USE OF THE PRINCETON SCOREKEEPING METHOD TO EVALUATE GAS FURNACE RETROFITS IN THE DENVER AREA: RESULTS AND LIMITATIONS

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ABSTRACT

The Princeton Scorekeeping Method (PRISM) was used to estimate the energy savings resulting from gas furnace tune-ups performed on 69 Denver area residences from 1982-1984. The apparent average savings was 4.9%. However, the average Public Service Company gas customer realized weather adjusted savings of 4% during the same period. Hence no significant savings can be unambiguously attributed to the furnace tune-ups.

Twenty-five cases receiving more extensive tune-ups showed apparent average savings of 7.9% while 44 cases receiving minor tune-ups showed apparent average savings of 3.1%. Hence the more extensive tune-ups realized appreciable savings when compared to the average PSCo customer or to the minor tune-ups. Examination of tune-ups by season of retrofit and comparison to solar radiation availability changes did not expose greater savings than those indicated above.

A prototypical Denver residence was simulated using the DOE2.1B computer program to generate synthetic input for PRISM. Monthly consumption data from several parametric DOE2 runs were used to test PRISM's sensitivity to changes in thermostat setpoint, solar gain variations, and furnace curve adjustments. The consumption changes predicted by PRISM for these "billing data" agreed with the DOE2 changes within 0.1%.

INTRODUCTION

The Sunpower Consumer Cooperative was funded by the Colorado Office of Energy Conservation (OEC) to conduct Denver area gas furnace tune-ups beginning in 1982. The project was very labor intensive, with a total of 652 gas forced-air furnaces tuned. Furnaces examined were generally found to be poorly maintained and the average tune-up took three hours (1).

Single-family residences made up 84% of the retrofit population, while the remaining 16% were duplexes. Sixty percent of the residences were owner occupied.

Sunpower provided all training of furnace technicians, supervised by the OEC. Technicians completed standard forms for each furnace tuned, with the forms being reviewed by inspectors. Furthermore, the inspectors checked 29% of the retrofit furnaces for quality and completeness of work. As required by building code, contractors were hired to complete special work, such as repair of gas leaks and replacement of electrical and furnace components. The following list summarizes the work performed when needed:

1) Ducts were reconnected and duct joints taped to prevent loss of heated air to unheated spaces.

2) The blower was cleaned, oiled, and adjusted for longer life and greater efficiency.

3) Air filters were installed or replaced to prevent obstruction of air paths and to provide cleaner air to the heated space.

4) Fan on and off temperatures were lowered to lengthen furnace cycles and deliver lower temperature air more quickly to the heated space.

5) Airflow restrictions, such as furniture and carpeting obstructing delivery and return ducts and registers, were removed.

6) The thermostat anticipator was set higher or lower to lengthen or shorten the furnace cycle as needed for efficient and comfortable operation.

A more detailed explanation of the retrofits done is available in Ref. 1.

METHODOLOGY

This paper examines the gas savings produced by these retrofits, as indicated by the Princeton Scorekeeping Method (PRISM), as well as the "savings" indicated by PRISM when synthetic data (from DOE2.1B simulations) corresponding to expected changes in building and weather parameters are analyzed.

Sample

For the purpose of this study, 62 residences, which we refer to as the aggregate, were drawn from the retrofit group of 652 houses. Selection was based on the presence of at least ten gas consumption readings each, including at least one baseload reading, for the pre-retrofit and post-retrofit periods, as well as certainty of the dates during which the tune-up work was performed. (The chosen quantity of data required is intermediate between suggestions made in Refs. 2 and 3, and is based on the amount of data available for this study). Consumption readings corresponding to the periods when the work was being done were not included. In addition, residences with supplemental wood heating were not included in the analysis.

The retrofits were later broken down by Sunpower Consumer Cooperative into categories numbered 1 and 2, according to the extent of tune-up, with 2 being the more extensive. Table 1 shows the criteria used to divide the retrofits into categories. At least one retrofit measure listed under a category was performed for each residence assigned to that category. Each residence had retrofit measures from only one category. The billing data requirement was relaxed to eight readings each, including at least one baseload reading, for the pre-retrofit and post-retrofit periods for category 2. This allowed the addition of six more cases to this subgroup from the retrofit population, in order to enhance the statistical value of the results. Thus the number of cases examined was as follows: 44 cases for category 1 and 25 cases for category 2, for a total of 69 cases. (Note that the additional six cases for category 2 were not included in the aggregate.)

Fuel Use Analysis

The PRISM program (4) uses files of daily average temperatures, long-term average heating degree-days per day at various reference temperatures, and utility billing (consumption) data. Consumption data for each residence are regressed against degree-days for a succession of reference or balance temperatures until the program determines a balance temperature TBopt for which the square of the linear regression correlation coefficient, R^2, is maximized. The constants A (intercept) and B (slope) corresponding to TBopt, as well as the annual heating degree-days

TABLE 1: CRITERIA DEVELOPED FOR RETROFIT CATEGORIES

	Category 1	Category 2
Furnace cycling	Didn't cycle on limit	Cycled on limit, corrected
Fan-on temperature	Orig. less than 200°F, lowered to approx. 110°F	Orig. above 200°F, lowered to 170°F or less
Disconnected ducts	None found	One or more found and fixed
Anticipator	More than .75 times gas valve amperage, corrected	Less than .75 times gas valve amperage, corrected
Cold air	Air flow restrictions in cold air return removed	Cold air return pulled in outside air, repaired
Blower	Was dirty, cleaned	Fan broken, repaired
Filter	Was dirty, replaced	
Joints	Leaks in ducts and plenum taped	

to TBopt, can then be used to compute the normalized annual consumption (NAC), defined as follows:

$$NAC = Aopt * 365 + Bopt * HDD(TBopt) * 365$$

where

NAC is the normalized annual consumption in ccf/year

Aopt is the baseload for optimum TB in ccf/day

Bopt is the increase in consumption per increase in heating degree-days in ccf/F-day

HDD(TBopt) is the normalized heating degree-days per day to base temperature TBopt.

The NAC represents the gas consumption which would have occurred during the hypothetical "normal" weather year, and is computed for both the pre-retrofit and post-retrofit periods for each residence. We then define the ratio of post-retrofit NAC (post NAC) to pre-retrofit NAC (pre NAC) as the consumption index

(CI). The difference between CI and unity is the fraction of energy saved. If CI is equal to or greater than unity, no energy savings can be demonstrated.

Similarly, pre NAC, post NAC, and CI can be determined for electricity usage based on available billing data corresponding chronologically to the gas billing data. A substantial change in the electric NAC would indicate that more internal gains on the average had been furnished to the conditioned space during one period. The need for gas heating, and thus the gas NAC, should be reduced for that period. (Comparison of yearly totals of electric usage could have been used alternatively).

PRISM RESULTS FOR RETROFITS

The mean PRISM results for the retrofits (with corresponding standard errors in parentheses) are shown in Tables 2, 3, and 4. The value of R^2 output by the PRISM program is a measure of the explanable variation in consumption. Thus it is indicative of the reliability of the associated NAC. A minimum R^2 of 0.75 for both pre- and post-retrofit values was selected for screening purposes. Hirst et al (5) proposed this R^2 cutoff value in studying the precision of PRISM.

Table 2 shows the mean values of various PRISM outputs for the 62 aggregate cases. In both the pre- and the post-retrofit cases, the PRISM model fails to account for only about 3% of the variation in consumption on the average. The consumption index (CI), the ratio of the post-retrofit NAC to the pre-retrofit NAC for each residence, is used as the indicator of group savings. The mean CI for the aggregate shows an average reduction in NAC of about 5%.

Mean values of pre-retrofit and post-retrofit heating intercept A, heating slope B, and balance temperature TB are also shown in Table 2. The average A and B values decreased by about 10% each, while TB increased by 1.2°F. A decrease in B with an increase in TB is consistent with the findings in the Princeton studies (2). Since TB is the outdoor temperature below which heating is required for a given house, an increase in TB corresponds to an increase in heating degree-days. The product (B * HDD(TB)) is more stable because of the offsetting effects of the decreased slope and the increased heating degree-days. A substantial change in A has less effect on NAC since A is the relatively smaller contribution to NAC. Thus the average drop in NAC is only half as large (5%) as the decrease in A or B.

The correlations in parameter estimates for A, B and TB described above are due to mathematical properties of the PRISM program such that a shift in one parameter (possibly a very large and spurious shift) tends to be countered by an opposite shift in

TABLE 2: STATISTICAL RESULTS FOR AGGREGATE RETROFITS *

	Pre-retrofit	Post-retrofit
R^2	.968	.970
TB (°F)	60.30 (3.26)	61.50 (3.32)
A (ccf/day)	1.32 (.30)	1.18 (.27)
B (ccf/°F-day)	.21 (.02)	.19 (.02)
NAC (ccf/year)	1462.3 (49.5)	1375.9 (47.2)
CI	.951	
Electric CI	.999	
No. of cases	62	

TABLE 3: STATISTICAL RESULTS FOR CATEGORY 1 RETROFITS *

	Pre-retrofit	Post-retrofit
R^2	.972	.973
TB (°F)	59.95 (3.09)	61.45 (3.20)
A (ccf/day)	1.30 (.27)	1.17 (.24)
B (ccf/°F-day)	.19 (.02)	.18 (.02)
NAC (ccf/year)	1378.1 (42.9)	1325.7 (42.0)
CI	.969	
Electric CI	.970	
No. of cases	44	

TABLE 4: STATISTICAL RESULTS FOR CATEGORY 2 RETROFITS *

	Pre-retrofit	Post-retrofit
R^2	.953	.964
TB (°F)	60.91 (4.00)	62.58 (3.82)
A (ccf/day)	1.31 (.41)	1.14 (.37)
B (ccf/°F-day)	.25 (.04)	.21 (.02)
NAC (ccf/year)	1646.2 (74.1)	1510.1 (59.2)
CI	.921	
Electric CI	1.061	
No. of cases	25	

* Corresponding mean standard errors for each PRISM output are shown in parentheses.

the other parameters. This leads to the generally recognized property of PRISM results that A, B, and TB are estimated with far less precision than NAC.

The average electric CI, analogous to the gas CI, is 0.999, indicating that the electricity usage changed little on the average from the pre- to the post-retrofit period. Therefore the change in gas heating consumption was not strongly influenced by changes in internal heat gains from electric appliances on the average.

The majority of cases (44) included in the aggregate are from category 1, the lower level of tune-up. Table 3 shows the statistical results for category 1 retrofits. The mean A, B, and hence the NAC values for both the pre- and the post-retrofit periods are lower than those for the aggregate. The mean CI for category 1 is 0.969, indicating slightly less savings on the average than for the aggregate, as expected. The mean electric CI is 0.970; this slight average drop in electrical consumption from pre- to post-retrofit period indicates minimal effect from changed internal gains.

Table 4 shows the statistical results for category 2 retrofits. The mean balance temperatures for category 2 are higher than those for the aggregate, but show the same trend of increase from pre to post. The mean values of B and NAC are greater for the category 2 retrofits than for the aggregate. The same decreasing trends for A and B from pre to post are still evident in the category 2 retrofits. The mean CI of 0.921 indicates substantially more energy savings for category 2. This value is significant in comparison to the errors associated with mean pre and post NAC values. The electric CI (1.061) indicates a substantial increase in internal gains in the post-retrofit period on the average, but this would explain only part of the gas savings.

The aggregate retrofit group was also divided into groups according to the year of the pre-retrofit heating season. Cases for which the retrofit was performed in mid-heating season were not included in this segment of the analysis. Table 5 shows the statistical results for each of the three retrofit years.

For the 12 cases with retrofits performed after the 1981-82 heating season, the mean CI is 0.878, while the corresponding mean change in TB is -1.2°F. For retrofits after 1982-83, 35 cases, the mean CI and change in TB are 0.950 and 1.6°F, respectively. There are only five cases retrofit after the 1983-84 heating season, for which the mean CI and change in TB are 1.044 and 2.6°F. Although the 1981-82 cases show the greatest apparent savings, the 1982-83 cases influence the aggregate results the most. The few 1983-84 cases show an apparent increase in consumption.

TABLE 5: STATISTICAL RESULTS FOR AGGREGATE BY SEASON OF RETROFIT *

	1981-82	1982-83	1983-84
Pre-retrofit			
R^2	.954	.969	.988
TB (°F)	60.67 (3.52)	60.07 (3.43)	60.28 (2.08)
A (ccf/day)	1.31 (.44)	1.36 (.30)	1.15 (.15)
B (ccf/°F-day)	.27 (.03)	.21 (.02)	.15 (.01)
NAC (ccf/year)	1845.3 (80.2)	1443.1 (45.1)	1143.4 (28.7)
Post-retrofit			
R^2	.974	.973	.973
TB (°F)	59.49 (3.03)	61.68 (3.05)	62.88 (3.54)
A (ccf/day)	1.20 (.31)	1.17 (.27)	1.18 (.21)
B (ccf/°F-day)	.26 (.02)	.18 (.02)	.14 (.01)
NAC (ccf/year)	1618.5 (51.2)	1365.2 (47.1)	1182.3 (38.4)
CI	.878	.950	1.044
Electric CI	1.025	.976	1.034
No. of cases	12	35	5

TABLE 6: SUMMARY OF RETROFIT RESULTS, AVERAGE CUSTOMER CONSUMPTION, AND SOLAR RADIATION

Pre-retrofit season	81-82	82-83	83-84
Post-retrofit season	82-83	83-84	84-85
Retrofit group			
CI	.878	.950	1.044
Change in TB (°F)	-1.2	+1.6	+2.6
Average customer			
CI	.97	.93	1.02
Change in TB (°F)	-1.1	+1.1	+3.9
Available solar radiation (Btu/day)			
Pre-retrofit season	52,056	41,254	43,692
Post-retrofit season	41,254	43,692	49,431
% change	-20.2	+5.2	+13.1

* Corresponding mean standard errors for each PRISM output are shown in parentheses.

The average customer usage data from the Public Service Company are a useful standard with which to compare the retrofits on a year-by-year basis. Average customer data for the pertinent period was divided into May-to-May years to include entire heating seasons. The seventh day of each month was taken as the meter reading date, according to PSCo information. These data were run using PRISM, and CI and change in TB were determined from the outputs for each pair of pre- and post-retrofit years. These results appear in Table 6 along with pertinent retrofit results.

Also appearing in Table 6 are average daily solar radiation data for the heating seasons of interest. These data were calculated using monthly percent possible sunshine data for Denver.

For the first season of retrofits, the drop in consumption beyond that for the average customer is significant. This same group experienced a pre-to-post drop in solar radiation of more than 20%. Savings thus occurred in spite of decreased solar gains which would ordinarily increase gas usage.

The second and largest group of retrofits differs little in savings from the average customer. The third group is also similar to the average customer result for the same period in showing an apparent increase in energy usage. In addition, both of these groups experienced pre-to-post increases in daily average solar radiation, which should have meant a significant drop in heating needed.

Test of Prism Accuracy Using DOE2.1B

To explore the sensitivity of the PRISM methodology to small changes in consumption, a prototype residence was modeled using the DOE 2.1B energy simulation program (6). The assumed prototype thermal characteristics were similar to those of many houses retrofit, based on construction characteristics described by Sunpower Consumer Cooperative.

The prototype residence used was a one-story, single-family house with 1050 sf of floor area. Single glazing was evenly distributed on the four walls and was equivalent to 10% of floor area. A shading coefficient of 0.7 was used to account for average indoor and outdoor shading conditions. Typical frame wall construction was used, with no wall, attic, or floor insulation. An above-grade crawl space was specified.

The building was assumed to have three occupants and the following appliances: gas hot water heater, washer, dryer, range, refrigerator, and television. The thermostat setpoint was taken to be 68°F. Gas furnace heating with no mechanical cooling was specified.

The following parametrics were run for this building using DOE2:

1) Base case

2) Thermostat setpoint raised 2°F to 70°F

3) Thermostat setpoint lowered 2°F to 66°F

4) Solar availability Qs decreased by 10%

5) Solar availability Qs decreased by 20%

6) Alternate furnace efficiency curve F1: $z = 0.04 + 1.10x - 0.14x^2$

7) Alternate furnace efficiency curve F2: $z = 0.02 + 1.07x - 0.09x^2$

All other data used in the parametric runs were the same for each case.

DOE2 monthly consumption results were used as inputs to the PRISM program, along with Denver TMY data. The PRISM results are shown in Table 7. Column numbers refer to the parametrics listed above.

R^2 values for all parametrics are 0.997 or higher, indicating that over 99% of the variation in heating consumption is accounted for by the PRISM model. The NAC values for all parametrics are within the range of values encountered in the real gas furnace retrofits described above.

For all parametrics, the standard errors on B and NAC were small percentages of those outputs. The values of A had much larger associated standard errors. These results are in keeping with the findings of the Princeton group (2).

The 2°F adjustments on either side of the thermostat setpoint produced approximately equal changes in the balance temperatures of +1.7°F and -1.7°F, respectively, corresponding closely to the heating degree-day changes expected from the adjustments. The remainder of the change in consumption occurs due to a change in A.

Decreases in solar availability by 10% and 20% increased the NAC by 1.9% and 4.0%, respectively, again as expected. The greater heating requirements resulted in predictable balance temperature increases.

TABLE 7: PRISM RESULTS FOR TYPICAL HOUSE PARAMETRICS

No. in text	1 (base)	2 (+2F)	3 (-2F)	4 (.9Qs)	5 (.8Qs)	6 (F1)	7 (F2)
R^2	.998	.997	.998	.998	.998	.988	.988
TB (°F)	58.4 (.9)	60.1 (1.0)	56.7 (1.0)	58.9 (.9)	59.5 (.9)	60.3 (.8)	58.5 (.9)
A (ccf/day)	.36 (.122)	.44 (.147)	.31 (.116)	.36 (.121)	.38 (.128)	.36 (.118)	.36 (.118)
B (ccf/°F-day)	.339 (.011)	.338 (.011)	.341 (.013)	.337 (.011)	.333 (.011)	.358 (.009)	.335 (.011)
NAC (ccf/year)	1630.6 (22.5)	1786.9 (25.6)	1484.8 (21.8)	1662.3 (22.2)	1695.6 (23.2)	1875.8 (20.6)	1620.9 (21.6)
DOE2 Consumption	1671	1830	1523	1703	1737	1922	1660
CI (PRISM)	-	1.0959	0.9106	1.0194	1.0399	1.1504	0.9939
CI (DOE2)	-	1.0952	0.9114	1.0192	1.0395	1.1502	0.9934

The NAC values determined by PRISM are consistently 97.5-97.6% of the consumption given by DOE2. The consistency of these changes indicates that the PRISM model does an excellent job of determining NAC for changed building or equipment properties. However, the changes in A when thermostat setting was changed indicate that weather adjustment from year-to-year is not exact. The CI determined by PRISM (relative to the base case) differs from the CI determined from the DOE2 simulation by less than 0.001 in every case.

CONCLUSIONS

PRISM analysis of 69 Denver area gas furnace retrofits indicated an average savings of 4.9%. But the average Public Service Company customer realized weather adjusted savings of 4% during the same period. Hence no savings can be unambiguously attributed to the furnace tune-ups for the aggregate sample of 69 residences.

Twenty-five cases receiving more extensive tune-ups showed apparent average savings of 7.9%, while 44 cases receiving minor tune-ups showed apparent average savings of 3.1%. Hence the more extensive tune-ups apparently realized appreciable savings when compared to the average PSCo customer or to the minor tune-ups.

PRISM proved very responsive to consumption changes in simulation data caused by changes in thermostat setpoint, solar availability, and furnace efficiency. The CI values based on PRISM analysis differed from those based on the DOE2.1B analysis by less than 0.001 for every case examined.

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