UNIVERSITY OF ILLINOIS
BULLETIN

Vol. 46 | June, 1949 | No. 76

ENGINEERING EXPERIMENT STATION
BULLETIN SERIES No. 383

PROGRESS REPORT ON PERFORMANCE OF A ONE-PIPE STEAM SYSTEM IN THE I=B=R RESEARCH HOME

THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS
IN COOPERATION WITH
THE INSTITUTE OF BOILER AND RADIATOR MANUFACTURERS

BY

WARREN S. HARRIS

PRICE: TWENTY-FIVE CENTS
PUBLISHED BY THE UNIVERSITY OF ILLINOIS
URBANA

Published seven times each month by the University of Illinois. Entered as second-class matter December 11, 1912, at the post office at Urbana, Illinois, under the Act of August 24, 1912. Office of Publication, 358 Administration Building, Urbana, Illinois.

THE Engineering Experiment Station was established by act of the Board of Trustees of the University of Illinois on December 8, 1903. It is the purpose of the Station to conduct investigations and make studies of importance to the engineering, manufacturing, railway, mining, and other industrial interests of the State.

The management of the Engineering Experiment Station is vested in an Executive Staff composed of the Director and his Assistant, the Heads of the several Departments in the College of Engineering, and the Professor in charge of Chemical Engineering. This Staff is responsible for establishing general policies governing the work of the Station, including the approval of material for publication. All members of the teaching staff of the College are encouraged to engage in scientific research, either directly or in cooperation with the Research Corps, composed of full-time research assistants, research graduate assistants, and special investigators.

To render the results of its scientific investigations available to the public, the Engineering Experiment Station publishes and distributes a series of bulletins. Occasionally it publishes circulars of timely interest presenting information of importance, compiled from various sources which may not be readily accessible to the clientele of the Station, and reprints of articles appearing in the technical press written by members of the staff and others.

The volume and number at the top of the front cover page are merely arbitrary numbers and refer to the general publications of the University. *Above the title on the cover* is given the number of the Engineering Experiment Station bulletin, circular, or reprint which should be used in referring to these publications.

For copies of publications or for other information address

THE ENGINEERING EXPERIMENT STATION,
UNIVERSITY OF ILLINOIS,
URBANA, ILLINOIS

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION
BULLETIN SERIES No. 383

PROGRESS REPORT ON PERFORMANCE OF A ONE-PIPE STEAM SYSTEM IN THE I=B=R RESEARCH HOME

A REPORT OF AN INVESTIGATION

CONDUCTED BY

THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

IN COOPERATION WITH

THE INSTITUTE OF BOILER AND RADIATOR MANUFACTURERS

BY

WARREN S. HARRIS
Special Research Associate Professor of Mechanical Engineering

PUBLISHED BY THE UNIVERSITY OF ILLINOIS

PRICE: TWENTY-FIVE CENTS

ABSTRACT

This bulletin is a progress report covering the results of tests made on a one-pipe steam system in the I=B=R Research Home during the winter of 1945-46. At the end of one season of testing, the investigation of the operating characteristics of steam systems was discontinued so that another investigation pertaining to the performance of different types of radiation, which had been started before 1945, might be completed. It is expected that at some later date, when it can be worked into the over-all research program sponsored by the Institute of Boiler and Radiator Manufacturers, further work on steam heating systems will be undertaken.

The tests herein reported were undertaken to determine the operating characteristics of a gas-fired, one-pipe steam system using small-tube radiators equipped with nonvacuum venting valves when it is operating under actual use conditions. Other purposes were to observe the effectiveness of the adjustable radiator vents in balancing a system and to observe the effect of opening the valve on a cold radiator upon the water levels in the boiler and in the return mains. The tests also served as an experimental verification of the limiting installation conditions established in I=B=R Installation Guide No. 2.

The room thermostat, located at the 30-in. level in the living room, was of the heat-anticipating type and turned the gas burner on and off according to the heat requirements of the living room. A pressure control and low-water cutoff, located in the boiler, served as safety controls by turning off the burner at any time when the steam pressure exceeded 2.5 p.s.i. gauge or when the water level in the boiler dropped 5 in. below the normal level. The burner was also provided with a safety pilot which would not permit the thermostat to turn on the main burner in the event of pilot failure.

A gas-burning rate of approximately 100 cu ft of gas per hr was maintained during nearly all of the tests. The burner was so adjusted that a CO_2 content of 9 to 10 percent was obtained in the flue gases at the smoke outlet of the boiler.

The doors between rooms were open, and windows remained closed at all times. Observations of the room air temperatures in each room were recorded four times daily. The temperature of the air in the basement and the attic, and the relative humidity in the heated portion of the house, were also observed at these times. Complete daily records were made of the operating time and the number of cycles of the gas burner, and the cubic feet of gas consumed. Recording instruments were used to obtain continuous records of the stack temperature and draft, the CO_2, the temperature of the water returning to the boiler, and the temperature of the steam at the boiler nozzle.

The radiator venting rate had no appreciable effect on the floor-to-ceiling air temperature differentials. At an indoor-outdoor temperature difference of 70 deg F, equivalent to an outdoor temperature of about 2 deg F, the floor-to-ceiling temperature difference was approximately 7¾ deg F; at an indoor-outdoor temperature difference of 34 deg F, representative of average winter temperatures in Urbana, Illinois, the floor-to-ceiling temperature difference was about 3½ deg F. It was observed that some improvement in the room temperature balance could be obtained by increasing the radiator venting rates in the cooler rooms.

No appreciable effect on the seasonal fuel consumption resulted from changes in venting rates or increasing the fuel burning rate from 100 cu ft per hr to 135 cu ft per hr.

It was observed that under normal operating conditions about 3.5 min elapsed between the time the thermostat started calling for heat and the time the first steam was generated in the boiler. Approximately another 5 min elapsed before steam entered the radiators. The length of the average burner on-period was about 18–20 min. At no time during a normal operating cycle did the radiators attain an average temperature of 212 deg F.

The over-all operating efficiency for the steam system in the I=B=R Research Home was about 68.5 percent at an indoor-outdoor temperature difference of 34 deg F.

The observations of water levels in the boiler and in the return mains indicated very erratic conditions. In general, however, there was no appreciable increase in the water level in the returns at any time except for a very short period after the opening of the radiator valve on a cold radiator equipped with a fast venting valve and when the system was under a steam pressure of approximately 2-lb gauge. Under this condition the water surged upward in the returns about 6 in. above the normal level.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

PERFORMANCE OF A ONE-PIPE STEAM SYSTEM IN THE I=B=R RESEARCH HOME

I. Introduction

1. *Preliminary Statement*

This is the sixth bulletin to be published under a cooperative agreement, formally approved January 2, 1940, between The Institute of Boiler and Radiator Manufacturers and the University of Illinois. Under the terms of the agreement, the Institute is represented by a Research Committee consisting of five members whose function it is to propose such problems for investigation as are of the greatest interest to the manufacturers and installers of steam and hot-water heating equipment. Of these problems, the Engineering Experiment Station staff selects for study those which can best be investigated with the facilities and equipment available at the University. The Institute provides funds for defraying a major part of the expense of this research work.

At the time the investigation discussed in this bulletin was undertaken, the following men were serving on the Research Committee:

- S. K. Smith, H. B. Smith Company, Inc., Westfield, Massachusetts (chairman).
- J. P. Magos, Crane Company, Chicago, Illinois.
- L. N. Hunter, National Radiator Company, Johnstown, Pennsylvania.
- J. F. McIntire, United States Radiator Corporation, Detroit, Michigan.
- G. L. Cheasley, Thatcher Furnace Company, Garwood, New Jersey.
- H. F. Randolph, International Heater Company, Utica, New York, ex officio.

This bulletin is a progress report covering the results of tests made on a one-pipe steam system in the I=B=R Research Home during the winter of 1945-46. During the test period the daily average outdoor temperature ranged from a high of 57 deg F to a low of 6 deg F. At the end of one season of testing, the investigation of the operating characteristics of steam systems was discontinued upon the recommendation of the Research Committee in order that another investigation pertaining to the performance of different types of radiation, which had been started before 1945, might be completed. The results here presented are therefore incomplete in some instances.

It is expected that at some later date, when it can be worked into the over-all research programs sponsored by the Institute of Boiler and Radiator Manufacturers, further work on steam heating systems will be undertaken.

2. *Acknowledgments*

This investigation has been carried on as a part of the work of the Engineering Experiment Station of the University of Illinois and as a project of the Department of Mechanical Engineering. The investigation was conducted under the general administrative direction of DEAN M. L. ENGER, Director of the Engineering Experiment Station, and of EMERITUS PROFESSOR A. P. KRATZ, former Acting Head of the Department of Mechanical Engineering. Acknowledgment is hereby made to the various manufacturers who cooperated by furnishing materials and equipment used in the investigation.

3. *Objects of Investigation*

The tests herein reported were undertaken primarily to determine the operating characteristics of a one-pipe steam system equipped with nonvacuum venting valves when operating under actual use conditions. Other objectives were to observe the effectiveness of adjustable radiator vents in balancing a system and to observe the changes in the water levels in the boiler and in the return mains that resulted from opening the supply valve on a cold radiator. The tests also served as an experimental verification of the limiting installation conditions established in I=B=R Installation Guide No. 2.[1]

---

[1] I=B=R Installation Guide No. 2, One Pipe Steam Heating Systems, published by The Institute of Boiler and Radiator Manufacturers, 60 East 42nd Street, New York 17, New York. Price 25 cents.

II. Description of Equipment

4. *Research Home*

The Research Home, described in detail in Engineering Experiment Station Bulletin 349, is a two-story building typical of the small, well-built American home. The construction is brick veneer on wood frame, and all outside walls and the second-story ceiling are insulated with mineral wool bats 3⅝ in. thick. A vapor barrier of glossy-finished, asphalt-impregnated paper between the studs and the plaster base prevents condensation on the sheathing by retarding the passage of water vapor from the rooms into the insulation in the walls. The calculated coefficient of heat transmission, U, for the wall section is 0.074 Btu per sq ft per hr per deg F temperature difference. All windows and the two outside doors are weatherstripped. Two storm doors were used.

Table 1 gives a summary of the calculated heat losses, the room volumes, and the quantity of installed radiation for each room in the house. The heat losses have been calculated by the method recommended by the American Society of Heating and Ventilating Engineers, in which infiltration is based on the amount and size of crackage around windows and doors, and by the method suggested in I=B=R Installation Guide No. 2, in which the infiltration loss is based on a fixed number of air changes dependent on the number of walls containing windows or outside doors. The total calculated heat loss for the house, though not the calculated heat loss for individual rooms, is in close agreement. These values do not include basement heat loss.

5. *Heating System*

A gas-fired, one-pipe, steam heating system was used in the Research Home for all tests made during the 1945-46 heating season. On the basis of the program approved by the Research Committee, the steam system was installed in accordance with the minimum requirements of I=B=R Installation Guide No. 2. The radiation was installed in accordance with calculated heat losses for the various rooms at an indoor-outdoor temperature difference of 80 deg F; it consisted of 19-in., 4-tube small-tube radiators set in open recesses under windows. There was about 4 in. of clearance between the ends of the radiator and the sides of the recess, 2¼ in. between the top of the radiator and the top of the recess, and ¼ in. between the back of the radiator and the wall of the recess. The front of the radiator was approximately flush with the wall of the room. All radiator venting valves and main venting valves were of the nonvacuum type. The venting rates of the radiator venting valves were adjustable. The locations

TABLE 1

DATA ON RESEARCH HOME AND HEATING SYSTEM

Rooms	Dimensions	Heated Space, Cubic Feet	Calculated Heat Loss,* Btu per Hr Without Storm Sash ASHVE Guide†	Calculated Heat Loss,* Btu per Hr Without Storm Sash I=B=R Installation Guide No. 2‡	Installed Radiation¶ 19-in., 4-Tube, Small-Tube Type		
					No. of Radiators	No. of Sections	Sq Ft, E.D.R.
	(First Floor)						
Living Room	24 ft 0 in. x 13 ft 4 in.	2641	5749	7000	2	18	28.8
Dining Room	13 ft 1 in. x 11 ft 3 in.	1183	8742	7800	1	20	32.0
Kitchen	10 ft 5 in. x 11 ft 3 in.	799	3199	3700	1	10	16.0
Lavatory	7 ft 0 in. x 2 ft 8 in.	152	1484	1100	1	4	6.4
Vestibule	7 ft 5 in. x 5 ft 4 in.	284	4848	4100	1	10	16.0
Vestibule Closet	....	54	....	....	..	..	....
Totals (1st Floor)	....	5113	24022	23700	6	62	99.2
	(Second Floor)						
Northeast Bedroom	10 ft 7 in. x 9 ft 9 in.	800	4393	4800	1	12	19.2
Northwest Bedroom	10 ft 6 in. x 13 ft 4 in.	1148	4944	5800	1	16	25.6
Southwest Bedroom	13 ft 0 in. x 11 ft 4 in.	1108	5250	6100	1	16	25.6
Bath	6 ft 6 in. x 7 ft 6 in.	374	2606	2400	1	6	9.6
Stair Landing and Hall	....	505	2155	1900	1	6	9.6
Closets	....	345	....	....	..	..	....
Totals (2nd Floor)	....	4280	19348	21000	5	56	89.6
Totals (1st and 2nd Floors)	....	9393	43370	44700	11	118	188.8

* Outdoor temperature = −10 deg F, indoor temperature = 70 deg F.
† Infiltration loss based on crackage.
‡ Infiltration loss based on air changes.
¶ Based on calculated heat loss using I=B=R Installation Guide No. 2 Method, no storm sash or storm doors.

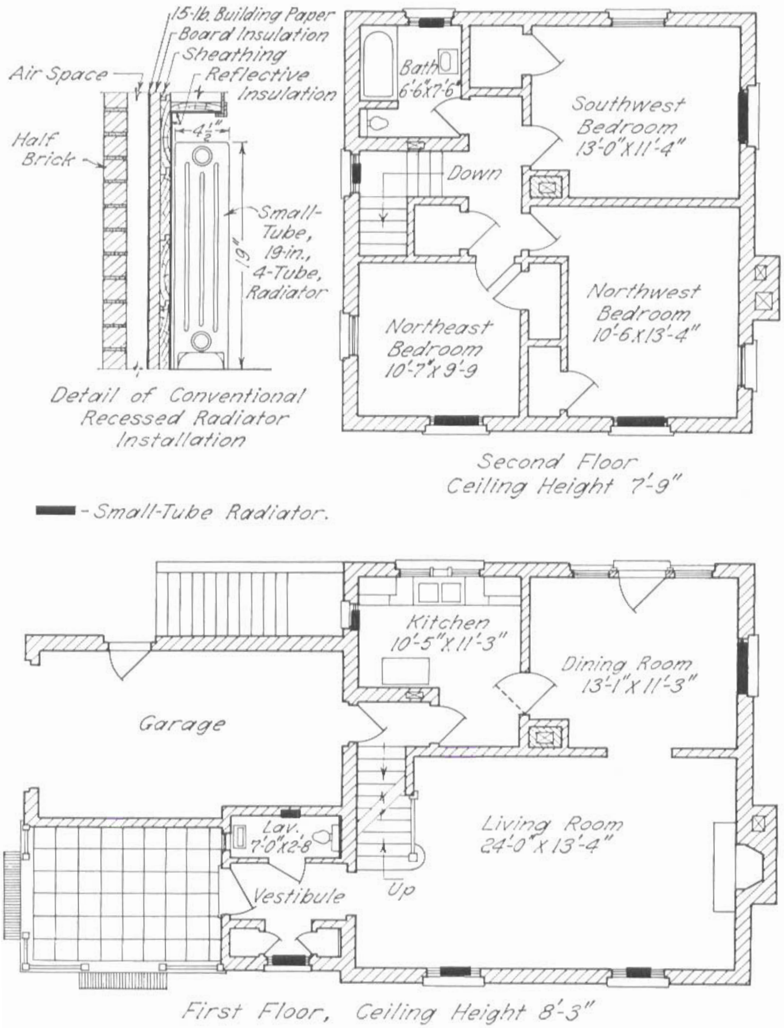


Fig. 1. Floor Plans of I=B=R Research Home, Showing Radiator Locations

of all radiators are indicated on the floor plans of the house (Fig. 1).

A wet-bottom, cast-iron boiler composed of two 6-in. sections and one 4-in. section was used in the tests. The boiler was insulated on top, sides, and back with an air cell insulation approximately 1 in. thick, and was completely enclosed in an enameled sheet-metal jacket. All cracks between sections were sealed with asbestos cement. The net I=B=R rating was 55,000 Btu per hr and the gross I=B=R output

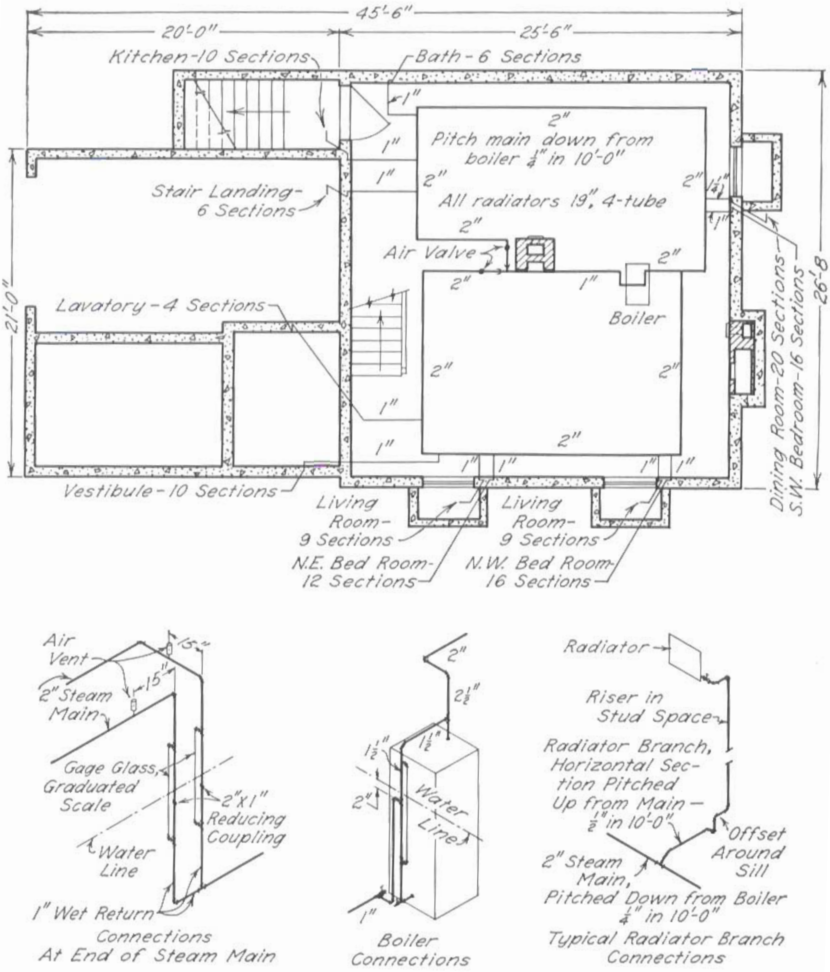


FIG. 2. BASEMENT PLAN, SHOWING PIPING SYSTEM FOR ONE-PIPE STEAM SYSTEM

was 84,000 Btu per hr. The boiler was supplied with a conversion-type gas burner, adjusted to a burning rate of approximately 100 cu ft per hr of natural gas having a heating value of 1000 Btu per cu ft.

The details and arrangement of the piping system are given in Fig. 2 and Table 2. The piping was sized and pitched in accordance with the minimum provisions of I=B=R Installation Guide No. 2.

6. *Control System*

A schematic diagram of the control system used is shown in Fig. 3. The room thermostat, located at the 30-in. level in the living room, was of the heat-anticipating type and turned the gas burner on and off according to the heat requirements of the living room. A pressure control and a low-water cutoff in the boiler served as safety controls by shutting the burner off at any time when the steam pressure exceeded 2.5 p.s.i. gauge or when the water level in the boiler dropped 5 in. below the normal level. The burner was also provided with a safety pilot which would not permit the thermostat to turn on the main burner in the event of pilot failure.

7. *Testing Apparatus*

The instrumentation of the Research Home is described in detail in Engineering Experiment Station Bulletin 349. It suffices here to say that thermocouples were installed for the measurement of the temperature of all important points in the structure and of air temperatures at various levels in the center of each room, in the attic, and in the basement. Provision was made for measuring the temperature of the steam entering each radiator as well as the temperature of the steam leaving the boiler and the temperature of the water returning to the boiler.

Recording thermometers were used to make continuous records of the air temperatures in each of the six rooms at 3 in. below the ceiling and at 3 in. and 30 in. above the floor; of the outdoor air; and of the temperature of the flue gases at the smoke outlet of the boiler and at the levels of the basement and second-story ceilings. Continuous records of the CO_2 in the flue gases were obtained by means of a thermal-conductivity type recorder calibrated against an Orsat apparatus. The moisture content of the air was measured by four humidity indicators and two recording hygrometers, which were checked periodically with an aspirated psychrometer. Drafts were measured either by inclined manometers or by a recording draft gauge, as the occasion demanded. Gauge glasses with scales readable to 0.1 in. were installed on the boiler, on the Hartford loop, and on the return mains, so that the water levels at these points could be observed at all times. A mercury manometer was used to measure the boiler pressure.

TABLE 2
RADIATION, PIPE, AND FITTINGS FOR ONE-PIPE STEAM SYSTEM, 1945-46 HEATING SEASON

Section	Installed Radiation	Pipe Size, in.	Length of Pipe, ft	Elbows		Tees		Reducing Couplings		Valves		Air Vents
	4-tube, 19-in. Small Tube Sections			Size, in.	Number	Size, in.	Number	Size, in.	Number	Size, in.	Number	Number
Basement Main												
North Loop	..	2 ...	47.0	2	4 ..	2 x 2 x 1 2 x 2 x ¾	6 1	2 x 1	1 ..	.. ..	.. ..	1 ..
South Loop	..	2	48.75	2	6	2 x 2 x 1¼ 2 x 2 x 1 2 x 2 x ¾	1 4 1	2 x 1	1	.. .. ..	.. .. ..	1 .. ..
Supply Trunk	..	2½ 2 1½	2.5 4.5 5.0	2½ x 2 2 1½	1 1 1	.... 2 2½ x 2½ x 1½	.. 1 1	....	.. .. ..	.. .. ..	.. .. ..	.. .. ..
Return Trunk	..	2½ 1 ¾	0.6 20.0 1.0	...... 1	.. 3	.... 2½ x ½ x 1 1 1 x 1 x ½ 1 x 1½ x 1	.. 1 1 1 1	....	.. ..	.. ½	.. 2	.. ..
Risers												
Southwest Bedroom	16	1 ...	13.25	1-90° 1-45°	5 1	....	.. ..	....	.. ..	1 ..	1 ..	1 ..
Northwest Bedroom	16	1 ...	13.5	1-90° 1-45°	5 1	....	.. ..	....	.. ..	1 ..	1 ..	1 ..
Northeast Bedroom	12	1 ...	13.5	1-90° 1-45°	5 1	....	.. ..	....	.. ..	1 ..	1 ..	1 ..
Bath	6	1 ...	18.0	1-90° 1-45°	6 1	....	.. ..	....	.. ..	1 ..	1 ..	1 ..
Stairway	6	1 ...	13.5	1-90° 1-45°	5 1	....	.. ..	....	.. ..	1 ..	1 ..	1 ..
Kitchen	10	1 ...	7.0	1-90° 1-45°	5 1	....	.. ..	....	.. ..	1 ..	1 ..	1 ..
Dining Room	20	1¼ ...	4.5	1¼-90° 1¼-45°	5 1	....	.. ..	....	.. ..	1¼ ..	1 ..	1 ..
Living Room, West	9	1 ...	4.5	1-90° 1-45°	5 1	....	.. ..	....	.. ..	1 ..	1 ..	1 ..
Living Room, East	9	1 ...	4.5	1-90° 1-45°	5 1	....	.. ..	....	.. ..	1 ..	1 ..	1 ..
Vestibule	10	1 ...	12.0	1-90° 1-45°	6 1	....	.. ..	....	.. ..	1 ..	1 ..	1 ..
Lavatory	4	1 ...	11.5	1-90° 1-45°	5 1	....	.. ..	....	.. ..	1 ..	1 ..	1 ..

TABLE 2 (CONTINUED)
RADIATION, PIPE, AND FITTINGS FOR ONE-PIPE STEAM SYSTEM, 1945-46 HEATING SEASON

Summary

Pipe	Ft	Lb
2½″	3.1	18.0
2″	100.25	374.0
1½″	5.0	13.6
1¼″	4.5	10.2
1″	131.25	121.0
¾″	1.0	1.1
Totals	245.1	637.9

Tees	No.	Lb
2½ x 2½ x 1½	1	4.9
2½ x ½ x 1	1	3.7
2 x 2 x 2	1	4.5
2 x 2 x 1¼	1	3.3
2 x 2 x 1	10	31.4
2 x 2 x ¾	2	6.0
1½ x 1 x 1	1	2.0
1 x 1 x 1	1	1.3
1 x 1 x ½	1	0.9
Totals	19	58.0

Elbows, 90 deg	No.	Lb
2½ x 2	1	3.5
2	11	33.9
1½	1	1.8
1¼	5	7.4
1	55	50.0
Totals	73	96.6

Elbows, 45 deg	No.	Lb
1¼	1	1.5
1	10	9.1
Totals	11	10.6

Reducing Couplings	No.	Lb
2 x 1	2	2.4

Unions	No.	Lb
2½	1	7.0
1½	1	1.8
1¼	1	1.5
1	12	10.0
Totals	15	20.3

Total Weight, Iron Pipe and Fittings = 825.8 lb

Valves

1¼ radiator valve	1
1 radiator valve	10
½ gate valve	2
Main air vents	2
Radiator air vents	11

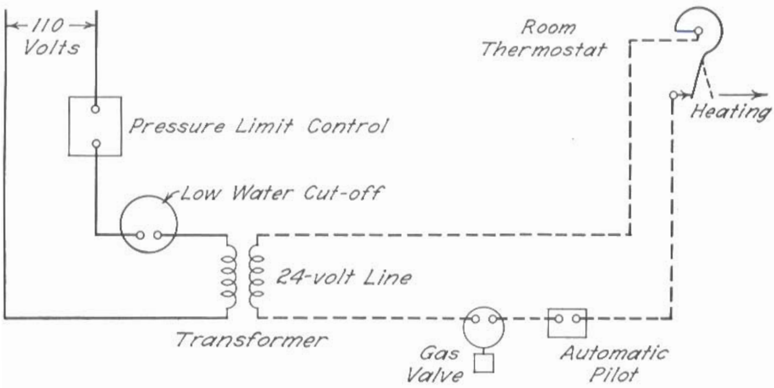


FIG. 3. CONTROL SYSTEM

III. Test Procedure

8. *General Procedures*

During all tests except those in series H-45 a burning rate of approximately 100 cu ft of gas per hr was maintained. The burner was so adjusted that a CO_2 content of 9–10 percent was obtained at the smoke outlet of the boiler. The natural gas used was supplied from the Texas-Oklahoma Pipe Line; it had a high heating value of 1000 Btu per cu ft.

The doors between rooms were open. Windows remained closed at all times. Observations of the room air temperatures, as determined by the thermocouples located 3 in., 30 in., and 60 in. above the floor, and 3 in. below the ceiling, were recorded at 7:00 a.m., 11:00 a.m., 5:00 p.m., and 10:00 p.m. The temperature of the air in the basement and the attic, and the relative humidity in the heated portion of the house, were also observed at these times. Complete daily records were made of the operating time and the number of cycles of the gas burner and of the cubic feet of gas consumed. Recording instruments were used to obtain continuous records of the stack temperature and draft, the CO_2, the temperature of the water returning to the boiler, and the temperature of the steam at the boiler nozzle.

Three principal series of tests were conducted. The operating conditions for each are given in Sections 9, 10, and 11.

9. *Series C-45*

The average room air temperature at the 30-in. level was maintained constant at approximately 72 deg F both day and night. The venting rates of the adjustable radiator venting valves were so adjusted as to give, as nearly as possible, *a uniform heating rate of all radiators.*

When heat was required the gas burner was started, and continued to operate until stopped by the room thermostat. If the period of operation was long enough to raise the pressure in the boiler above 2.5 p.s.i. gauge, the burner was shut off by the pressure-limit switch.

10. *Series D-45*

The operating conditions for series D-45 were the same as for series C-45 except that the venting rates of the adjustable radiator venting valves were so adjusted as to produce *a uniform rate of heating rooms.*

11. *Series H-45*

The operating conditions for series H-45 were the same as for series D-45 except that the gas-burning rate was increased to about 135 cu ft per hr and there was some change in the venting rates of several of the radiators. However, tests made between the running of series D-45 and series H-45 demonstrated that these changes in venting rates, though they caused some overheating of second-story rooms, did not affect the fuel consumption or air temperature differentials.

12. *Special Tests*

During the course of the year various special tests were made to determine the behavior of the water levels in the boiler, in the Hartford loop, and in the return mains, for various conditions of operation. The procedure for these tests is described in the section in which the test results are discussed.

IV. Room Air Temperatures

13. *Effect of Radiator Venting Rate on Indoor Air Temperature Differentials*

For series C-45 the venting rates of the radiator venting valves were so adjusted that approximately the same length of time was required to heat every radiator in the system, starting with the whole system at room temperature. After the valves had been so set a number of 24-hr tests were run over a range of outdoor temperatures.

The broken-line curves in Fig. 4 show the indoor air temperature differentials obtained with the steam system operated under conditions of series C-45, plotted against the indoor-outdoor temperature difference. The solid-line curves show the indoor air temperature differentials obtained during series D-45, in which the venting rates of the radiators in those rooms tending to be a little cool in series C-45 were increased and the venting rates of the radiators in the rooms tending to be a little warm in series C-45 were reduced. In both series the thermostat, at the 30-in. level in the living room, was adjusted to maintain a constant temperature of 72 deg F.

The change in radiator venting rates had no appreciable effect on the floor-to-ceiling air temperature differentials. At an indoor-outdoor temperature difference of 70 deg F, equivalent to an outdoor tempera-

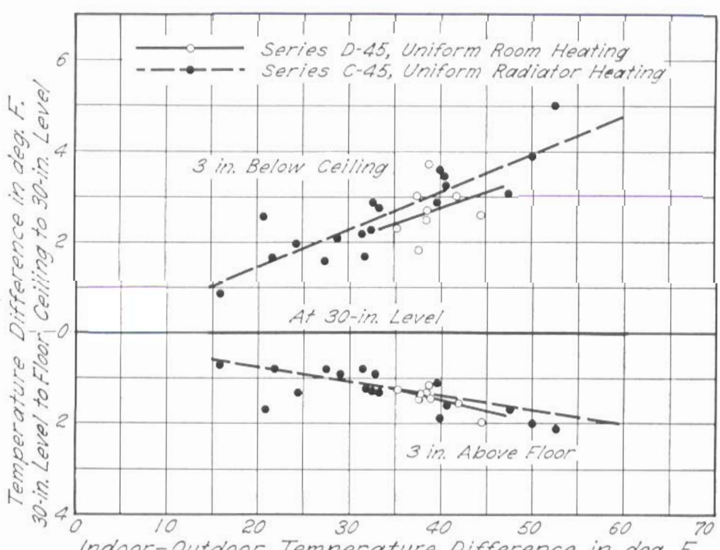


Fig. 4. Room Temperature Differentials, Two Radiator Venting Rates

ture of about 2 deg F, the floor-to-ceiling temperature difference was approximately 8 deg F; at an indoor-outdoor temperature difference of 34 deg F, representative of average winter temperatures in Urbana, the floor-to-ceiling temperature difference was about 3½ deg F. The preceding values were obtained from the curves of Fig. 4. These, obviously, had to be extrapolated in order to determine the floor-to-ceiling temperature difference at an indoor-outdoor temperature difference of 70 deg F, as the largest indoor-outdoor temperature difference during series C-45 was about 50 deg F. Previous investigations have demonstrated that the indoor air temperature differential curves are straight lines over the normal range of outdoor temperatures and that an extrapolation of 20 deg F beyond the range of indoor-outdoor temperature differences encompassed by the test data can be made with safety.

For both series C-45 and series D-45, at an indoor-outdoor temperature difference of 34 deg F the average air temperature at the 30-in. level on the first story averaged 73.3 deg F whereas the corresponding temperature on the second story was 72.8 deg F. Though the air temperature at the 30-in. level of the second story increased about 0.5 deg F for each 10 deg F increase in the indoor-outdoor temperature difference, the indoor-outdoor temperature difference had little effect on the air temperature at the 30-in. level of the first story. Evidently, changes in venting rate of the radiators had no significant effect on the average temperature of the air at the 30-in. level on either floor.

14. *Effect of Radiator Venting Rate on Air Temperature Difference Between Rooms*

The rate of venting of each radiator for series C-45 is roughly indicated in Table 3 by the time required for each radiator to become hot over its entire length. The radiator that heated fastest was the one in the lavatory, heating throughout in 25 min measured from the time the boiler started to steam. The radiator in the kitchen was slowest, taking 29½ min — 4½ min longer than the lavatory radiator.

The total time required to vent the system in series C-45 was undoubtedly more a function of the steaming rate of the boiler than of the combined capacity of all the venting valves. Air cannot be expelled from the system at a faster rate than steam is added. Section 21 points out that with a gas input rate of 100 cu ft per hr, the gas-burning rate used in series C-45, no pressure was built up in the system during a normal operating cycle. Studies made at a gas-burning rate of approximately 135 cu ft per hr indicated that with no change in the

TABLE 3
RATE OF HEATING OF RADIATORS, SERIES C-45

Unit	Time First Steam Enters Radiator, minutes*	Time Radiator Is All Hot, minutes*
Dining Room Radiator	5	29
Living Room, West Radiator	6	26
Living Room, East Radiator	7	26
Southwest Bedroom Radiator	7	28
Northwest Bedroom Radiator	10	28
Northeast Bedroom Radiator	8	29
Kitchen Radiator	13	29½
Vestibule Radiator	11	26
Bath Radiator	15	27
Stair Radiator	16	29
Lavatory Radiator	14	25

* Measured from time boiler started to steam.

Steam reached the venting valves, located 15 in. from drop to wet return, approximately 11 min after boiler started to steam.

venting valve adjustments the venting time of the kitchen radiator was reduced to about 20 min as compared to 29½ min when the gas burning rate was 100 cu ft per hr. Similar reductions in venting time were noted in all other radiators when the gas-burning rate was increased.

In series D-45 the venting rate of the kitchen radiator was further reduced from that of series C-45 by adjustment of the radiator venting valve, since in series C-45 this room showed a tendency to overheat (Table 4). The average air temperatures in Table 4 were obtained by taking an average of all the daily readings for each series without regard for the indoor-outdoor temperature difference.

It will be observed from Table 4 that the difference in temperature between the warmest and the coolest room of the house was approxi-

TABLE 4
AVERAGE AIR TEMPERATURES AT 30-IN. LEVEL

Series	C-45		D-45	
Room	Temperature, deg F	Difference from Liv. Rm. Temp., deg F	Temperature, deg F	Difference from Liv. Rm. Temp., deg F
Living Room	72.7	0	72.7	0
Dining Room	73.7	1.0	73.7	1.0
Kitchen	74.0	1.3	73.3	0.6
Southwest Bedroom	73.6	0.9	73.5	0.8
Northwest Bedroom	72.1	−0.6	72.9	0.2
Northeast Bedroom	72.3	−0.4	73.0	0.3
Max.-Min.	1.9		1.0	

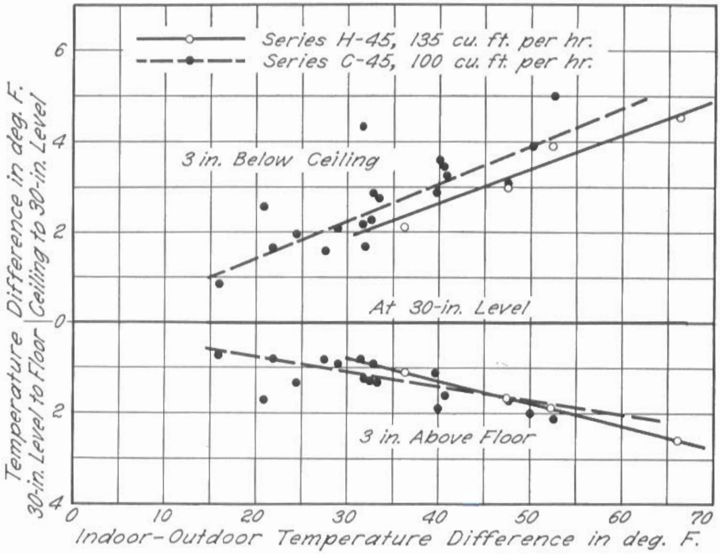


FIG. 5. ROOM TEMPERATURE DIFFERENTIALS, TWO GAS-BURNING RATES

mately 2 deg F for series C-45, in which the venting rates of the radiators were adjusted to give a uniform rate of heating of all radiators. For series D-45, in which the venting rates were adjusted to give as uniform a rate of room heating as possible, there was only 1.0 deg F difference in temperature between the coolest and the warmest room in the house. Though the balance of room temperatures was somewhat better in series D-45 than in series C-45, it was good for both methods of operation of this particular system, in which the radiation was selected in accordance with the calculated heat losses of each room and no allowance was made for exposure.

15. *Effect of Gas-Burning Rate on the Indoor Air Temperature Differentials*

A short series of tests, series H-45, was run in which the gas-burning rate was adjusted to 135 cu ft per hr as compared with a gas-burning rate of 100 cu ft per hr in all other series. The CO_2 content of the flue gases at the smoke collar was unchanged.

It will be observed from Fig. 5 that increasing the gas-burning rate from 100 cu ft per hr to 135 cu ft per hr had no appreciable effect on the indoor air temperature differentials.

16. *Effect of Gas-Burning Rate on Air Temperature Difference Between Rooms*

Too few tests were run at a gas-burning rate of 135 cu ft per hr to permit a conclusive comparison of the air temperature difference between rooms for the two gas-burning rates. Furthermore, when the gas-burning rate was changed, a change was made in the venting rate of two of the radiators. The limited data taken seemed to indicate that, for given settings of the radiator venting valves, the gas-burning rate had little effect on the air temperature difference between the rooms of the house.

17. *Air Temperature Variation Within Rooms*

Heating systems operating on the "off" and "on" principle invariably produce air temperature fluctuations in the rooms being heated. The room air temperatures increase during the on-periods and decrease during the off-periods. The degree of fluctuation depends on the rates of heat loss from the room and heat input during both the on- and the off-periods, and on the sensitivity of the control system. The values in Table 5 represent typical room temperature variations that occurred with the use of the one-pipe steam system operating in accordance with the conditions of series D-45. Only the conditions in the living room and dining room are shown, as these represent the extremes in the amount of temperature variation.

In both rooms the difference between the maximum and minimum air temperatures at the 30-in. level was 0.9 deg F. The maximum variation at the floor was 1.4 deg F in the living room. At the ceiling the maximum variation was 4.5 deg F in the dining room. Air temperature variations near the ceiling of a room are not usually noticed by persons in a room, as this area is above the zone of occupancy. However, a temperature variation of 1.4 deg F near the floor is likely to be objectionable unless the thermostat is so set that the minimum temperature is sufficiently high for comfort. In other words, as air temperature variations near the floor increase it is usually necessary to increase the thermostat setting slightly in order to avoid chilly sensations at the times of minimum floor-level temperatures in the rooms.

TABLE 5
MAXIMUM AND MINIMUM AIR TEMPERATURES, SERIES D-45

Location	Maximum Temperature, deg F	Minimum Temperature, deg F	Difference, deg F
Living Room*			
Ceiling	76.3	74.6	1.7
30-in. Level	73.0	72.1	0.9
Floor	71.6	70.2	1.4
Difference, Ceiling-Floor	4.7	4.4	...
Dining Room*			
Ceiling	77.9	73.4	4.5
30-in. Level	73.5	72.6	0.9
Floor	70.8	70.2	0.6
Difference, Ceiling-Floor	7.1	3.2	...

* Approximate outdoor temperature = 40 deg F.

V. Burner Performance

18. *Effect of Radiator Venting Rate on Burner Performance*

The burner operating time, number of operating cycles, and daily fuel consumption for a range of indoor-outdoor temperature differences are given in Fig. 6 for both series C-45 and series D-45. It is at once evident from Fig. 6 that for any given indoor-outdoor temperature difference the change made in the venting rate of the radiators between series C-45 and series D-45 did not affect in any way the operation of the burner or the daily fuel consumption. During these two series the gas burning rate was approximately 100 cu ft per hr.

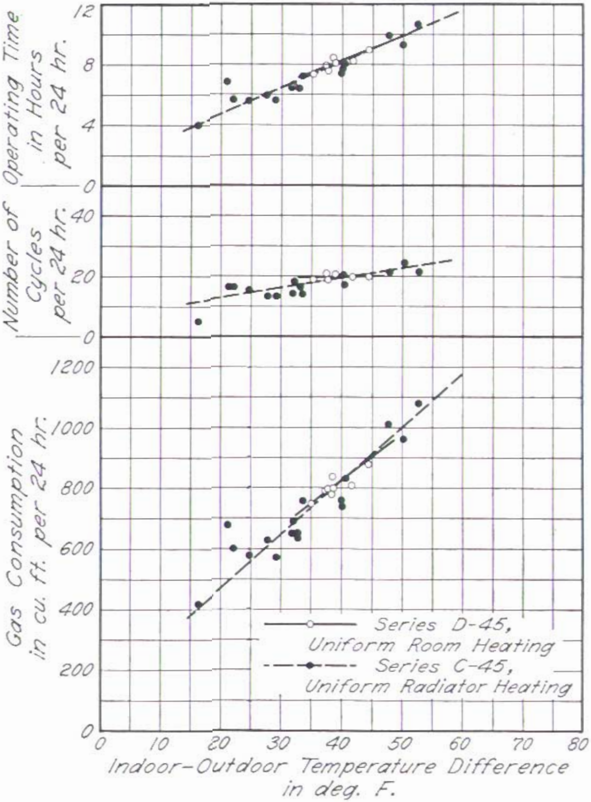
19. *Effect of Gas-Burning Rate on Burner Performance*

When the gas-burning rate was changed from 100 cu ft per hr to 135, a reduction was made in the operating time of the burner, as is shown in the top group of curves in Fig. 7. This change in gas-burning rate had no effect on the number of operating cycles per day up to an indoor-outdoor temperature difference of approximately 53 deg F. At this indoor-outdoor temperature difference in series H-45, with a gas input rate of 135 cu ft per hr the boiler pressure would build up to 5 in. of mercury (the setting of the pressure-limit switch) in a normal on-period. Therefore, as the indoor-outdoor temperature difference increased above 53 deg F the burner was cycled through short on- and off-periods by action of the pressure-limit switch, with a resulting sudden increase in the total number of operating cycles.

The lower group of curves in Fig. 7 indicate that up to an indoor-outdoor temperature difference of 53 deg F the gas-burning rate had little or no effect on daily fuel consumption. As the indoor-outdoor temperature difference increased above 53 deg F it appeared that the daily fuel consumption with the gas-burning rate adjusted to 135 cu ft per hr was slightly less than when adjusted to 100 cu ft per hr. Not enough tests were obtained at the higher gas-burning rate to make this observation conclusive.

20. *Estimated Seasonal Fuel Consumption*

As pointed out in Sections 18 and 19, the daily fuel consumption was not affected greatly by changes in radiator venting rates or by changes in gas-burning rate. Therefore it is only necessary to determine the seasonal fuel consumption for one condition of operating the steam system: this will approximate quite closely the seasonal fuel consumption for the other test conditions. Conditions of series C-45 have been selected as the basis of estimating the seasonal fuel



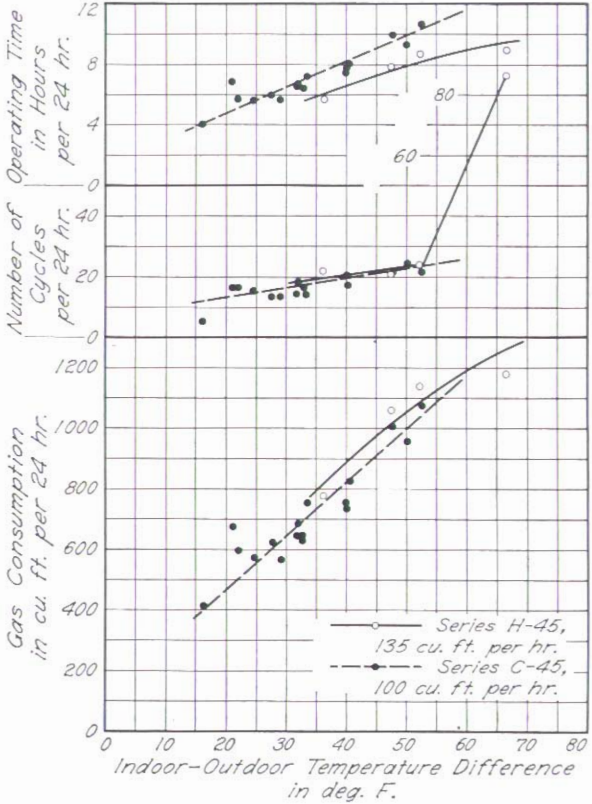


FIG. 6. (AT LEFT). BURNER PERFORMANCE CURVES, TWO RADIATOR VENTING RATES
FIG. 7. BURNER PERFORMANCE CURVES, TWO GAS-BURNING RATES

TABLE 6
FREQUENCY DISTRIBUTION OF AVERAGE DAILY OUTDOOR TEMPERATURES AND CORRESPONDING FUEL CONSUMPTION FOR TYPICAL HEATING SEASON

Average Daily Outdoor Temperature, deg F	No. of Days, Total*	Ave. No. of Days per Heating Season	Gas Required, cu ft†	
			Per Day	Per Heating Season
(1)	(2)	(3)	(4)	(5)
−10 to −5.1	1	0.2	1490	298
− 5 to −0.1	2	0.4	1410	564
0 to 4.9	4	0.8	1330	1,064
5 to 9.9	11	2.2	1240	2,728
10 to 14.9	23	4.6	1160	5,336
15 to 19.9	38	7.6	1070	8,132
20 to 24.9	68	13.6	990	13,464
25 to 29.9	127	25.4	900	22,860
30 to 34.9	169	33.8	820	27,716
35 to 39.9	150	30.0	740	19,200
40 to 44.9	117	23.4	660	15,444
45 to 49.9	113	22.6	570	12,882
50 to 54.9	104	20.8	490	10,192
55 to 59.9	99	19.8	410	8,118
60 to 64.9	110	22.0	320	7,040
65 to 69.9	95	19.0	240	4,560
70 to 74.9	68	13.6	0	0
75 to 79.9	47	9.4	0	0
80 to 84.9	17	3.4	0	0
85 to 89.9	2	0.4	0	0
	1365	273.0		159,598

* Based on records of U. S. Weather Bureau Station at University of Illinois, Urbana, Illinois. Includes months of January, February, March, April, May, September, October, November, and December from September, 1936, through May, 1941.
† Heating value = 1000 Btu per cu ft.

consumption because this series is typical of usual operating conditions with respect to both venting rates and fuel input rates and because more tests were run under the conditions of series C-45 than under other conditions and therefore the fuel consumption curve for this series was the most firmly established.

The frequencies of the daily average outdoor temperatures during the nine months of a typical heating season in Urbana, Illinois, are shown in Table 6. The data for this table were obtained from records of the United States Weather Bureau Station at the University of Illinois, Urbana, Illinois, for the 5-year period September 1, 1936—May 31, 1941. Column 4 gives the daily fuel consumption as obtained from the fuel consumption curve for series C-45 in Fig. 6 at the indoor-outdoor temperature differences represented by the mean outdoor temperature of each bracket in column 1 and an indoor temperature of 72 deg F. The values in column 5 represent the product of the value in columns 3 and 4 for each outdoor temperature bracket. The total for column 5 represents the estimated total cubic feet of gas having a heating value of 1000 Btu per cu ft required to heat the I=B=R Research Home through an average winter with a one-pipe steam system.

Obviously the fuel consumption curve in Fig. 6 had to be extrapolated somewhat in order to obtain the daily fuel consumption for the lower outdoor temperatures listed in column 1 of Table 6, inasmuch as average outdoor temperatures below about 20 deg F were not experienced during the running of series C-45. There is often danger of introducing errors by extrapolating test results beyond the range of actual test conditions. However, it may be noted from column 5 of Table 6 that the total fuel consumption for all days having an average temperature of less than 20 deg F was of the order of magnitude of only 11 percent of the total seasonal fuel consumption. Hence, even large errors in the daily fuel consumption over the extrapolated part of the fuel consumption curve of Fig. 6 would not greatly change the estimated total seasonal fuel consumption.

VI. Boiler and Radiator Temperatures

21. *Boiler Temperature, Normal Operation*

Figures 8 and 9 show respectively the temperature variations of the water in the boiler for a complete cycle of normal operation at gas-burning rates of approximately 100 and 135 cu ft per hr. Locations in the boiler at which the temperatures were taken are indicated in the diagram under the curves. When the gas-burning rate was 100 cu ft per hr (Fig. 8) the temperature of the water at the top of the boiler at the end of the off-period was still 198 deg F, whereas at the bottom of the boiler it had dropped to approximately 178 deg F. The first steam was generated 2.5 min after the burner started. At no time was steam generated rapidly enough to cause more than 1 or 2 oz per sq in. gauge pressure in the boiler, as was indicated by the fact that there was no further increase in the temperature of the water once the boiler began to steam. The boiler stopped steaming within 1 min of the time the burner stopped operating; within 4 min of the end of the burner operating period the temperature of the water returning at the bottom of the boiler decreased rapidly, indicating that steam was no longer being condensed in the radiators. During the off-period of the burner the water in the boiler cooled at the approximate rate of 20 deg F per hr.

The irregular shape of the curve representing the temperature of the water at the bottom of the boiler during the on-period of the burner is the result of the boiling action taking place within the boiler. The violent agitation of the water associated with boiling made the water surge back and forth through the boiler return connection and thus caused the temperature fluctuation noted. This surging flow during burner on-periods was further demonstrated in the fluctuations in water levels occurring at the ends of the main at these times (see Fig. 2). The subject is discussed further in Section 25.

Figure 9 shows the variations in boiler water temperature over a normal operating cycle when the gas-burning rate was approximately 135 cu ft per hr. Under these conditions the temperature of the water in the boiler began to increase within 1 min of the time the burner began to operate, and the first steam was generated approximately 3 min after the start of burner operation. Thirteen minutes after the start of burner operation the temperature (and therefore the boiler pressure) again began to increase, and by 21 min after the start of burner operation the pressure had so increased that the burner was shut off by the pressure-limit switch. By action of the pressure-limit switch the burner remained off for 1.5 min; it then operated for 2.75 min, at which time it was stopped by action of the room thermostat.

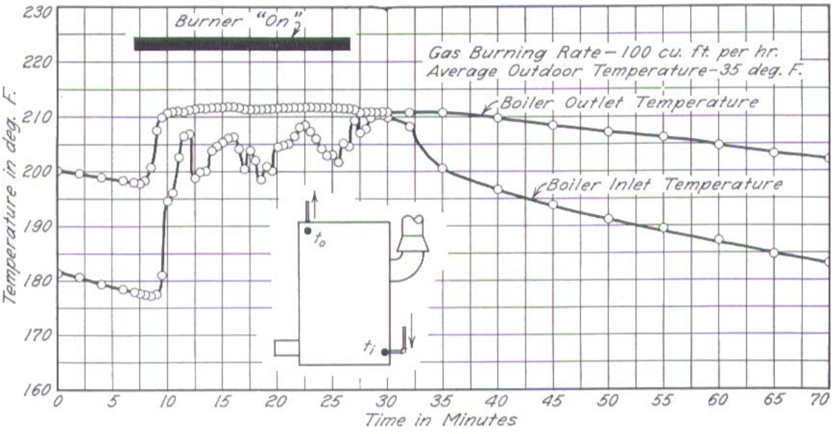


FIG. 8. BOILER WATER TEMPERATURES, NORMAL CYCLE, GAS-BURNING RATE = 100 cfh

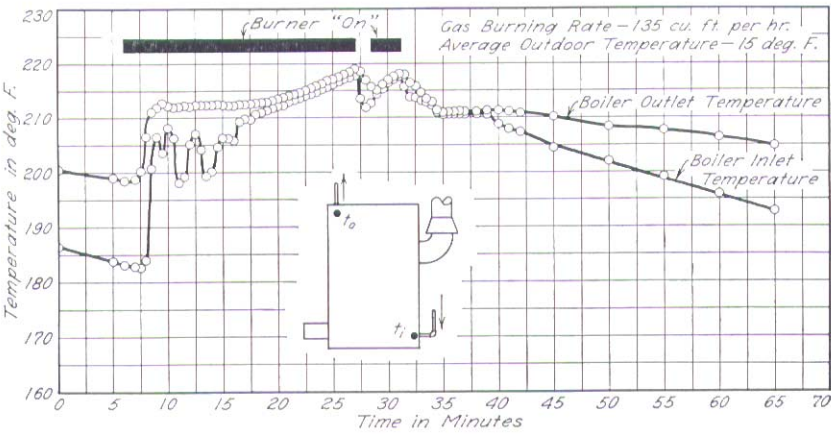


FIG. 9. BOILER WATER TEMPERATURES, NORMAL CYCLE, GAS-BURNING RATE = 135 cfh

At the time the burner was stopped by the room thermostat, the temperature of the boiler water was about 218 deg F, indicating a boiler pressure of approximately 2 p.s.i. gauge. Two and one-half minutes later the temperature had dropped to 211 deg F. Not until 7.7 min after the end of the burner on-period did a drop in the boiler inlet water temperature indicate that the radiators were no longer condensing steam. During the off-periods the water in the boiler cooled at the approximate rate of 20 deg F per hr, the same rate as when the gas-burning rate was 100 cu ft per hr.

The curves of Figs. 8 and 9 illustrate that the venting rate of a system is dependent on the fuel burning rate as well as on the capacity of the venting valves. As long as any appreciable quantity of air remains in the system the temperature of the condensate returning to the boiler will be lower than the saturated steam temperature. As the air is expelled the temperature of the condensate will approach the saturation temperature of the steam. In Fig. 8 it will be observed that with a gas-burning rate of 100 cu ft per hr the return temperature, t_i, was always well below the steam temperature, t_o, throughout the entire on-period of 18.5 min. In other words, with the method of operation and gas-burning rate indicated in Fig. 8, air still remained in the radiators at the end of normal on-periods. In Fig. 9 it will be noted that when the gas-burning rate was increased to about 135 cu ft per hr t_i approached t_o in value after only about 12 min of burner operation. It should also be noted that from the time the first steam was generated t_o (and therefore the steam pressure) was consistently higher in Fig. 9 than in Fig. 8. Because of the higher steam-generating rate the air was expelled more rapidly from the radiators and piping, even though no changes in the adjustments of the venting valves were made. If quick venting is desired, it is necessary to use venting valves with ample capacity and a boiler with a sufficiently high steaming rate to maintain pressure during the time air is being expelled. This will also result in better temperature control in the rooms, because there will be less time for the rooms to continue to cool after the thermostat has called for heat.

22. *Heating and Cooling Rates of Boiler and Radiators*

Figure 10 shows the temperature variations occurring in the boiler and on the surface of one of the living room radiators over a long operating cycle. This radiator is that nearest the boiler on the north supply circuit. The points at which the surface temperatures of the radiator were measured are indicated in Fig. 11. Three minutes after the start of the test the burner was started. Almost immediately the temperature of the water in the boiler began to increase. After 7 min of burner operation steam was being generated in the boiler; 5 min later steam began to enter the radiator. After 44 min of burner operation most of the air had been expelled from the system, the boiler pressure had built up to 5 in. of mercury (about 2.5 p.s.i.), and as this was the setting of the pressure-limit control, the burner was automatically shut off until the boiler pressure dropped to 2 in. of mercury.

The test was continued through 4 cycles of operation controlled by the pressure-limit control. During this part of the test the temperature at the boiler outlet corresponded at all times to the steam saturation

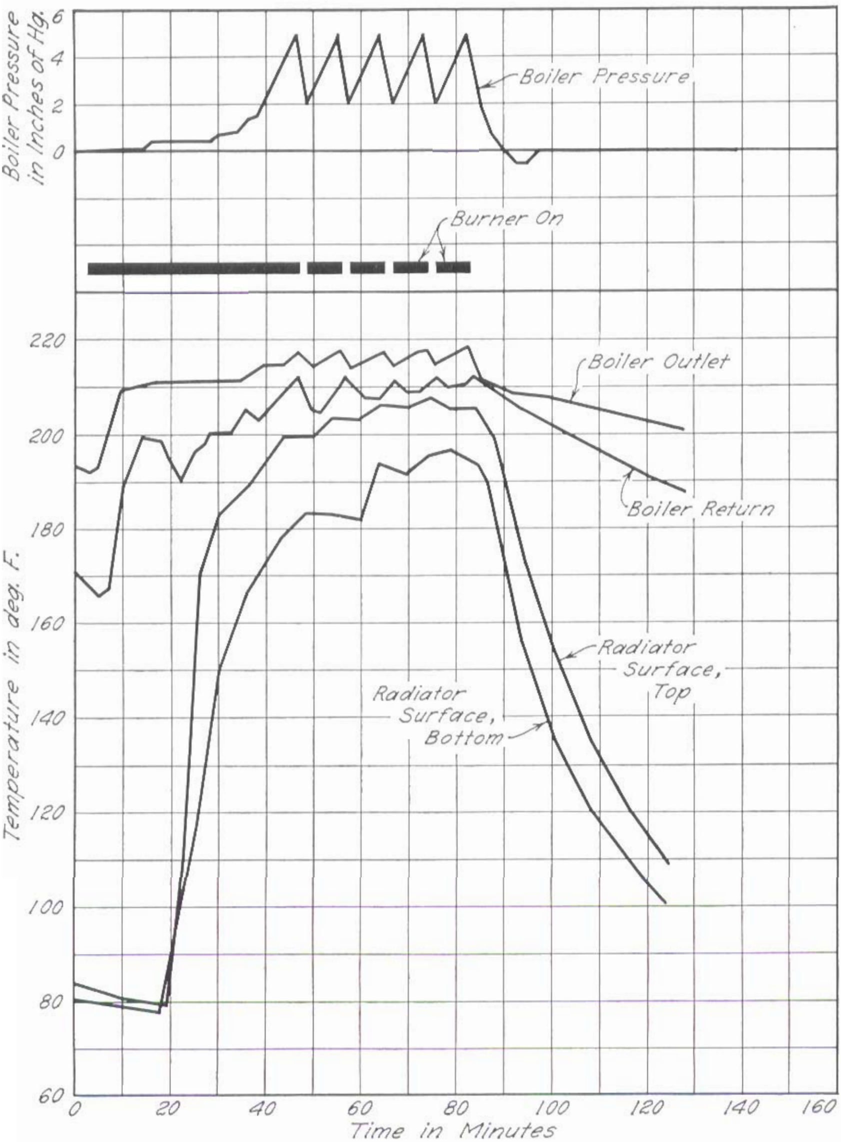


Fig. 10. Boiler and Radiator Temperatures, Long-Run Operation

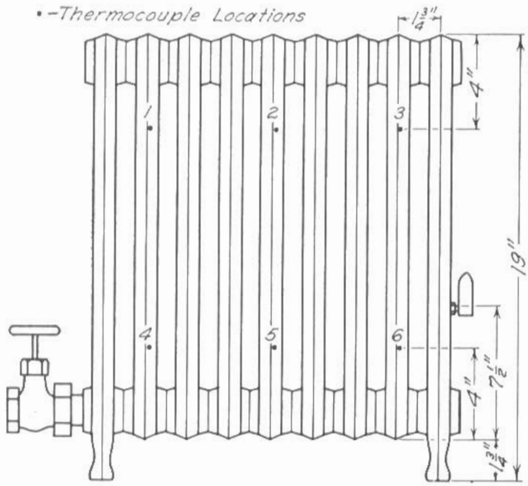


FIG. 11. LIVING ROOM RADIATOR, SHOWING LOCATION OF THERMOCOUPLES

temperature. The temperature of the water at the boiler return was some 10–15 deg F lower than the steam saturation temperature, due to the cooling of the return condensate.

The living room radiator — the radiator nearest the boiler on the north circuit of the main — continued to cool for 15 min after the burner was first started. Then, as steam entered the radiator, the surface temperature of the radiator rapidly increased, so that within about 10 min the average reading of thermocouples 1, 2, and 3 (Fig. 11) indicated that the top part of the radiator had been heated from 80 deg F to 180 deg F and the reading of thermocouples 4, 5, and 6 indicated that the bottom part of the radiator attained a temperature of about 150 deg F. Throughout the rest of the burner operating period there was a more gradual increase in the temperature of the radiator.

On first thought, it would seem impossible that the temperature of the entire radiator could be below the temperature of the condensate returned to the boiler. However, this condition is not an impossibility. In the first place, this study was made on only one radiator; other radiators may have been operating at a higher average temperature. Secondly, and more important, from the time the condensate left the radiator until it entered the wet return main it was in an insulated pipe and in contact with the live steam in the main, which was at the steam saturation temperature (approximately 217 deg F) because the air in the main had been expelled through the main air valves. Therefore, even though the temperature of the condensate leaving this radiator was only about 190–195 deg F, it was heated to about 210 deg F by contact with live steam in the main by the time it entered the wet return. Of course, even though the wet return main was insulated, some cooling took place as the condensate passed through it on its way back to the boiler, resulting in a boiler return temperature 7–10 deg lower than the steam temperature.

Eighty minutes after the start of the test the bottom of the radiator was still 10 deg F cooler than the top, and the average radiator temperature was almost 10 deg F below the steam saturation temperature — facts which indicate that air still remained in the radiator. At the average rate of increase in radiator temperature during the time the burner was being controlled by the pressure-limit control, the radiator temperature should have reached the steam saturation temperature at about 120 min after the start of the test. Since the length of a normal thermostat operating period, even in cold weather, was 30 min or less, it is evident that the air was never completely expelled from the system under conditions of normal operation.

A traverse of the radiator surface temperature made during the period of rapid temperature rise indicated that the entering steam rose to the top of the radiator in the first 2 or 3 sections at the inlet end. It then filled the top of the radiator, and as air was expelled through the radiator venting valve the steam worked its way down at a more or less uniform rate in all sections of the radiator except the section on which the venting valve was located. This section heated at a somewhat faster rate than the others. As a rule, the presence of steam would close the venting valve while the intermediate sections were still relatively cool halfway up from the bottom. When this occurred there was a period after the first closing of the venting valve during which the venting valve intermittently opened and closed as the air trapped in the intermediate sections found its way through the bottom push nipples to the venting valve, where it was expelled. While the action of the venting valve was not being observed at the time the data for Fig. 10 were obtained, it is quite probable that up to the time when the boiler quit steaming, air was being intermittently expelled from the radiator venting valve.

Had it been possible to expel all the air from the radiator before the presence of steam closed the venting valve, the surface temperature of all parts of the radiator would have continued to rise at the high rate of increase observed early in the test until the radiator surface temperature approximated the temperature of the steam leaving the boiler.

Eighty-three minutes after the start of the first burner on-period in Fig. 11, the burner was turned off manually and the system allowed to cool. In 7 min the boiler pressure had dropped to 0 p.s.i. gauge. Then the boiler cooled at the average rate of about 20 deg F per hr. Within 40 min of the time at which the burner was stopped the radiator temperature dropped about 95 deg F, representing an exceedingly high cooling rate of approximately 142 deg F per hr. In the one-pipe steam system operating with intermittent firing and nonvacuum venting valves, most of the residual heat in the radiators to be delivered to the rooms during the off-periods of the burner was that contained in the iron of which the radiators were made. Had the cooling rate of the radiators been slower, the air temperature fluctuations in the rooms would have been less than is reported in the discussion in Section 17.

VII. Heat Utilization: Over-All House Efficiency

When a central heating system is used in connection with an inside chimney, as in the tests on a steam system in the Research Home, the only part of the total heat input to the house that is not actually utilized in offsetting heat losses is the heat lost in the chimney gases at the level of the upper boundary of the heated space. This boundary usually consists of the attic floor. One hundred times the ratio of total input minus the heat in the chimney gases at the level of the attic floor to the total heat input has been defined as the "over-all house efficiency." This efficiency is an index of the effectiveness of heat utilization, and a convenient basis in comparing different heating installations.

Under any condition the actual heat loss from the house is equal to the difference between the total heat input and the heat lost in the chimney gases at the level of the attic floor. The actual heat loss from the house is largely a function of the indoor-outdoor temperature difference and the type of construction; it is independent of the type and method of operation of the heating system. Hence, a single curve showing the relation between the actual heat loss from the house and the indoor-outdoor temperature difference constitutes the characteristic heat loss curve for the house. This characteristic curve (No. 1, Fig. 12) was established for the I=B=R Research Home during the first two seasons the house was in operation. A discussion of its derivation is given in another bulletin.[2] Curve 2, Fig. 12, showing heat input to house from electricity, gas water heater, and occupants was also derived from earlier tests.[3] Though the heat input from these sources undoubtedly changes somewhat from year to year, the total amount is small in comparison to the heat input to the burner, so that even large percentage variations in these heat inputs would not cause variations outside of the normal limits of experimental error in the total amount of heat supplied to the house. In addition, the operation of the house is such that variations in the use of lights and in occupancy from year to year are held to a minimum. Therefore the curve showing the heat input from sources other than the heating system may be applied to the tests on the one-pipe steam system even though it was derived from data taken during earlier tests and on another type of heating system which was then in operation in the Research Home. Curve 3 was derived from the fuel consumption curve for series C-45 (Fig. 6)

[2] "Performance of a Hot-Water Heating System in the I=B=R Research Home at the University of Illinois," Univ. of Ill. Eng. Exp. Sta. Bul. 349, pp. 26-62 and 63-72.
[3] *Ibid.*

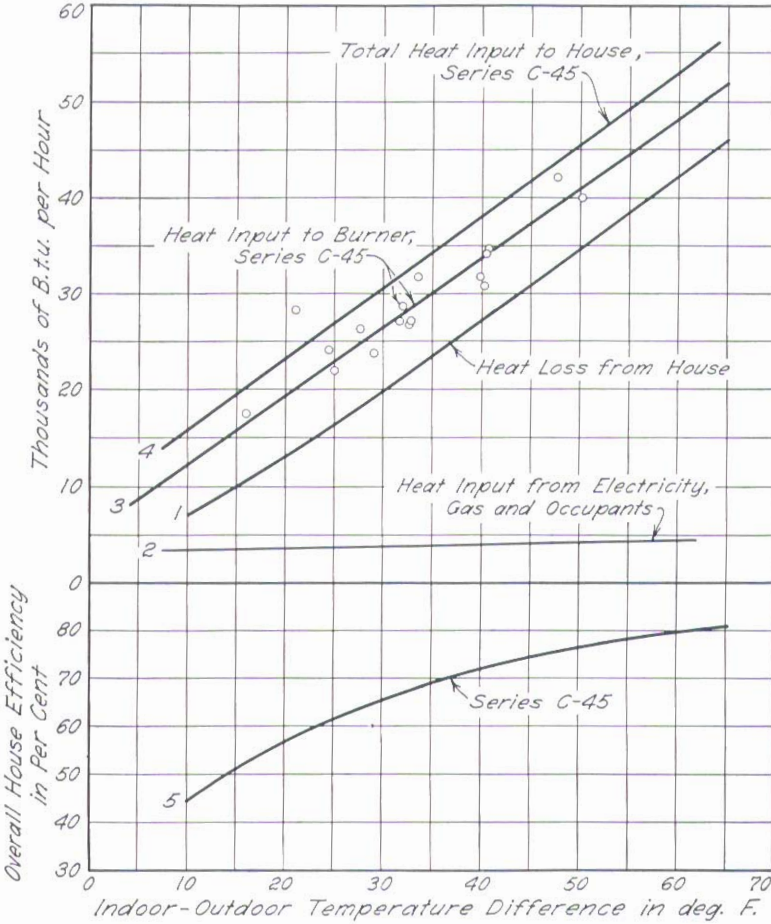


Fig. 12. Heat Utilization and Over-All House Efficiency

and is equivalent to the daily fuel consumption in cubic feet multiplied by the heating value of the fuel in Btu per cu ft. The total heat input to the house was obtained by adding values read from curve **2** at given indoor-outdoor temperature differences to corresponding values read from curve **3**; it is represented by curve **4**.

The over-all house efficiency, or the ratio of the actual heat loss from the house to the total heat input, as calculated from curves **1** and **4**, is shown by curve **5**. This curve indicates that the over-all house efficiency for a one-pipe steam system operating with intermittent firing and using nonvacuum venting valves drops off as the indoor-outdoor temperature difference is reduced. At an indoor-outdoor temperature difference of 34 deg F, representative of average winter conditions in Urbana, Illinois, the over-all house efficiency was 68.5 percent.

The average hourly heat lost in the chimney gases at any given indoor-outdoor temperature difference is represented by the difference in values read on curves 1 and 4, Fig. 12, at the given temperature difference. This loss was almost a constant over the range of indoor-outdoor temperature differences encountered while tests in series C-45 were being made. This checks with previous experience that the chimney loss is a function of average boiler temperature. In series C-45 the average boiler water temperature at an indoor-outdoor temperature difference of 20 deg F was only about 10 deg F less than that obtained at an indoor-outdoor temperature difference of 55 deg F.

VIII. Special Tests

23. *Effect of Adding Cold Radiator to Hot System*

Two special tests were made in order to observe the behavior of the water levels in the boiler and the return mains at the instant the valve on a cold radiator was opened and the rest of the system was under steam pressure. For these tests the valves at the inlet of two 10-section, 19-in., 4-tube, small-tube radiators were closed one evening so that no steam could enter. One of these was the vestibule radiator connected to the north circuit, and the other was the kitchen radiator connected to the south circuit. The next morning the burner was set in operation, and operated until it had cycled several times, by action of the pressure-limit control on the boiler. After this warming-up period the valve on one of the radiators was quickly opened at the instant the boiler pressure reached 4 in. of mercury. At 10-sec intervals observations were made of the water levels in the boiler and the return mains and of the boiler pressure. The test was then repeated, using the second radiator.

Figure 13 is a graphic log of the first of these tests. The venting valve on the radiator was set to its fastest venting rate. At the instant the radiator valve was opened the water in the return mains surged upward about 7 in. Within 30 sec it had dropped to a level even lower than that observed before the valve was opened. At the same time that this surge in the return mains took place, the water level in the boiler dropped about 1 in. and the boiler pressure was reduced by 1.3 in. of mercury. Two minutes after the radiator valve was opened the system was again operating normally.

Figure 14 is a graphic log of the second test. Conditions differed from those of the first test only in that the venting valve was set to its slowest venting rate. Opening the valve on this radiator had no appreciable effect on the general operating conditions other than to retard slightly the rate of increase in boiler pressure.

24. *Water Levels in Boiler and Return Mains*

Figures 13 and 14 show that while the boiler was steaming, the water level in the return as well as in the boiler was generally below the normal water level existing when the entire system was cold. Furthermore, the water level in the return was usually lower than the level in the boiler. At other times during normal operation the water level in the return was some 4 in. above the water level when the system was cold while at the same time the water level in the boiler

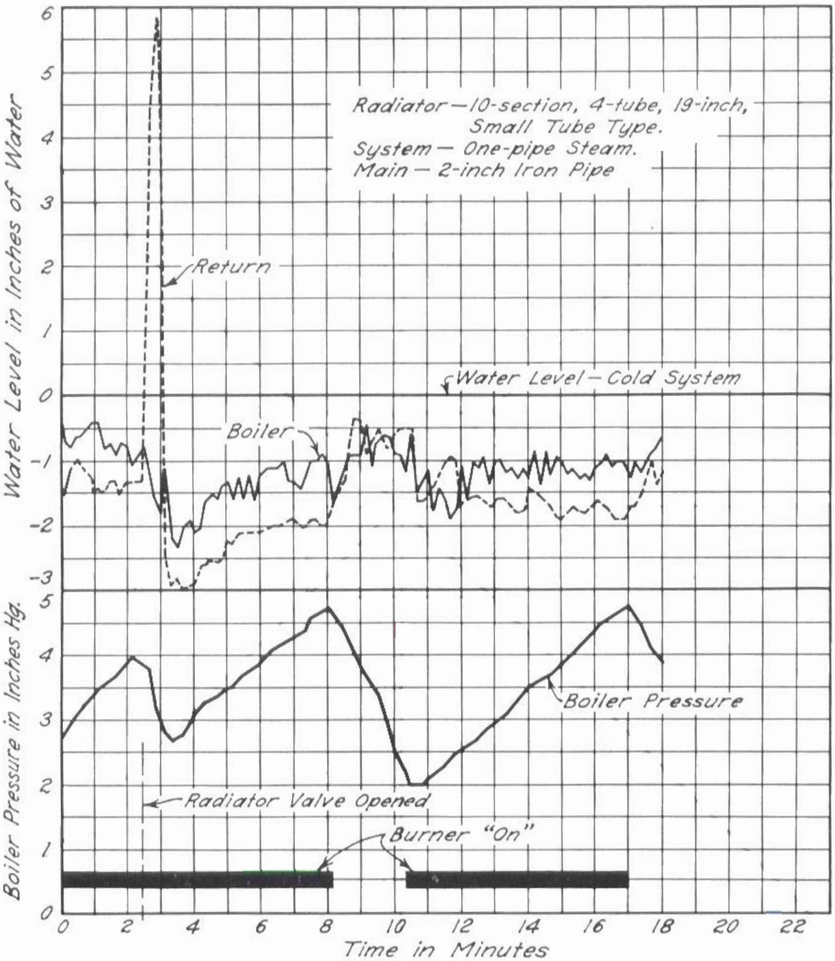


FIG. 13. WATER LEVELS IN BOILER AND RETURNS, COLD RADIATOR TURNED ON, FAST VENTING RATE

was about 1 in. below the cold system water level. Some of the factors influencing the water levels are:

1. Friction pressure loss in piping.
2. Amount of condensate held in the radiators and piping.
3. Temperature of water in return mains and in the boiler.
4. When the boiler is steaming, the water in the boiler is filled with steam bubbles, thus reducing its apparent density.
5. The violent agitation of the water in the boiler may result in a false water level in the boiler gauge glass.

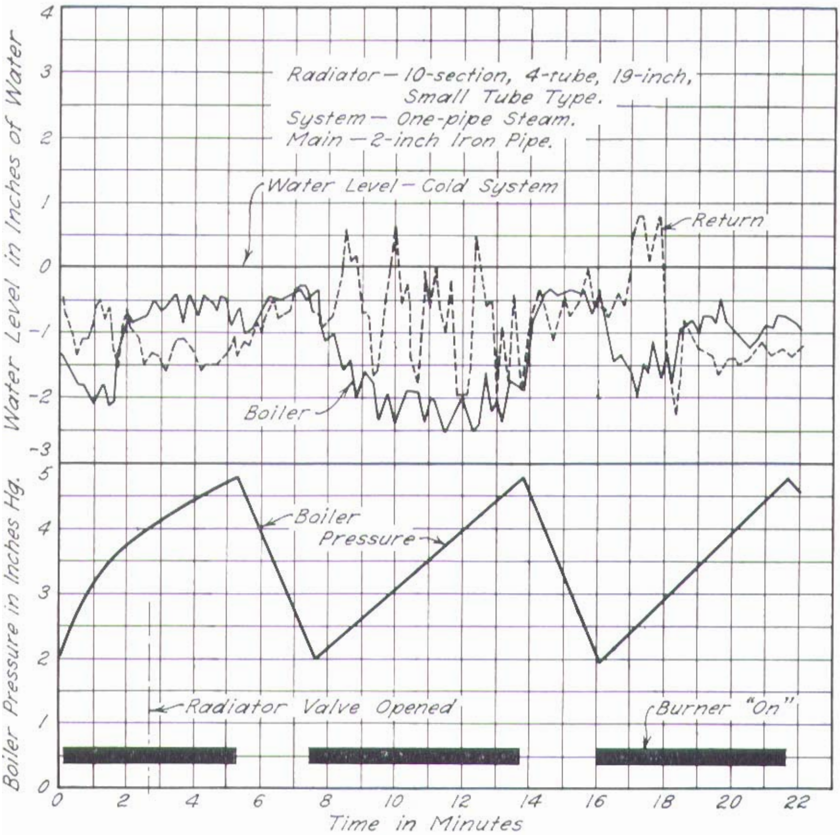


FIG. 14. WATER LEVELS IN BOILER AND RETURNS, COLD RADIATOR TURNED ON, SLOW VENTING RATE

6. Rate of condensation of steam.

It is highly improbable that all these factors remain constant; and since changes in any affect the level of the water in the boiler, in the return, or in both, erratic observations are to be expected. Furthermore, for normal operation of the system used in these tests the pipe friction had a negligible effect on the difference in water levels at the boiler and in the returns. The longest main had an equivalent length of 79.2 ft and the radiation connected to this circuit totaled approximately 23,000 Btu per hr. If, for simplicity, it is assumed that all the steam required to supply the 23,000 Btu per hr flowed through the entire length of the main, the pressure drop in the main may be calculated by using Babcock's empirical formula:

$$P = 0.000{,}000{,}0367\left(1 + \frac{3.6}{D}\right)\frac{W^2L}{dD^5}$$

in which

P = Loss in pressure in p.s.i.
D = Inside diameter of pipe in in.
L = Equivalent length of circuit in ft
d = Weight of 1 cu ft of steam in lb
W = Rate of steam flow in lb per hr.

Substituting actual values,

$$P = 0.000{,}000{,}0367\left(1 + \frac{3.6}{2.067}\right)\frac{\left(\frac{23{,}000}{969.6}\right)^2 \times 79.2}{\frac{1}{26.3} \times (2.067)^5}$$

P = 0.00312 p.s.i., or 0.087 in. of water.

The actual pressure loss during normal operation was even less than the value just calculated, because only a small fraction of the total steam flowed through the entire circuit, the rest being shunted off to different radiators through the radiator branches connected to the main at various points. In other words, any difference in the water levels in the boiler and returns during normal operation was caused by such factors as the difference in the temperature of the water in the boiler and in the returns, the presence of steam bubbles in the boiler water, and the possibility of a false water level in the boiler gauge glass. However, for a very short period of time after opening the valve on the inlet of a radiator equipped with a fast venting valve, steam rushes into the cold radiator and is condensed at a very rapid rate, so that momentarily the pressure loss is considerable and, consequently, the water level in the return surges upward to compensate for this pressure loss. The magnitude of the surge will depend primarily upon the venting rate of the cold radiator.

Figures 13 and 14 clearly illustrate the erratic behavior of the water levels in the boiler and returns during the time the boiler was steaming. Except for a short period immediately after opening the radiator valve, the operating conditions for both tests represented by these figures were identical. Yet for one complete burner on-period in Fig. 14 the water level in the return averaged 1.5 in. higher than the water level in the boiler, whereas during the remaining on-periods shown in Fig. 14 and in both on-periods shown in Fig. 13 the water level in the return averaged about 0.5 in. lower than the water level in the boiler. No explanations of this difference can be made other than the six factors listed in the first paragraph of this section. In all probability factors 4 and 5 contributed the most to the erratic behavior of the water levels.

Bulletins

NO.

358. A Study of Radiant Baseboard Heating in the I=B=R Research Home, by A. P. Kratz and W. S. Harris. 1945. *Twenty cents.*
359. Grain Sizes Produced by Recrystallization and Coalescence in Cold-Rolled Cartridge Brass, by H. L. Walker. 1945. *Free upon request.*
360. Investigation of the Strength of Riveted Joints in Copper Sheets, by W. M. Wilson and A. M. Ozelsel. 1945. *Free upon request.*
361. Residual Stresses in Welded Structures, by W. M. Wilson and Chao-Chien Hao. 1946. *Forty cents.*
362. The Bonding Action of Clays: Part II—Clays in Dry Molding Sands, by R. E. Grim and F. L. Cuthbert. 1946. *Free upon request.*
363. Studies of Slab and Beam Highway Bridges: Part I—Tests of Simple-Span Right I-Beam Bridges, by N. M. Newmark, C. P. Siess, and R. R. Penman. 1946. *Free upon request.*
364. Steam Turbine Blade Deposits, by F. G. Straub. 1946. *Fifteen cents.*
365. Experience in Illinois with Joints in Concrete Pavements, by J. S. Crandell, V. L. Glover, W. C. Huntington, J. D. Lindsay, F. E. Richart, and C. C. Wiley. 1947. *Free upon request.*
366. Performance of an Indirect Storage Type of Hot-Water Heater, by A. P. Kratz and W. S. Harris. 1947. *Free upon request.*
367. Influence Charts for Computation of Vertical Displacements in Elastic Foundations, by N. M. Newmark. 1947. *Twenty cents.*
368. The Effect of Eccentric Loading, Protective Shells, Slenderness Ratios, and Other Variables in Reinforced Concrete Columns, by F. E. Richart, J. O. Draffin, T. A. Olson, and R. H. Heitman. 1947. *Sixty-five cents.*
369. Studies of Highway Skew Slab-Bridges with Curbs: Part I—Results of Analyses, by V. P. Jensen and J. W. Allen. 1947. *Free upon request.*
370. The Illinois Smokeless Furnace, by J. R. Fellows, A. P. Kratz, and S. Konzo. 1947. *Forty cents.*
371. Rate of Propagation of Fatigue Cracks in 12-inch by ¾-inch Steel Plates with Severe Geometrical Stress-Raisers, by W. M. Wilson and J. L. Burke. 1947. *Free upon request.*
372. The Effect of Non-Uniform Distribution of Stress on the Yield Strength of Steel, by D. Morkovin and O. Sidebottom. 1947. *Forty cents.*
373. History of Building Foundations in Chicago, by R. B. Peck. 1948. *Thirty cents.*
374. The Free Surface Around, and Interference Between, Gravity Wells, by H. E. Babbitt and D. H. Caldwell. 1948. *Free upon request.*
375. Studies of Slab and Beam Highway Bridges: Part II—Tests of Simple-Span Skew I-Beam Bridges, by N. M. Newmark, C. P. Siess, and W. M. Peckham. 1948. *Free upon request.*
376. Highspeed Freight Train Resistance: Its Relation to Average Car Weight, by John K. Tuthill. 1948. *Free upon request.*
377. Flexural Fatigue Strength of Steel Beams, by W. M. Wilson. 1948. *Twenty cents.*
378. An Investigation of Creep, Fracture, and Bending of Lead and Lead Alloys for Cable Sheathing—Series 1946, by C. W. Dollins. 1948. *Free upon request.*
379. Non-Pressure Treatments of Round Northern White Cedar Timbers with Creosote, by E. E. King. 1948. *Free upon request.*
380. Fatigue Strength of Fillet-Weld, Plug-Weld, and Slot-Weld Joints Connecting Steel Structural Members, by W. M. Wilson, W. H. Munse, and W. H. Bruckner. 1949. *Free upon request.*

Bulletins (Continued)

NO.

381. An Investigation of the Backwater Profile for Steady Flow in Prismatic Channels, by W. M. Lansford and W. D. Mitchell. 1949. *Free upon request.*
382. The Fatigue Strength of Various Details Used for the Repair of Bridge Members, by W. M. Wilson and W. H. Munse. *In press.*
383. Progress Report on Performance of a One-Pipe Heating System in the I=B=R Research Home, by W. S. Harris. 1949. *Free upon request.*

Circulars

NO.

48. Magnetron Oscillator for Instruction and Research in Microwave Techniques, by J. T. Tykociner and L. R. Bloom. 1944. *Twenty cents.*
49. The Drainage of Airports, by W. W. Horner. 1944. *Twenty-five cents.*
50. Bibliography of Electro-Organic Chemistry, by S. Swann, Jr. 1948. *Free upon request.*
51. Rating Equations for Hand-Fired Warm-Air Furnaces, by A. P. Kratz, S. Konzo, and J. A. Henry. 1945. *Thirty cents.*
52. The Railroad Dynamometer Car of the University of Illinois and the Illinois Central Railroad, by J. K. Tuthill. 1947. *Free upon request.*
53. Papers Presented at the Seventh Short Course in Coal Utilization, held at the University of Illinois, September 17-19, 1946. 1948. *Free upon request.*
54. Papers Presented at the First Short Course on Hot Water and Steam Heating Systems, held at the Undergraduate Division, University of Illinois, Navy Pier, Chicago, September 9-11, 1947. 1948. *Free upon request.*
55. Contributions to Proceedings of the Second International Conference on Soil Mechanics and Foundation Engineering. 1949. *Free upon request.*
56. Papers Presented at the First Annual Short Course on Industrial Packaging and Materials Handling, held in Chicago, October 4-7, 1948. 1949. *One dollar.*

Reprints

NO.

29. Second Progress Report of the Investigation of Shelly Spots in Railroad Rails, by R. E. Cramer. 1944. *Free upon request.*
30. Second Progress Report of the Investigation of Fatigue Failures in Rail Joint Bars, by N. J. Alleman. 1944. *Free upon request.*
31. Principles of Heat Treating Steel, by H. L. Walker. 1944. *None available.*
32. Progress Reports of Investigation of Railroad Rails and Joint Bars, by H. F. Moore, R. E. Cramer, N. J. Alleman, and R. S. Jensen. 1945. *Free upon request.*
33. Progress Report of the Effect of the Ratio of Wheel Diameter to Wheel Load on Extent of Rail Damage, by N. J. Alleman. 1945. *Ten cents.*
34. *Progress Report of the Joint Investigation of Methods of Roadbed Stabilization*, by R. B. Peck. 1946. *Fifteen cents.*
35. Progress Reports of Investigation of Railroad Rails and Joint Bars, by R. E. Cramer, N. J. Alleman, and R. S. Jensen. 1946. *Free upon request.*
36. Electro-Organic Chemical Preparations: Part III, by S. Swann, Jr. 1947. *Fifteen cents.*
37. Progress Reports of Investigation of Railroad Rails and Joint Bars, by R. E. Cramer, N. J. Alleman, and R. S. Jensen. 1947. *Thirty cents.*
38. Second Progress Report of the Investigation of Methods of Roadbed Stabilization, by R. Smith, R. B. Peck, and T. H. Thornburn. 1947. *Fifteen cents.*
39. Progress Reports of Investigation of Railroad Rails and Joint Bars, by R. E. Cramer and R. S. Jensen. 1948. *Fifteen cents.*
40. Third Progress Report of the Investigation of Methods of Roadbed Stabilization, by R. Smith. 1948. *Fifteen cents.*
41. Phase-Sensitive Indicating Devices, by H. C. Roberts. 1948. *Fifteen cents.*

UNIVERSITY OF ILLINOIS

Divisions of Instruction

Institute of Aviation
College of Agriculture
College of Commerce and Business Administration
College of Dentistry
College of Education
College of Engineering
College of Fine and Applied Arts
Graduate College
School of Journalism
Institute of Labor and Industrial Relations
College of Law
College of Liberal Arts and Sciences
Library School
College of Medicine
Department of Military Science and Tactics
Department of Naval Science
College of Pharmacy
School of Physical Education
Division of Social Welfare Administration
Division of Special Services for War Veterans
Summer Session
University Extension Division
College of Veterinary Medicine

University Experiment Stations and Research and Service Organizations at Urbana

Agricultural Experiment Station
Bureau of Community Planning
Bureau of Economic and Business Research
Bureau of Institutional Research
Bureau of Research and Service
Engineering Experiment Station
Extension Service in Agriculture and Home Economics
General Placement Bureau
High School Testing Bureau
Institute of Communications Research
Institute of Government and Public Affairs
Radio Station (WILL)
Services for Crippled Children
Small Homes Council
Student Counseling Bureau
University of Illinois Press

State Scientific Surveys and Other Divisions at Urbana

State Geological Survey
State Natural History Survey
State Water Survey
State Diagnostic Laboratory (for Animal Pathology)
U. S. Regional Soybean Laboratory

For general catalog of the University, special circulars, and other information, address The Director of Admissions and Records, University of Illinois, Urbana, Illinois