures in both the freezer compartment and fresh food compartment are monitored and recorded on strip chart recorders. At the completion of the test, the pull down and cycling characteristics of the unit on test can be checked and compared to norms for that particular model. For the ESTR-18D, since norms had not been established, all units were given the 5 hour thermal performance test. This allowed for mututal comparison and the building of the data base needed for establishing performance criteria for the production line tests.

Because of the uniqueness of this model design, Amana Engineering elected to conduct a series of tests in their "hot rooms" where all performance characteristics could be tested and measured against expected criteria as determined through the prototype testing program. The test plan included these tests:

1.	Continuous operation (control shorted) in a 90° ambient for thermal balance	All units
2.	Cycling tests - no door openings, 90° ambient mid-mid control settings	All units
3.	Operating sound tests including frequency scans recording sound	7 units
4.	Exterior condensation tests (sweat) in high humidity chamber	2 units

In addition, three units were also tested for energy consumption in accordance with the DoE standard test procedure. The annual energy input for this model had been previously established by tests on pre-production prototypes. This testing was to confirm the energy numbers already established and was conducted on units not used for the field test. These tests confirmed the results of the previous testing within 1%.

The thermal performance tests proved to be quite encouraging. The 36 units exhibited a very acceptable degree of uniformity, particularly in temperature and run time characteristics. The follwoing Table summarizes the cycling performance of the 36 units manufactured.

Table 7-1
ESTR-18D PILOT PRODUCTION PERFORMANCE RESULTS

Characteristic	Average	Standard Deviation	Range
Freezer Temperature	+ 2.5°F	1.2°F	-1.2° to 5.0°F
Fresh Food Temperature	+36.8°F	1.6°F	+33.2° to 39.6°F
Energy Input - KWH/Day	2.217	.1505	1.93 to 2.56
Cycles Per Day	13.89	3.12	7.7 to 22.7
Run Time	48.06%	3.32%	42.5 to 57.6%

The intial sound testing uncovered more variability in sound performance than desired. As a result, a minor modification was made in the evaporator fan motor mounting to correct the problem. This modification was made to all units. After testing and modification, 25 units for the field performance test were selected to fill the color mix desired. These units were then fitted with the instrumentation package.

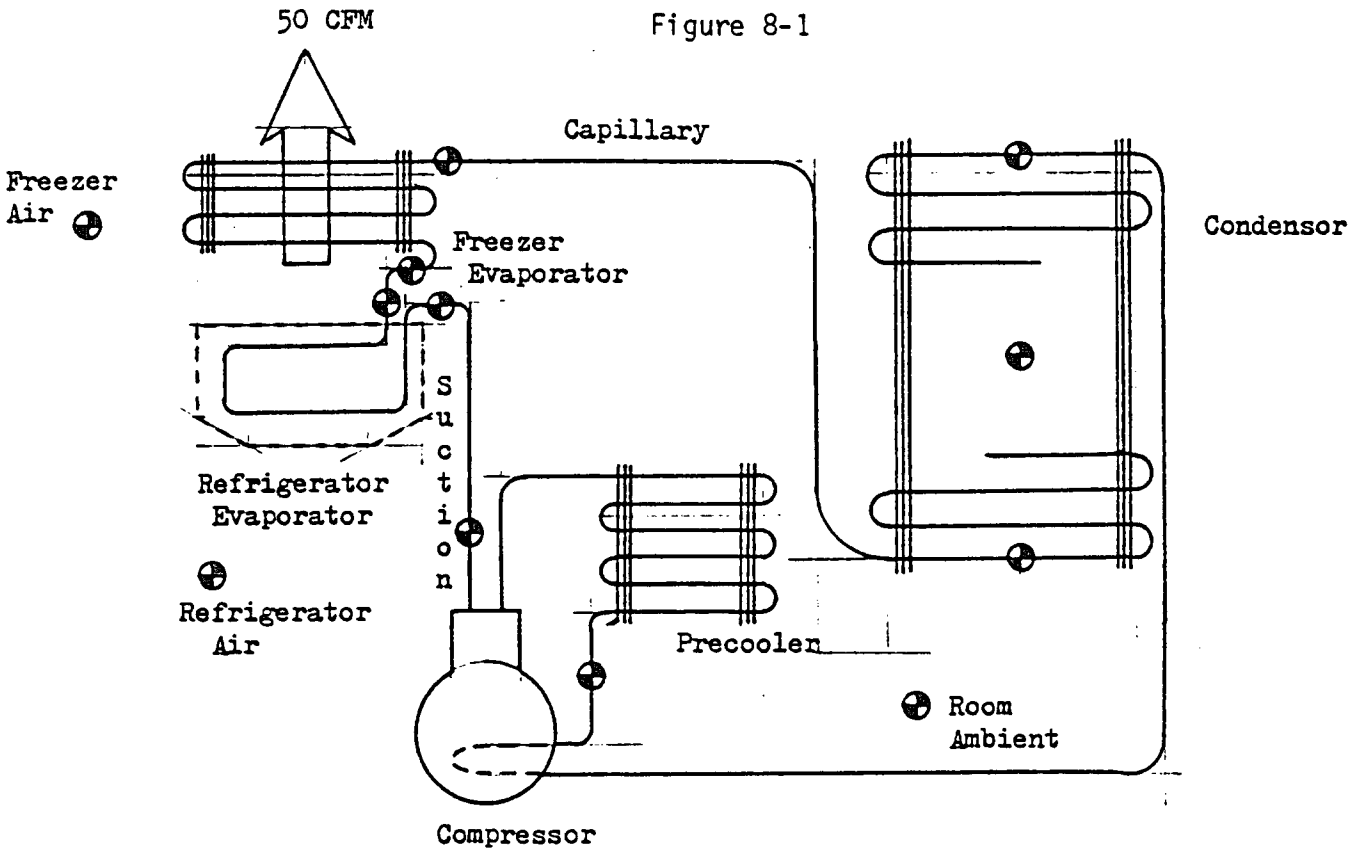
8. INSTRUMENTATION FOR FIELD TEST

One of the goals of the planned market field test was the determination of the degree of correlation between energy usage as estimated by the DoE test procedures and the actual energy usage observed in a field test enviroment. Each test unit was outfitted with instrumentation to measure energy consumption, twelve temperatures located at specific test points on each unit, and two auxilliary switches to record the frequency and duration of each compartment's door openings. The kilowatt-hour meter was designed by A.D. Little and was located at the rear of the refrigerator in close proximity to the power supply cord. The meter box had its own power cord which was connected to the customers outlet and a receptacle which accepted the refrigerator's power cord. The meter circuit measured energy in increments of 0.1 KWH and powered a digital recording meter located behind the air grille in the front of the refrigerator. This location provided a convenient accessible data collection point and also housed two digital timers which were energized whenever the compartment doors were opened.

The thermocouple harness consisted of twelve copper-constantan thermocouples terminating in two twelve circuit connector blocks (located near the instrumentation box). The harness was foamed in place and provided access to the following thermocouple locations:

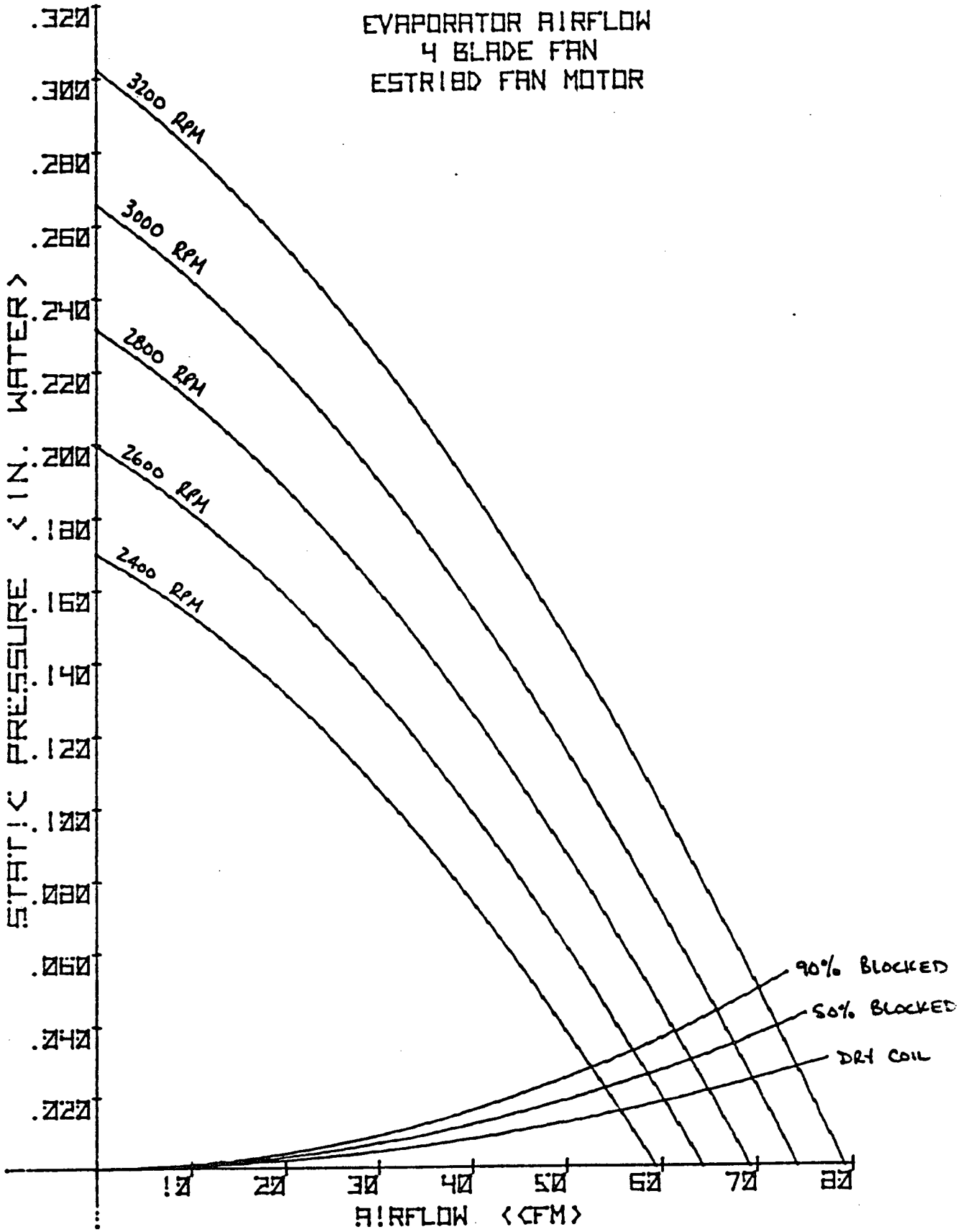
- Freezer evaporator inlet and outlet (2)
- Refrigerator evaporator inlet and outlet (2)
- Condenser inlet, midpoint, and outlet (3)
- Freezer and refrigerator compartment air (2)
- Suction line (1)
- Precooler coil outlet (1)
- Room ambient (1)

Figure 8-1



With this array of instrumentation, each test unit was equipped for the collection of complete diagnostic information, should a need for such information arise during the field test. With all modifications and instrumentation completed, the units were returned to the assembly line for final inspection, minor repairs as needed and crating. By the end of October, 1980 these refrigerator/freezers were ready for shipment to Norfolk, VA, the site selected for home usage tests.

FIG. 4-1


EVAPORATOR AIRFLOW
4 BLADE FAN
ESTRIBD FAN MOTOR
STATIC PRESSURE (IN. WATER)
.320
.300
.280
.260
.240
.220
.200
.180
.160
.140
.120
.100
.080
.060
.040
.020
3200 RPM
3000 RPM
2800 RPM
2600 RPM
2400 RPM
90% BLOCKED
50% BLOCKED
DRY COIL
10
20
30
40
50
60
70
80
AIRFLOW (CFM)

REFERENCE LIST

1 "Development of a High Efficiency, Automatic Defrosting Refrigerator-Freezer" -- Symposium paper C1-81-8, No. 3, by Richard F. Topping and W. David Lee (Presented at the 1981 Annual Meeting of ASHRAE at Cincinnati, Ohio)

2 "Development of a High Efficiency Automatic Defrosting Refrigerator-Freezer, Phase I Design and Development, Final Report, Volume II - R & D Task Reports" by W. David Lee, ORNL/fab-7255/2, U.S. Dept. of Energy, Washington DC, February, 1980