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BULLETIN 484

HEATING AND COOLING A TRI-LEVEL HOUSE WITH A HYDRONIC BASEBOARD-VALANCE SYSTEM

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Edited by
Rudy Berg

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ABSTRACT

THIS BULLETIN, ONE OF A SERIES* REPORTING RESEARCH CONDUCTED COOPERATIVELY BY THE INSTITUTE OF BOILER AND RADIATOR MANUFACTURERS AND THE UNIVERSITY OF ILLINOIS, DESCRIBES TESTS MADE IN THE I=B=R HYDRONIC RESEARCH HOUSE DURING 1961 AND 1962 ON A BASEBOARD-VALANCE HEATING AND COOLING SYSTEM.

THE I=B=R HYDRONIC RESEARCH HOUSE IS A TRI-LEVEL HOME HAVING A TOTAL FLOOR AREA OF APPROXIMATELY 1600 SQUARE FEET. IT HAS A MINIMUM OF INSULATION AND IS OPERATED WITHOUT STORM SASH, UNDER CONDITIONS WHICH AMPLIFY ANY POTENTIAL WEAKNESS IN THE PERFORMANCE OF THE HEATING OR COOLING SYSTEM. BOTH BASEBOARD AND VALANCE UNITS WERE USED FOR HEATING, BUT ONLY VALANCE UNITS WERE IN OPERATION WHEN COOLING WAS REQUIRED.

RESULTS OF THIS STUDY INDICATED THAT THE BASEBOARD-VALANCE SYSTEM GAVE THE SAME EXCELLENT SUMMER PERFORMANCE AS THE VALANCE SYSTEM REPORTED IN ENGINEERING EXPERIMENT STATION BULLETIN NO. 466. WINTER PERFORMANCE WAS MUCH IMPROVED, ESPECIALLY IN THE LIVING ROOM, WHERE MORE THAN HALF THE GROSS EXPOSED WALL AREA CONSISTED OF SINGLE GLASS. HERE THE BASEBOARD-VALANCE SYSTEM PERFORMANCE COMPARED FAVORABLY WITH THE WINTER PERFORMANCE OF A BASEBOARD SYSTEM ALONE.

IT APPEARS THAT THE INSTALLATION COST OF A BASEBOARD-VALANCE SYSTEM FOR HEATING AND COOLING WOULD BE ABOUT TEN PER CENT GREATER THAN THE COST OF A VALANCE SYSTEM DESIGNED TO BOTH HEAT AND COOL. THE YEAR AROUND OPERATING COST OF THE BASEBOARD-VALANCE SYSTEM WAS ABOUT ELEVEN PER CENT LESS THAN THAT OF THE VALANCE SYSTEM. ALL OF THE REDUCTION WAS OBTAINED DURING THE WINTER SEASON.

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*See inside the back cover for a list of publications by the Engineering Experiment Station in related fields.

ACKNOWLEDGMENTS

This report is a result of a cooperative investigation jointly sponsored by the University of Illinois Engineering Experiment Station and the Institute of Boiler and Radiator Manufacturers. The investigation was carried on as a project of the Department of Mechanical Engineering under the administrative direction of Professor H. H. Korst, Department Head. Acknowledgement is made to organizations which furnished equipment and materials used in the experimental program, and also to Mr. R. R. Laschober, Research Associate in Mechanical Engineering, and to Mr. W. J. Graham, Instrument Technician, for their assistance in setting up test equipment and in conducting the experimental portion of the program.

The assistance of the following reviewers is also gratefully acknowledged: E. T. Selig, Jr., Director of Engineering, Heating and Cooling Division, Burham Corporation; Glenn R. Sward, Chief Engineer, I=B=R Laboratory; and Professor W. F. Stoecker, Department of Mechanical Engineering, University of Illinois.

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I. INTRODUCTION

A. PRELIMINARY STATEMENT

This report is one of a series of Engineering Experiment Station publications reporting heating and air conditioning research conducted under a cooperative agreement between the Institute of Boiler and Radiator Manufacturers and the University of Illinois. This program began in 1940. Under the terms of the contract two houses have been built for experimental purposes. The first was a compact two-story, thoroughly insulated home built in 1940 and used until 1959, when the second house was built. This house was a tri-level residence, larger and not as well insulated as the first house.

Tests have been conducted in the latter house on both hydronic baseboard and valance systems and on fan-coil and valance cooling systems. In each case the systems were zoned by house levels. The results of these tests have been previously reported.[1, 2]

The report on valance heating[2] pointed out that the operating characteristics of the valance heating system were similar to those of a ceiling panel system. The valance system produced warmer floor surface temperatures than did the baseboard system, but in rooms having large glass areas the valance did not prevent cool air movement across the floor. It was also found that air movement in the staircase and heat transmission through third level floors resulted in a much lower winter load for the third level than had been anticipated. At the same time the actual loads on the first level were well above the calculated loads. With radiation installed in accordance with the calculated loads, this transfer of load made it impossible to maintain proper air temperatures on the lower levels of the house during very cold weather. These unexpected results prompted a study of a combination baseboard-valance system in which shifts in load for both summer and winter operation were considered in the design procedures.

B. OBJECTIVES OF INVESTIGATION

The objectives of this investigation were to observe the operating characteristics of a system using valance units for cooling and both valance and baseboard units for heating, and to compare these operating characteristics with those of a valance system used for both heating and cooling. The investigation included comparative studies of comfort conditions, temperature distributions, shifts in loads, effects of shade on cooling loads, relative economy of installation and operation, and methods of control for heating.

II. DESCRIPTION OF EQUIPMENT

A. I=B=R HYDRONIC RESEARCH HOUSE

The I=B=R Research House shown in Figures 1 and 2 is described in detail in an earlier publication.[2] This is a tri-level home with 1638 square feet of floor area, exclusive of the garage and equipment room. The design heating load was 76.01 MBh at an indoor-outdoor temperature difference of 80°F. No storm doors or storm sash were used during any of the tests discussed in this report. The design cooling load was 29.00 MBh based on indoor and outdoor temperatures of 75°F and 95°F, respectively. The design heating and cooling loads for the residence were determined in accordance with the procedures outlined in I=B=R Guide H-20[3] and cooling load calculation procedures adopted by ARI, NWAHACA, and I=B=R.[4]

B. HEATING AND COOLING SYSTEMS

Information on the shift of loads obtained when studying the valance system[2] was used in adjusting design loads for the combination baseboard-valance heating and cooling system. Also the entering air temperature in winter was assumed to be 80°F in the design of the valance system. Test results[2] indicated that 120°F would have been more appropriate; therefore, 120°F was used as the winter entering air temperature in the design of the baseboard-valance system. The design procedure was as follows:

1. The design heating and cooling loads for each room were obtained by conventional calculation procedures.
2. The design cooling loads for first-level rooms were reduced by 25 per cent. The cooling loads subtracted from first-level rooms were then added to third-level rooms. No change was made in the design cooling loads for second-level rooms.
3. The design heating loads on third-level rooms were reduced by 58 per cent. The heating loads subtracted from the third level were then added to the calculated loads of rooms on the first and second levels of the house.
4. Using a design water temperature of 45°F, the length of valance for each room was determined so that its cooling capacity matched the adjusted design cooling load for that room.
5. Using a design water temperature

of 215°F and a design entering air temperature of 120°F, the winter heating output of the valance selected in step 4 was determined and subtracted from the adjusted design heating load for the room.

6. In those rooms in which the heating output of the valance selected in step 4 was less than the adjusted design heating load of the room, baseboard was selected to make up the deficit.

The design loads, the required valance, and the required baseboard for each room of the house are shown in Table 1.

The system used during the summer season consisted of the valance units indicated in column 4 of Table 1, which were located along outside walls of the room near the ceiling as shown in Figure 3. Other equipment included a chiller, pump, piping, valves, and necessary controls. During the winter season a boiler was substituted for the chiller, and the valance units were supplemented by the baseboard as indicated in column 9 of Table 1. A schematic diagram of the complete system is shown in Figure 2.

A cross section drawing of the valance unit, consisting of a finned tube, hanger, cover, and trough for collecting condensate, is shown in Figure 3. Drain connections were provided at one end of each assembly to allow the water in the trough to be removed. Figure 4 illustrates the appearance of the finished installation in the dining room.

In both summer and winter, air circulation through the valance unit was by gravity. In the summer chilled water was circulated through the tube, while heated water was used in the winter season. The same piping system was used for both seasons, except that provision was made to prevent circulation of chilled water through the boiler in the summer and heated water through the chiller in the winter. Except for the sections located directly over the condensate collection trough, all piping used to carry chilled water was insulated with a foamed plastic insulation approximately 1/2 inch in thickness. All joints in this insulation were sealed with a plastic cement to make the insulation vapor tight throughout.

The piping arrangement used was a three-zone, series-connected system. This piping was so arranged that in summer chilled water was circulated through the valance units only. However, during the winter, heated water was circulated through both baseboard and valance. All thermostats were located 30 inches above the floor. Their locations are shown in Figure 2.

A five-horsepower water chiller was used for summer operation. The compressor and evaporator sections of the chiller were located in the boiler room, but the air-cooled condenser was located outside at the rear of the house. Sixty-cycle, single-phase electrical energy was supplied to the compressor at 230 volts and to the condenser at 115 volts.

A sectional cast iron boiler completely enclosed by an insulated sheet metal jacket was used for heating. The boiler had a net I=B=R water rating of 90,000 Btuh. The fuel used was natural gas having a heating value of 976 Btu per cubic foot. The average gas burning rate was approximately 165 cfh and the burner was adjusted to give a CO_2 concentration in the flue gas of approximately eight per cent.

C. SYSTEM CONTROL

1. Winter

In winter the controls consisted of three room thermostats, three relays, and three pumps which responded to the demand of the room thermostats. Gravity circulation of water was prevented by flow control valves located in the supply main of each zone just above the boiler. The boiler was equipped with a high limit control and pressure relief valve.

The operating sequence of the system was as follows. As soon as any one of the zone thermostats demanded heat for its area, the circulating pump supplying water to that area was put into operation. At the same time the gas burner in the boiler was turned on. As heating was required in additional zones the thermostats put the appropriate pumps into operation. As long as any circulating pump was in operation the gas burner continued to operate until the temperature of the water in the boiler was raised to the setting of the high limit control (225°F). When the setting of the high limit control was reached the burner was turned off, but as long as heating was required in any area the pump remained in operation. In the event that one or more pumps were in operation and the burner had been turned off by action of the high limit control, it would restart automatically when the temperature of the water in the boiler dropped approximately 40°F below the setting of the high limit control.

When sufficient heat had been supplied to a zone, the thermostat in that zone stopped the pump. When the last zone received sufficient heat the burner also stopped operation. During these tests no provision was made to supply hot faucet water from the boiler by means of an indirect heater.

2. Summer

The controls used for summer operation of the valance system consisted of three room thermostats, three relays, and three motorized zone valves which controlled the flow of chilled water to each zone by responding to the demand of the zone thermostats. The high and low side controls in the chiller acted as safety controls to prevent operation of the chiller if for any reason the refrigerant pressure on the high side became excessive or if the temperature in the evaporator section became too low. The operating control consisted of a water temperature control located in the chiller outlet. The chilled water was circulated through the system by a single high-head pump.

The operating sequence of the system was as follows. When any one of the zone thermostats indicated need of cooling in its area, the circulating pump was started and the motorized valve for that zone was opened. As additional zones required cooling, the zone valves of those circuits also opened. The pump continued to run as long as any thermostat demanded cooling. As long as the circulating pump was in operation, the chiller operated sufficiently to maintain the temperature of the water leaving the chiller between 40° F and 45° F.

When any zone was sufficiently cooled, the thermostat signal caused the motorized valve to close, stopping the flow of water in that part of the system. When all the zones were sufficiently cooled, the pump and chiller also turned off, and the entire system remained idle until cooling was again required in at least one zone.

D. INSTRUMENTATION

Approximately 250 copper-constantan thermocouples made of 28 gauge wire were installed in and around the house to measure temperatures. These temperatures can be best grouped in the following categories:

1. House
   a. Air temperatures at 3 inches, 30 inches, and 60 inches above the floor, and 3 inches below the ceiling in each room of the house. Air temperature at 90 inches above the floor in rooms with ceiling height exceeding 9 feet.
   b. Surface temperatures of floors, walls, ceilings, roof, and of intermediate sections of building members.
   c. Air temperatures in the attic and crawl space.
2. Outdoor Air
3. Ground

   Temperature of the ground to depths of approximately 7 feet below grade level both under and around the house to distances of 18 feet from the foundation.
4. Cooling System
   a. The temperatures of the water entering and leaving each valance unit and the inlet and outlet water temperatures for the chiller.
   b. Temperatures of the air entering and leaving the air-cooled condenser.
   c. Temperatures of refrigerant entering and leaving the condenser.
5. Heating System
   a. Temperatures of the water entering and leaving each heating unit (both baseboard and valance) used in the heating system, and the inlet and outlet water temperatures for the boiler.
   b. Temperatures of the flue gas at the top of the boiler and at two locations in the chimney.

All thermocouples were connected to selector switches on a central switchboard. The emf produced by each thermocouple could be read to 0.001 mv on a precision potentiometer used with a highly sensitive galvanometer. Two 10-point recording potentiometers used with an auxiliary switchboard made it possible to obtain continuous printed records of the readings of selected groups of thermocouples.

Elbow meters[(5)] connected to differential pressure recorders or manometers were used to measure the rate of water flow in each zone of the cooling and heating systems. All flow meters were calibrated in place and were capable of measuring the existing flow rates with an error not exceeding 5 per cent.

The operating times of each of the circulating pumps, the burner, chiller compressor, and the chiller condenser were obtained by the use of self-starting electric clocks wired into the electrical circuits. Watt-hour meters readable to 10 watt-hours were used to measure the power consumption of each of these units. An Orsat apparatus graduated to read CO_2 content to 0.2 per cent was used to measure the completeness of combustion.

Humidity indicators and recorders using sensing elements made of hair were used to determine the moisture content of the room air. The wet- and dry-bulb temperatures of the outdoor air were obtained with a recording instrument in which a fan continuously drew outdoor air over liquid-filled temperature sensing elements. All humidity indicators and recorders were calibrated periodically with an aspirated psychrometer which was shielded from radiation effects.

Other instruments included heat meters used to measure heat flow through building components, a specially designed Thomas meter used to measure the rate of gas flow up the chimney, and a micromanometer used to measure indoor-outdoor pressure differences across the walls of the house. The public utilities' meters were used to measure water consumption, total electric energy consumption, and total gas consumption. Boiler gas consumption was separately metered with a meter calibrated to read in cubic feet.

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III. TEST CONDITIONS AND PROCEDURES

A. TEST CONDITIONS

Two series of tests were made. One, designated as series A-61, was made during summer weather; the other, designated as series C-61, was run during the winter. Each series was continued until data were obtained over a wide range of outdoor temperatures and general weather conditions. The following conditions were common to both the summer and winter series of tests: All windows were closed at all times. Outside doors were closed except while persons were entering or leaving the house. Room doors were open at all times. All draperies except those in bedrooms 2 and 3 were pulled to the side of the glass area as far as they would go, and remained in this position at all times. The draperies in bedrooms 2 and 3 were drawn across the glass at night. The door to the equipment room was left closed. The access opening from the equipment room to the crawl space was closed.

In addition to the above conditions, the three zone thermostats in series A-61 were all set to maintain and average air temperature of 75°F at a height of 30 inches above the floor. Crawl space vents were open. In series C-61 each of the three zone thermostats was set to maintain an average air temperature of 73°F 30 inches above the floor. The high limit control in the boiler was set at 225°F, and crawl space vents were closed.

B. TEST PROCEDURES AND OBSERVATIONS

Basically the test procedure was the same for both test series. Each test was 24 hours in length and the test day started and ended at 8:00 a.m. Observations common to both summer and winter tests included:

1. All temperatures included in paragraphs 1, 2, and 3 of Section II D.
2. Water flow rates through the different zones.
3. Operating time and power consumption of each pump.
4. Heat flow rates through building elements.
5. Sky conditions, wind speed, and wind direction.
6. Relative humidity of indoor air.

Additional observations made during the summer tests included:

1. All temperatures included in paragraph 4 of Section II D.
2. Operating time and power consumption of zone valves, compressor, and condenser fan motors.
3. Occupancy of the house.

4. Comfort votes.

Additional observations made during winter tests included:

1. All temperatures included in paragraph 5 of Section II D.
2. Operating time of the gas burner.
3. Carbon dioxide content of the flue gas.
4. Fuel consumption.

Important water and refrigerant temperatures were continuously recorded by recording potentiometers. Recording instruments also provided continuous records of the heat meter readings; outdoor air temperature; room air temperatures in the living room, bedroom 1, and the recreation room; air temperature in the attic above the dining room and in the crawl space; water flow rates through the different zones; and static pressure in the system.

Most other observations were made manually four times per day: at 8:00 a.m., 1:00 p.m., 4:00 p.m., and 10:00 p.m. A few observations such as comfort votes, occupancy, CO_2 content, and rate of flow of the flue gas were taken less frequently.

The test conditions and procedures used when testing the baseboard-valance system were the same as those for the valance tests reported in Engineering Experiment Station Bulletin No. 466, "Hydronic Heating and Cooling with Valance Units." Thus results obtained with the two systems may be compared.

IV. SYSTEM PERFORMANCE — WINTER

A. FUEL CONSUMPTION

The daily fuel consumption obtained with the baseboard-valance system is correlated with indoor-outdoor temperature difference in Figure 5. Similar correlations transferred from previous bulletins[1, 2] are included for both valance and baseboard systems. The daily fuel consumption obtained with the baseboard-valance system was significantly lower than that obtained with the valance system. At the mean test condition, indoor-outdoor temperature difference of 42°F, the combination system used about 9 per cent less fuel than the valance system. At design indoor-outdoor temperature difference of 80°F the combination system used 13 per cent less fuel.

The daily fuel consumption obtained with a comparable three-zone baseboard system was about 9 per cent less than that obtained with the baseboard-valance system at an indoor-outdoor temperature difference of 80°F, and about 8 per cent less at an indoor-outdoor temperature difference of 40° F. A large part of these differences in fuel consumption can be attributed to differences in floor and ceiling temperatures maintained by the various systems. The valance system produced the highest floor and ceiling temperatures, while the baseboard system gave the lowest values.

In Figure 6 the fuel consumption obtained with the baseboard-valance system has been reduced to a unit fuel consumption. In other words, the observed daily fuel consumption has been divided by the average indoor-outdoor temperature difference for the day in question and the design heat loss of the house. For all practical purposes, the unit fuel consumption was independent of indoor-outdoor temperature difference, and amounted to approximately 0.36 cubic feet of gas per degree indoor-outdoor temperature difference per MBh design load. The theoretical unit fuel consumption for this house, based on the calculated design heat loss and assuming 100 per cent efficiency, was 0.308 cubic feet of gas per degree difference in indoor-outdoor temperature per MBh design load. If the theoretical unit fuel consumption is divided by the observed unit fuel consumption, the overall house efficiency based upon heat input to the boiler is obtained. This efficiency is represented by curve 5 in Figure 6.

The overall house efficiency based upon energy input to the boiler can be misleading, since it assumes that this is the only source of energy to take care of heat losses from the house. It is a well-known fact that there are many sources of heat input to a house other than the heating system. Common examples are electric lighting, cooking, ironing, occupancy, and the use of electric motors and appliances. During the tests, daily records were maintained of the occupancy and total energy consumption in the house. These represented an average energy input of 3, 750 Btuh. No means were available for measuring the energy received from solar radiation, but based on studies made in ten houses located in Chicago[6, 7] it was estimated that the average solar gain was approximately 3, 000 Btuh, making a total extraneous gain of 6, 750 Btuh. Curve 3 in Figure 6 represents the total unit energy input to the house. It includes the fuel used by the boiler plus an allowance of 6, 750 Btuh for other miscellaneous heat inputs. Curve 4 is the overall house efficiency based upon curves 1 and 3. Assuming that the calculated heat losses of the house agree with the actual heat losses of the house at design conditions, and that the allowance for miscellaneous energy inputs to the house is correct, curve 4 approximates the utilization efficiency of the heating system. It will be observed that this efficiency was above 65 per cent at all indoor-outdoor temperature differences in excess of 20°F and above 70 per cent at indoor-outdoor temperature differences in excess of 30°F. At indoor-outdoor temperature differences below 20°F the efficiency dropped off rapidly. This drop in efficiency is of little consequence since less than 10 per cent of the total fuel used during a winter season is used at these conditions.

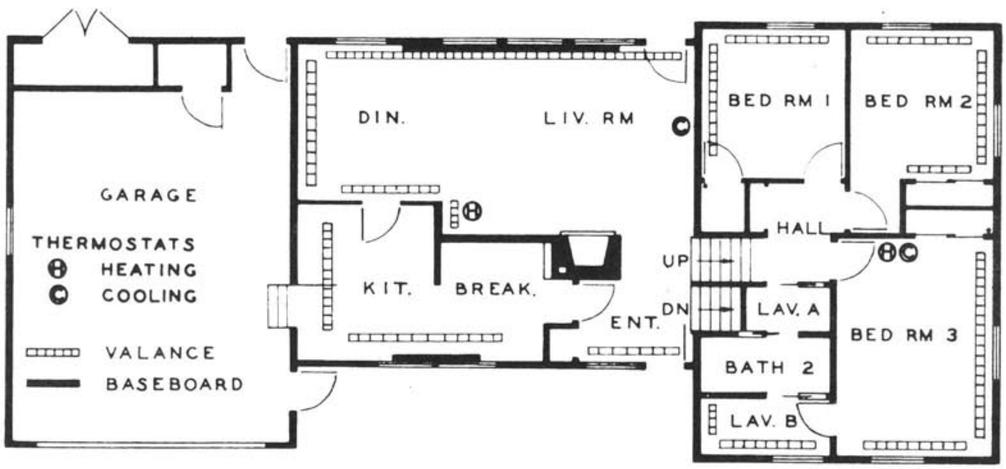
B. SYSTEM WATER TEMPERATURES AND SYSTEM OUTPUTS

Figure 7 shows the relationship between the mean temperature of the water at the boiler outlet and the indoor-outdoor temperature difference. There was a gradual increase in the mean temperature of the water with increasing indoor-outdoor temperature difference, up to a temperature difference of approximately 40°F. At this point, action of the high limit control prevented further increase in the maximum boiler water temperature. The dotted curve in Figure 7 represents the mean temperature of the water leaving the boiler as used for design purposes of the system. While at indoor-outdoor temperature differences less than 40°F the slope of the curve representing the actual mean boiler water temperature was essentially the same as the slope of the curve representing the water temperature used for design, the actual temperatures were about 45°F higher than those assumed in the design of the system. Since the actual boiler water temperature remained almost constant for indoor-outdoor temperature differences in excess of 40°F, the actual water temperature at an indoor-outdoor temperature difference of 80°F was about 15°F less than the design water temperature.

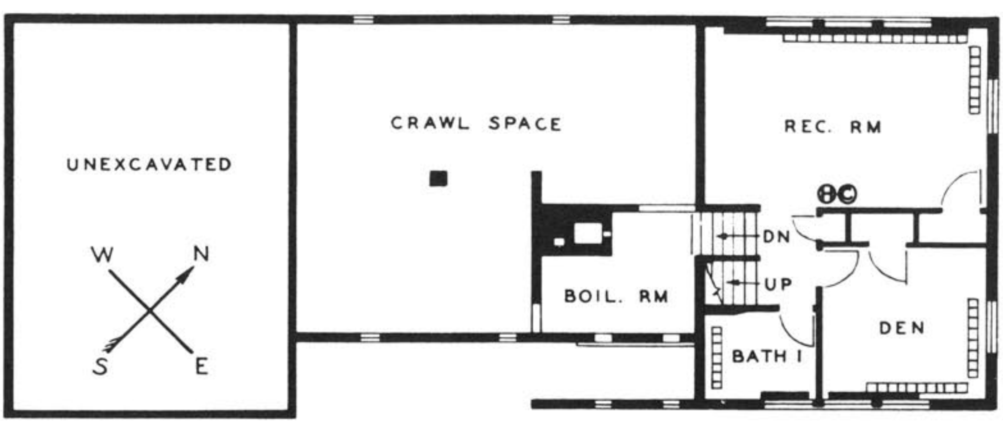
The results of a test to determine system outputs at conditions representative of those prevailing at an indoor-outdoor temperature difference of 80°F are given in

FIGURES and TABLES

FIGURE 1. I=B=R HYDRONIC RESEARCH HOUSE



SECOND AND THIRD LEVEL PLAN



FIRST LEVEL PLAN

FIGURE 2. FLOOR PLANS OF I=B=R HYDRONIC RESEARCH HOUSE

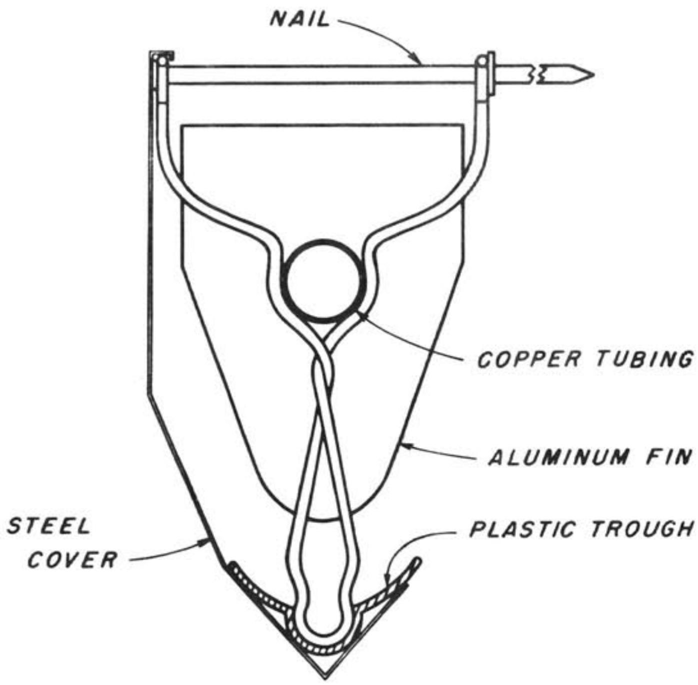


FIGURE 3. CROSS SECTION - VALANCE UNIT

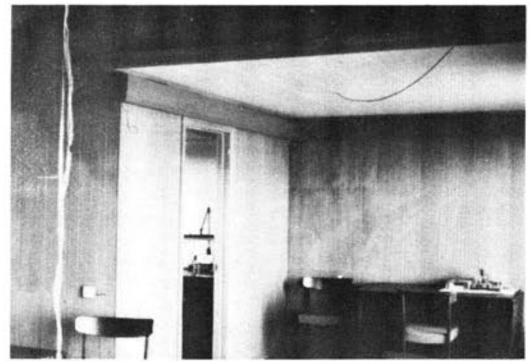


FIGURE 4. VALANCE INSTALLATION IN DINING ROOM

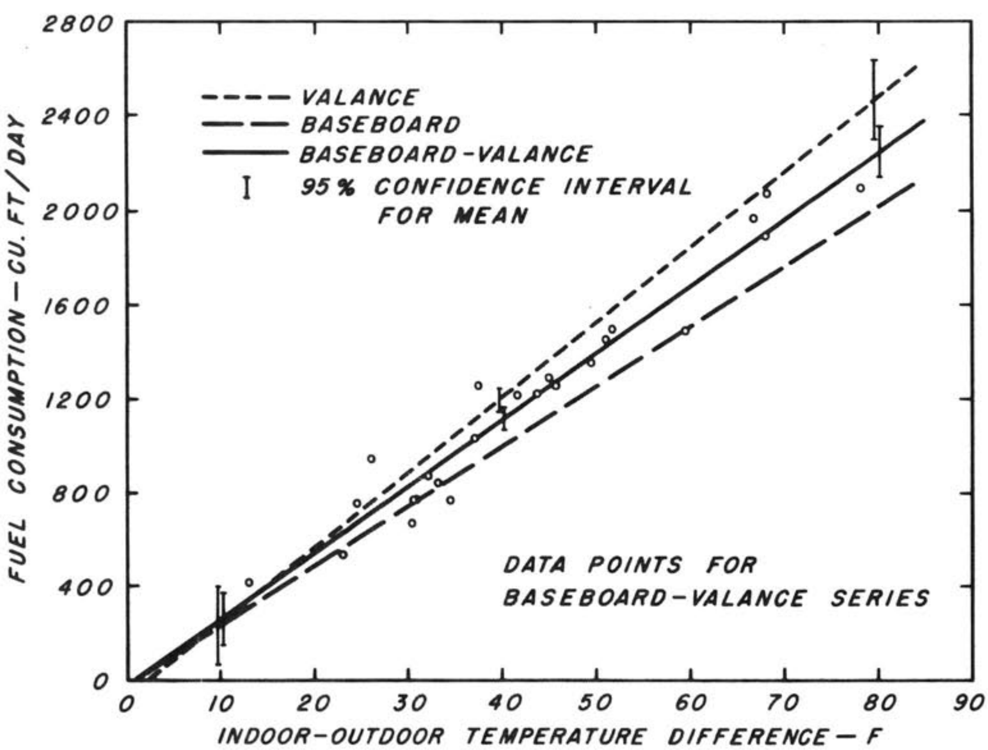


FIGURE 5. DAILY FUEL CONSUMPTION

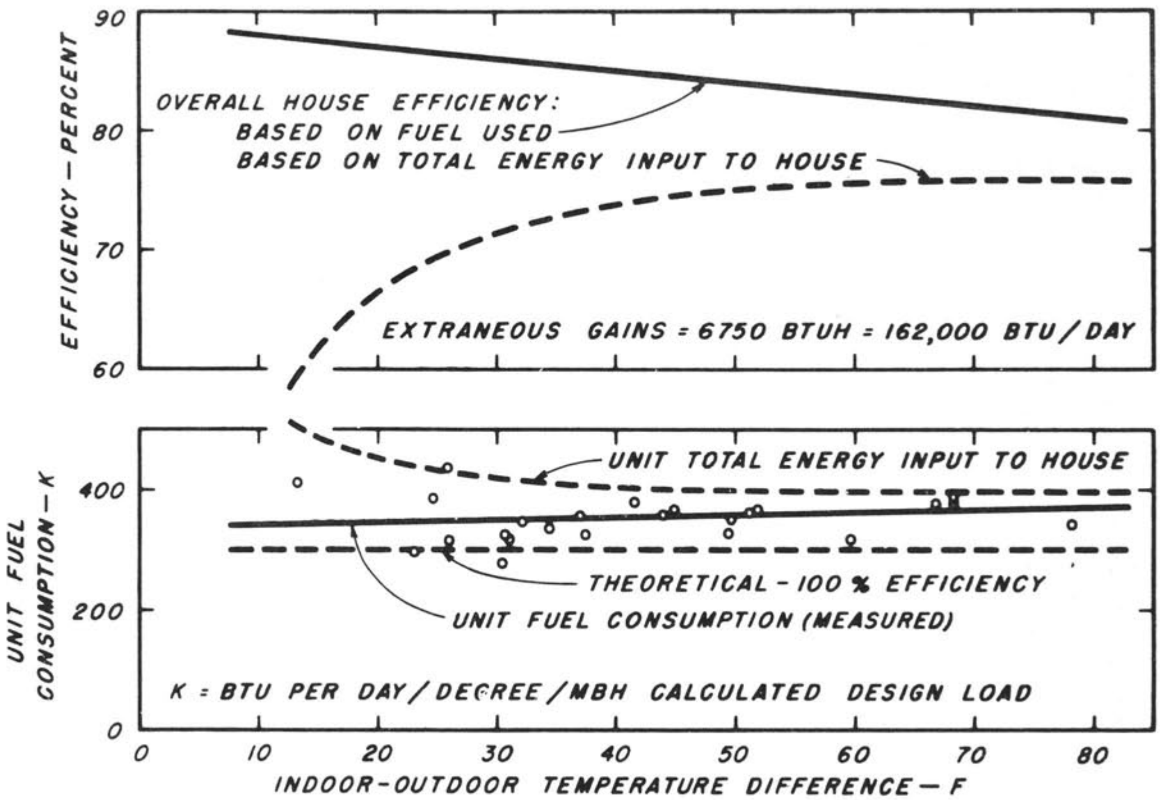


FIGURE 6. UNIT ENERGY CONSUMPTION - BASEBOARD-VALANCE SYSTEM

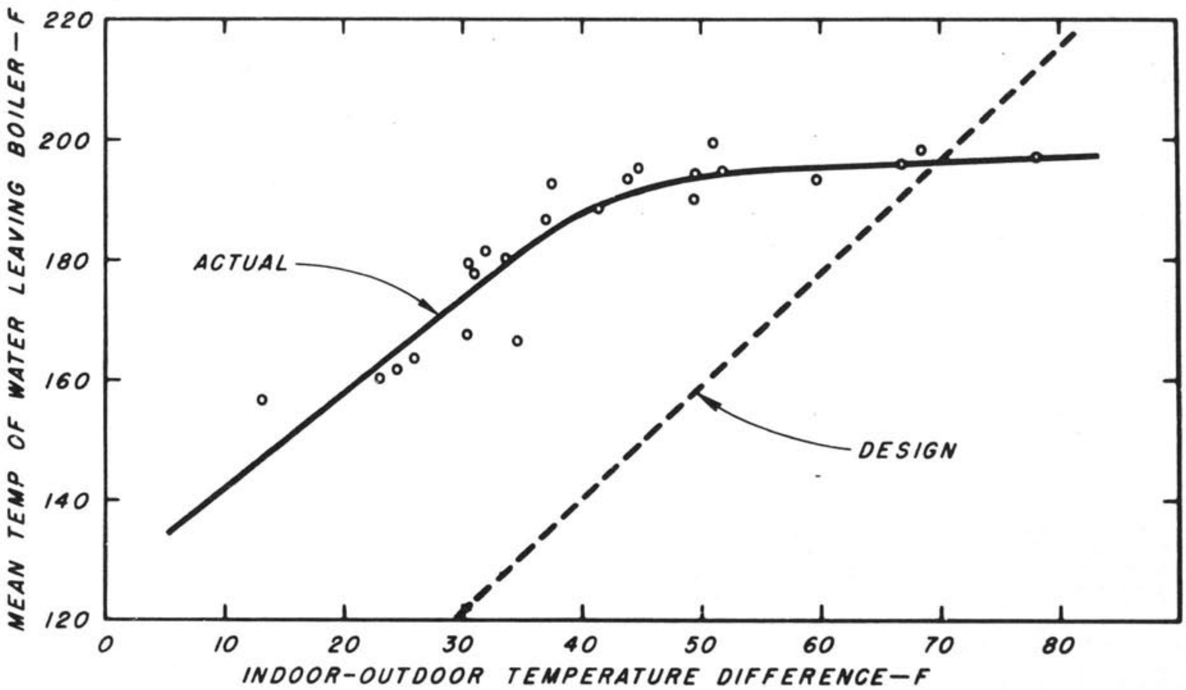


FIGURE 7. MEAN TEMPERATURE OF WATER LEAVING BOILER

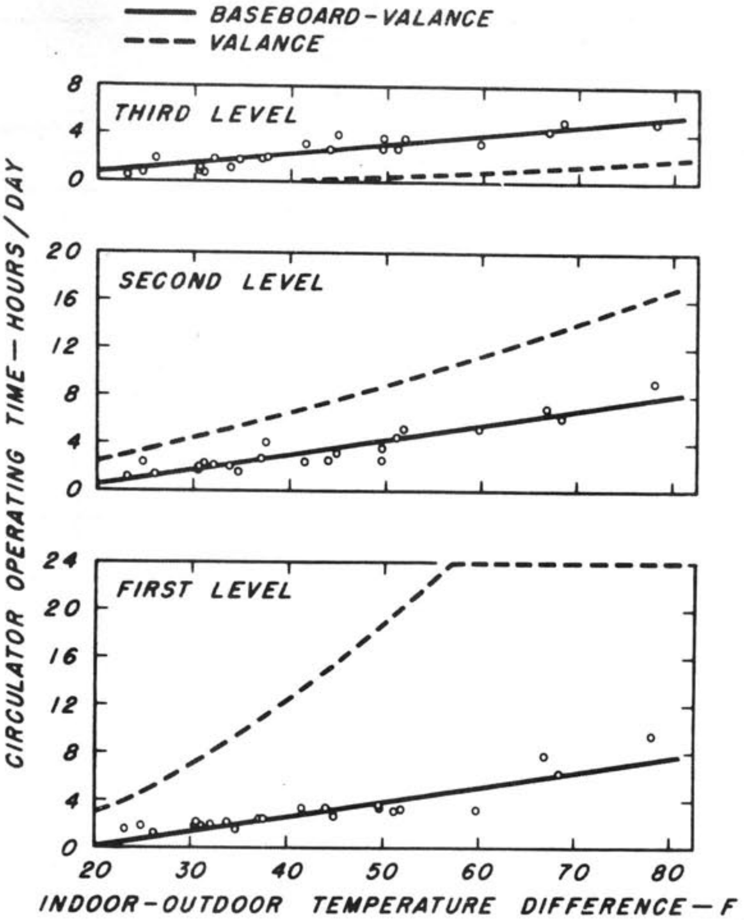


FIGURE 8. CIRCULATOR OPERATING TIMES

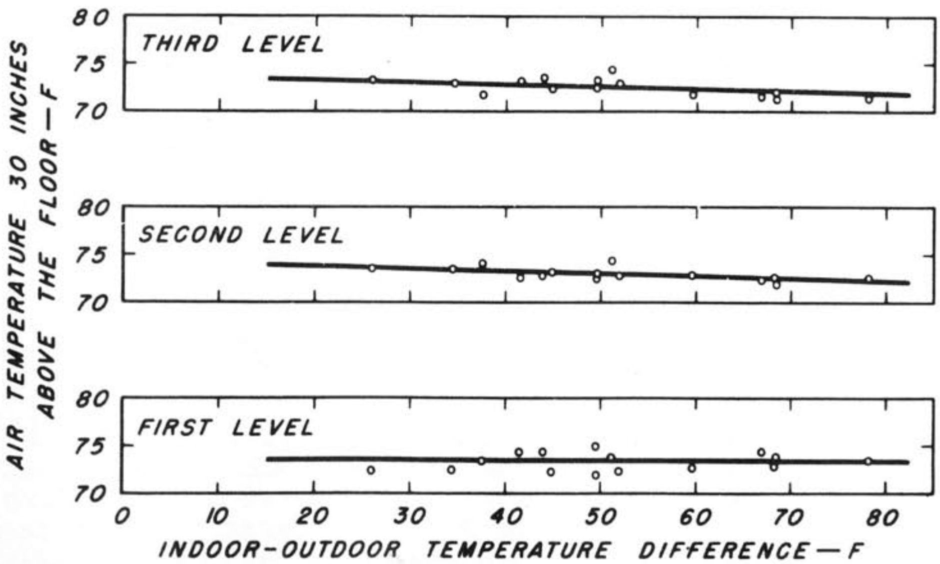


FIGURE 9. AIR TEMPERATURES 30 INCHES ABOVE THE FLOOR

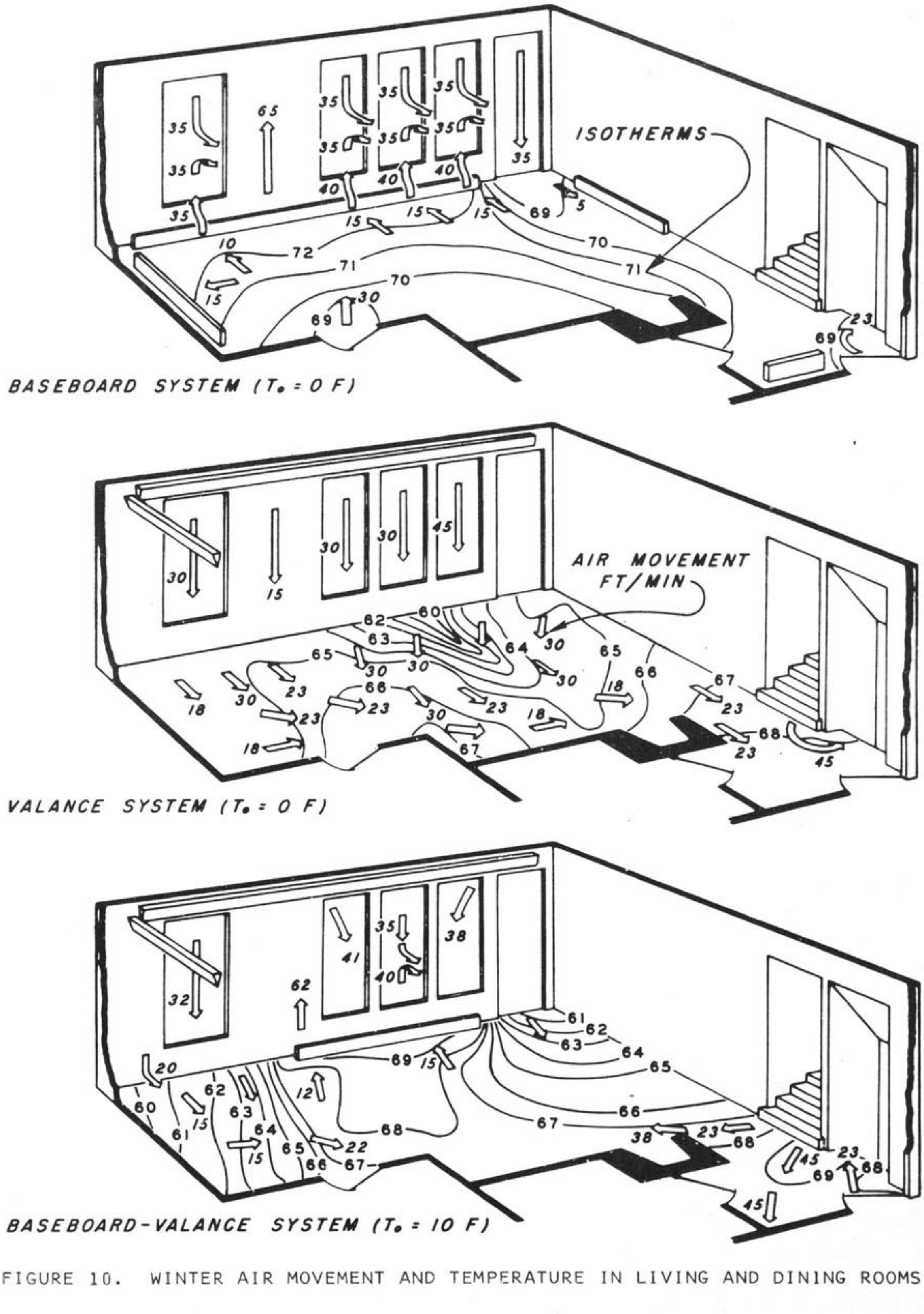


FIGURE 10. WINTER AIR MOVEMENT AND TEMPERATURE IN LIVING AND DINING ROOMS

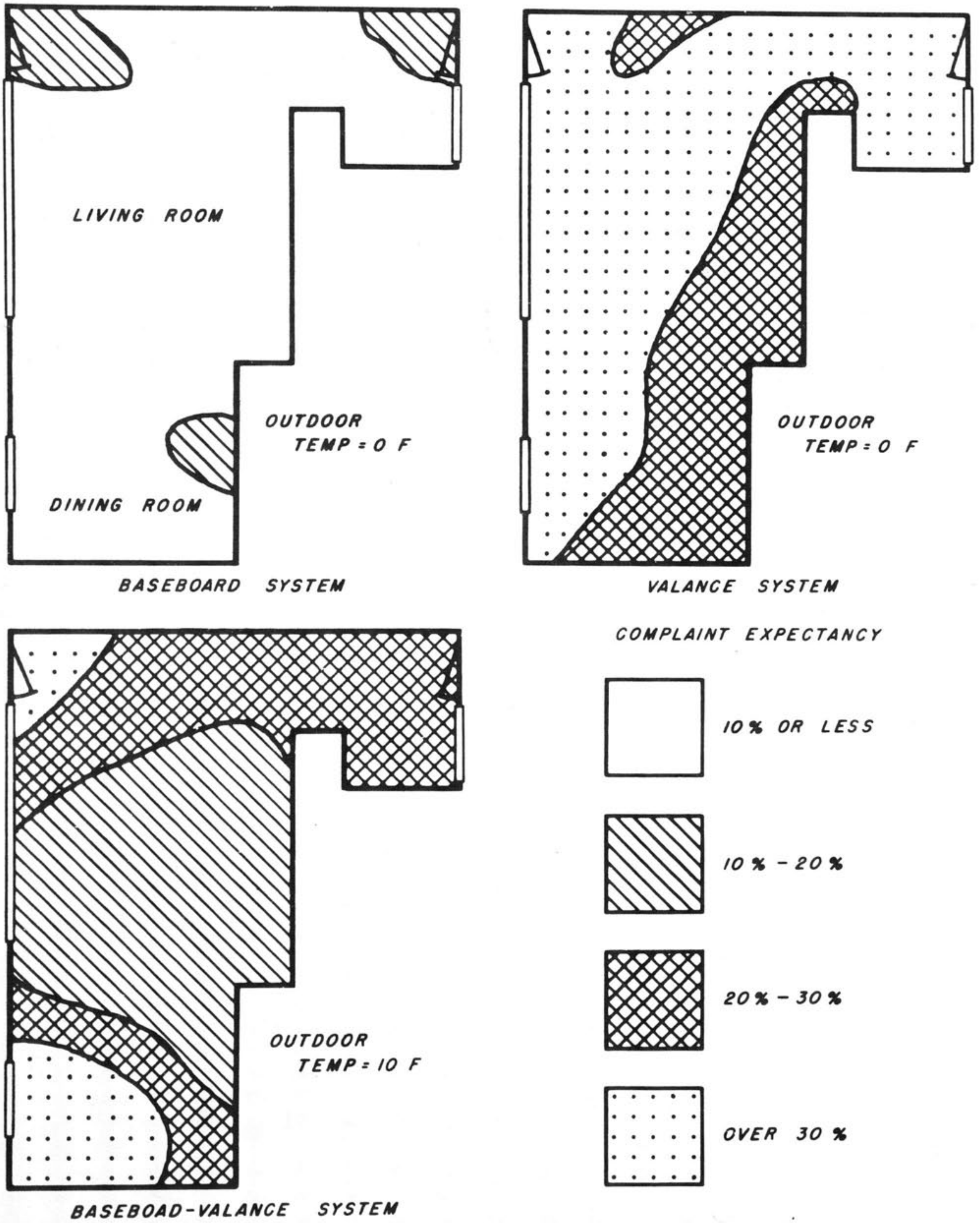


FIGURE 11. COMPLAINT EXPECTANCY OF COOL FEET AND ANKLES IN LIVING DINING AREA

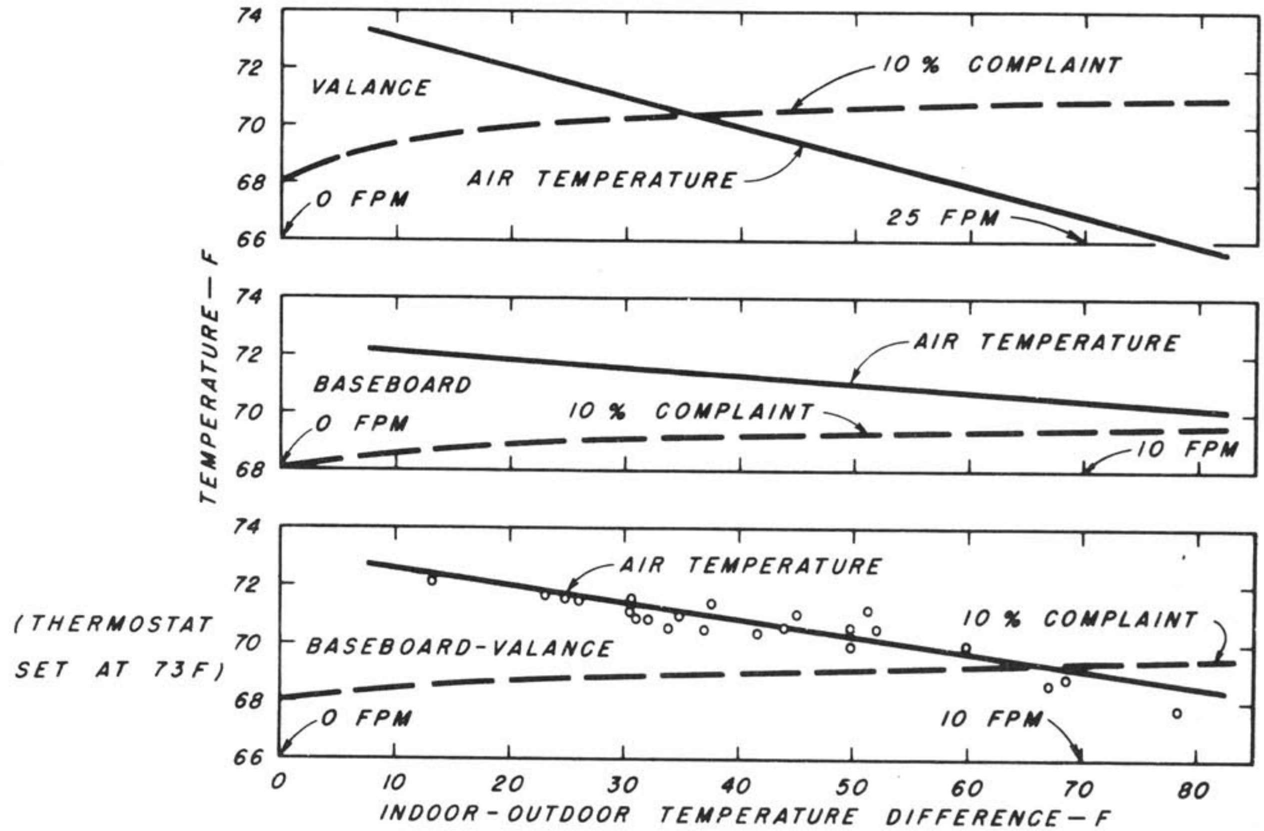


FIGURE 12. LIVING ROOM AIR TEMPERATURES THREE INCHES ABOVE THE FLOOR

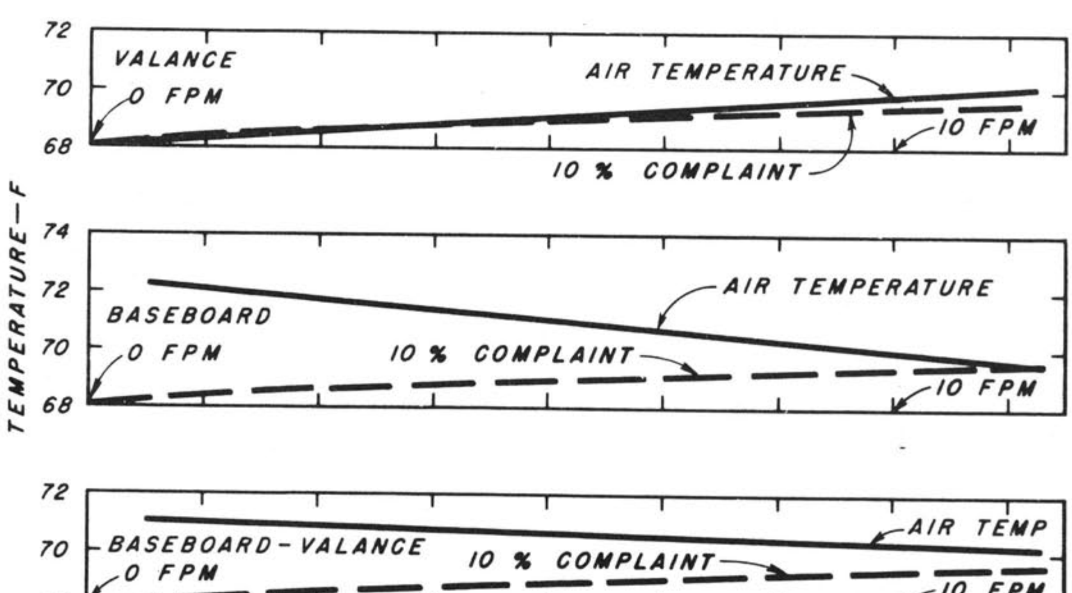


FIGURE 13. FIRST LEVEL AIR TEMPERATURE THREE INCHES ABOVE THE FLOOR

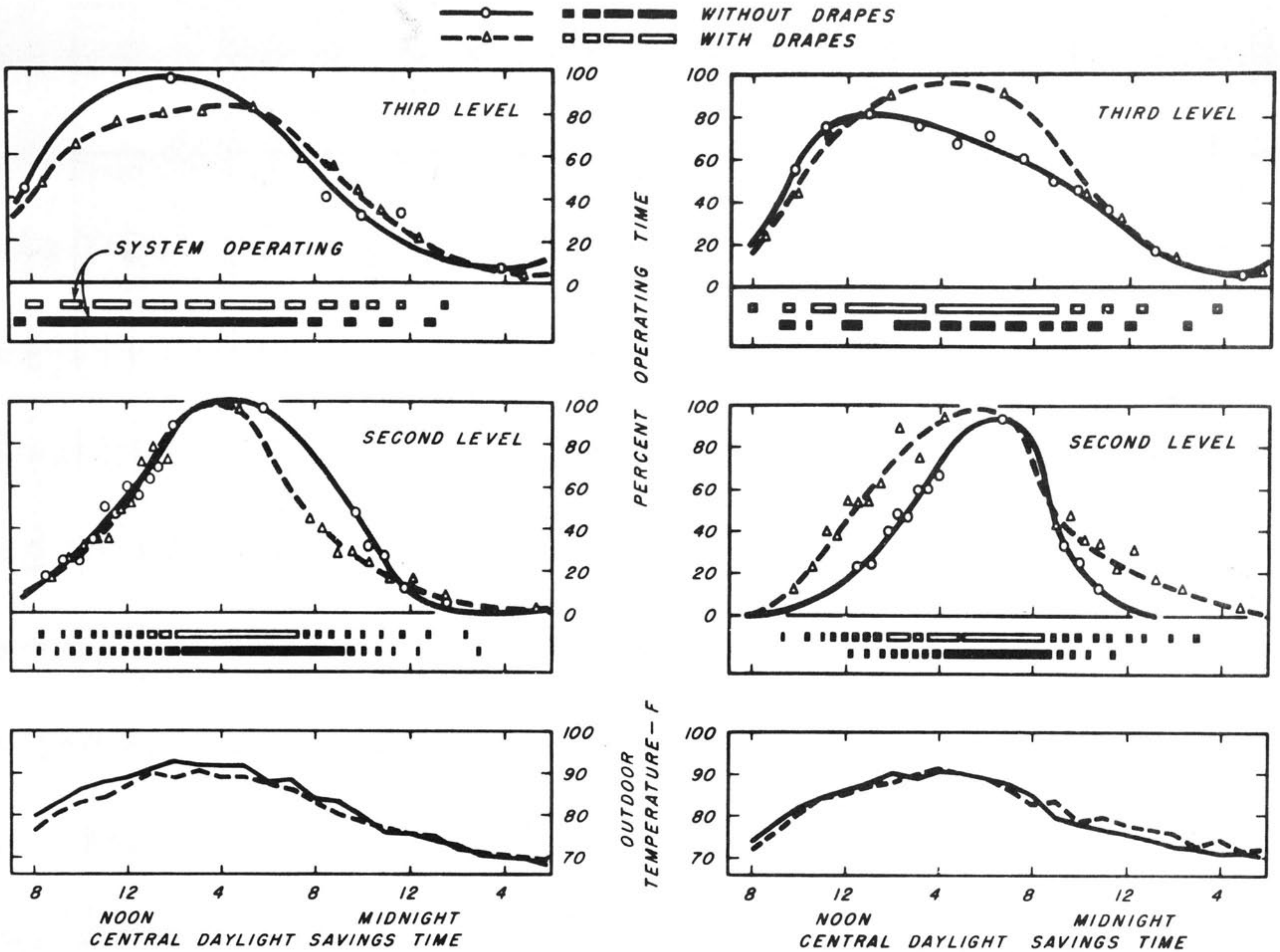


FIGURE 14. EFFECT OF INTERNAL SHADING ON ZONE OPERATION

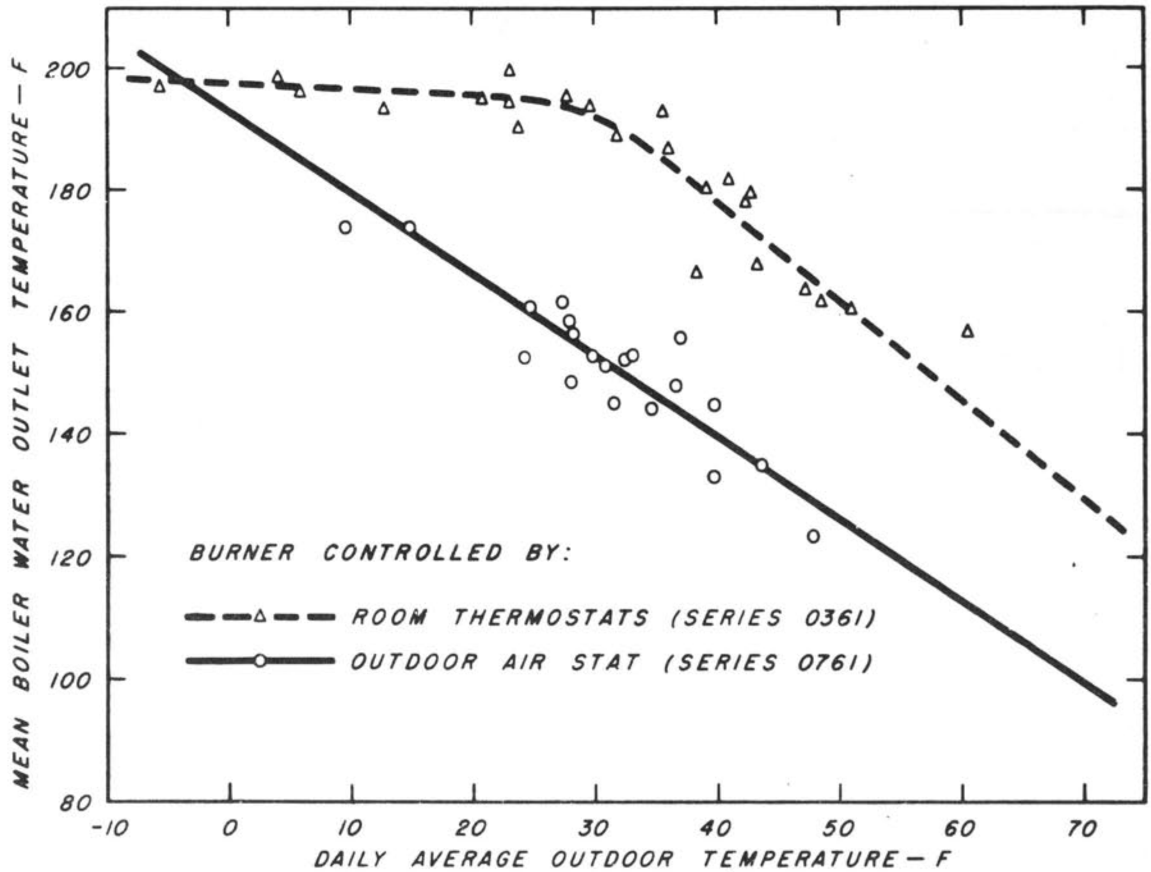


FIGURE 15. MEAN TEMPERATURE OF WATER AT BOILER OUTLET - TWO METHODS OF CONTROL

TABLE 1

DESIGN LOADS AND EQUIPMENT SELECTION

	Cooling			Heating				
Room	Calculated Design Load-MBH (Inside Shading with Draperies)	Proposed Load to Compensate for Cooling Load Shift, MBh[(a)]	Valance Installed, Feet	Calculated Design Load, MBh, Guide H-20	Proposed Loads to Compensate for Heating Load Shift, MBh[(b)]	Output of Valance Installed in Column (4), MBh[(c)]	Additional Output Required to Match Proposed Load, Column (6), MBh	Baseboard Installed to Supply Additional Output, Column (8), Feet[(d)]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Rec.	4.400	3.300	18.9	11.89	16.36	7.19	9.17	17
Den	2.667	2.000	13.4	6.06	8.34	5.16	3.18	6
Bath. I	0.768	0.580	4.0	2.29	3.16	1.52	1.64	3
Hall A	0.000	0.000	0.0	0.11	0.11	0.00	0.00	0
1st Lev.	7.835	5.880	36.3	20.35	27.97	13.87	13.99	26
Liv.-Din.	6.767	6.767	44.6	18.98	21.99	17.12	4.87	14[(e)]
Entry	1.233	1.233	6.6	4.57	5.30	2.62	2.68	0
Kit.-Bkf.	3.400	3.400	21.1	9.94	11.52	8.03	3.49	6
2nd Lev.	11.400	11.400	72.3	33.49	38.81	27.77	11.04	20
Bed. I	2.066	2.582	16.0	4.80	1.99	6.08		
Bed. II	2.900	3.625	22.5	6.63	2.75	8.55		
Bed. III	2.866	3.580	22.3	6.86	2.84	8.46		
Lav. B	1.500	1.500	9.8	2.74	1.14	3.80		
Lav. A	0.067	0.067		0.11	0.05			
Bath. II	0.233	0.233		0.69	0.29			
Hall B	0.133	0.133		0.34	0.14			
3rd Lev.	9.765	11.720	70.6	22.17	9.20	26.89		
House	29.000	29.000	179.2	76.01	75.98			46

Notes:

(a) Calculated load on 1st level reduced by 25%. This amount then added to 3rd level. 2nd level remained unchanged.

(b) Calculated load on 3rd level reduced by 58.5%. The 58.5% then divided, with 34.4% of the 3rd level calculated load going to the 1st level and 24.1% going to the 2nd level.

(c) $T_w - T_a = 215 - 120 = 95^oF$. Output = 380 Btuh/ft.

(d) Average water temp. = 215°F. Water heat capacity = 560 Btuh/ft.

(e) Additional output required in Liv.-Dn. and Entry.

TABLE 2

SYSTEM OUTPUT TEST - WINTER

November 21, 1961

Zone	Inlet Temp. °F	Outlet Temp. °F	ΔT °F	Flow Lb/hr	Output MBh	Adjusted Design Load MBh	Calculated Design Load MBh
1st level	203.1	181.1	22.0	1245	27.39	27.97	20.35
2nd level	202.0	179.9	22.1	1545	34.14	38.81	33.49
3rd level	204.1	183.6	20.5	1055	21.63	9.20	22.17
Total				3845	83.16	75.98	76.01
Boiler	180.5	205.2	24.7	3900	96.33		

TABLE 3

COMPARISON OF VERTICAL TEMPERATURE DIFFERENTIALS - WINTER

	Floor surface minus 30" above floor	3" above floor minus 30" above floor	60" above floor minus 30" above floor	3" below ceiling minus 30" above floor
40°F Indoor-outdoor temperature difference				
* Baseboard				
1st level	-1.9	-2.0	0.6	1.3
2nd level	-3.0	-1.7	0.3	0.6
3rd level	--	-0.5	0.4	0.8
Valance				
1st level	1.8	-2.9	3.2	25.4
2nd level	--	-3.3	2.3	20.0
3rd level	2.5	-1.2	1.3	4.3
Baseboard-Valance				
1st level	0.2	-2.3	2.0	11.7
2nd level	-1.9	2.1	1.5	8.3
3rd level	1.7	-1.7	1.3	6.3
80°F Indoor-outdoor temperature difference				
* Baseboard				
1st level	-4.4	-4.5	1.9	3.5
2nd level	-5.7	-3.7	1.5	2.6
3rd level	--	-3.3	1.0	2.8
Valance				
1st level	6.1	-5.0	6.2	66.3
2nd level	--	-6.8	5.0	53.4
3rd level	3.6	-2.3	3.5	11.8
Baseboard-Valance				
1st level	1.9	-2.8	2.9	22.3
2nd level	-3.1	-3.0	3.2	19.3
3rd level	2.6	-2.3	2.8	14.0

* From I=B=R-3, "Research Progress Report 1959-60
The I=B=R Hydronic Research House."

TABLE 4

COOLING SYSTEM OPERATING TIMES BETWEEN 1:00 P.M. AND 9:00 P.M.

Maximum Outdoor Temperature, Degrees F.	Operating Time in Per Cent of Total Elapsed Time							
	Valance System				Baseboard-Valance System			
	First Level Zone	Second Level Zone	Third Level Zone	Chiller	First Level Zone	Second Level Zone	Third Level Zone	Chiller
75	16	15	24	24	23	26	10	19
80	24	30	46	37	35	41	33	33
85	33	45	69	50	47	56	55	47
90	42	60	92	64	59	72	78	61
95	52	76	100*	78	71	87	100**	74

* 100 per cent operation reached at a maximum outdoor temperature of 92°F.

** 100 per cent operation reached at a maximum outdoor temperature of 95°F.

TABLE 5

BASIS OF LABOR ESTIMATES

A. BASIS OF LABOR TIME ESTIMATES

Item	Unit Installation Time, Hours	Source
Boiler	8.00	Mechanical Estimating
Chiller	52.00	Mechanical Estimator's Guide
Fan-Coil	3.00	Mechanical Estimator's Guide
Pump	*	*assumed equal to three fittings of same size
Valve	*	*assumed equal to one fitting of same size
Valance		
Element	0.04	Estimated by staff after installing system
Cover	0.01	
Trough	0.02	
Baseboard	0.05	Estimated by staff
Insulation, Flexible	0.017	Mechanical Estimator's Guide
Grilles	0.33	Mechanical Estimating

B. BASIS OF LABOR COST ESTIMATES--PIPE AND FITTINGS

Nominal Pipe or Tube Size	Unit Installation Time, Hours			
	Iron Pipe**	Copper Tube**	Iron Fittings*	Copper Fittings*
1/8"	....	....	0.11	....
1/4"	....	....	0.12	0.09
3/8"	0.06	0.05	0.12	0.09
1/2"	0.07	0.05	0.14	0.10
3/4"	0.09	0.07	0.15	0.11
1"	....	....	0.17	0.13
1 1/4"	0.12	0.09	0.20	0.15
2 1/2"	....	....	0.32	....

** Man-hours per foot

* Man-hours per piece

Information on iron pipe and fittings obtained from Time Study on Pipe Fitting

Time for copper tube and fittings assumed at 0.75 that for iron. Average for all estimation references.

Average wage scale assumed to be $3.60 per hour.

TABLE 6

ESTIMATED INSTALLATION COSTS

System	Material	Labor	Total
Valance	$2051.00	$398.00	$2449.00
Baseboard and Fan-Coil	$2536.00	$482.00	$3018.00
Baseboard-Valance	$2250.00	$466.00	$2715.00

Material and labor for controls required are not included.

Labor based on average rate of $3.60 per hour.

TABLE 7

SEASONAL FUEL AND POWER COMSUMPTION - WINTER OPERATION

(Based on records of U. S. Weather Bureau Station at University of Illinois. Includes months of January, February, March, April, May, September, October, November, and December from September, 1936 to May, 1941).

Avg. Outdoor Temperature, ° F	Avg. No. of Days Per Year	Fuel Consumption		Power Consumption	
		cu ft/day	cu ft/season	watt-hr/day	watt-hr/season
1	2	3	4	5	6
-10 to -5	0.2	2240	448	2619	524
- 5 to 0	0.4	2100	840	2419	968
0 to 5	0.8	1935	1548	2220	1776
5 to 10	2.2	1810	3982	2021	4446
10 to 15	4.6	1670	7682	1821	8377
15 to 20	7.6	1530	11628	1620	12312
20 to 25	13.6	1390	18904	1443	19625
25 to 30	25.4	1245	31623	1220	30988
30 to 35	33.8	1105	37349	1025	34645
35 to 40	30.0	960	28800	825	24750
40 to 45	23.4	820	19188	631	14765
45 to 50	22.6	675	15255	436	9854
50 to 55	20.8	555	11544	239	4971
55 to 60	19.8	395	7821	98	1940
60 to 65	22.0	250	5500	40	880
65 to 70	19.0	110	2090	20	380
70 to 75	13.6	0	0	0	0
75 to 80	9.4	0	0	0	0
80 to 85	3.4	0	0	0	0
85 to 90	0.4	0	0	0	0
Summer	92.0	0	0	0	0
Seasonal Total			204202		171201

TABLE 8

OPERATING COSTS

System	Winter Operation		Heating Total	Summer Operation	Year Around Total
	Power	Fuel			
Valance	$9.71	$159.91	$169.62	$110.13	$279.75
Baseboard and Fan-Coil	4.98	133.19	138.17	149.19	287.36
Baseboard-Valance	5.14	142.94	148.08	110.13	258.21

Cost of power = 3¢ per kwhr
Cost of fuel (natural gas) = 7¢ per therm (100 cu ft)

TABLE 9

DESIGN COOLING LOADS - WITH AND WITHOUT INTERNAL SHADING

Location	Design Cooling Load, MBh		Per Cent Reduction in Design Load Due to Inside Shading
	With Inside Shading	Without Inside Shading	
First Level	7.83	9.83	20
Second Level	11.40	14.23	20
Third Level	9.77	12.00	19
Total	29.00	36.06	20

TABLE 10

EFFECT OF DRAPERIES ON SYSTEM OPERATING TIMES VERSUS AVERAGE OUTDOOR TEMPERATURE

Location	Correlation Coefficient	Mean	Std. Error of Mean	t-test of Mean	Regression Coefficient	Std. Error of Regression Coefficient	t-test of Regression Coefficient
Series A-61-62 (no draperies) 52 tests							
Daily Average Outdoor Temp., ° F.		75.4					
1st level operation, hrs.	0.648	5.57	0.362		0.477	0.078	6.13
2nd level operation, hrs.	0.780	6.21	0.227		0.436	0.053	8.19
3rd level operation, hrs.	0.837	8.30	0.284		0.669	0.059	11.23
Chiller operation, hrs.	0.871	6.50	0.183		0.501	0.040	12.62
Pump operation, hrs.	0.849	11.30	0.268		0.680	0.065	10.40
Series B-62 (draperies) 12 tests							
Daily Average Outdoor Temp., ° F.		77.2					
1st level operation, hrs.	0.676	6.83	0.671		0.822	0.313	2.63
2nd level operation, hrs.	0.593	6.69	0.657		0.646	0.214	3.01
3rd level operation, hrs.	0.866	8.53	0.439		1.014	0.240	4.23
Chiller operation, hrs.	0.817	7.25	0.371		0.700	0.160	4.38
Pump operation, hrs.	0.883	12.29	0.400		1.000	0.263	3.80
Series A-61-62 minus Series B-62							
1st level operation, hrs.		0.36*	0.83*	0.43	-0.345	0.326	1.06
2nd level operation, hrs.		0.33*	0.57*	0.57	-0.210	0.216	0.97
3rd level operation, hrs.		1.01*	0.64*	1.57	-0.345	0.241	1.45
Chiller operation, hrs.		0.17*	0.43*	0.41	-0.199	0.163	1.22
Pump operation, hrs.		0.26*	0.70*	0.37	-0.320	0.269	1.19

* Means and standard errors adjusted to an average outdoor temperature of 75.8° F.

TABLE 11

DAILY FUEL CONSUMPTION - TWO CONTROL SYSTEMS

Series	Number of Tests	Multiple Correlation Coefficient	Mean ΔT	Mean $W \Delta T$	Mean Daily Fuel Consumption, Cu. Ft.	Standard Error of Mean, Cu. Ft.	t	Significance	Regression Coefficient of Daily Fuel Consumption on ΔT	Standard Error of Regression Coefficient - ΔT	$t_{\Delta T} = \frac{\text{Regression Coefficient}}{\text{Standard Error}}$	Significance of ΔT Regression	Regression Coefficient of Daily Fuel Consumption on $W \Delta T$	Standard Error of Regression Coefficient - $W \Delta T$	$t_{W \Delta T} = \frac{\text{Regression Coefficient}}{\text{Standard Error}}$	Significance of $W \Delta T$ Regression
0361	23	.979	41.7	255.4	1144	20.0			26.14	1.327	19.70	(sig)	0.385	0.127	3.02	(sig)
0761	20	.968	41.3	372.2	1212	17.7			25.43	2.886	8.81	(sig)	0.393	0.122	3.22	(sig)
Series 0361 - Series 0761					-68	26.7	2.54	(sig)	0.70	3.18	0.22		-0.009	0.174	0.01	

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Table 2. The total output of the baseboard and valance units was approximately 83,200 Btuh, while the output of the boiler was approximately 96,300 Btuh. Assuming that the difference between these two values represents the heat loss of the piping, it would appear that the piping loss was about 13,100 Btuh or 13.6 per cent of the gross boiler output.

The last two columns of Table 2 show the design calculated heat loss for each level and the adjusted design heat losses used to size the baseboard-valance system. As described in Section II B these adjustments were made to compensate for the expected shift in load due to air movement from one house level to another. The actual output of the radiation installed on the first level of the house was almost identical to the adjusted design load. The output on the second level was about 12 per cent below the adjusted design load, while on the third level the output of the installed valance was about 2.3 times the adjusted design load for this level. There were no baseboard units installed on the third level, and the valance units were selected on the basis of an adjusted design cooling load which accounts for the excess radiation available for winter heating.

The principal reason for making adjustments in the design heating and cooling loads when sizing the baseboard-valance system was to attempt to secure better year around balance of the system. No such adjustments were made in the design of the valance system, and it was found that the shift in load due to air movement between house levels and heat transfer through the floor was so large that the first level zone operated continuously at indoor-outdoor temperature differences of 60°F and above. On the other hand, the third level zone operated only about 2 hours per day, even at an indoor-outdoor temperature difference of 80°F. The observed operating times of each zone, when the baseboard-valance system was used, are shown in Figure 8. For purposes of comparison, the corresponding operating times obtained with the valance system are also shown. When the baseboard-valance system was in use, the daily operating times of the zones were almost identical, indicating that the new design procedure was successful to the extent that the output of the installed radiation was proportioned to the actual loads on each level. This is in sharp contrast to the unequal zone operating times obtained when using the valance system, in which the radiation in each level was proportioned to the design heat losses of the rooms on that level with no adjustment made to compensate for air movement from one level to another.

Since in Figure 7 it was shown that at a design indoor-outdoor temperature difference of 80°F the system water temperature was about 20°F lower than design, and Figure 8 indicates that at an indoor-outdoor temperature difference of 80°F no zone operated more than eight hours per day, it is apparent that the entire load required of the heating system was somewhat less than the adjusted design loads indicated in Table 2.

V. COMFORT CONDITIONS — WINTER

A. ROOM AIR AND ROOM SURFACE TEMPERATURES

In the discussion of heating results with the valance system[2] it was pointed out that even though the system was designed in accordance with the calculated heat losses of the different rooms of the house, the room temperature balance obtained was not particularly good. This imbalance was because of the unexpectedly high entering air temperature and the large shift in load between house levels. In fact, the amount of radiation installed on the first level of the house was insufficient to maintain proper room air temperatures on this level at indoor-outdoor temperature differences in excess of 50°F. One of the principal reasons for undertaking the study of a combination baseboard-valance system was to determine if such an arrangement would result in better balance for both summer and winter operation.

As seen in Figure 9, the baseboard-valance system provided good control of the air temperature 30 inches above the floor (thermostat level) on all three house levels and at all indoor-outdoor temperature differences. The small variations in temperature that did occur could be attributed to thermostat characteristics and adjustments.

In Table 3, the vertical temperature differentials obtained with baseboard, valance, and baseboard-valance systems are compared. Only temperature differences measured from the 30-inch air temperature are reported in this table in order to eliminate minor differences which did occur from test to test in the temperature of the air 30 inches above the floor.

Floor surface temperatures and the air temperatures near the floor are particularly significant because in heated rooms the most frequent complaints are of cold feet and ankles. This is especially true when the outdoor temperature is 0°F or less. The warmest floor surface temperatures were obtained with the valance system. Moreover, with the valance system the floor surface temperature increased as the indoor-outdoor temperature difference increased. At an indoor-outdoor temperature difference of 80°F, the floor surface temperature was from 3.6° to 6.1°F warmer than the air 30 inches above the floor. The baseboard system produced the coolest floor surface temperatures, averaging about 4.0° to 6.0°F cooler than the air 30 inches above the floor.

At design conditions, the baseboard-valance system maintained the highest air temperatures 3 inches above the floor with the baseboard system running a close second.

Air temperature variations above the 30 inch level are not as important from the standpoint of comfort as are the temperatures at the lower part of the room. As a general rule, the temperature variations above the 30 inch level and below the 60 inch level are not sufficiently large to cause discomfort from overheating, and while the temperatures near the ceiling may affect comfort through radiation, the effects on ceiling losses and cost of operation are of more interest. On the first and second levels of the house, the air temperatures 3 inches below the ceiling were the coolest when using the baseboard system, and warmest when using the valance system. Except on the third level of the house, the air temperatures 3 inches below the ceiling produced by the baseboard-valance system were approximately halfway between those obtained with the baseboard and with the valance systems. On the third level, however, the temperatures at this height produced by the baseboard-valance system were slightly warmer than those produced by either the baseboard or the valance systems. In the discussion of seasonal fuel consumption it was pointed out that the lowest fuel consumption was obtained with the baseboard and the highest with the valance systems. The relationship between room surface temperatures and fuel consumption was discussed in Chapter V of the valance report.[2]

B. LIVING ROOM STUDIES

Over 50 per cent of the exposed walls of the living room consisted of single glass. There was only one inch of insulation in the walls and two inches in the cathedral ceiling. The room was located over an unheated crawl space. The design heat loss of this room at an indoor-outdoor temperature difference of 80°F was about 55 Btuh per square foot of floor area. Because of the high heat loss rate and the large exposed single glass area, this room presented an unusually difficult heating problem. For this reason special studies were made in the living-dining area with each of the heating systems tested in the I=B=R Hydronic Research House.

Air movement along the outside walls and across the floor obtained with each of the three heating systems is indicated in Figure 10. The isothermal lines represent the temperature of the air 3 inches above the floor. The most uniform air temperatures and the lowest air velocities across the floor were obtained when operating with the baseboard heating system. The air velocities were the highest and the air temperatures lowest when operating with the valance system. The isotherms in Figure 10b clearly indicate the effect of the movement of cool air from the windows across the floor of the living room when no heat was supplied under the glass area.

Mr. Houghten and others[8, 9] have made statistical studies of the relationships between air velocity, air temperature, and comfort. As a result of these studies, the ASHRAE Guide contains a chart expressing the expected incidence of complaints of cool feet and ankles resulting from various combinations of air temperatures and air movement at ankle height.[10] Using this chart, the data in Figure 10 were translated into terms of complaint expectancy as shown in Figure 11.

When operating with the baseboard system, the only area in which the expected complaint level exceeded 10 per cent was the immediate vicinity of the two outside doors. When operating with the valance system, the expected incidence of complaints exceeded 30 per cent for more than half of the room area. In the remainder of the room the expected complaint level was between 20 and 30 per cent. When baseboard was used to supplement the valance system, conditions were much improved. However, as shown in Figure 10c, the absence of baseboard in the dining area when using the baseboard-valance system did permit the movement of a considerable quantity of cool air from the dining room wall and window. Some of this air moved into the living room so that even though baseboard units were located under the living room windows, the air temperatures near the floor in the living room were not as warm, and the air movement was more rapid when operating with the baseboard-valance system than when operating with the baseboard system.

Figures 10 and 11 describe comfort conditions at ankle height in the living-dining area of the Research House as obtained with the three systems considered when operating at an outdoor temperature of approximately 0°F. The figures give no indication of how these systems would operate at other outdoor temperatures. To show the effects of outdoor temperature on the performance of these three systems in the living room, the observed air temperature 3 inches above the floor at the center of the living room has been plotted against indoor-outdoor temperature difference in Figure 12. Air velocities are indicated on each chart.

The dotted lines in Figure 12 represent the combination of air temperature and velocity at which one would expect 10 per cent of the occupants to complain of cool feet and ankles. For the valance system operating at an indoor-outdoor temperature difference of 80°F and maintaining an air temperature of 73°F 30 inches above the floor, the temperature of the air 3 inches above the floor was 5°F below the 10 per cent complaint line. The measured air temperature 3 inches above the floor crossed the 10 per cent complaint line at an indoor-outdoor temperature difference of approximately 35°F. Assuming that the conditions represented by the 10 per cent complaint line signify the lowest acceptable level for satisfactory performance, the above results indicate that at indoor-outdoor temperature differences of 35°F or less the valance system would give satisfactory performance in any house or room having construction and heat loss characteristics comparable to those of the living room of the Research House.

There is nothing to indicate that one must maintain an air temperature of 73°F 30 inches above the floor. In fact it is generally agreed that temperatures of 75° to 77°F are in common use today. Raising the thermostat setting 3°F would increase the temperature of the air 3 inches above the floor approximately 3°F at all indoor-outdoor temperature differences. This temperature increase would have little effect on the rate of air movement across the floor and therefore little or no effect upon the position of the 10 per cent complaint line. Thus by raising the thermostat setting 3°F, the intersection of the 10 per cent complaint line and the air temperature 3 inches above the floor would occur at an indoor-outdoor temperature difference of approximately 60°F. In other words, if the air temperature 30 inches above the floor is maintained at 76°F, the valance system should provide satisfactory performance for outdoor temperatures in excess of about 15°F.

For the baseboard system, the line representing the temperature of the air 3 inches above the floor is above the 10 per cent complaint line at all indoor-outdoor temperature differences below 80°F. For the baseboard-valance system, the intersection of the curves representing the air temperature 3 inches above the floor and the 10 per cent complaint level occurs at an indoor-outdoor temperature difference of approximately 65°F. At an indoor-outdoor temperature difference of 80°F, the air temperature 3 inches above the floor was about 1°F below the 10 per cent complaint line.

C. COMFORT CONDITIONS - FIRST LEVEL OF RESEARCH HOUSE

Most houses do not have as high a heat loss per square foot of floor area as does the living room of the I=B=R Research House. More insulation is used in the walls and ceiling, and more frequently than not storm sash or double glazing is used on the windows. To determine how the three heating systems might perform when operating in houses that have lower heat loss rates, data obtained on the first level of the Research House may be used. The calculated heat loss of this level was about 43 Btuh per square foot of floor area, which is typical of one-story, slab-on-ground houses with nominal insulation in the walls and ceiling.

The observed air temperatures 3 inches above the floor on the first level of the Research House are shown in Figure 13. The 10 per cent complaint line is also included, and since on this level the air velocity 3 inches above the floor was essentially the same for all three systems, the location of the 10 per cent complaint line is in the same position for all three systems. In each case, the curves of the air temperatures 3 inches above the floor were approximately coincident with or higher than the 10 per cent complaint line. For all practical purposes it may be concluded that all three systems should be equally effective in maintaining comfortable conditions at ankle height when used in houses having heat loss rates and construction characteristics similar to those of the first level of the Research House. ●

VI. SUMMER OPERATION

A. COMFORT

The summer comfort conditions produced by the operation of the valance system in the I=B=R Hydronic Research House were discussed in a previous publication.[2] The general conclusions reached in that publication were that, from a comfort standpoint, the performance of the valance system was excellent. It maintained uniform temperatures throughout the house with very little cyclic variation; no drafts were produced; and the relative humidity was maintained at a satisfactory level. Since, with the baseboard-valance system, the valance units only are in operation during the summer, one would expect the summer operating conditions for this system to be comparable to those obtained earlier with a valance system. The only exception would be the effects that redistribution of the valance units may have had on temperature balance, operating time of the zones, and cost of operation. Indeed, the summer tests on the baseboard-valance system did confirm that there were no significant differences between the comfort conditions produced by the baseboard-valance system and the valance system tested previously. For this reason it is not considered necessary to repeat the discussion of summer comfort. Instead, the reader is referred to the discussion of this subject in Engineering Experiment Station Bulletin No. 466, "Hydronic Heating and Cooling with Valance Units." The effect of the redistribution of the valance units on the operating times and costs is discussed in the following sections.

B. LOAD BALANCE BETWEEN ZONES

In Table 4 the operating times of each of the zones and the chiller are expressed in terms of per cent of total elapsed time between the hours of 1:00 p. m. and 9:00 p. m. This table contains data for both the valance and the baseboard-valance systems. Insofar as summer operation was concerned, the only difference between these two systems was the distribution of the valance units. In the valance system, the amount of valance installed in each room was in proportion to the design heating load of that room. In the case of the baseboard-valance system, the valance units in each room were proportioned to the adjusted summer cooling design loads as described in Section II B. It will be observed that the redistribution of valance units in the baseboard-valance system made a significant increase in the operating time of the first level zone. There was a somewhat smaller increase in the operating time of the second level zone and a decrease in the operating time of the third level zone. All in all, the operating times of the three zones were much more uniform for the baseboard-valance system than for the valance system tested previously, indicating that the redistribution of valance units in the baseboard-valance system did provide better balance between the zones.

In the valance system, the third level zone started continuous operation when the maximum outdoor temperature reached 92°F. In the baseboard-valance system, continuous operation of the third level zone started when the maximum outdoor temperature reached 95°F. At this temperature the first level and second level zones were operating 71 per cent and 87 per cent of the time, respectively. Thus, it appears that the adjustments made in the design cooling loads should have been even greater than those used when designing the baseboard-valance system.

Table 4 indicates that the operating time of the chiller was somewhat less when using the baseboard-valance system than when using the valance system. The reason for this is not fully understood, but perhaps the better balance between the zones resulted in more efficient chiller operation. In any case, the difference in operating time was too small to be of any practical significance.

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VII. COSTS — HEATING AND COOLING SYSTEMS

A. INSTALLATION

An accurate estimate of the installation cost of a heating and air conditioning system is difficult to obtain, since there is no satisfactory way to estimate the amount of labor required. Five references on estimating installation time were reviewed.[11,12,13,14,15] These references differed from one another by as much as five to one for unit installation times for iron pipe and fittings. They differed by as much as four to one for copper. Since the estimating procedures contained in the references just cited were intended as a guide in estimating for bidding purposes, all tended to be liberal in time allowances. For this reason the lowest unit installation time for each item quoted by any of the references has been used in making estimates of probable installation times for the systems included in this study.

The prices used for the boiler, chiller, fan-coils, insulation, and grilles when making material cost estimates were those suggested in the 1960 issue of Mechanical Estimator's Guide. Trade prices for pipe, tube, and fittings were obtained from wholesalers' price sheets and the price of all other equipment used was obtained from the manufacturer. The basis of labor estimates is shown in Table 5A and Table 5B.

A summary of total installation costs for several hydronic heating-cooling systems is given in Table 6. This table indicates that the probable installed cost of a baseboard-valance system would be about 90 per cent of the probable cost of a combination baseboard-heating, fan-coil cooling system. On the other hand, it appears that the cost of a baseboard-valance system for heating and cooling would be approximately 10 per cent greater than the cost of a valance system designed to both heat and cool. For the additional 10 per cent, improved winter performance characteristics and a better balance of the system for both summer and winter operation are gained.

To provide a rough check on the methods used to estimate installed costs of year around systems, two local contractors were asked to submit estimates on the cost of installing a baseboard heating system and a direct expansion cooling system of conventional design. These estimates were $2,280.00 and $2,470.00, which, while somewhat less than the estimated cost of the combined baseboard and fan-coil system shown in Table 6, are sufficiently close to indicate that the methods of estimation used were reasonable. As stated earlier, the unit labor times suggested by the references cited appeared to be high, especially for the installation of the boiler and chiller. Also, the cost of a chiller is somewhat higher than the cost of a direct expansion air-conditioning unit of comparable size. Both of these factors would tend to make the estimated cost of the baseboard and fan-coil system higher than the estimates submitted by the contractors.

It is interesting to note that, even though the unit installation times used as a basis of estimating labor costs all appeared to be liberal, the total direct labor costs for the installation of a hydronic system represented only about fifteen per cent of the total installation cost. Therefore, if any appreciable reduction in installation cost is to be made, ways of reducing material costs must be considered.

B. OPERATION

The relationship between daily fuel consumption and indoor-outdoor temperature difference is shown in Figure 5. Corresponding plots of the power consumptions of the circulators and the burner have not been made; however, a regression analysis has shown that these may be expressed by the following equations:

$$P_1 = -342.8 + 19.3\,\Delta T \qquad (1)$$

$$P_2 = -113.9 + 9.5\,\Delta T \qquad (2)$$

$$P_3 = -88.9 + 7.2\,\Delta T \qquad (3)$$

$$P_b = 5.8 + 3.5\,\Delta T \qquad (4)$$

in which

P_1 = Power consumption of first level circulator in watt-hours per day.

P_2 = Power consumption of second level circulator in watt-hours per day.

P_3 = Power consumption of third level circulator in watt-hours per day.

P_b = Power consumption of the burner in watt-hours per day.

ΔT = The daily average indoor-outdoor temperature difference.

Table 7 presents the estimated fuel and power consumptions for heating obtained by multiplying the daily fuel consumptions of Figure 5 and the daily power consumptions calculated from equations 1, 2, 3 and 4 by the frequency of occurrence of each outdoor temperature for a typical winter in Urbana, Illinois. The totals of columns 4 and 6 of Table 7 are the estimated seasonal fuel and power consumptions, respectively, which are used as the bases for figuring the estimated seasonal operating costs.

In Table 8 the yearly cost of operating the baseboard-valance system is compared with the yearly operating costs for both valance and baseboard-fan coil systems. The winter heating cost for the baseboard-valance system is obtained from the seasonal totals reported in Table 7. All other costs were obtained from a previous report(2) but were determined by the procedure just described. It was assumed that the cost of cooling with the baseboard-valance system would be identical to the cost of cooling with the valance system since the same chiller, condenser, and pump were used and, for all practical purposes, the operating times of these components were the same for both systems.

On a year around basis, the operating cost of the baseboard-valance system was about 7.7 per cent less than that of the valance system. All of the reduction was obtained during the heating season. Similarly, the annual operating cost of the baseboard-valance system was about 10.1 per cent less than that of the baseboard-fan coil system; however, in this case the reduction resulted from lower cooling costs. In fact, the heating cost with the baseboard-valance system was 7.2 per cent greater than that of the baseboard-fan coil system.

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VIII. SPECIAL TESTS

A. EFFECT OF INTERNAL SHADING ON COOLING LOADS

According to the ordinarily accepted procedures for estimating design cooling loads, inside shading devices are effective in reducing cooling loads. For example, Table 9 contains the results of design cooling load calculations for the I=B=R Research House for the following two conditions:

1. No internal shading devices on any window.
2. Draperies drawn across all windows.

These calculations indicate that the use of draperies should reduce the design cooling load by 20 per cent. A reduction of this magnitude should certainly be sufficient to affect the performance of a cooling system.

To determine the effect of inside shading on cooling loads, two series of tests were run. In one of these, designated as series A-61-62, there was no inside shading on any of the windows in the Research House. In the other series, designated as series B-62, draperies completely covered all glass areas at all times. If internal shading of glass areas has a material effect upon the cooling load, one would expect that for any given daily average outdoor temperature there would be a significant difference in the daily operating times of the compressor and zones for these two series.

In Table 10 the operating times of each zone, the circulating pump, and the chiller are correlated against the daily average outdoor temperature. In the analysis of covariance at the bottom of Table 10, the low values of t indicate that draperies over the windows had no significant effect on any of the regression coefficients or the mean operating times after adjusting to the mean outdoor temperature for all tests. From these data it must be concluded that draperies were ineffective in reducing total daily load and operating cost.

While it has been established that draperies were ineffective in reducing the total daily load, it is conceivable that their use did redistribute the load during the day in such a way as to alter the maximum load without changing the total daily load. To determine whether or not this did happen an hour-by-hour analysis of the operating times of the second and third level zones was made. It was not possible to include the operating times of the first level zone, the chiller, or the circulating pump because these were not continuously recorded. For this study, two comparable days were selected from each series of tests. The results of the study are shown in Figure 14. Present design factors allow for a 20 per cent reduction in the total cooling load of the Research House if draperies are used. However, the tests indicated that while the use of inside shading devices on the glass did seem to shift the position of the operating curves in Figure 14, there was no indication that the use of these shading devices reduced the maximum load occurring during the day. In fact, there is evidence that the maximum load on the third level was even higher in those tests in which draperies were used on all windows than in tests in which no draperies were used. Furthermore, the actual measured cooling loads without draperies were in better agreement with the design load calculations for which inside shading was assumed than for those for which no shading was assumed.

B. WINTER CONTROL METHODS

Two common methods of controlling the burner operation in zoned hydronic systems are (1) operating the burner at any time a thermostat indicates that the zone in which it is located requires heat, and (2) using an outdoor control to operate the burner in such a way as to modulate the boiler water temperature with changes in outdoor temperature. With both systems a high limit control is used to stop operation of the burner at any time the boiler water temperature reaches the highest safe level. To determine the relative merits of these two methods of control, two series of tests were conducted in which only the method of control was changed. In each series of tests a three-zone, baseboard-valance hydronic system was used and, except for the method of control, all general operating conditions and characteristics of the house remained constant. The series of tests in which the burner was controlled by the room thermostats has been designated as series 0361 while the series of tests in which the burner was controlled by an outdoor control is designated as 0761.

Figure 15 shows the daily mean temperature of the water at the boiler outlet for both series 0361 and 0761. In series 0761 (outdoor control) the mean temperature of the water at the boiler outlet was modulated inversely with change in outdoor temperature. The boiler water outlet temperature ranged from a low of about 90°F at an outdoor temperature of 65°F to a high of approximately 205°F at an outdoor temperature of -10°F. Since a mean water temperature of 215°F was used for design purposes, it is evident that this control system maintained the system water at a temperature slightly lower than that selected for design.

In series 0361 there was also an inverse relationship between outdoor temperature and the mean temperature of the water leaving the boiler at outdoor temperatures above approximately 30°F. However, throughout this range the mean temperature of the water in series 0361 was 30°F to 40°F higher than in series 0761. At outdoor temperatures below 30°F, the high limit control began to limit the amount of burner operation, thus preventing further increase in the temperature of the water leaving the boiler. The high limit control was set to turn the burner off when the outlet water temperature reached 225°F, but since the operating differential of this control was about 50°F, the mean temperature of the water leaving the boiler was limited to a maximum of about 200°F.

Figure 15 clearly shows that at all outdoor temperatures above -5°F, the temperature of the water leaving the boiler was higher in series 0361 than in series 0761. In a previous report[16] it was shown that chimney losses increase with increasing boiler water temperature. Therefore, it would be logical to expect that the higher water temperatures maintained in series 0361 would be accompanied by higher fuel consumptions. The daily fuel consumption for each series of tests was correlated against both indoor-outdoor temperature difference and the product of the average wind velocity times the indoor-outdoor temperature difference. The results of these correlations are shown in Table 11. For both cases the correlation coefficients were very high and all regression coefficients were significantly established. By an analysis of covariance, the results of which are shown at the bottom of Table 11, it was found that there was no significant difference between the regression coefficients for series 0361 and 0761. However, the difference in the mean values of fuel consumption was significant and amounted to approximately 68 cubic feet per day with a standard error of approximately 27 cubic feet per day. In other words, the analysis of covariance indicates that in series 0761, in which the room thermostats controlled the operation of the burner, the fuel consumption was from 40 to 95 cubic feet per day higher than that obtained in series 0361. This difference of fuel consumption was fairly uniform over the entire range of indoor-outdoor temperature differences. Thus it may be concluded that the use of an outdoor control to regulate burner operation did reduce fuel consumption 3 to 9 per cent below that obtained by controlling the operation of the burner by action of the room thermostats. ●

IX. SUMMARY OF RESULTS

The results of this study indicated that the baseboard-valance system had the same excellent summer performance characteristics as did the valance system reported in Engineering Experiment Station Bulletin No. 466. The winter performance was much improved as compared to the performance of the valance system, especially in the living room in which more than 50 per cent of the gross exposed wall area consisted of single glass. In the living room, the combination of air temperature and velocity 3 inches above the floor produced by the baseboard-valance system was such that the probability of complaints of cool feet or ankles would be 10 to 25 per cent at 0°F outdoor temperature. Using the valance system and maintaining the same air temperature 30 inches above the floor, the probability of complaints of cool feet or ankles would run between 20 and 50 per cent.

For heating as well as cooling, differences in the operating times of the three zones were much less for the baseboard-valance system than for the valance system tested previously, indicating that redistributing the valance units and supplementing them with baseboard in the lower levels of the house did provide better balance between zones.

It appears that the installation cost of a baseboard-valance system for heating and cooling would be approximately ten per cent greater than the cost of the valance system designed to both heat and cool. For the additional ten per cent, improved winter performance characteristics and a better balance of the system for both summer and winter operation are gained.

On a year around basis, the operating cost of the baseboard-valance system was about eleven per cent less than that of the valance system. All of the reduction was obtained during the winter season.

A special series of tests to investigate the effect of internal shading of glass areas on cooling loads revealed that the use of draperies had no significant effect on either the average daily load or the maximum load occurring during the day.

The use of an outdoor control to regulate burner operation reduced fuel consumption three to nine per cent below that obtained by controlling the operation of the burner by the zone thermostats.

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