COMPUTER ANALYSIS OF THE ENERGY PERFORMANCE OF UNBALANCED SINGLE-PIPE STEAM HEATING SYSTEMS IN OLDER MULTI-FAMILY BUILDINGS

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ABSTRACT

A data base of hourly building loads has been created using the DOE-2.1C program for 16 prototype multi-family buildings in 15 U.S. cities. The prototype buildings reflect typical conditions in multi-family buildings of various vintages in four U.S. regions, and range from 2-story 4-unit brick buildings built with single-pipe steam heat to large 5-story buidings of over 30 units with central forced-air systems.

The purpose of the data base is to provide a consistent basis for assessing the performance and applicability of different equipment and conservation measures to the multi-family building sector. The full data with hourly heating, cooling (sensible and latent), and domestic hot water loads, and the estimated electric consumption, by apartment unit will be released on floppy disks together with an interactive PC program that will allow users to extract monthly totals, binned loads, or hour-of-day profiles depending on their research interests. A supporting summary report will also be available giving monthly and binned totals, and the methodology used in calculating the data base.

As part of the data base effort, the DOE-2.1C computer program was modified to model the typical characteristics of a single-pipe steam heating system. Additions were made to the DOE-2 system simulation to account for (1) the amount of heat available to each zone due to the anticipator, (2) the time needed for steam to reach the radiator after the boiler is turned on, (3) the residual heat capacity of the radiator and piping system, and (4) the location of the thermostat. The simulation methodology is discussed and a sensitivity analysis done to investigate the influence of these factors on the total energy use in older multi-family buildings in the North Central and Northeast cities.

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INTRODUCTION

For the past two years, Lawrence Berkeley Laboratory (LBL), with support from the Gas Research Institute (GRI), has been conducting computer analysis of the space conditioning loads of prototype multi-family buildings in different parts of the United States. According to the 1984 Energy Information Administration's Residential Energy Consumption Survey (EIA, 1984), the multi-family sector includes 22.3 million units with an annual energy consumption of 1.9 Quads, both representing roughly a quarter of the total residential sector.

The EIA survey also indicates that roughly 9 million multi-family units are heated by centralized steam or hot water systems, of which nearly half (3.8 million) units were built before 1940. The great majority of these older units probably have single-pipe steam heating systems, and are located in cities in the Northeast and Midwest regions. Because of the importance of this subsector, it was an important objective in this study to better understand the energy use characteristics of these older multi-family buildings that have single-pipe steam heating systems.

As part of their computer analysis of multi-family buildings, the authors modified the DOE-2.1C computer program to model the typical characteristics of a single-pipe steam heating system, and then simulated its performance under various operating conditions in several prototype buildings representative of pre-1940's apartments located in six cities (Boston, Chicago, Kansas City, Minneapolis, New York, and Washington).

A COMPUTER-GENERATED DATA BASE OF ENERGY USE IN MULTI-FAMILY BUILDINGS

Over the past year (1987-1988), a data base of hourly building loads has been created using the DOE-2.1C program for 16 prototype multi-family buildings in 15 U.S. cities. This research was sponsored by the Gas Research Institute (GRI) and the U.S. Department of Energy (DOE). The major objective of this research is to provide GRI and its contractors with a reference set of multi-family building loads for use in the planning and analysis of gas technology R&D programs. The results will provide a reference set of multi-family energy requirements for use by energy analysts in general.

The 16 prototype multi-family buildings were determined based on the age and size of buildings occurring in the stock within the four Census regions of the country. In each Census region, from three to five prototypical buildings were defined to represent the existing stock as well as new construction (Zwack and Bernstein, 1987). The shell characteristics, space conditioning equipment, and domestic hot water configuration of the prototype buildings were based on analysis of public and private data sources such as EIA's Residential Energy Consumption Survey, and the National Association of Home Builder's survey of builder practices (NAHB 1984). The prototype buildings range from small 4-unit uninsulated brick buildings with single-pipe steam, representing the pre-1940's stock in older Eastern cities, to larger multi-story buildings with wall and ceiling insulation, double-pane windows, and central HVAC systems, representing current construction practices (Table I).

Due to the climatic diversity within each Census region, from three to five cities were selected per region for locating the buildings (Table II). In all, 15 different climates were considered and 60 building/climate combinations modeled. The computer simulations were done using an enhanced version of the DOE-2.1C program. To cover the diversity of loads within each building, multi-zone simulations were done that differentiated between top, middle (if any), and ground units, and between end-units (adjoining units on one side) and mid-units (adjoining units on two sides).

Although most of the effort was spent on simulating the building loads, procedures were also developed for estimating average apartment hourly domestic hot water loads and aggregate electric consumption. Annual domestic hot water loads per apartment were estimated using standard DOE calculation procedures, and apportioned by month and hour using data and hourly water use profiles from several studies (Sauter 1986; Brown et al. 1987; ASHRAE, 1988). Annual aggregate electric consumption per apartment were estimated using previous LBL studies (Huang et al., 1987), and apportioned by using multi-family hourly appliance use profiles from other studies (United Industries, 1985).

The full version of the data base has hour-by-hour heating and cooling (sensible and latent) loads, domestic hot water loads, and electric consumption for each apartment unit. Due to the size of this data, the project has decided to present it on floppy disks, together with an interactive microcomputer program which will allow users to derive monthly totals, binned loads, or hour-of-day profiles from the full data. As supporting documentation, the project also will produce a user's guide for the PC program and a technical report describing the simulation methodology and presenting abridged monthly and binned loads by apartment building, as well as samples of the hourly data. Table III shows typical binned data for the pre-1940's prototype building in Boston.

The entire package is scheduled to be completed by late 1988 and represents a major effort by GRI to provide the research community with a unified and flexible set of prototypical loads by building type. There is a companion effort at Pacific Northwest Laboratories (PNL), also supported by GRI, to develop similar prototypical loads for office buildings. When both data sets are completed, workshops will be conducted in early 1989 to introduce the data to interested parties.

AN OVERVIEW OF SINGLE-PIPE STEAM HEATING SYSTEMS

General discussions of the characteristics of single-pipe steam heating systems can be found in earlier ACEEE papers (Petersen 1982, Katrakis, 1984). These heating systems are generally controlled by a single thermostat, which results in uneven temperature distribution between different rooms due to varying travel times for the steam from the boiler, the substantial amount of residual heat in the radiators and piping system, and improper anticipator settings.

The steam travel time is a function of numerous factors, such as the distance from the boiler to the radiator, the capacity of the main line vent, the size of the radiator vents, and the amount of insulation of the piping. Steam travel time plots by Katrakis showed elapsed times of 10 minutes from the boiler to the main header, and 12-16 minutes to individual radiators (Katrakis, 1986). Petersen estimated that in a typical single-pipe steam system it took up to 25 minutes for steam to reach a radiator, and another 10-20 for the radiator to be completely filled and hot (Petersen, 1984).

The residual heat of the radiator and piping acts to delay the delivery of heat into the space. When the system is warming up, heat is absorbed by the thermal mass of the radiators and piping before it can be delivered to the space. Conversely, when the system is cooling down, the hot radiators and piping continue to supply residual heat until they reach room air temperature. The amount of residual heat stored in a hot single-pipe steam system is quite substantial. Petersen calculated the total weight of a single-pipe steam system in a typical seven unit multi-family building to be 14,000 lbs. Assuming that the radiators and piping are at 212 F when hot, this translates into a residual heat of 33,000 Btu's per apartment, or 16.8 Btu/ft^2 of floor.

To offset the delayed effects of the residual heat, almost all single-pipe steam systems have anticipators that shut off the boilers before the thermostat temperature is reached, allowing the building to coast up to that temperature from the residual heat. Since anticipator settings are, at best, set by trial-and-error and do not correct for climate changes, they frequently cause improper heating in single-pipe steam systems. If the anticipator is set too late, the residual heat will cause overheating and energy waste. If the anticipator is set too early, the boiler will cycle too frequently and cause uneven heating and large temperature differences between apartments units, as well as energy waste.

A SIMPLIFIED COMPUTER MODEL FOR SINGLE-PIPE STEAM HEATING SYSTEMS USING THE DOE-2.1C PROGRAM

After reviewing the ACEEE reports mentioned above and earlier studies (Gay and Fawcett, 1945; McGuiness and Stern, 1955), a simplified model for typical single-pipe steam heating systems was developed based on the Residential (RESYS) Systems portion of the DOE-2.1C program. This model treats a single-pipe steam heating system as functionally similar to baseboard heaters, but with three new variables for *fill-fraction*, *mass-heat*, and *anticipator-fraction*. There is a single thermostat located in one of the apartment units or common area that controls the boiler. The amounts of heat delivered to the individual apartment units or common area depend on the interactions between the boiler capacity, radiator size, and the three variables.

Fill-fraction is defined as the time required for steam to completely fill the radiators in a thermal zone after the boiler is turned on. This delay is due mostly to the time required by the boiler to generate enough steam to displace the cold air in the piping, and partially to heat absorption by the piping mass. In the model, the input *fill-fraction* for the control zone is the fraction of an hour needed for steam to fill completely the radiator in that zone. For a non-control zone, the input *fill-fraction* is the difference in time when steam fills completely the zone radiator as compared to the one in the control zone. *Fill-fractions* are negative for zones receiving heat earlier, and positive for zones receiving heat later than the control zone.

Anticipator-fraction is defined as the reduction in maximum heat available from the radiators in a zone due to the anticipator setting. By shutting off the boilers, an anticipator prevents the radiators from delivering heat continuously over an hour even though the thermostat may be asking for heat. This variable is defined only for the control zone, but affects the amount of heat delivered to all conditioned zones. In the model, the input *anticipator-fraction* is the maximum fraction of an hour that the boiler can stay on. If there is no anticipator, the *anticipator-fraction* is 1.00, indicating that the boilers will operate continuously if required by the thermostat. If the anticipator shuts off the boiler for 10 minutes out of an hour, the *anticipator-fraction* is 0.83 (50/60).

Mass-heat is defined as the maximum residual heat capacity in Btu's of the radiators and supply piping within each thermal zone. The variable is used to calculate the amount of residual heat that is stored or released to the zone each hour. In the model, the input *mass-heat* is the total heat capacity of the radiators and piping within a zone at a temperature difference of 140 F, i.e., assuming that the temperature of the radiators and piping changes from room temperature to 212 F. Depending on the amount and change in boiler on-time, the residual heat captured in the radiators and piping will be either released during the same hour, or stored and released during subsequent hours.

The amount of residual heat released in the same hour is assumed to be a linear function of the boiler Part-Load-Ratio (PLR), ranging from the total *mass-heat* when the PLR is small down to 0 as the PLR approaches 1 :

$$\begin{aligned} Q_{mass0}\ (\text{in Btus}) &= \textit{Mass-heat} \cdot (1 - \text{PLR}) \qquad (\text{if PLR} > 0) \\ &= 0 \qquad\qquad (\text{if PLR} = 0) \end{aligned} \tag{1}$$

where Q_{mass0} = Residual heat released this hour
PLR = Boiler Part-Load-Ratio during hour

The PLR indicates the amount of time the boiler is on during the hour. If the PLR is zero, the system is cold the entire hour and there is no residual heat. If the PLR is small but nonzero, the radiators and piping are hot for a short period during the hour, but then release most of their residual heat during the same hour. As the PLR approaches one, the radiators and piping are hot continuously, and the residual heat is not released, but stored until the PLR declines in following hours.

The amount of residual heat that is stored or released from previous hours is calculated as a linear function of the change in boiler Part-Load-Ratio (ΔPLR) form the previous hour:

$$Q_{mass1}\text{ (in Btus)} = \textit{Mass–heat} \cdot (\Delta PLR) \tag{2}$$

where Q_{mass1} = Residual heat stored or released
ΔPLR = $PLR_{current\ hour} - PLR_{past\ hour}$

This delayed residual heat effect is positive when ΔPLR is negative, indicating heat storage, and negative when ΔPLR is positive, indicating heat release. If the PLR is constant, the amount of heat stored in the radiators and piping during the hour does not change; hence Q_{mass1} is 0. In the extreme case where ΔPLR is 1, i.e., boiler on the entire previous hour and then completely shut off, the entire *mass-heat* of the radiator and piping will be released to the zone.

In the implementation of the single-pipe steam model, two distinct calculations are done each hour. First, the system PLR ,i.e, boiler on-time during the hour, is computed. Once the system PLR is known, the heat delivered to or stored as residual heat to the zones can then be computed.

Step 1. Calculating the System Part-Load-Ratio

To compute the system PLR, it is first necessary to derive the maximum heat available that hour (ERMIN in the DOE-2 terminology). If the ΔPLR from the previous hour is negative or 0, ERMIN is simply the input *radiator capacity*. However, if ΔPLR is positive, indicating more boiler on-time, ERMIN is reduced proportionally by ΔPLR times (1 - *anticipator-fraction* + *fill-fraction*). This relationship is expressed mathematically in Equation 3 :

$$ERMIN = Cap \cdot [1 - (\max(\Delta PLR, 0.0)) \cdot (1.0 - ANTF + FILLF)] \tag{3}$$

where Cap = Radiator capacity
ANTF = input *anticipator-fraction* (always +)
FILLF = input *fill-fraction* (may be + or -)

The PLR is derived by comparing ERMIN to the hourly heating load of the control zone (HENOW in DOE-2 terminology).* If HENOW is less than or equal to ERMIN, the boiler is able to meet the load, and PLR is HENOW/ERMIN. If HENOW exceeds ERMIN, the boiler is unable to meet the load, but will supply heat at its maximum rate (ERMIN). The PLR will be 1.00, but the zone temperature may drop below the thermostat set point.

$$PLR = \text{minimum}((HENOW/ERMIN), 1.00) \tag{4}$$

Since ERMIN is a function of the current PLR, an iterative procedure was used to solve for the ERMIN and PLR each hour.

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* This procedure in DOE-2 requires solving the weighting factor equations for the zone. Readers should refer to the DOE-2 Engineering manual (BES 1980) for technical details on this step if interested.

Step 2. Calculating the Heat Supplied to the Zones

Once the PLR is know, the amount of heat supplied to each zone (QHBZ in DOE-2 terminology) can be computed. For the control zone, QHBZ is the maximum heat available (ERMIN) times the fill-fraction and the system PLR, plus the effects of the residual heat.

$$\mathrm{QHBZ} = (\mathrm{ERMIN^{*}FILLF^{*}PLR}) + Q_{mass0} + Q_{mass1} \tag{5}$$

where ERMIN = Maximum heat available that hour
PLR = Part-load-ratio that hour
Q_{mass0} = Residual heat stored = *Mass–heat* · ΔPLR
Q_{mass1} = Residual heat released = *Mass–heat* · PLR

For the non-control zones, the QHBZ differs from that of the control zone by their difference in *fill-fraction* from that of the control. This difference is used first to calculate a modified PLR for each zone, which is then used in Equation 5 to calculate the amount of heat delivered. The effect of different *fill-fractions* on the heat supplied to each zone is illustrated in Figure 1. If a zone's fill-time is the same as that of the control zone (i.e.,*fill-fraction* = 0), its QHBZ is proportional to the control zone PLR (line B in Figure 1). If a zone's fill-time is faster from that of the control zone (i.e., *fill-fraction* < 0), its QHBZ is positively offset by its *fill-fraction* (line A in Figure 1). Conversely, if the zone fill-time is slower (i.e.,*fill-fraction* > 0), its QHBZ is negatively offset (line C).

The physical interpretation for these offsets is best understood by looking at what happens when the PLR is near zero. The radiators in an apartment with a faster fill-time will have been hot for the time defined by its *fill-fraction* before the control zone receives any heat. Therefore, when the control zone PLR is near 0, the closer apartment already has received heat proportional to its *fill-fraction* times its radiator capacity. The radiators in an apartment with a slower fill-time, however, will remain cold unless the PLR rises above the zone's *fill-fraction.* At which point, the boiler on-times will be longer than that indicated by the *fill-fraction,* and the zone's radiators will begin to warm up. At high PLR's, the differences in QHBZ disappear since the system has ample steam for all apartments.

RESULTS

Simulations were done using the model described to study the energy consumption of single-pipe steam heating systems under various operational conditions in four of the older prototype buildings in the GRI data set (Prototypes 1, 3, 5, and 9 in Table I). The resultant indoor temperatures in different zones of the buildings were also noted.

The thermostat was modeled at a constant 70 F, with window venting assumed if room temperatures exceeded 78 F. The radiator capacity per apartment unit was varied depending on the climate, but assumed constant for all units (Table IV). To develop a better understanding of the impact of individual parameters on the system performance, a sensitivity analysis was done for two cities (Boston and Chicago) where the following parameter were varied: *mass-heat, fill-fraction, anticipator-fraction,* and thermostat location. Because of space limitations, this paper will show results for only the pre-1940's 2-story multi-family prototype in Chicago.

Three variations of *mass-heat* have been considered : 0, ½ lb./ft^2, and 1 lb./ft^2 of system mass in the conditioned zones. The first ignores any residual heat effects from radiators and piping. The last is based on an estimate of 100 lbs. of radiator and 20 lbs. of piping mass within a typical 120 ft^2 apartment room, and corresponds roughly to the amount found by Petersen. The second is selected simply as half way between the other two variations. Results are shown in Tables V and VI for the Chicago prototype. As more residual heat is considered, the system without any anticipator action will progressively overshoot the thermostat. With a *mass-heat* of ½ lb./ft^2, the control zone will overshoot by 1 to 3 degrees; with a *mass-heat* of 1 lb./ft^2, the overshoot will be from 1 to 6 degrees. Compared to a system with no residual heat effects, the average energy penalties are 15% for the ½ lb./ft^2 cases and 25% for the 1 lb./ft^2 cases.

Three variations of *fill-fractions* have been considered : none, fast, and slow. *None* ignores the effects of fill time and assumes that heat from the boiler appears instantaneously within each zone. *Fast* is based on post-retrofit steam travel plots (Katrakis, 1986), and represents the best possible response of a steam system. *Slow* is based on pre-retrofit steam travel plots and other qualitative descriptions (Katrakis, 1986; Petersen, 1984) and reflects a more typical response of a steam system. Table VII gives the assumed fill times (in minutes) for different zones in typical two- and three-story buildings.

Three variations of *anticipator-fractions* have been considered : 1.00, .83, and .67. These correspond to anticipators that shut off the boiler for 0, 10, or 20 minutes out of a full hour. Lastly, two thermostat locations have been investigated, with the control zone located either on the top or the ground floor.

Table VIII and IX show the heating loads and zone temperatures for the Chicago prototype with various combinations of *anticipator-fraction*, *fill-fraction*, and thermostat location, assuming a fixed *mass-heat* of 1 lb./ft^2. For comparison, the tables also give the heating load and temperatures when the same building is modeled with individual forced-air systems in each unit. The sensitivity results show substantial temperature variations between the top and ground floors because of the mismatch between the zone loads, which are larger on the top floor, and the systems output, which are larger for the ground floor because of its proximity to the boiler. * Even though window venting is assumed when temperatures exceed 78 F, the simulations still showed temperature differences ranging from 6 F to 15 F between the top and ground units.

If the comfort criteria is for all units to be maintained at above 70 F, the best control option among those modeled is with a top floor thermostat, an *anticipator-fraction* of :67 (or 20 minutes/hour), and a fast *fill-fraction*. The corresponding annual system load is 284.7MBtu, or still 30% higher than that for individual forced-air systems. The worst control option is with a top floor thermostat, no anticipator, and a slow *fill-fraction*, resulting in a system load 82% greater than that of the forced-air systems.

If the thermostat is placed on a ground floor unit, the total building load will be greatly reduced, but the top units will tend to be underheated. For a system with no anticipator and a fast *fill-fraction*, temperatures in the top unit are tolerable, ranging from 58 to 67 F, and the total system load roughly equal to that of the forced-air system. In the worst case of a .67 *anticipator-fraction* and a slow *fill-fraction*, the temperatures in the top unit drop to between 51 and 57 F, although the system load is now only 75% of the forced-air system.

SUMMARY

A technique has been devised using the DOE-2 program to simulate the energy consumption of and interior conditions maintained by single-pipe steam heating systems in older multi-family buildings. A preliminary analysis has been performed for several prototypical buildings in Northeast and North Central cities. The results correspond generally to the performance of these systems as reported in the literature. The effects of the residual heat in the system has been found to be significant, adding as much as 20% to the system load in the absence of an anticipator. Thermostat location and steam fill times have also been found to have significant effects on both the system energy consumption and the indoor temperatures.

Since the initial analysis was done on prototypical buildings, the critical inputs for radiator capacities, fill time, anticipator, etc., have all been generalized from published sources. The authors hope to validate this model in the future by simulating actual buildings with single-pipe steam systems for which there are measured data on their systems and shell characteristics.

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* It is possible in the model to balance the system better by matching the radiator capacities to the zone loads. Since this is a study of a prototypical building, such adjustments were not done.

In developing this simplified model, the authors are aware of some of its limitations, and the realization that it is not derived from first principles. Most of these simplifications were necessary because of the one-hour time step that is used by the DOE-2.1C program. If these simplifications yield untrustworthy simulation results, a simulation program with a time step below one hour may be needed to analyze single-pipe steam systems.

REFERENCES

American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) 1988. "Proposed ASHRAE.90 residential energy standards, Section 5" (draft).

Brown, M., White, D., and Purucker, S. 1987. "Impact of the Hood River Conservation Project on electric use for residential water heating", Oak Ridge Report CON-238, Oak Ridge TN.

Building Energy Simulation Group (BES) 1982. "DOE-2 engineers manual", Lawrence Berkeley Laboratory Report LBL-11353, Berkeley CA.

Energy Information Administration, 1984. *Residential Energy Consumption Survey* (RECS), U.S. Department of Energy, Washington DC.

Gay, C. M. and Fawcett, C. D. 1945. *Mechanical and electrical equipment for buildings.* New York : Wiley and Sons.

Huang, Y.J., et al. 1987. "Methodology and assumptions for evaluating heating and cooling energy requirements in new single-family residential buildings (technical support document for the PEAR Microcomputer Program)." Lawrence Berkeley Laboratory Report LBL-19128, Berkeley CA.

Katrakis, J. 1986. "Reducing temperature imbalance in single-pipe steam buildings", *Proceedings of the American Council for an Energy-Efficient Economy (ACEEE) 1986 summer study on energy efficiency in buildings*, Vol. 2, pp. 174-187. Santa Cruz CA.

McGuiness, W. and Stern, B. 1955. *Mechanical and electrical equipment for buildings.* New York : Wiley and Sons.

National Association of Home Builders (NAHB) Research Foundation 1984. *Construction Trends in Residential/Commercial Buildings*, Rockville MD.

Petersen, G. 1987. "The art and science of balancing single-pipe steam systems", *Energy Auditor and Retrofitter*, Vol. 4, No. 2, pp. 24-29. Berkeley CA.

Petersen, G. 1984. "Correcting uneven heating in single-pipe steam buildings: the Minneapolis Steam Control System", *Proceedings of the American Council for an Energy-Efficient Economy (ACEEE) 1984 summer study on energy efficiency in buildings*, Vol. C, pp. 154-176. Santa Cruz CA.

Sauter, E. 1986. "Energy consumption in multifamily buildings: end-use profiles in one case study", Conservation and Solar Division, Seattle City Light, Seattle WA.

United Industries Corporation 1986. "Multi-family hourly end use study", for Seattle City Light, Seattle WA.

Zwack, W. and Bernstein, H. 1987. "U.S. multifamily building prototype specifications", Gas Research Institute Topical Report GRI-87/0032, Gas Research Institute, Chicago IL.

Table I. Multi-family prototype buildings.

Census region	Proto-type no.	Year built	Number of units	floors	Flr area per unit	Wall type	Insulation Level ceil	wall	panes	HVAC system
Northeast	1	pre-1940's	4	2	1143	Wood	0	0	2	1-p steam
	2	1950-1959	4	2	1357	Brick	7	0	2	Forced air
	3	pre-1940's	40	4	675	Brick	0	0	1	1-p steam
	4	1980's	40	4	920	Brick	30	13	2	Forced air
North Central	5	pre-1940's	4	2	1130	Brick	0	0	2	1-p steam
	6	1960-1969	4	2	968	Brick	7	7	2	Forced air
	7	1970-1979	18	3	954	Brick	19	11	2	Baseboards
	8	1980's	8	2	1050	Wood	30	13	2	Forced air
South	9	pre-1940's	4	2	863	Wood	0	0	1	Forced air/ 1-P steam*
	10	1960-1969	4	2	893	Brick	0	0	1	Forced air
	11	1960-1969	9	3	947	Brick	0	0	1	Forced air
	12	1970-1979	24	3	1022	Brick	3	0	1	Forced air
	13	1980's	24	3	968	Brick	21	12	2	Forced air
West	14	pre-1940's	4	2	679	Wood	0	0	1	Forced air
	15	1970-1979	24	3	960	Wood	6	3	1	Forced air
	16	1980's	9	3	955	Wood	23	13	2	Forced air

* Single-pipe steam modeled only for Washington DC.

Table II. Base cities for multi-family data base.

Census region	Base cities	Weather tape	Heating degree days (60 F)	(65 F)	Cooling degree days (65 F)	Cooling degree hours/24 (75 F)
Northeast	Boston	WYEC	4396	5627	699	186
	New York	WYEC	3784	4882	1005	256
North Central	Chicago	WYEC	4929	6098	952	313
	Kansas City	WYEC	3799	4799	1605	632
	Minnneapolis	WYEC	6733	8004	727	238
South	Atlanta	WYEC	2050	2965	1543	405
	Fort Worth	WYEC	1571	2329	2495	1044
	Lake Charles	WYEC	927	1504	2631	849
	Miami	WYEC	91	222	3922	1193
	Washington	WYEC	3184	4180	1388	403
West	Denver	WYEC	4621	5879	611	329
	Los Angeles	WYEC	635	1636	428	54
	Phoenix	WYEC	675	1320	3609	2144
	San Francisco	TMY	1682	3172	66	28
	Seattle	WYEC	3583	5136	90	39

Table III. Space conditioning loads in Btu's for prototype pre-1940's 5-story multi-family building (Prototype 3) in Boston MA by 5 degree and 3 time-of-day bins.

Heating Loads for Total Building

	12am-8am	8am-4pm	4pm-12am	No setback Hours	Setback Hours	All Hours
72.5	0	26	0	26	0	26
67.5	11	126	11	149	0	149
62.5	961	1740	309	3011	0	3011
57.5	5223	8737	3941	17883	19	17902
52.5	8404	12572	6342	26988	332	27320
47.5	10552	23221	16033	48121	1685	49807
42.5	26886	62775	44102	124968	8796	133765
37.5	40365	60228	60453	142815	18231	161046
32.5	64568	62769	45370	135503	37205	172708
27.5	34839	39527	44510	99529	19347	118877
22.5	31445	27223	23799	59221	23245	82467
17.5	20202	12338	12285	35450	9375	44826
12.5	13853	10364	3042	17659	9601	27261
7.5	9770	3068	6221	12195	6865	19061
2.5	3836	2457	1653	5850	2098	7948
-2.5	4284	717	879	2806	3075	5881
-7.5	0	0	0	0	0	0
-12.5	0	0	0	0	0	0
-17.5	0	0	0	0	0	0
-22.5	0	0	0	0	0	0
Heat	275207	327895	268958	732182	139879	872061

Total Cooling Loads for Total Building

	12am-8am	8am-4pm	4pm-12am	No setback Hours	Setback Hours	All Hours
117.5	0	0	0	0	0	0
112.5	0	0	0	0	0	0
107.5	0	0	0	0	0	0
102.5	0	0	0	0	0	0
97.5	0	2504	0	2504	0	2504
92.5	0	10413	373	10787	0	10787
87.5	207	19956	7596	27760	0	27760
82.5	1193	27436	15577	44104	102	44207
77.5	3101	13186	18489	32273	2503	34776
72.5	1354	2459	9700	11870	1643	13514
67.5	122	304	1225	1481	169	1651
62.5	0	0	0	0	0	0
57.5	0	0	0	0	0	0
52.5	0	0	0	0	0	0
Cool	5977	76261	52962	130781	4420	135201

Table IV. Radiator heating capacity per apartment unit for prototypical multi-family buildings assumed for DOE-2.1C analysis of single-pipe steam systems

Prototype number	Census region	Floor area per unit (ft^2)	Radiator rating per unit (Btu/hour)
Prototype 1	Northeast	1143	50,000
Prototype 3	Northeast	675	25,000
Prototype 5	North Central	1130	60,000
Prototype 9	South	863	30,000

Table V. Heating loads for single-pipe steam system in typical pre-1940's two-story multi-family building (Prototype 5) in Chicago IL with different mass-heat values.

Control zone	Anticip.– fract.	Fill– fract.	Mass– heat (lbs/ft^2)	Annual heating loads (MBtu)				Peak heating loads (kBtu)			
				Top	Ground	Bsmnt	Bldg	Top	Ground	Bsmnt	Bldg
Top	0	none	0	**59.3**	59.6	14.9	267.6	**34.0**	34.5	8.6	154.1
Top	0	none	½	**68.1**	69.0	17.2	308.5	**34.7**	35.2	8.7	157.1
Top	0	none	1	**74.7**	78.8	19.8	346.6	**35.3**	36.1	9.2	160.2
Top	0	fast	0	**57.4**	76.2	21.5	310.3	**34.0**	36.5	9.4	159.6
Top	0	fast	½	**67.6**	85.3	23.6	353.1	**34.7**	37.1	9.5	162.3
Top	0	fast	1	**74.6**	92.9	25.1	385.2	**35.3**	37.9	9.9	165.2
Top	0	slow	0	**57.3**	82.7	25.1	330.0	**34.0**	37.2	9.8	161.8
Top	0	slow	½	**67.6**	91.2	26.8	371.2	**34.7**	37.8	9.9	164.4
Top	0	slow	1	**74.5**	98.0	27.9	400.7	**35.3**	38.6	10.3	167.3
Ground	0	none	0	46.0	**45.7**	11.5	206.4	25.3	**24.5**	6.3	112.1
Ground	0	none	½	52.5	**51.7**	13.1	234.6	25.8	**25.1**	6.3	114.2
Ground	0	none	1	59.0	**54.0**	14.8	255.7	26.4	**25.6**	6.8	116.4
Ground	0	fast	0	28.6	**48.9**	15.3	185.7	22.7	**25.0**	6.9	109.1
Ground	0	fast	½	34.9	**54.9**	16.7	213.1	23.3	**25.6**	6.9	111.2
Ground	0	fast	1	44.8	**56.8**	17.6	238.4	24.0	**26.1**	7.3	113.4
Ground	0	slow	0	22.0	**49.5**	18.2	179.5	21.5	**25.2**	7.3	107.8
Ground	0	slow	½	27.2	**55.9**	19.4	205.0	22.1	**25.8**	7.3	109.9
Ground	0	slow	1	38.0	**57.7**	19.8	231.0	22.8	**26.2**	7.7	112.1

bold indicates control zone

Table VI. January zone temperatures for single-pipe steam system in typical pre-1940's two-story multi-family building (Prototype 5) in Chicago IL with different mass-heat values.

Control zone	Anticip.– frac.	Fill– frac.	Mass– heat (lbs/ft^2)	Maximum zone temp (F)			Minimum zone temp (F)		
				Top	Ground	Bsmnt	Top	Ground	Bsmnt
Top	0	none	0	**70.2**	79.0	70.0	**70.0**	75.4	64.4
Top	0	none	½	**73.2**	78.0	70.8	**71.7**	77.6	65.8
Top	0	none	1	**75.7**	78.0	71.5	**71.3**	75.7	65.3
Top	0	fast	0	**70.2**	78.0	71.7	**70.0**	78.0	67.3
Top	0	fast	½	**73.3**	78.0	72.3	**71.7**	78.0	68.3
Top	0	fast	1	**75.7**	78.0	72.9	**71.3**	76.0	67.4
Top	0	slow	0	**70.2**	78.0	72.5	**70.0**	78.0	68.6
Top	0	slow	½	**73.3**	78.0	73.0	**71.7**	78.0	69.5
Top	0	slow	1	**75.7**	78.0	73.5	**71.3**	76.1	68.6
Ground	0	none	0	65.9	**70.2**	66.6	57.3	**70.1**	59.8
Ground	0	none	½	68.5	**73.2**	67.7	59.4	**72.2**	61.7
Ground	0	none	1	71.5	**75.6**	68.6	61.6	**71.1**	61.8
Ground	0	fast	0	60.5	**70.2**	67.4	53.1	**70.1**	61.1
Ground	0	fast	½	63.3	**73.2**	68.5	55.4	**72.2**	63.0
Ground	0	fast	1	67.1	**75.6**	69.6	57.7	**71.1**	62.8
Ground	0	slow	0	58.1	**70.2**	68.1	51.2	**70.1**	62.2
Ground	0	slow	½	60.9	**73.1**	69.2	53.5	**72.2**	64.0
Ground	0	slow	1	64.6	**75.6**	70.2	55.9	**71.2**	63.7

bold indicates control zone

Table VII. Steam fill times in typical multi-family buildings assumed for DOE-2.1C analysis
(minutes required for steam to fill radiators after boiler is turned on)

Apartment location	Slow fill		Fast fill	
	fill-frac.	(in minutes)	*fill-frac.*	(in minutes)
Basement	.00	0	.00	0
First Floor	.10	6	.05	3
Second Floor	.22	13	.13	8
Third Floor	.33	20	.22	13

Table VIII. Heating loads for single-pipe steam system in typical pre-1940's two-story building (Prototype 5) in Chicago IL.

Control zone	Anticip.– fract.	Fill– fract.	Annual heating loads (MBtu)				Peak heating loads (kBtu)			
			Top	Ground	Bsmnt	Bldg	Top	Ground	Bsmnt	Bldg
Balanced forced-air			64.6	45.4	0.0	220.0	35.4	23.9	0.0	118.8
Top	0	none	**74.7**	78.8	19.8	346.6	**35.3**	36.1	9.2	160.2
Top	0	fast	**74.6**	92.9	25.1	285.2	**35.3**	37.9	9.9	165.2
Top	0	slow	**74.5**	98.0	27.9	400.7	**35.3**	38.6	10.3	167.3
Top	10	none	**65.7**	66.1	16.5	256.7	**34.6**	34.1	8.6	144.1
Top	10	fast	**65.0**	82.9	23.1	342.0	**34.6**	36.1	9.4	151.6
Top	10	slow	**64.9**	89.2	26.5	361.2	**34.6**	36.8	9.8	161.8
Top	20	none	**54.3**	56.2	14.1	249.2	**33.6**	34.4	8.7	152.4
Top	20	fast	**51.7**	70.7	19.9	284.7	**33.6**	36.3	9.5	157.7
Top	20	slow	**51.4**	76.4	23.2	302.0	**33.6**	37.0	9.9	149.8
Ground	0	none	59.0	**54.0**	14.8	255.7	26.4	**25.6**	6.8	116.4
Ground	0	fast	44.8	**56.8**	17.6	238.4	24.0	**26.1**	7.3	113.4
Ground	0	slow	38.0	**57.7**	19.8	231.0	22.8	**26.2**	7.7	112.1
Ground	10	none	50.7	**50.3**	12.7	227.3	25.1	**24.9**	6.5	111.7
Ground	10	fast	32.6	**53.7**	16.4	205.3	22.6	**25.4**	7.0	108.7
Ground	10	slow	25.6	**54.4**	19.2	198.2	21.4	**25.6**	7.4	107.4
Ground	20	none	43.1	**41.7**	10.8	191.2	24.7	**24.0**	6.4	102.6
Ground	20	fast	27.0	**44.7**	14.4	172.2	22.2	**24.5**	7.0	105.7
Ground	20	slow	20.8	**45.3**	17.1	166.4	21.0	**24.7**	7.4	104.4

bold indicates control zone

Table IX. January zone temperatures for single-pipe steam system in typical pre-1940's two-story building (Prototype 5) in Chicago IL.

Control zone	Anticip.– frac.	Fill– frac.	Maximum zone temp (F) Top	Ground	Bsmnt	Minimum zone temp (F) Top	Ground	Bsmnt
Balanced forced-air			70.2	70.2	61.6	69.9	70.0	53.6
Top	0	none	**75.7**	78.0	71.5	**71.3**	75.7	65.3
Top	0	fast	**75.7**	78.0	72.9	**71.3**	76.0	67.4
Top	0	slow	**75.7**	78.0	73.5	**71.3**	76.1	68.6
Top	10	none	**72.4**	78.0	70.6	**71.3**	77.1	65.4
Top	10	fast	**72.4**	78.0	72.1	**71.3**	78.0	67.9
Top	10	slow	**72.4**	78.0	72.9	**71.3**	78.0	69.2
Top	20	none	**69.0**	78.8	69.8	**68.3**	73.7	63.6
Top	20	fast	**69.0**	78.0	71.4	**68.3**	77.2	66.8
Top	20	slow	**69.0**	78.0	72.2	**68.3**	78.0	68.2
Ground	0	none	71.5	**75.6**	68.8	61.6	**71.1**	61.8
Ground	0	fast	67.1	**75.6**	69.6	57.7	**71.1**	62.8
Ground	0	slow	64.6	**75.6**	70.2	55.9	**71.2**	63.7
Ground	10	none	67.8	**72.4**	67.4	58.8	**71.6**	61.1
Ground	10	fast	62.5	**72.3**	68.2	54.7	**71.6**	62.4
Ground	10	slow	60.1	**72.3**	68.8	52.9	**71.6**	63.4
Ground	20	none	64.5	**68.8**	66.0	56.7	**68.4**	58.7
Ground	20	fast	59.2	**68.9**	66.8	52.5	**68.4**	60.1
Ground	20	slow	57.1	**68.9**	67.5	50.6	**68.4**	61.2

bold indicates control zone

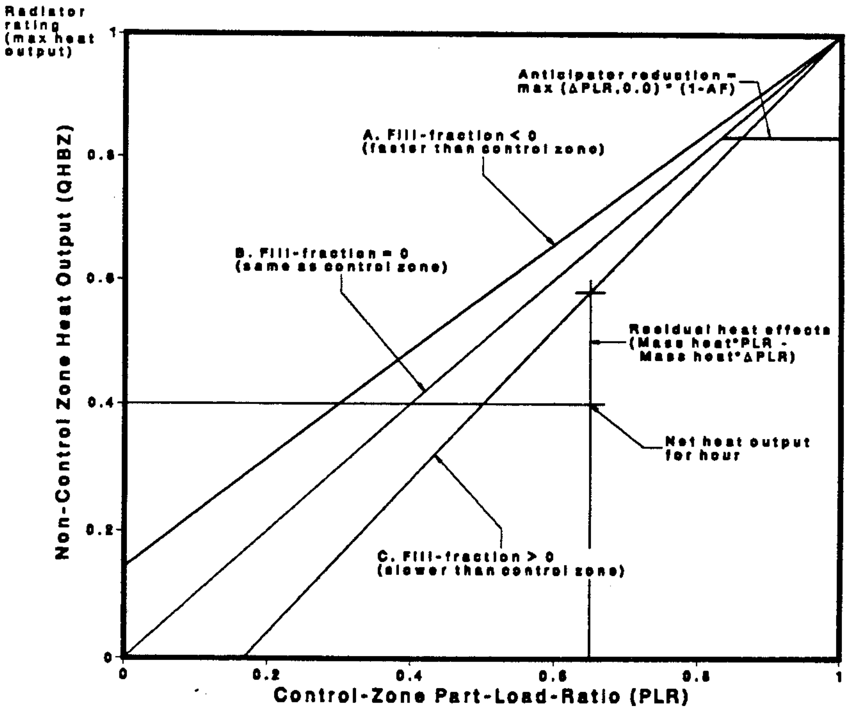

Figure 1. Heat supplied to non-control zones

Heavy line indicates the net heat output into a zone with a slower fill time than the control zone, during a hour when the ΔPLR is positive and the PLR is less than the anticipator-fraction limit