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Prepared by:
Proctor Engineering Group, Ltd.
San Rafael, CA 94901
(415) 451-2480

SUN POWER
HOUSE NURSE PROGRAM

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Final Report

Contributors:
John Proctor, P.E.
Rob de Keiffer
Sun Power Consumer Association

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SUN POWER HOUSE NURSE PROGRAM

(Revised 9/26/88)

John P. Proctor and Robert C. deKieffer
Sun Power Consumer Association

INTRODUCTION

This paper is the result of our experience applying the set of procedures and criteria we have called "House Nursing" to over 1500 houses. The project was originally proposed late in 1982. In 1985, it was funded as a pilot project of 100 homes by the Colorado Office of Energy Conservation (O.E.C.). Subsequent to the pilot project, O.E.C. continued to fund the House Nurse program. It was delivered to low income households using Low Income Energy Assistance (L.I.E.A.P.) funding. One weatherization agency in Colorado now uses the Sun Power House Nurse program as the "General Heat Waste" portion of their D.O.E. weatherization program.

The House Nurse program is part of a comprehensive set of weatherization procedures (see Proctor, 1984, 1986 and 1987). These procedures have in common the goal of maximizing the long term energy savings while minimizing the program cost.

When the savings associated with individual conservation retrofits and programs are studied one thing becomes clear. The savings (and therefore the cost effectiveness) for the same procedures varies dramatically from unit to unit. We therefore take a twofold approach to the situation. First, continually refine and monitor the program to improve the "hit ratio" (percentage of units that have savings exceeding 5%). Second, keep the investment in each house low to minimize the program's financial risk on each unit.

The published weatherization research over the last fifteen years has shown that savings in the order of 20% could be commonplace. Nevertheless, evaluations continue to show that even with expenditures in the $1000 to $1600 range that savings are often below 10%. The difference between a trained individual systematically addressing the heat loss problems of a house and the conventional caulk, weatherstrip and storm window approach can be very impressive. In 1982-83 a comparison study was done in New York City. The results were that conventional weatherization saved 2.5% at a cost of $1116. However by using House Doctor procedures and personnel, a savings of 20.2% was achieved for $1393 (Rodberg, 1984).

Background

In the 1970's the Center for Energy and Environmental Studies at Princeton University began to show the efficacy of the House Doctor approach. At the same time more information became available that the traditional foci of weatherization efforts, such as doors and windows accounted for only a small part of the air leakage in a house (Harrje, 1979).

House Nurse was created to emulate House Doctoring in a low cost environment. Many of the technical components of the program come from the work at Princeton (Dutt, 1977, 1979, 1982, 1983). Compared with House Doctoring, the Sun Power program uses less - less program money ($300 per unit), less sophisticated equipment and less technician time. It also produces less - less total savings. House Nursing adds a management component that oversees both the technical aspects and employee management. As a total system, the House Nurse program evaluates the major air leakage areas, documents their location, repairs them at a low cost, and makes sure that the technicians get feedback on the work that they have done.

Principles of House Nurse Program

The first principal of House Nursing is to know what is wrong with the house before attempting to fix it (**Diagnosis**). This allows the House Nurse Crew to apply the second principal - immediately work on the largest heat loss items that are the cheapest and easiest to fix (**Cost Effectiveness**). On a practical level this means seal the BIG HOLES in the attic and crawlspace/basement first. Then tackle the medium holes followed by large cracks. The third principal is to know whether or not you have fixed the problems of that house (**Control**). This requires rediagnosing the "leakiness" of the house after the work is considered complete. Fourth, if the house fails to meet the criteria and you have to guess what is still wrong, test to see if your guess was right (**Test your Hypothesis**).

PROGRAM COMPONENTS

Technical Measures

The items which result in the largest reduction in heat waste that are the cheapest and easiest to fix include:

1. Thermostat set backs - Client Education on manually setting down the thermostat.

2. Lower domestic hot water temperature - Mark existing temperature setting, then with client present, set to lower setting. Client Education on this point is essential. Without the education the client will often reset it higher than its original setting.

3. Insulate the domestic hot water tank and first three feet on both the hot and cold water lines.

4. Reduced shower flow - When flow exceeds 3.75 gpm replace shower head with low flow head.

5. Heating system adjustments - check safety and cycle efficiency of heating system - refer to heating system program if warranted. Also check safety of water heater.

6. Insulate uninsulated horizontal surfaces - have insulation crew install cellulose to R19.

7. Eliminate major air leaks.

8. Reduce or eliminate convective loops.

9. Reduce or eliminate wind washes.

Combustion Appliances. An unusual technical component of the program is a screening of the furnace and hot water systems. If these combustion appliances are operating inefficiently or pose a safety problem, the crew refers the unit to the Sun Power furnace modification crew. This screening process increases the potential that the furnace modification program will deal with furnace systems that truly need assistance and assures that the weatherization program is leaving the unit in a safe & efficient operating condition.

Air Leakage. Not unlike House Doctoring programs, the House Nurse program spends a great deal of time in the basement and attic. Other than a few large holes (such as missing windows and open fireplace chimneys), the "hot spots" are in the attic and basement. A majority of the homes have large holes that can be repaired cheaply. Many of the holes were identified in early Princeton research including: open flue chases, open plumbing walls, open end walls, open interior walls and drop ceilings. These leaks are sealed with the appropriate material: sheet metal - flue chase, heavyweight plastic film and acoustic sealant - open walls and drop ceilings, foam "stuffers" - open walls, floors adjacent to knee walls and cathedral ceilings. Additional major leakage sites include: a large crack around the perimeter of the lower floor on masonry construction. In these houses the subfloor does not extend to the exterior wall, leaving a substantial gap accessible from the crawlspace. Another major leakage site occurs in block homes. On some of these homes the drywall is affixed to the block via 1x2 furring strips. This leaves a vertical "chimney" around the perimeter of the building open from the basement to the attic. Both of these gaps are filled with one or two component foam sealant.

Pressurizing the house is essential to insuring the largest holes are found and effectively plugged. With the help of the ELA (Equivalent Leakage Area) estimation form, the House Nurse crew has an excellent shot at finding and sealing many significant leakage points of the house.

Convective Loops. A convective loop is not detectable by pressurization methods unless it also communicates with a significant leak to the interior of the house. Under proper conditions an infrared scanner would assist in finding these locations. The House Nurse does not have a scanner and uses the ELA estimation form to assist in finding them. Many open convective loops are physically the same as major leakage sites (open end walls, open interior walls, etc.) and are sealed in the same manner.

Wind Washes. Wind washes cause heat loss in the same manner as convective loops. Heat is lost as the exterior surface of the drywall (or equivalent) is cooled by the *movement* of cool air against that surface. In the case of the wind wash, this air movement is caused by wind conditions. The classic example of a wind wash is open crawlspace vents on opposite sides of the house. This is sometimes accompanied by the addition of batt insulation loosely placed between the joists. This provides a "wind tunnel" to funnel the movement of cold air against the bottom of the floor. Wind washes are eliminated through the crawlspace by closing crawlspace vents. Wind washes due to attic soffit vents are redirected with air deflectors to prevent air movement directly over the ceiling surface.

Production

The system is designed to accomplish high production at the same time minimizing the number of significant leaks that are missed. The basic work uses three technicians for a total of up to 4 hours, or 12 person hours. This allows each crew to do two houses a day. Each technician has an assigned job and a step by step checklist to assist in locating leakage areas. The breakdown of work responsibilities is shown in Figure 1.

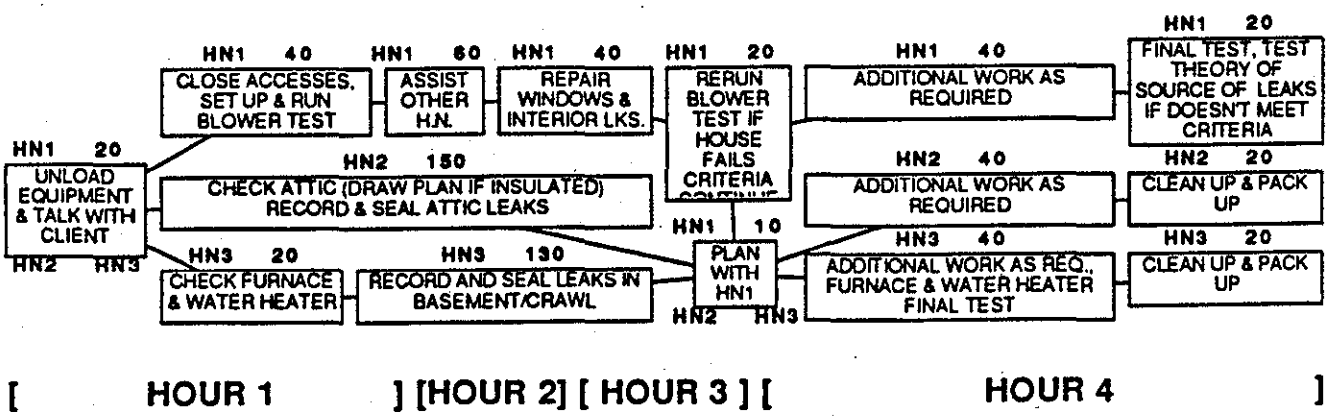

Figure 1. Work flow path for the House Nurse Crew

House Nurse 1/is in charge of the process. They conduct leakage tests, client education and "get their hands dirty" sealing leaks. They recheck the pressurization measurement at the 3 hour mark. If the the criteria are met, the house is completed and the crew moves on to the next house. If the criteria are not met they continue to work on the home to reach the criteria.

The pressure test is rerun near the end of the fourth hour. If the criteria are still not met , they reach their best estimate of the source of the problem, isolate that area and test the house again. For example, if they believe the source of the large leaks they have been unable to control is an old porch converted to use as a heated area, they seal off the porch from the house and retest. This information gives the program manager the information necessary to determine if additional work is worthwhile on this house.

The Most Important Components

The most important components of the system are the House Nurses. While often weatherization programs require that the technicians blindly follow the prescriptions of some other person (usually called an auditor), the Sun Power program utilizes the experience, and intelligence of all three members of the team. Since the brain is the most important "tool" in the "toolbox", much of the program is designed to facilitate its use and sharpen its capabilities.

Training. The initial training begins with four hours of classroom instruction on the dynamics of heat loss, concentrating on air movement and exchange. That is immediately followed by demonstration of the use of the equipment used in the program. The second day of training begins by using the House Nurse system on a house and is followed by questions and answers. The concentration is on the technicians having both an explaining and doing level of understanding of the subject. The third day is spent doing two houses with the trainer present. The initial training is important to ground the House Nurse in the theory of what they will be doing. It also sets the tone and expectations of the program. At the same time the training creates some familiarity with the materials and devices to be used. However people really learn while doing work on the houses. This is one reason the program uses feedback on every house (via the ELA Estimation Form and the Blower Window). It is also one of the reasons that inspection of a significant number of the houses is important.

Criteria. The crews must have a measure to determine if the home is successfully completed. The measure used is known as Equivalent Leakage Ratio (E.L.R.). The E.L.R. is simply the Equivalent Leakage Area in square inches divided by the surface area of the home in hundred square feet. The goal of the House Nurse crew is to lower the leakage ratio by 50%, but to achieve an E.L.R. of not less than 3 (in order to avoid houses being "too tight"). The minimum acceptable reduction is 30%.

Regardless of the initial E.L.R. the crew must meet all the other criteria, including reducing all accessible convective loops and wind washes, heating system safety/efficiency screening and client education.

Ability to meet criteria. As part of the Sun Power Accelerated Monitoring Program (SPAM) (deKieffer, 1987) six units were tested using a blower door before and after the House Nurse program was applied. The results are shown in Table I.

Table I. Change in E.L.R. due to application of the House Nurse program.

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Average
Initial E.L.R.	7.16	3.66	7.69	6.24	9.19	8.02	6.99
E.L.R. Reduction	43%	24%	36%	41%	36%	37%	36%

E.L.A. Estimation Form. This form lists the most commonly found leakage areas in rough priority order and provides an estimate of the overall leakage that is expected from each. Points (actually E.L.A. in sq. cm.) are calculated based on the number of linear feet of open wall, number of open flue chases etc. This provides quick estimates of the magnitude of the problems. Each technician records all the leakage sites they know to exist and records which of those they have sealed. This form provides important information on the amount of E.L.A. reduction you would expect to see by using a pressurization technique. The form also lists those items that are convective loops and wind washes.

The sources of the numbers used in this form were primarily empirical data. The largest source is Harrje (1984). Whenever empirical data was not available estimations were created based on similar holes that had been tested.

This form provides a method of "inspection at a distance". It provides the manager with a solid understanding of the original building type and condition, the types of holes that were sealed and the probable effect they should have on leakage. When this is compared to the data from the pressurization tests, it gives a strong indication of the effectiveness of the work that was done and the need for additional work. Very importantly it also institutionalizes the feedback to the technician.

Does the form work? As a part of the program the form definitely aids in identifying problems in the work or abnormalities in the building. It forces the technician to locate the holes, document which ones were able to be sealed and indicates what is left open. The program manager compares the estimated ELA sealed with the reductions found by the blower window.

Inspections. By using this "inspection at a distance", it is possible to adequately control a program with on the spot inspections of only 30% of the units. It is essential however that these inspections are regularly done throughout the program and include verification of the pressurization measurements as well as the actual work done. The savings analysis that follows illustrates why that is essential.

Blower Window. Pressurizing the house is essential to insuring the largest holes are found and effectively plugged. The pressurization device should be easy to use, provide the technicians with a measure of the "leakiness" of the building (before and after) and assist them in finding the holes that most need their attention. At the time that the program started, blower doors were a very expensive tool. The original blower doors provided a measure of CFM or RPM and the pressure difference between inside and out. They then cost $3,000.

In order to avoid this substantial investment the House Nurse program uses a window fan with a high speed capability of 6500 CFM in free air. This is referred to as the blower window. It is used in conjunction with a draft gauge that reads the inside/outside pressure differential in .01 inches of water. The cost of the fan is $49. Using this device on high speed, the technician records the pressure differential in both the pressurization and depressurization modes. Figure 2 converts the pressure differential to E.L.A. for this fan. The fan is also used to pressurize the building in order to locate leaks into the attic and crawlspace. Used in the depressurization mode the fan assists in finding leaks into the interior.

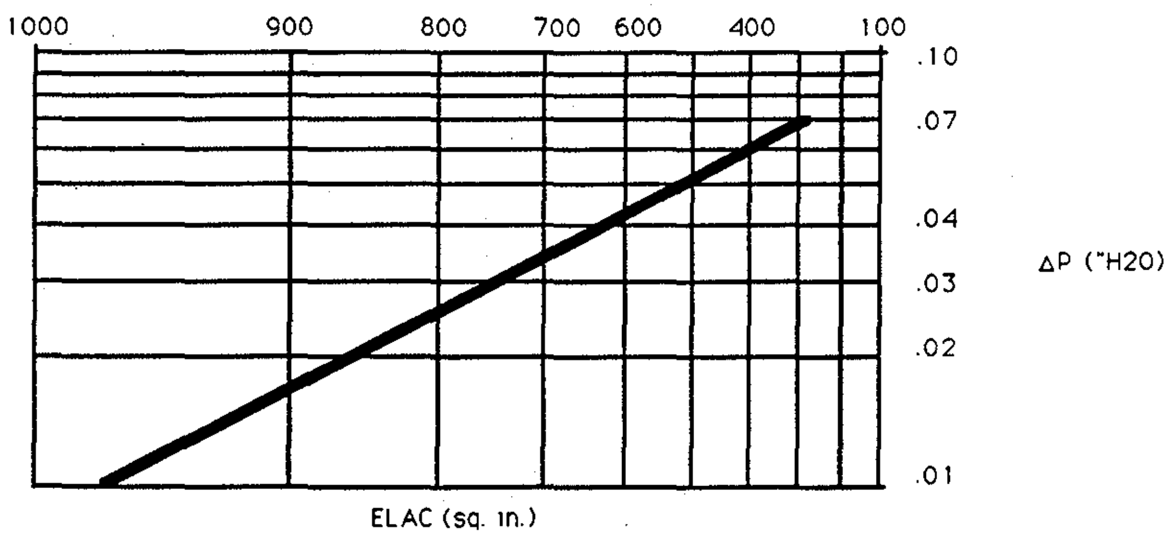

Figure 2. Conversion of measured pressure differential to E.L.A. for the Blower Window.

Measurement of the E.L.A. using the blower window is subject to substantial error. Errors in reading the draft gauge are common. The pressure data is not corrected for changes in density. Only one reading is made in each mode, pressurization and depressurization. With large E.L.A.'s, the fan does not generate enough pressure to be able to determine the E.L.A. This is easily demonstrated by figure 3, which plots the calibration curve in linear coordinates along with data from actual houses measured with both a calibrated blower door and the blower window.

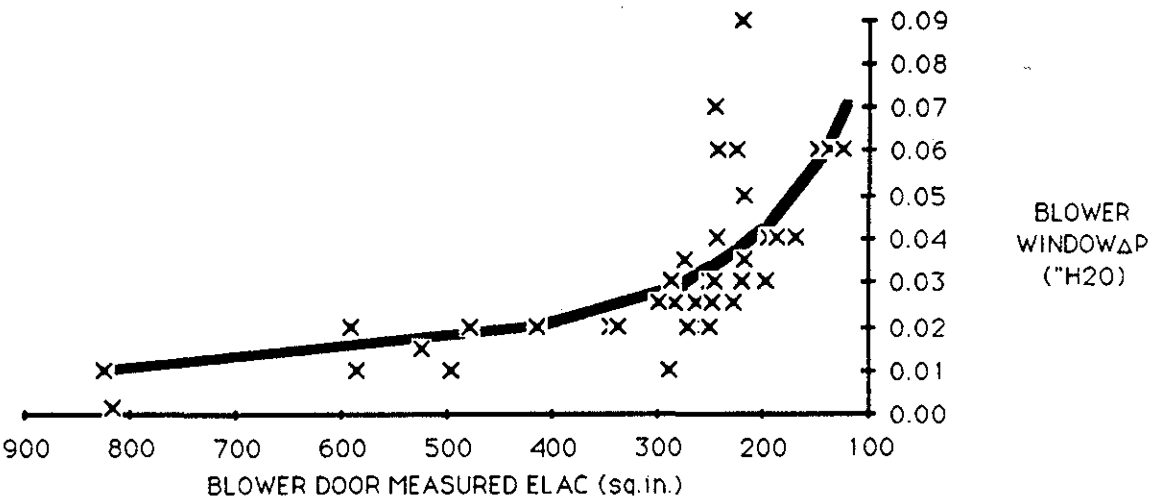

Figure 3. Data scatter for measurements using the blower window.

The deviation of these measured points from the calibration curve are due to errors both in the use of the blower window and the blower door. However, it is clear the majority of the error is in the use of the window fan.

Our conclusions concerning the use of a low cost pressurization device are:

1. The blower window used doesn't prove much for E.L.A. above 200 sq. in. It is a helpful indicator below 200 sq. in.

2. If the technician has a blower door available, it is a preferable tool to the blower window.

3. If a low cost pressurization device is all a weatherization entity can afford, the device should be equipped with accurate easy to read gauges, results should be calculated from multiple readings and the fan should be capable of high CFM at pressures above .20 " of water.

Administrative

The management system, used to support the technical approach, can keep the quality and energy savings on a consistent level. The management system used on the House Nurse program is the same as is used on the heating system programs (Proctor, 1986). It includes evaluation of the work done on every house, feedback to the technician within one week about each house and inspection of sufficient houses to insure the accuracy of the information being received from the technicians. In this study there was a drop from an average 9.5% savings to an average 2.4% savings, when the management system was not followed.

Barriers to Implementation. Implementing this program is not easy. It requires that adequate money be spent on training the technicians and the managers. It requires overcoming the inertia of many years of caulking and weatherstripping homes. It means that the supervisor has to know more about the science of weatherization and be willing to insist that the technicians follow the program. The managers and technicians have to be rewarded for their competency as well as their production.

SAVINGS

Method

Utility Data was obtained by the Colorado Office of Energy Conservation (O.E.C.) on the first 100 pilot homes. 72 units were dropped from the analysis because of other weatherization work, change in occupancy, shutoffs, estimates and other lack of utility data. The remaining 28 units were analyzed by a method developed by Sun Power as a portion of SPAM.

The analysis technique starts with the same basic assumption as PRISM (Fels 1986), that is, heating fuel use can be modeled by the linear equation:

$$F = b_a \times t + s \times D_{Tbal}$$

where

- F = the amount of fuel used in a particular time period in CCF
- b_a = The base amount of fuel used when there is no heating load in CCF/Day
- t = The time period between data points in days
- s = The amount of fuel used per Degree Day at the derived balance temperature (Tbal) in CCF/Degree Day
- D_{Tbal} = Degree Days calculated from the derived balance temperature in °Fdays
- Tbal = The balance temperature determined to give the best fit line.

Unlike PRISM, the base fuel use is not allowed to float to obtain the best fit. Instead the base use is determined from the summer fuel use. This results in what we believe to be a closer approximation to the true heating slope and balance temperature. For further discussion of this technique see (Proctor, 1987). When the values of b_a, s and Tbal are determined the fuel consumption for a year of "normal weather" is calculated. This value is called the normalized annual consumption and given the symbol NAC. This is evaluated for the time period prior the the intervention (NAC_1), and after (NAC_2). The % total savings (S) is determined by the formula:

$$S = \%\ \text{total savings} = (NAC_1 - NAC_2) / (NAC_1)$$

Results

Date Dependent Savings. S (percent total savings) was found to be dependent on the date the work was done. This is shown in figure 4.

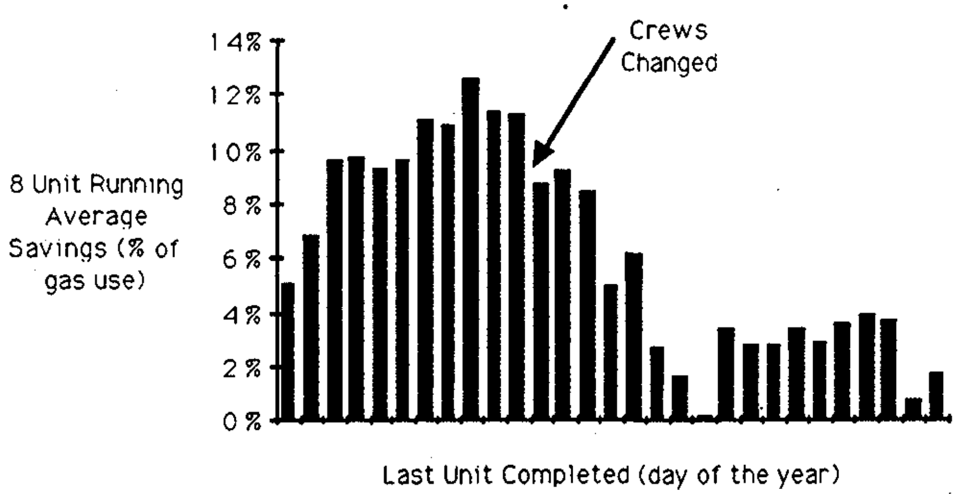

Figure 4. Date dependency of savings.

In Figure 4, the units are ordered by date done and the average savings of the last 8 units is plotted. Initially there is a rise in savings. The savings levels, then falls to a new substantially lower level.

This pattern could be the result of any of these three items:

1. Random variation.

2. Differences in houses treated in the time period.

3. Differences in what was done to the houses.

The initial period during which the savings rose, began in early June and continued to mid July. The data base for that period consists of only 4 units, so no statistical conclusions can be drawn. That time period covers the initial development of the program. The crews were individuals temporarily assigned to the program from other programs. It is reasonable to assume that the savings increase is due to program development and learning in this period.

Period 2 began in August, with the complete training of a "permanent" House Nurse crew. The data suggests that it ended at the end of September. During that period the program was run as designed. There was feedback to the crews on every house. Inspections were regular and the supervisor was often there checking the pressurization numbers while the crew was in the house. This period ended and the next began when the two most experienced individuals from the "permanent" crew each become a House Nurse #1 for two new crews. The utility analysis of the ten units in this data set shows, **the average savings for work done during period 2 was 9.5%,** while heating only savings averaged 11.5%.

Period 3 began with the first house of the two new inexperienced crews. Creating two crews was a response to the need for increased production. The new individuals were not given the full three day initial training. They got about a half day on theory, and some attention in the field. Training was primarily relegated to "on job training" with the more experienced crew member. This period continued until the end of the program cycle. In the first month of this period the supervisor's attention was focused on other tasks. Form review and feedback was sparse and irregular. Inspections were rare. Late in this period form review, feedback and inspections increased, although the inspections did not check the pressure readings that were reported by the crews. Analysis of the fourteen units in this data set shows, **the average savings for work done during period 3 was 2.4%.** Heating only savings for period 3 averaged 3.0%.

Are the differences in savings between period 2 and period 3 random variation? To answer that question a t test was run on the % total savings (S) for the units completed in period 2 vs the savings for the units completed in period 3. The result was a t of 1.76 which is significant at the .10 level. Therefore it is inferred that **the differences in savings between the two periods are not due to random variation.**

Are the savings differences due to variations in the house/occupant systems that existed prior to the work of the House Nurses? Fifteen numerical indicators of the house condition and its performance before intervention were analyzed using t tests. These indicators included: Balance Temperature, Heating Slope, Base NAC, Heating NAC, Total NAC, ELA recorded and Initial Pressure Reading. None of these indicators produced t test results that showed any significant difference. It is therefore inferred that **there was no significant difference in house/occupant systems between the units treated during the two periods.**

Since the significant differences in savings between periods 2 and 3 are not random nor due to initial differences in the houses, they must be due to differences in how the program was applied to the house. We conclude that **failures in applying the management system (including training) resulted in failures to do the work correctly on the house. These failures are responsible for the difference between 9.5% natural gas savings and 2.4% savings.**

Correlations

S (% savings) for the data sets from period 2, period 3 and all units were analyzed with respect to thirty two variables by calculating the Pearson Product Moment Correlation Coefficient (r). The results are shown in Table II.

Table II/ Variables showing significant correlation with percent savings.

Data Set	Variable	Correlation Coef.	Level of Sig.
All Units	Initial T_{bal}	.5314	.01
N = 28	Basement ELA sealed	.3413	.10
	LN(est. ELA remaining)	-.3775	.10
Period 2 Units	Initial T_{bal}	.6897	.05
N = 10	Initial Heating Slope	-.6168	.10
Period 3 Units	Basement ELA sealed	.6967	.01
N = 14			

The correlation between the estimated ELA sealed in the crawl/basement and savings reinforces the focus on the crawl/basement area. It also should come as no surprise that the larger the number of known leaks you leave in the house the less likely savings will occur.

Original Balance Temperature. The original balance temperature is a good predictor of how successful the program will be in creating savings. Further analysis shows that such a correlation is reasonable if the primary effect of the program is reduction of air leakage.

On days when the average temperature is near the balance temperature of the home, the short term variations in indoor temperature are very important in determining whether the heating system uses fuel to heat the house. When the inside (air mass) temperature responds rapidly to changes in the outdoor temperature then even short periods below the "balance temperature" result in the use of fuel. Conversely, when the inside temperature changes slowly, short term dips in the outside temperature do not result in the use of fuel.

For a home with a given amount of heat loss, the higher the percentage of heat loss due to infiltration, the shorter the time lag, the higher the balance temperature and the more likely the House Nurse program can produce significant savings. Figure 5 shows this relationship. This is analyzed more fully in Appendix A of this paper.

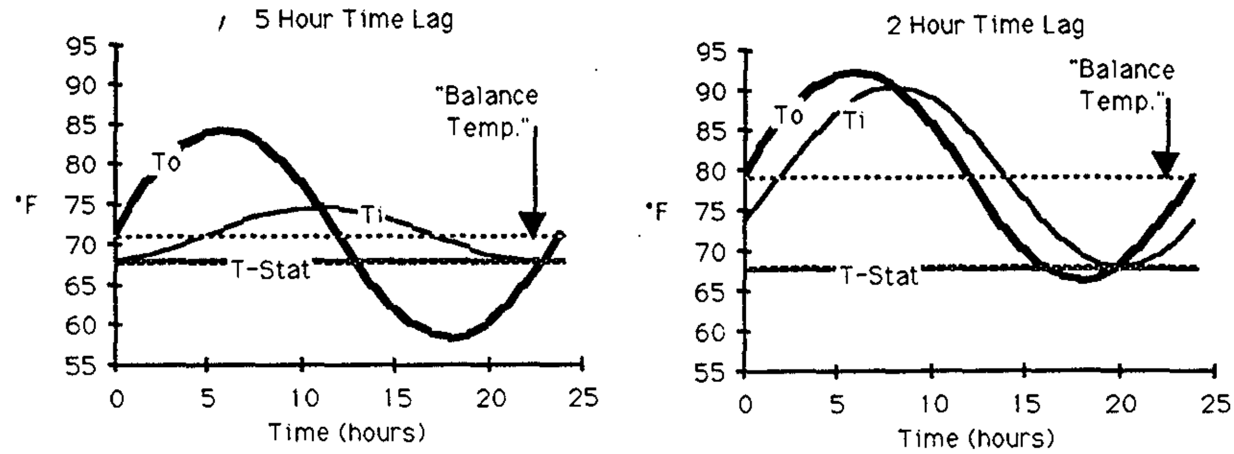

Figure 5. Shift in "balance temperature" due to differences in infiltration rate.

It is probably a corollary to this finding that a house with a steep initial heating slope has a higher percentage of conductive heat loss.

Correlation Between Blower Window Readings and Visually Estimated ELA. The estimated ELA and the pressure measurements made with the blower window are related at the interval level. Specifically the log of the estimated change in ELA correlates with the log of the difference between the pre and post window generated pressures. This correlation is significant at the .05 level for the entire data set. This means that the ELA estimation form provides reasonable information on the actual ELA sealed on each house.

COST PAYBACK

Cost. The total **cost for the House Nurse program averages $300** a unit. This covers all materials, labor and administration. The breakdown of these costs for the units monitored in SPAM is: Materials 26%, Labor 39%, Administration & Overhead 35%.

Payback. The average annual natural gas use for the units in this study was 132.41 million BTU. At a cost of $5.25 per million BTU, the annual gas bill would average $695. Following the complete House Nurse program, including following the management system - as in period 2, the savings would be $66.30 per year. That results in a **payback time of 4.52 years**. This payback compares favorably with the House Doctoring in the Rodberg (1984) study. The House Doctor's 20.5% savings on a $695 gas bill would save $142.47. At a cost of $1393, that would yield a payback of 9.78 years for House Doctoring.

CONCLUSIONS AND RECOMMENDATIONS

1. The House Nurse program is capable of meeting the criteria of 30% to 50% reduction in ELR.

2. The ELA estimation form aids in focusing the technician on the areas of the building that need attention. It also helps the program manager spot problem areas.

3. Inspections must include pressurizing the house to see if the data obtained from the technicians is accurate.

4. Using a pressurization device to assist in locating leaks and to measure results is essential to any air leakage program. A calibrated blower door is preferable to a blower window.

5. In this study, the average savings from the house nurse program delivered as designed was 9.5%. This results in a payback time of 4.52 years.

6. The controls in the house nurse management procedures are critical to the success of the program. Failure to follow those procedures can be measured in the savings from the program. In this study that failure reduced the savings to 2.4%.

7. The calculated balance temperature for the house before the work is done is a strong indicator of the potential for house nurse program success. This is because balance temperature is more heavily effected by air leakage than by conductive losses through walls and ceilings.

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APPENDIX A

For a home with a given amount of heat loss, the higher the percentage of heat loss due to infiltration, the shorter the time lag, the higher the interior temperature swing and therefore the higher the balance temperature. We will examine that assertion in those three steps.

As we proceed with the analysis, we will occasionally have to use data specific to an individual house. When we do we will use the following data for a "typical" Denver low income weatherization house:

Building Total UA	600 BTU/°F hr
Air Volume of the House (V)	14,000 ft^3
Heated Surface Area	3600 ft^2
Window Area	108 ft^2
Window Coefficient of Heat Transfer (h)	1 BTU/ft^2°F hr

Step #1 The higher the percentage of infiltration heat loss the shorter the time lag.

Assumptions applying to both models:

1. The outside temperature (T_o) drops as a step function to T_f = 59°F.
2. The outside temperature and inside temperature (T_i) are initially = (T_1) = 72°F.
3. There are no internal gains.
4. The thermostat will call for heat when the air mass reaches 68°F
5. The air mass of the house has no significant temperature gradients (constant air circulation).

Assumptions for the infiltration heat loss model:

1. All the heat loss is through infiltration (Therefore, a = 2.34 ach/hr)

the energy balance is:

$$dQ = a\,V(ro)\;c\,(T_f - T_i)\,dt = V(ro)\;c\,dT$$

where:
a = air changes per hour, *(ro)* = density of air and c = specific heat of air

This solves to $dt = \dfrac{dT}{a\,(T_f - T_i)}$, Solving by integration $t = \dfrac{1}{a}\ln\dfrac{T_f - T_1}{T_f - T_2}$

where t is the time for the house air volume to go from T_1 to T_2.

This solution applies to any heat loss mechanism that does not involve significant mass other than the house air volume. One such loss is the heat loss through windows, where:

$$a \text{ becomes } \frac{A\,h}{V(ro)\,c}$$

Assumptions for the conductive heat loss model:

1. All the heat loss is through insulated frame walls and ceiling. (Therefore, $k_s = .0694$)
2. There is a temperature gradient through the mass of the walls and ceiling.
3. The walls and ceiling are modeled as two infinite slabs with the house air volume between them. The slabs are homogeneous and have the following properties:

   r = thickness = 5", $(ro)_s$ = slab density = 30 lb_m/ft^3, c_s = .20 Btu/lb_m °F,

   $$m = \frac{k_s}{(ro)_s \times c_s}$$

4. The insulating value of the inside air film is contained in the thermal conductivity (k_s) of the slab and therefore the house air volume temperature is given by the inside surface temperature of the slab.

Using the solution for the temperature history of an infinite slab given in Rohsenow and Choi (1961) the ***minimum*** time lag for the inner surface of the slab to reach the specified temperature occurs when: $\frac{k_s}{h\,r} = 0$
Since that is the most conservative estimate of the time lag we will use Hottel's solution for that case. When $\exp\left[-2.467 \times \frac{mt}{r^2} + .2393\right] < 1$, Hottel's solution is approximated by:

$$\mathrm{LN}\left(\frac{T_i - T_f}{T_1 - T_f}\right) = -2.467 \times \frac{mt}{r^2} + .2393$$

we get :

$$T_2 = T_f + \left[\left\{\exp\left[-2.467 \times \frac{mt}{r^2} + .2393\right]\right\} \times (T_1 - T_f)\right]$$

where t is the time for the house air volume to go from T_1 to T_2.

Four solutions tó these models are plotted in Figure 6. Cases 1, 3 and 4 have identical steady state heat loss. Case 1 - all the heat loss is through due to infiltration. Case 2 - 18 % of the heat loss is through the windows and there is no infiltration loss. Case 3 - all the heat loss is through the moderate mass of the insulated frame walls and ceiling. Case 4 - all the heat loss is through the high mass of the brick walls and insulated ceiling, *(ro)* $_s$ = slab density = 100 lb_m/ft^3.

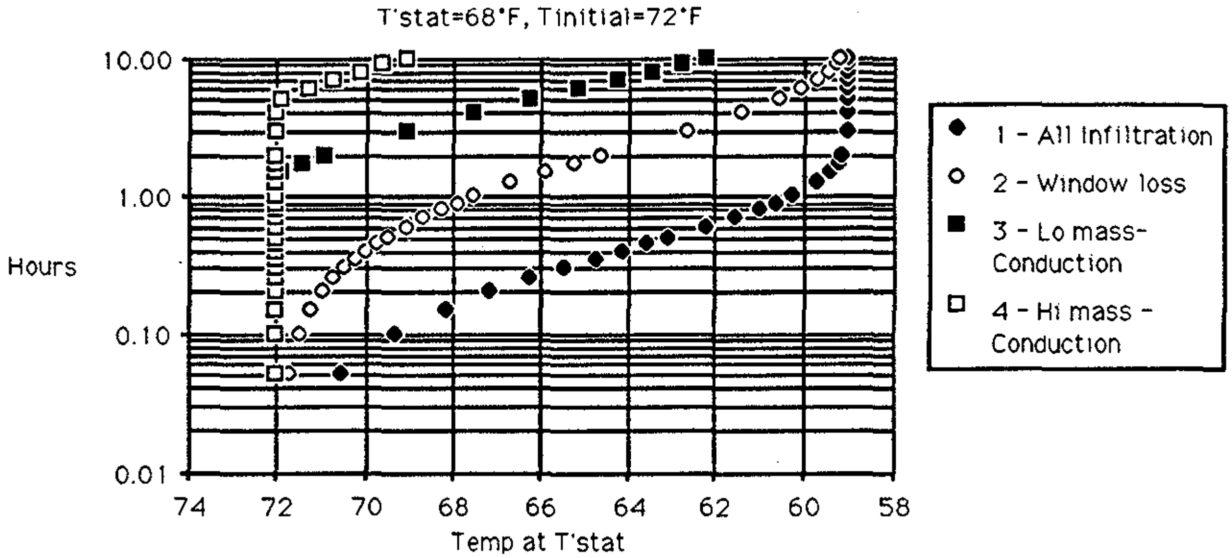

Figure 6. Inside temperature time lag due to differing heat loss modes.

Step #2 The shorter the time lag the larger the interior temperature swings.

Assumptions:

1. The outside temperature $T_o = T_{avg} + T_{os} \times \sin t_r$. where t_r = time in radians .
2. There are no internal gains.
3. The thermostat will call for heat when the air mass reaches 68°F
4. The air mass of the house has no significant temperature gradients (constant air circulation).
5. Since heat loss through a mass has a very long time lag and we want to know what happens in the shorter term transients, we will concentrate on infiltration and window heat loss.

the energy balance is:

$$dQ = a\,V(ro)\;c\,(T_o - T_i)\,dt = V(ro)\;c\,dT$$

therefore:

$$a\,(T_o - T_i)\,dt = dT_i$$

This is solved by:

$$T_i = T_{avg} + T_{is} \times \cos(t_r - z), \quad dT_i = -T_{is} \times \sin(t_r - z)\,dt_r$$

Looking at conditions when $t_r = \frac{\pi}{2} + z$ and when $t_r = z$ we derive:

$$T_{os} \times \sin z = T_{is}$$

and

the lag time (in radians), **$z = \arctan(-a)$ remember a = air changes / hr.**

This confirms that the interior temperature swing T_{is} is dependent on the time lag z, which is dependent on a. This relationship is plotted in Figure 7.

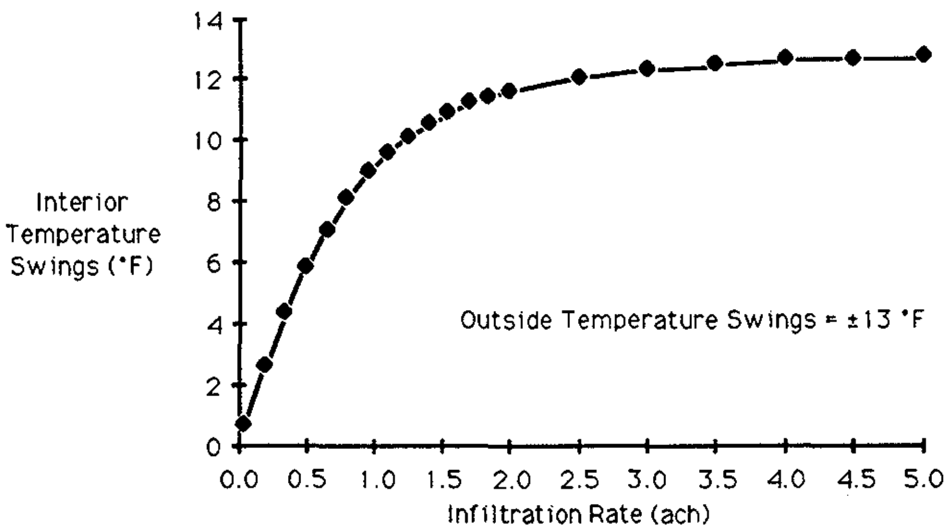

Figure 7. The effect of increased air changes on interior temperature swings.

This solution applies to any heat loss mechanism that does not involve significant mass other than the house air volume. One such loss is the heat loss through windows, where a becomes $\frac{Ah}{V(ro)\,c}$

Step #3 The larger the interior temperature swings the higher the balance temperature.

Figure 8 plots two theoretical houses that have the same steady state heat loss. One home has a larger temperature swing since a greater portion of the heat loss is due to infiltration. In "swing seasons" a good deal of the time is spent near the conditions plotted here. The result is that the home with the higher air infiltration will need heating at a higher average temperature than the other home. Since this fuel use occurs at the higher average temperature, the regression analysis program assigns a higher balance temperature to this house.

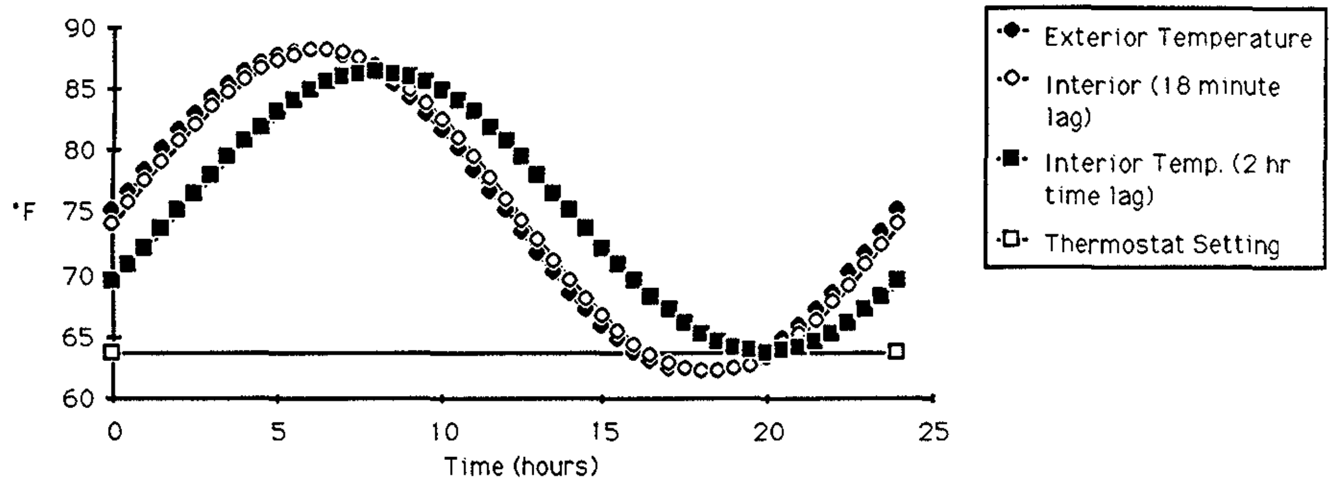

Figure 8. Temperature swings effecting the calculated balance temperature.

Since all homes have heat loss through the windows and through infiltration they all exhibit this behavior in the short term. The more rapidly air changes in the house the higher the analysis program will have to adjust the balance temperature to account for the fuel use in the "swing periods".