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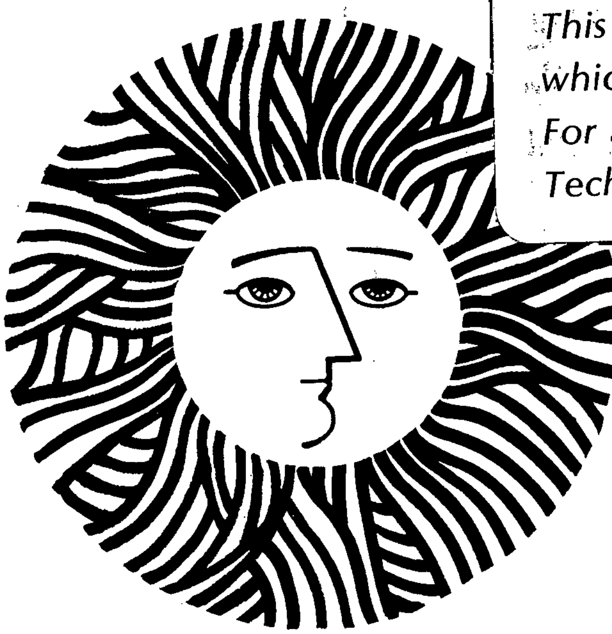

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ABSTRACT

One hundred forty-two low-income homes in 12 cities across the United States underwent "optimal weatherization," which included insulation, reduced infiltration, and modifications to windows and heating systems. Average savings of 40% were achieved at a cost of $1,800. After the cost-effectiveness of optimal weatherization was measured, some houses were further upgraded with house-doctoring, solar air collectors, circulating fans, and wood stoves; then another set of measurements were taken. Four years of data have been collected and analyzed. From it conclusions can be drawn about the cost-effectiveness of introducing a combination of wood stoves, furnace retrofits, infiltration controls, small solar air collectors, and reductions in thermal conductivity of the building shell.

1. INTRODUCTION

The Community Services Administration (CSA) and the National Bureau of Standards (NBS) designed a demonstration/research project to measure changes in energy consumption resulting from optimal weatherization of residences occupied by low-income households. Optimal weatherization in this case meant installing that combination of architectural and mechanical system options which would generate the greatest benefit/cost ratio for net savings over 20 years given a real rate for fuel escalation of 5% to 8%, a real discount rate of 6%, and a cost of fuel equal to 1978-79 prices. The options considered for each house are described below. Water heaters were also upgraded and and evaluated as part of the CSA demonstration, but results from that effort are not reported in this paper.

Architectural Options:

1. Seal holes and cracks.
2. Weatherstrip and caulk.
3. Insulate attic (R = 11, 19, 30, or 38).
4. Insulate basement and crawl spaces (R = 7).
5. Insulate walls (R = 11).
6. Install storm windows.
7. Install triple-glazing.
8. Install insulating shutters.

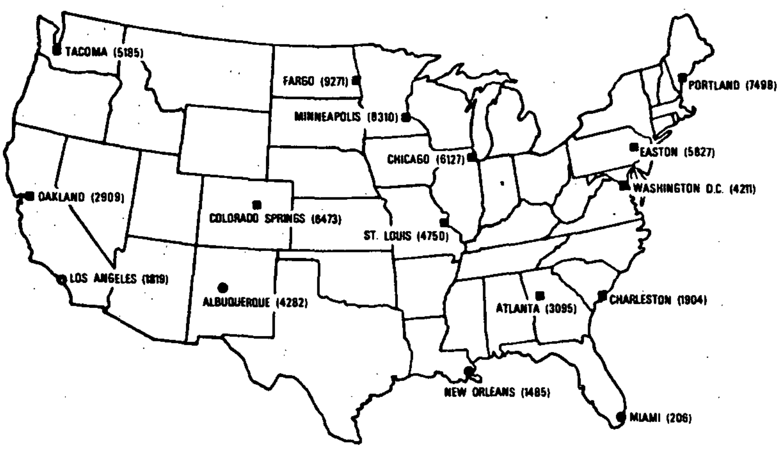
Mechanical Heating System Options:

9. Tune and clean furnace.
10. Install flue or vent damper or restrictor.
11. Install electronic furnace ignition.
12. Install two-stage gas valve or gas furnaces.
13. Derate furnace or optimize nozzle size for oil furnaces.
14. Replace oil furnace burner.
15. Insulate ducts and pipes.
16. Install night-setback thermostat.
17. Replace furnace.

The package of options selected for each house was determined by investigating each increment of weatherization to determine whether the additional dollars saved in fuel costs over the life of that increment would exceed the cost of installing it. Because of the introduction of new materials, changes in costs of materials, labor, and fuel, and because of variations in quality of workmanship and initial condition of each house, optimal weatherization packages varied even within the same city.

2. SAMPLE SELECTION

During 1979 the optimal weatherization project selected 222 houses to receive optimal weatherization and 68 houses as a control group (i.e., measured, but not weatherized) at 15 sites in the U.S. (see Fig. 1). The houses selected were identified by CSA from local Community Action Agencies' (CAAs') files of households eligible for CSA weatherization. Proposed houses had to meet a broad set of criteria defined by NBS (see p. 5 of Ref. 1). The most important of these criteria was that an accurate record of heating-fuel consumption be available. The accuracy of the fuel records was determined by NBS using standard methods for statisti-



LEGEND:

(0000)-Degree Days

From National Climatic Center's 1941-70 Heating Degree Day Yearly Normals

■ Sites That Submitted Data ● Sites That Did Not Submit Data

Figure 1. Locations of sites selected for CSA/NBS demonstration/research project.

cally correlating fuel consumption with degree days. A record showing a fuel consumption/degree day correlation coefficient (R^2) of 0.90 or better was acceptable. The control houses were selected to identify changes in energy consumption that occurred as a result of influences outside the demonstration. At the end of the demonstration period, data were submitted from 12 sites for evaluation of 142 experimental and 56 control houses. Of the 142 experimental houses for which data were submitted, only 74 received "optimal weatherization," that is the installation of all feasible cost-effective architectural and mechanical options; 68 houses received architectural options only. Some of the houses that received only architectural options had heating systems, such as space heaters, which are difficult to upgrade and therefore were already as weatherized as possible.

Of the 56 houses selected for the control group, 15 were eliminated because they were subsequently partially weatherized by their owners or had a change in occupants, leaving a control group of 41. After the weatherized houses had been measured for the savings associated with optimal weatherization, a subgroup of 29 houses was selected to see if more cost-effective savings could be achieved at sites that had performed well in terms of installing options and making measurements. These sites were Charleston, SC, at 1904 degree days; Colorado Springs at 6742 degree days; and Fargo, ND, at 9271 degree days.

3. OPTION SELECTION AND INSTALLATION

Architectural and mechanical options were selected separately at each site using the following life-cycle formula in which the present value factor covers the life of the option and the replacement factor covers maintenance.

$$\frac{\text{Savings}}{\text{Cost}} = \frac{\text{Fuel Savings x Present Value Factor x Cost of Fuel}}{\text{Replacement Factor x Cost of Option}}$$

The savings associated with each architectural option were evaluated by using ASHRAE steady-state calculations (by using "degree days" = 1/24 degree hours and the calculated balance temperature of the house) on a hypothetical house. In order not to make the evaluation building-specific, the estimated savings and costs associated with each square foot or linear foot of an option were examined. A building was divided into areas of parallel heat flow; each area was examined separately. This procedure assumed that any given square foot of weatherization would cost and save as much as the next. For each area every increment (layer) was evaluated. For attics, 3, 6, 9, and 12 inches of insulation were evaluated. For windows, each additional pane of glass was evaluated.

Because there were no cost limitations and all cost-effective options were to be installed, the interdependence of architectural and mechanical options was considered by evaluating options at the point where the optimum package had been installed. At this point, it was assumed that architectural options had reduced the building load by 50% and mechanical options had improved the heating system to the point where seasonal efficiencies for oil systems were 60%, for gas systems 70%, and for unvented space heaters 100%. Site-specific, 1978 fuel and installation costs were used in selecting both architectural and mechanical options. 1978 gas prices ranged from $0.23 to $0.31/therm; oil prices ranged from $0.46 to 0.49/gal. This methodology caused the architectural options to vary from site to site and from house to house depending on the fuel used, while the mechanical options varied on a house-by-house basis, depending on the type of heating system and its efficiency.

After the options were selected by NBS, they were installed by local weatherization crews and building contractors. It was the responsibility of each local CAA (using the Home Retrofit Manual)2 to assure that the options were installed using appropriate materials and methods and within cost limits set by NBS. Local CAAs also inspected each house before any options were installed to identify any fire or health hazards or code violations. The quality of the work was average. (See p. 47 of Ref. 3 for the options installed in each house.)

In 1980, after optimal weatherization had been performed and measurements taken, 20 of the houses in the subgroup were upgraded with solar collectors, stoves, circulation fans, and house-doctoring. From two to six solar air collectors (4 ft x 8 ft x 5 in) were mounted vertically on the south walls of several houses. The stoves that were installed could burn either coal or wood. Circulating fans were hung at a high point in several houses wherever temperature stratification was greater than 5° F or where a stove or solar collector was installed. After a thorough attempt was made to plug up all sources of air leakage, houses were house-doctored using a blower door and thermography equipment, and further attempts were made to reduce air leakage.

4. DATA COLLECTION

CAA personnel in the field, under the guidance of NBS, collected the data required to record the savings and costs associated with retrofitting each house. Extra meters were installed on many houses to separate fuel used by the furnace from that used by the water heater. These meters were usually owned and installed by utility companies, in some cases at no cost, or installed by local heating contractors. Existing utility meters on the houses or on oil trucks were used as backup sources of data. Generally, special meters were installed on the furnace (to record running-time and on-off cycles) and on the water heater (to record fuel and water used). The cost of metering averaged $300 per house. Data on the cost associated with installing the options (labor, material, and overhead) were collected on a house-by-house basis as the options were installed. Data are reported in Ref. 4. The procedures for collecting data were:

- To decide what would be done with the data before collecting it and to collect only that data needed for a predetermined calculation.
- To use inexpensive methods of collecting data.
- To collect the same data in several ways to cross-check it.
- To use non-technical people rather than data-loggers to collect data.
- To process the data as it was collected rather than stock-piling it for later use.

5. RESULTS

Weatherization doubtless can provide considerable savings for low-income households. The real question is at what point we should stop weatherizing. The answer depends on the future cost of fuel. Table 1 lists the dollars spent and savings accrued for each house in the study. Figure 2 shows the savings associated with a variety of intelligent expenditures of dollars for energy-conserving retrofits. The cost-effectiveness of weatherization stays constant up to about $2200, at which point the savings achieved by spending additional dollars drops off. The 68 houses which received only architectural options (labeled a in Fig. 2) at an average cost of only $1336 achieved 17% savings with a simple payback period of 15 years.* The 74 houses that received both mechanical system and architectural options (labeled m in Fig. 2) at an average cost of $1841 achieved savings of 41% with a payback period of 6 years. This equals a 41 minus 17, or 23% additional improvement at an average additional cost of only $505. The 20 houses that were later upgraded with house-doctoring, stoves, solar collectors, and circulation fans saved a total of 54% at an average cost of $2806. This is an additional increase of 13% at a cost of $965. This last increment cost twice as much for half the savings. The question is: was that last increment still cost-effective? Yes. For an average investment of $965, $1560 can be saved at a gas price of $0.60 per therm for the next 20

*Payback periods are based on 1979/80 fuel prices. Gas prices ranged from $0.23 to $0.67/therm. Oil prices ranged from $0.96 to $0.99/gal.

years. This provides a payback period of about 12 years. Included in this group of 20 houses are 5 successes that reduced energy use by an average of 80% at an average cost of $3343 and one super-success that reduced energy use by 91% at a cost of $5688.

Of the options installed, the house-doctoring (H) and circulation fans (N,P) seem to perform most cost-effectively and the stove (W, Z) least. If one adds the cost of stove fuel to the equations, the performance is even worse. Annual savings of $15 are not uncommon for the stove. While the sample from which these final conclusions are drawn is really too small to allow generalization, the cost-effectiveness of energy conservation beyond optimal weatherization is worth further investigation, and houses that can achieve total savings greater than 80% need to be better understood.

6. ACKNOWLEDGMENTS

This work was originally supported by the Community Services Administration (CSA) and performed by the National Bureau of Standards (NBS) and the Midland Energy Institute (MEI). After the abolishment of CSA and bankruptcy of MEI, this work was supported through Lawrence Berkeley Laboratory (LBL) by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. Special acknowledgments should be given to Richard Saul at CSA for keeping the project going, to John Cable at DOE for picking up the pieces, and to Brad Turk, Richard Prill, John Baker, and David Sharp at the sites for installing options and collecting and organizing data.

7. REFERENCES

(1) Crenshaw, R., et al., CSA Weatherization Project Plan, NBSIR 79:1706, National Bureau of Standards, March 1979.

(2) Energy Resources Center, Home Retrofit Manual, Energy Resources Center, University of Illinois at Chicago Circle, 1979.

(3) Crenshaw, R., and Clark, R., Optimal Weatherization of Low-Income Housing in the U.S.: A Research Demonstration Project, NBSS 82-144, National Bureau of Standards, 1982.

(4) Weber, S. F. Boehm, M.J., and Lippiatt, B.C., Weatherization Investment Costs for Low-Income Housing, NBSIR 80-2167, National Bureau of Standards, November 1980.

Table 1
DATA FOR FIGURE 2

House #	Savings (MBtu)	Cost ($)
ATL 01A	12.5	352.
ATL 02A	4.0	560.
ATL 17A	3.9	1949.
ATL 22A	-11.8	503.
ATL 23A	-2.0	178.
ATL 29A	53.6	528.
ATL 31A	33.1	3347.
ATL 32A	2.7	2274.
ATL 11C	4.7	0.
ATL 21C	16.9	0.
CHA 2A	17.4	741.
CHA 3M	20.5	927.
CHA 8M	21.3	966.
CHA 16A	19.5	1123.
CHA 18A	11.2	1231.
CHA 20A	10.4	1281.
CHA 23A	13.9	1600.
CHA 25A	14.9	837.
CHA 33A	43.9	773.
CHA 39A	49.8	1038.
CHA 44A	11.7	817.
CHA 47M	8.9	546.
CHA 49M	10.1	821.
CHA 5C	3.5	0.
CHA 19C	5.0	0.
CHA 21C	10.4	0.
CHA 24C	15.0	0.
CHA 28C	-6.2	0.
CHI 5M	101.4	1391.
CHI 9M	156.6	2758.
CHI 11M	73.5	1693.
CHI 12M	316.6	3976.
CHI 14M	78.8	813.
CHI 19M	103.3	3399.
CHI 25M	76.7	1803.
CHI 29M	110.1	2380.
CHI 32M	26.9	3434.
CHI 38M	106.2	1845.
CSP 7M	48.3	1591.
CSP 11M	56.4	1320.
CSP 13M	10.2	1082.
CSP 14M	32.7	2088.
CSP 17M	45.0	1879.
CSP 20M	15.0	954.
CSP 23M	61.6	2326.
CSP 24M	70.7	990.
CSP 26M	63.7	2348.
CSP 31M	81.6	2340.
CSP 37M	85.2	1655.
CSP 41M	49.0	1525.
CSP 43M	53.2	2056.
CSP 44M	96.7	2223.
CSP 47M	109.4	2308.
CSP 49M	87.8	1560.
CSP 1C	2.4	0.
CSP 5C	-43.3	0.
CSP 8C	14.7	0.
CSP 10C	26.8	0.
EAS 4M	15.2	319.
EAS 12M	28.0	1632.
EAS 20A	6.6	1132.

Table 1, continued
DATA FOR FIGURE 2

House #	Savings (MBtu)	Cost ($)
EAS 22M	39.9	1384.
EAS 23A	54.4	1466.
EAS 25M	55.4	719.
EAS 27M	56.9	1057.
EAS 28M	11.8	1359.
EAS 31M	15.1	516.
EAS 33M	.5	763.
EAS 39M	6.4	275.
EAS 42A	6.0	24.
EAS 44M	46.9	1823.
EAS 32C	14.0	0.
EAS 38C	2.9	0.
EAS 46C	37.2	0.
FAR 02M	49.2	1269.
FAR 06M	77.4	2825.
FAR 10M	59.9	2429.
FAR 11M	43.8	1654.
FAR 15A	28.9	1366.
FAR 17M	59.1	1993.
FAR 25M	31.3	2161.
FAR 27A	24.3	1776.
FAR 30M	54.2	1455.
FAR 32M	32.1	1213.
FAR 35M	125.1	312.
FAR 36M	23.5	1054.
FAR 13C	10.0	0.
FAR 22C	-.9	0.
FAR 23C	53.3	0.
FAR 26C	9.9	0.
FAR 34C	-2.9	0.
OAK 17A	7.2	187.
OAK 19A	4.7	305.
OAK 31A	-6.8	234.
OAK 33A	2.5	207.
OAK 34A	11.4	231.
OAK 35A	.4	281.
OAK 38A	24.9	473.
OAK 5C	-30.2	0.
OAK 6C	19.3	0.
OAK 9C	-34.0	0.
OAK 37C	-1.1	0.
POR 7M	95.4	2411.
POR 9M	90.2	1565.
POR 10M	10.5	849.
POR 11M	84.7	2363.
POR 12M	167.7	3840.
POR 15M	-40.9	2099.
POR 16M	46.1	1926.
POR 17M	43.0	2698.
POR 20M	83.9	1914.
POR 21M	33.8	2719.
POR 23M	72.6	1981.
POR 25M	202.1	1710.
POR 26M	107.3	1534.
POR 28M	150.5	3407.
POR 29C	5.9	0.
POR 30C	95.7	0.
POR 31C	-23.4	0.
POR 33C	36.3	0.
STL 5A	-16.0	1851.
STL 6A	-28.0	654.
STL 7A	79.9	3550.
STL 17A	-31.1	232.

Table 1, continued
DATA FOR FIGURE 2

House #	Savings (MBtu)	Cost ($)
STL 28A	-16.0	1334.
STL 29A	-64.3	338.
STL 34A	80.2	3270.
STL 38A	38.5	2875.
STL 40A	-80.0	1027.
STL 41A	-13.8	1180.
STL 42A	57.5	1953.
STL 46A	-31.6	688.
STL 49A	85.2	2586.
STL 55A	43.3	1853.
STL 56A	30.2	1588.
STL 77A	58.8	3214.
STL 92A	31.5	998.
STL 93A	89.0	2870.
STL 10C	45.1	0.
STL 23C	25.6	0.
TAC 4A	22.7	1210.
TAC 21M	86.6	2550.
TAC 39M	41.7	1551.
TAC 45A	73.2	2476.
TAC 49A	28.5	1178.
TAC 55M	54.7	2287.
TAC 81A	26.5	1380.
TAC 83M	49.5	2340.
TAC 87M	22.2	1291.
TAC 37C	-1.8	0.
TAC 58C	27.4	0.
TAC 75C	-1.6	0.
TAC 76C	6.3	0.
TAC 98C	16.8	0.
WAS 2M	48.4	2693.
WAS 7M	32.5	3593.
WAS 41M	32.0	2339.
WAS 53M	132.7	3071.
WAS 6C	-10.1	0.
WAS 57C	-59.9	0.
FAR 32H	18.97	1518.
FAR 30D	-.34	0.
FAR 6H	97.35	3168.
FAR 10F	51.45	2537.
FAR 15H	32.61	1694.
FAR 35S	34.2	1081.
CSP 47H	98.77	3308.
CSP 24P	193.46	1554.
CSP 11N	73.90	2435.
CSP 13P	21.28	1671.
CSP 17P	61.55	2337.
CSP 20F	13.30	1085.
CSP 23D	9.14	0.
CSP 31Z	135.12	5688.
CSP 34S	102.77	5727.
CSP 41D	-26.82	0.
CSP 44N	134.43	3637.
CSP 490	102.92	3871.
FAR 36S	19.04	1515.
FAR 17W	60.34	3316.
FAR 27W	21.28	3209.
CHA 44W	35.13	3067.
CHA 16W	5.0	3710.

End of Table 1. Figure 2 follows.

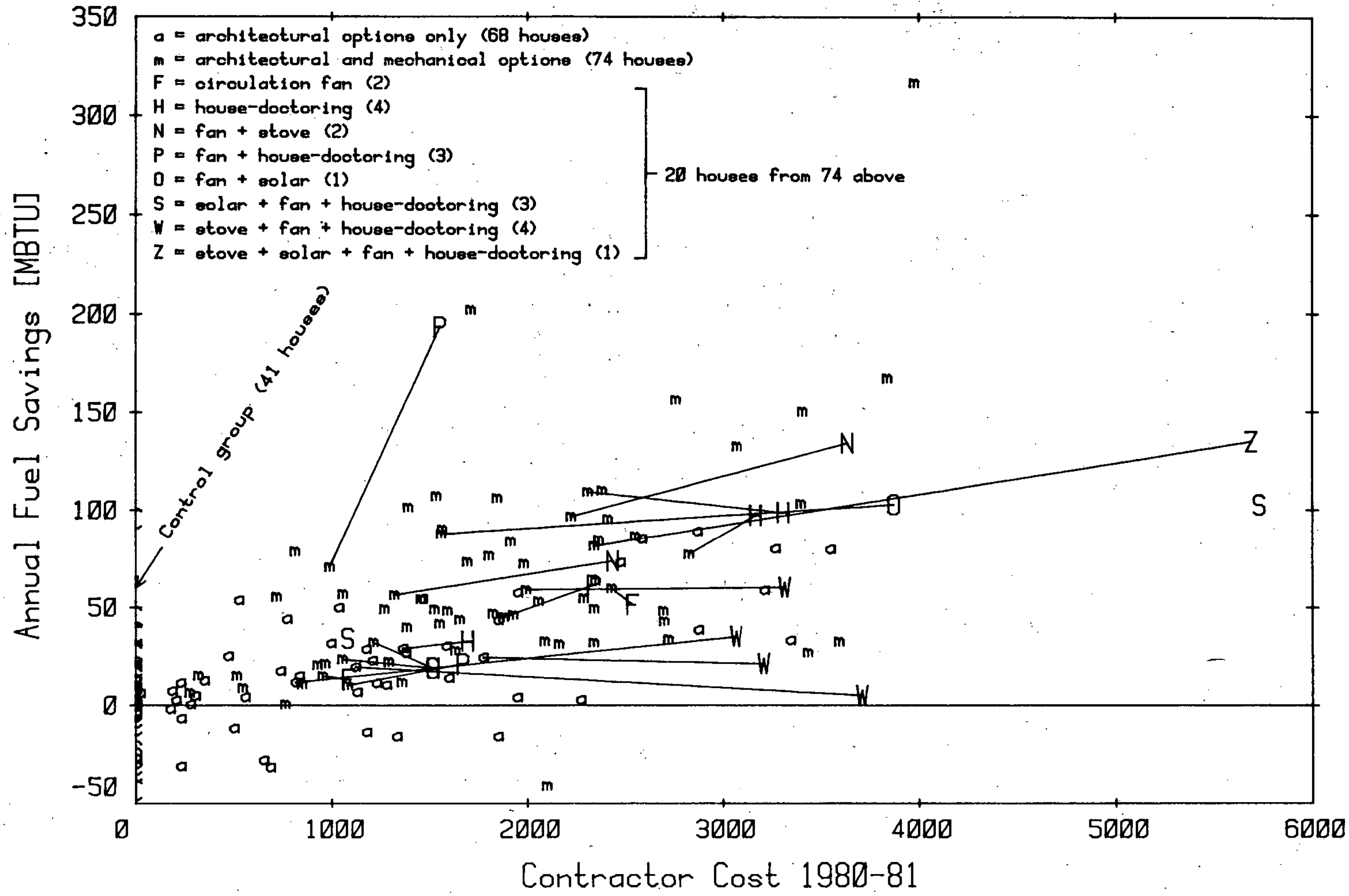


Figure 2. Annual fuel savings vs. contractor cost for 142 weatherized houses and 41 controls. The letters indicate 20 of the 74 houses that were further retrofit the following season; lines join the first and second retrofits.

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