SPACE HEATING IMPROVEMENTS IN STEAM-HEATED MULTIFAMILY BUILDINGS

John T. Katrakis
Center for Neighborhood Technology

ABSTRACT

This paper summarizes the results of ongoing research and testing of low-cost retrofits for single-pipe steam space heating systems in multifamily buildings. Five promising energy efficiency improvements (EEIs) were identified and tested: 1) indoor air thermostat boiler control; 2) main line vent replacements; 3) radiator vent replacements; 4) derating the heating plant; 5) vent damper.

Two of the measures--indoor thermostats and main line vents--were found to have a large impact on the overall performance of the retrofit package. If properly implemented they alone result in 5 to 15% savings with a payback of under two years. Derating was also found to be very cost-effective and widely applicable. Vent dampers and radiator vent treatments were found to be less cost-effective but appropriate in specific situations.

Also, a number of short-term diagnostic techniques and models were developed during the course of this research to enable quick characterization of the effectiveness of the control, distribution and heating plant components in heating systems. Finally, the research has provided the opportunity to develop an extensive and detailed data base on eleven of these buildings.

SPACE HEATING IMPROVEMENTS IN STEAM-HEATED MULTIFAMILY BUILDINGS

John T. Katrakis
Center for Neighborhood Technology

INTRODUCTION

About half of the low-income families in the urban areas of this country live in multifamily buildings. The predominant type of low-income multifamily building in Chicago is a low-rise walk-up structure of masonry construction with a centrally metered single-pipe steam heating system. These buildings require almost 50% more energy for space heating than more modern multifamily and single-family buildings. The measured performance of comprehensive energy conserving retrofits done in 1984-85 by the Chicago Energy Savers Fund (CESF) for single-pipe steam heated multifamily buildings, show an average energy savings of 20% per building, an average retrofit cost of $1300 per living unit, and a simple payback of 8 years (Evens and Katrakis, 1988). After retrofit, these buildings are still less efficiently heated than the typical multifamily building across the nation before retrofit. (Katrakis, 1987)

This situation prompted the Gas Research Institute to sponsor a study of Space Heating Improvements in Multifamily Buildings (SHIM) that was designed and implemented by the Center for Neighborhood Technology (CNT) with the assistance of the Institute of Gas Technology (IGT).

The goal of this study was to identify and disseminate more effective and lower-cost energy conserving retrofits for low- to moderate-income multifamily buildings with single-pipe steam heating systems.

In order to achieve this goal, four objectives were identified and pursued: 1) document the individual performance of promising measures; 2) determine their feasibility; 3) improve the procedures for selecting and specifying them; 4) improve the corresponding implementation and maintainance procedures. (Biederman & Katrakis, 1988)

APPROACH

The five promising retrofits that were identified installed and monitored are: 1)indoor air thermostat; 2) replacement main line vents; 3) radiator vent replacements; 4) heating plant derating; 5) vent damper.

The impact on gas usage was measured for the following interventions: a single-point thermostat and a six-point averaging thermostat; a 50% derate of a forced draft burner to reduce the gas input to the level that corresponds to the installed radiation capacity of the building; replacement main line vents at five buildings; a vent damper.

In Table I, the symbol "N" indicates the buildings where the above measures were tested and their impact on energy uwage was measured through January 1988. Six of the buildings received basic maintenance improvements prior to installing the test retrofits in order to distinguish the effect of good maintenance practice from the effect of the test retrofits. The test retrofits were installed in six of the buildings with the other five serving as control buildings. Where possible, the "flip-flop" testing procedure was applied; otherwise, the "before-after" test procedure was used.

New low cost-methods were developed to perform short-term on-site measurements of boiler part-load efficiency to indirectly document the performance of boiler retrofits such as vent dampers and derating. Also, models and measurement procedures were developed to document the effectiveness of indoor temperature controls and of main line and radiator vent treatments. In Table I, the symbol "P" indicates where these methods were used to project the performance of the installed test measures or of the original components. These methods were also used to project the performance of retrofits that were not actually installed at these buildings. One such measure is a low-cost derating option based on decreasing the firing rate to no more than 20% below the rated capacity of the boiler. It is assumed that this option does not require any capital-intensive modifications to the heating plant.

EXPERIMENTAL AND ANALYTICAL METHODS

The research was designed to measure three categories of variables: dependent, independent, and intermediate. These measurements were used to describe the performance of the retrofit measures by three corresponding methods: Normalized Annual Savings (NAS), Predicted Annual Savings (PRES), and Projected Annual Savings (PROS). The NAS method was the most fundamental form of documenting retrofit performance. It consists of monitoring the impact of the test measures on the dependent variables such as gas usage and indoor minimum temperature during at least one-half heating season. The measured data were weather-corrected using a least-squares linear regression model and the regression paramters were used with binned outdoor temperature data to calculate the NAS. The control buildings proved very helpful in improving the precision of the flip-flop experiments.

The independent variables such as building dimensions, U-values of building envelope components, type of heating plant and temperature controls, etc, were documented during a several hour visit at each building and became inputs to the computerized energy audit developed by CNT. (Evens, et.a., 1986) The audit program was used to calculate the predicted annual savings, PRES, for each of the test retrofits at a particular building.

The intermediate variables serve as the bridge between the independent variables that are used to predict retrofit performance and the dependent variables that are measured at considerable expense and over a full heating season to determine the weather-adjusted, or "normalized", actual performance of the retrofits. These intermediate parameters permit quick performance evaluation of various versions of the test measures. For example, by measuring intermediate variable such as steam travel time, at least five different main line vent combinations can be evaluated in less than one half-season; whereas measuring changes in gas usage would permit evaluating only one vent treatment in that same time period. The intermediate parameters and their corresponding models that were developed to project (PROS) the performance of each of the test measures are summarized below.

Boiler Part-Load Efficiency and Cycling Characteristics

A simple low-cost method of measuring the part-load efficiency of a boiler was developed and used to derive the set of part-load efficiency curves in Figure 1. This method--the Time-to-Make Steam procedure--was designed specifically for low-pressure steam boilers. The ratio of part-load efficiency to steady-state efficiency at a given fraction on-time, $E_{PL}[FOT]/E_{SST}$ can be shown to be

$$\frac{E_{PL}[FOT]}{E_{SST}} = 1 - \frac{Z_{ms}}{Z_{on}} \qquad (1)$$

where Z_{ms} = average boiler on-time per cycle required to make steam
Z_{on} = average boiler on-time per cycle

By measuring the boiler part-load efficiency it is possible to determine the performance of various boiler retrofits including derating, vent and flue restrictors, and vent dampers. It probably gives a conservative estimate of vent damper performance because it does not account for the possible impact of the vent damper on building infiltration and boiler room temperature. It is also possible to assess the performance of various types of boilers including sealed combustion/power burner systems and atmospheric boilers.

The measured part-load efficiency of a boiler is greatly dependent on the frequency of boiler cycling. In Figure 1, the part-load efficiency curve for the boiler at the Bosworth building is significantly lower than the other curves for buildings with similar boilers because its cycling rate is considerably higher. The measured part-load curves can be adjusted to account for variations in thermostat-induced boiler cycling frequency, W_t. The boiler thermostat-induced cycling frequency determines the duration of boiler off-time per cycle, $Z_{t,off}$, as shown below

$$Z_{t,off} = \frac{1 - FOT}{W_t} \tag{2}$$

where W_t = frequency of thermostat-induced boiler cycling (hr^{-1})

The boiler off-time in turn determines the time it takes for a boiler to make steam. Figure 2 displays the measured relationship for various boilers between the average off-time per cycle and the time-to-make-steam. With Equation 2 and the relationship in Figure 2 it is possible to adjust the part-load efficiency derived from Equation 1 to reflect different boiler cycling frequencies. Thus, it is also possible to project the effect of boiler control strategies on boiler efficiency without having to actually measure boiler performance under different cycling frequencies.

Boiler Control Effectiveness

The standard deviation of indoor building temperature parameter is the basis for a simple model that was developed to measure the performance of the various types of available boiler controls. The model is based on the following premises. First, the efficiency of a control is determined by its ability to maintain a consistent minimum average indoor air temperature throughout the heating season. This is a function of how well the thermostat can correct for changes in outdoor air temperature which affect the heating load.

Second, the minimum averrage building temperature is assumed to provide sufficient comfort and therefore any temperature excursions above this minimum are unecessary and contribute to control inefficiency, $INEF_C$, or

$$INEF_C = [SD_{W,TIBA}][S_{C,TIBA}] \tag{3}$$

where $S_{C,TIBA}$ = fraction change in annual space heating energy usage due to a 1^oF change in average indoor building temperature ($^oF^{-1}$).

$SD_{W,TIBA}$ = weekly standard deviation of daily average building temperature (^oF-1).

Third, as shown in Figure 3, $SD_{W,TIBA}$ is a good estimator of the degree of temperature excursion allowed by a particular control, or

$$T_{IBA})ave - T_{IBA})min = SD_{W,TIBA} \tag{4}$$

where $T_{IBA})ave$ = time-averaged average indoor building air temperature
$T_{IBA})min$ = time-averaged minimum indoor building air temperature

Therefore, according to this model, a good replacement thermostat is one that reduces the standard deviation of the daily averaged indoor building temperature. Table 2 summarizes the measured standard deviation for the various buildings during the first heating season of monitoring. The buildings with indoor thermostats had the lowest average temperatures and standard deviation. Buildings with time clocks and return line aquastats were the warmest and had the highest standard deviation.

Note that the original version of this model was based on using hourly indoor temperature data (Katrakis and Becker, 1984). However, during the course of this research, it was found that at an hourly time scale, higher standard deviations are desirable because they correspond to longer boiler on-times and therefore higher boiler part-load efficiencies. It is only by going to the longer time scale of one-day averages that it is possible to discern the ability of the thermostat to respond to changes in outdoor air temperature and to relate smaller standard deviations to improved control performance.

The projected energy savings, SP_C, resulting from a change from boiler control "0" to boiler control "1" is

$$SP_C = INEF_{C,0} - INEF_{C,1} \tag{5}$$

and the projected energy savings can be derived from the measured pre- and post-retrofit standard deviations of indoor temperature by combining Equations 3 and 5 as shown below:

$$SP_C = [SD_{W,TIBA})_0 - SD_{W,T_{IBA}})_1][S_{C,T_{IBA}}] \tag{6}$$

This method was used to project the effectiveness of various boiler controls at the eleven buildings, including two time clocks, various electro-mechanical and digital single-sensor thermostats, accustats, two-point cold spot locator thermostats, outdoor temperature reset steam cycle controls, accustat with a pressure control lockout, and a six-point averaging thermostat.

Main Line Vent Performance

The main line steam travel time and boiler on-time parameters are used to measure the performance of various main line vent configurations. It is based on the main line vent performance projection model shown below which defines the percent saving in space heating energy usage due to main line vent chages, SP_{mlv}, in terms of the impact of the vent changes on steam travel time.

$$SP_{mlv} = \frac{(Z_{mlv,0} - Z_{mlv,1})NC_t}{Z_{on}} \tag{7}$$

where $Z_{mlv,0}$ = average time per thermostat-induced cycle for steam to travel from boiler to end of main line with original main line vents (min)

$Z_{mlv,1}$ = average time per thermostat-induced cycle for steam to travel from boiler to end of main line with replacement main line vents (min)

Z_{on} = burner on-time (min)

NC_t = number of thermostat-induced cycles over the total period of measurement (-)

The basic assumption of this simple model is that the correct main line vent treatments will reduce the time it takes for steam to travel from the boiler to the end of each main line. Therefore, each boiler cycle will have a shorter on-time and use less energy in order to maintain apartment temperatures. The impact on steam travel time of two different main line vent treatments is determined by the following four-step procedure: 1) document the relationship between initial steam header temperature and fraction boiler on-time for the particular system as shown in Figure 4; 2) determine the average fraction on-time during the heating season and use this to pick-off the corresponding seasonal average initial header temperature; 3) establish the relationship between initial header temperature and steam travel time for each main line vent treatment as shown in Figure 5; 4) using the seasonal average IHT from Figure 4, pick-off the corresponding change in steam travel time in Figure 5.

Change in Range of Building Indoor Temperatures

It is assumed that effective radiator vent treatments will improve the spatial distribution of indoor building temperatures. The range, T_{IAR}, is used as a measure the effectiveness of radiator vent treatments. It is defined as

$$T_{IAR} = T_{IBA} - T_{AMN} \tag{8}$$

where T_{IBA} is the average building temperature

T_{AMN} is the air temperature in the coldest apartment.

Effective radiator vent treatments will decrease the range--the average building temperature will approach the temperature in the coldest apartment.

Infiltration Rate

Lawrence Berkeley Laboratory (LBL) used the DC pressurization method to estimate the infiltration rates and inter-apartment air flow patterns at two of the six-unit test buildings (Diamond et. al., 1986). The projected infiltration patterns indicate relatively high infiltration rates in the lower floors. This helps explain the surprizing prevalence of low indoor air temperatures in the first floor apartments.

RESULTS

Documented Performance

Operation and Maintenance Improvements. Adjusting the anticipator or span of the thermostatic boiler control was found to be a no-cost way of improving the boiler cycle efficiency up to 10%. Conventional boiler tune-ups to optimize the ratio of combustion air to gas input resulted in a neglible improvement in measured heating plant steady-state efficiency.

Energy Efficiency Improvements. The performance of the five test EEIs is summarized in Table II. The technical performance of the measures is described by their projected average savings (PROS) for the eleven test buildings. The main line vent treatments have the highest savings of 17%. The six- and single-point thermostats follow with 14% and 11% savings respectively. The other test measures--derating, vent damper, and radiator vent treatments--have projected savings in the range of 2 to 5%.

It is important to note that the savings presented in Table 2 are based on applying each measure individually. If these measures are combined at one building the resulting savings will be considerably less than the sum of the individual savings. The interaction between the replacement thermostat and main line vent treatments is one example of a strong interaction. A new thermostat that lengthens the boiler on-time per cycle, will reduce the savings resulting from large new main line vents. Derating a boiler will automatically lenghten the boiler on-time per cycle which also improves boiler part-load efficiency.

Feasibility

Code Compliance, Reliability, Longevity of the Heating System. The conventional boiler tune-up proved useful in reducing carbon monoxide levels in the flue gases down to levels that meet current codes. All the other measures can be implemented in a manner that will result in compliance with building codes or accepted practice. Current building codes dictate the allowable type of vent dampers.

System reliability is improved by boiler tune-ups, main line and radiator vent replacements. The new replacement digital thermostat did reduce reliability in one building due to short-cycling caused by a rapid fluctuation of the temperature signal. This still has not been totally resolved. The same model thermostat enhanced the reliability of another heating system that was previously controlled by an early-model electromechanical programmable thermostat. An improperly installed vent damper at one of the buildings did adversely affect system reliability. The installation was easily corrected and the vent damper is now in its seventh year of operation.

The longevity of certain heating system components can be affected by the way derating is specified. Derating which results in flue gas temperatures below 260^{o}F may result in excessive condensation which can corrode the boiler breaching and masonry-lined chimneys.

Comfort. Continuous indoor air temperature measurements show that derating, indoor air thermostats and radiator vent treatments can actually improve temperature distributions and increase the indoor air temperature without causing a corresponding increase in consumption. Preliminary monitoring of gas usage by tenants indicates that improved comfort will reduce their use of gas ranges for heating (CNT, 1987). This can result in direct economic benefits to the tenants as well as improved safety and air quality. Derating also resulted in improved comfort because the reduced firing rate resulted in a longer boiler on-time per cycle. Therefore the furthest apartments from the boiler were maintained at higher temperatures by the derated boiler. There is no evidence of reduced comfort due to any of these installed retrofits.

Cost-Effectiveness. The economic performance of the retrofits is indicated by two measures in Table 2: simple payback (SPB) and the Cost of Conserved Energy (CCE). The CCE is a convenient way of comparing the cost-effectiveness of a retrofit against the cost of buying gas. An owner who implements a retrofit with a CCE that is less than the retail price of gas will realize an economic benefit. For example, an economically rational gas user faced with a choice of paying $0.50 per therm for gas or paying $0.20 to not have to consume a therm of gas would choose the latter option in order to save $0.30. The CCE (Evens, et. al. 1986) takes into account the lifetime of the retrofit, the cost of money, and it assumes that the discount rate is equal to the rate of inflation.

Following in order of decreasing CCE are main line vent treatments, heating plant derating, indoor thermostat, vent damper, and radiator vent treatments. The main line vent treatment has the quickest payback at less than one-half year, and the lowest Cost of Conserved Energy (CCE) at $0.05/therm. This CCE is considerably lower than the retail price for a delivered therm of gas--$0.49--in the Chicago area. The indoor thermostat and derating options also exhibit a CCE that is considerably below the retail price of new gas.

The indoor air thermostat is cost-effective for all buildings that have heating plants controlled by a time clock. The replacement main line vent treatments are also cost-effective in all of the single-pipe steam heated buildings that are entering the CESF program. The low-cost derating option is feasible in over 80% of the buildings while the range of application for the deep retrofit option may be limited by the minimum allowable flue gas temperature.

The combination of the 6-point thermostat, main line vent treatments and the low-cost derating option results in a projected savings (accounting for interaction) of 25%, a CCE of 0.15/therm, a 1.2 year payback, at a cost of $150 per apartment. This package is a very cost-effective combination.

The one tested boiler vent damper had a CCE of $0.78/therm that is higher than the cost of new purchased gas. The two radiator vent options--"do-it-yourself" and fee-for-service--both have a projected savings of about 5%. Their relative high cost results in relatively long paybacks. Their estimated lifetime of 3 years is relatively short and is another major reason for the CCE being greater than the cost of gas. The CCE ranges from $0.89/therm for the do-it-yourself service where the intervention is done by the owner, to $1.64/therm where the owner retains a contractor to perform the radiator vent treatments.

Predicting Performance

A simple dynamic model of the distribution system was developed based on assumptions of one-dimensional and steady-state flow. Even this simple model produces results that correlated well with the normalized and projected savings of various main line vent treatments. The model has helped to develop a convenient main line vent sizing procedure based on independent variables such as length of the main lines.

Improved Specifications

The results of this research resulted in improved specifications for several of the test measures which are summarized below.

Main Line Vents. The new specifications call for main line vents that have 200% to 400% more capacity than the vents called for by the old specifications. Also, the new specs call for sizing vents according to line size whereas the older specs called for the same size vent on all lines.

Indoor Air Thermostats. The new specifications include specific information about the appropriate range of span settings of the thermostat. Not all digital thermostats are suitable. The most effective replacement thermostat is a multiple-point averaging thermostat.

Radiator Vents. The new specifications call for installing radiator vents with a total orifice area that is not more than twice the total orifice area of the radiator vents. The new specs call for installing radiator vents that are larger on the first floor radiators than on the second floor. The old approach of installing the smallest vents on the first floor is appropriate for apartments immediately over large boilers.

Derating. The new derating specifications use the same method used in specifying boiler replacements--by capacity of the existing radiation. It is important that the distribution system does not have any significant obstructions or other line resistances, the boiler firebox and heat exchange area are sized correctly for the new lower firing rate, and that flue gas temperature remains above 260°F. Also, it is important to specify the installation of a permanent nameplate that describes the new operating parameters and boiler modifications.

Vent Damper. The research results demonstrate the importance of specifying the proper installation of a vent damper. it is particularly important that the vent damper housing, flue and vent pipes are all rigidly secured to each other in order to avoid binding the vent damper blade. The research also indicates that there are several other types of vent dampers that may perform better than the current marketable versions but are not approved by the AGA.

SUMMARY AND CONCLUSIONS

This project provided insights into the benefits attainable by applying low-cost energy efficiency improvements to existing heating systems. The five measures that were evaluated are appropriate for most of the existing steam heated low and middle income buildings. The measures utilize products that are commercially available but are not widely known by building owners. A substantial data base is now available for these buildings which includes indoor temperature parameters, internal gains, heating plant part-load efficiency, control and distribution system efficiency, as well as building envelope and infiltration parameters. This will be valuable for calibrating and validating existing building and retrofit performance simulations.

ENDNOTES

1. Evens and Katrakis; Results of Performance Monitoring of the Chicago Energy Savers Fund Multifamily Buildings; to be published in Proceedings of ACEEE '88 Summer Study, August 1988.

2. Biederman and Katrakis; "Space Heating Improvements in Multifamily Buildings (SHIM)", Final Report #GRI-88/0111; Center for Neighborhood Technology; for Gas Research Institute, (to be published Summer 1988).

3. Evens, Burris, Katrakis, Becker; :Development of a Computerized Multifamily Audit: Technical and Implementation Issues; ACEEE Summer Study, Santa Cruz; August 1986.

4. Katrakis, "Demonstration of Comprehensive Retrofits of Multifamily Buildings in the Low-Income Weatherization Assistance Program--Progress Report"; Center for Neighborhood Technology; for the State of Illinois Department of Commerce and Community Affairs; July, 1987.

5. Katrakis and Becker; A Research Agenda for Promising Energy Conserving Measures for Steam Heating Systems in Multifamily Buildings; presentation at; ACEEE Summer Study, Santa Cruz; August 1984.

6. Diamond, Modera and Feustal; Ventilation and Occupant Behavior in Two Apartment Buildings; Lawrence Berkeley Laboratory; presented at 7th Air Infiltration Centre Conference, Stratford-upon-Avon, UK; September 1986.

Table I. Schedule of interventions at test sites.

N: includes measurement of impact on energy use
P: projects energy savings based on measured intermediate parameters

Building	Tstat	Main Vents	Radiator Vents	Boiler Derating	Vent Damper
Albany	P	N,P	P	P	N,P
Bosworth	N,P	N,P	P	P	
Rascher	N,P	N,P	P	P	
Michigan	P		CONTROL P	P	
Marquette	P		CONTROL P	P	
Winemac	P		CONTROL P	P	
Winchester	P	N,P	P	N,P	
Oakdale	N,P	N,P	P	P	
Spaulding	N,P		P	P	
Argyle	P		CONTROL P	P	
Sherman	P		CONTROL P	P	

Table II. Initial Indoor Temperature Parameters, 1985-86

Building	Size	Control	T_{IBA}	T_{AMN}	$SD_{W,T_{IBA}}$
Group A					
Albany	7	Tstat	71.5	67.8	0.8
Bosworth	6	Tstat	71.6	67.9	0.9
Rascher	6	Tstat	70.6	65.3	0.7
Argyle	24	Tstat	72.9	67.5	1.1
Average A			71.6	67.1	0.9
Group B					
Winchester	24	Accustat	72.3	67.2	1.7
Sherman	25	Cycler	74.3	67.5	1.0
Average B			73.3	67.4	1.4
Group C					
Spaulding	38	Faulty Tstat	75.9	69.2	1.6
Group D					
Oakdale	30	Clock/Aqstat	75.2	68.3	2.0
Winnemac	7	Clock/Aqstat	72.8	69.3	2.0
Michigan	6	Clock/Aqstat	78.4	72.8	3.2
Marquette	7	Clock/Aqstat	81.2	76.3	2.4
Average D			76.9	71.7	2.4

Table III. Performance of energy efficiency improvements.

MEASURE	UNIT SAVINGS (%)	COSTS ($/apt)	SIMPLE PAYBACK (years)	LIFE-TIME (years)	COST OF CONSERVED ENERGY ($/therm)
Main Line Vents	17	30	0.4	5	0.05
Derating					
Low-cost	2.3	7	0.8	25	0.04
Deep Retrofit	5.0	83	5.0	25	0.21
Thermostat					
1 point	11	58	1.4	15	0.12
6 point	14	120	2.3	15	0.19
Vent Damper	3.5	100	8.4	7	0.78
Radiator Vents					
Do-It-Yourself	5.2	64	4.7	3	0.89
Fee-for-Service	5.2	120	9.3	3	1.64

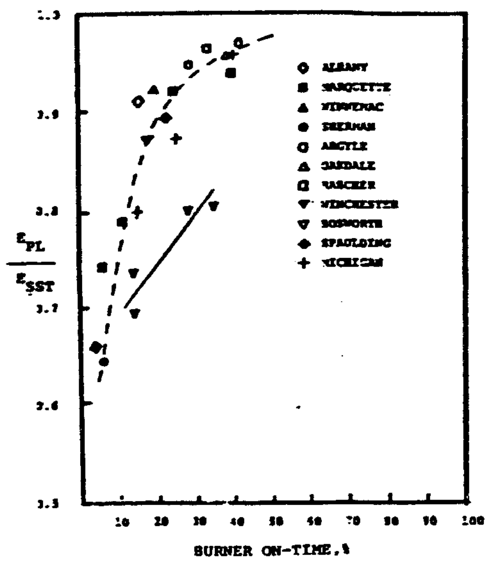

Figure 1. Part-load efficiency

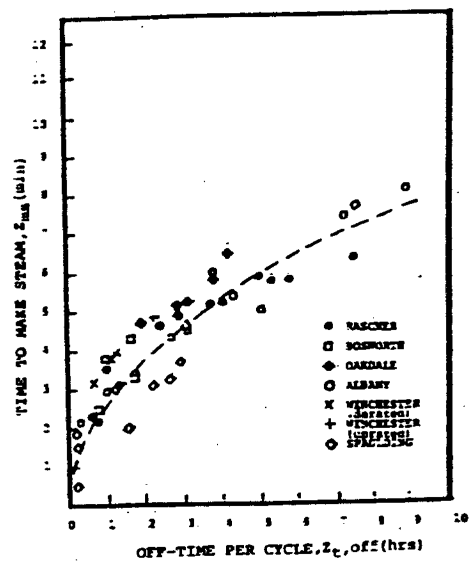

Figure 2. Time-to-make steam

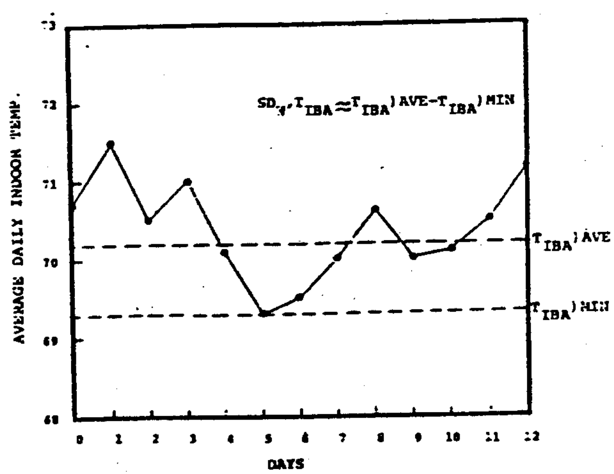

Figure 3. Boiler control effectiveness parameters

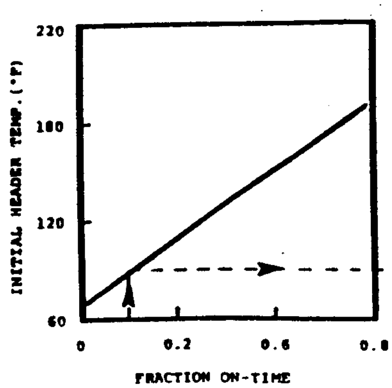

Figure 4. Initial header temp. vs. fraction on-time

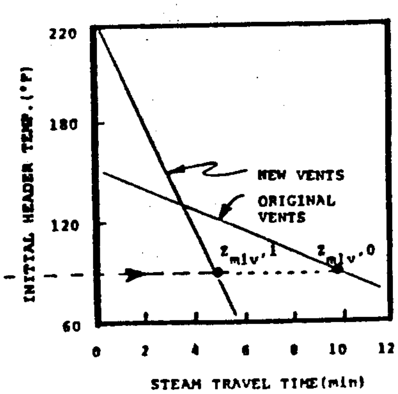

Figure 5. Steam travel time vs. fraction on-time