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ABSTRACT

This paper addresses the following question: How accurate are audits that include measured indoor temperatures, infiltration rates (SF_6), and furnace efficiencies (Bacharach) and that use a balance-point degree-hour method of calculation? This is the type of audit that most researchers say is needed to provide reasonable results, yet the type that most public agencies say they have neither the time nor the trained personnel to conduct.

To explore this question, two types of calculations were performed on 110 houses at nine sites across the U.S.; results were then compared to measured data. The first is a simple steady-state annual heat-loss calculation typical of those found in most current residential energy audits. The second is a balance-point degree-hour calculation performed on a monthly basis and including average measured indoor temperatures, estimated internal gains, site-measured infiltration rates, and furnace efficiencies.

From this sample of 110 homes it was found that the instrumented audit produced about a 20% average improvement on our ability to predict the actual consumption by residential buildings; however, the scatter is so great in both cases that it is difficult to state that any one method of calculation is better than another for any given house.

INTRODUCTION

In order to examine the cost-effectiveness of conserving energy used for heating homes, the Community Services Administration Weatherization Demonstration Research Project from 1978 to 1980 collected extensive data on 220 houses in 12 cities across the United States (1). During this demonstration, an instrumented audit was planned for each house before and after weatherization in order to separate and compare infiltration, conduction, and mechanical system losses. Because of a variety of problems, not all houses were audited, and the quality of completed audits varies greatly. Despite these problems 110 completed audits in 9 cities measured infiltration rates and mechanical system efficiencies and were done with sufficient care that they would qualify as instrumented audits. Audits in the CSA demonstration were defined as an examination and accounting of all energy used by each building component in order to locate heat gains and losses in a building. Since this demonstration, the definition has been expanded to include recommendation of options based on their cost-effectiveness. This difference is pointed out to avoid confusion, but the difference is irrelevant to the results presented in this paper. Each of the 110 audits had at least four grab-bag tests, measured average interior temperature, and performed a Bacharach steady-state furnace efficiency test. The calculation procedure included local solar data, hourly ambient temperature, and the balance temperature of the house. Both the calculated and measured data were normalized to a typical year for comparison.

DATA COLLECTION

The data for the audits were collected throughout several months by trained auditors whose work was monitored by the staff at the National Bureau of Standards. Infiltration measurements were made using a "grab-bag" technique. This technique calls for sulfur hexafluoride (SF_6) to be distributed on each floor and allowed to mix for half an hour. An initial bag is collected, and an hour later a final bag is collected. These bags, two for each floor, were sent to NBS for analysis. At NBS the concentration of SF_6 in the first bag was compared to that in the second, and the air-exchange rate for each one-hour measurement was calculated. In order to arrive at an average yearly air-exchange rate, four or more sets of bags were collected under different conditions (with no guarantee that they represented average yearly weather conditions).

Seasonal mechanical efficiency was calculated with data from the Bacharach test. As called for in the Bacharach test, CO_2 and temperature were measured and used with tables provided with the testing unit to calculate steady-state furnace efficiencies. Seasonal efficiencies were then derived from these steady-state efficiencies using partial load curves typical of the heating system being measured. Architectural data on each house were collected using a standard form for all sites (See Appendix F, p. 69 of Project Plan (2)). This form was completed by field personnel and then checked for consistency and reasonableness both in the lab and in the field. The most important part of the field check by NBS was determining heated and unheated portions of the house, checking overall measurements, and counting windows.

CALCULATIONS

After the data had been collected, heat losses were calculated using equations (1) and (2):

$$T_b = T_i - \frac{I + S}{UA_c + UA_i}, \tag{1}$$

where:

T_b = balance temperature (^oF),

T_i = interior temperature (^oF),

I = internal gains from appliances and people (2214 Btu/hr),

S = average solar gains through windows (BTU/hr),

UA_c = conductive losses (BTU/hr-^oF), and

UA_i = losses due to infiltration (BTU/hr-^oF).

$$Q = 24\ HDD_b\ (UA_c + UA_i)\ /M_e, \qquad (2)$$

where:

Q = monthly heating energy used (BTU),

HDD_b = average heating degree days at balance temperature (^oF-day), and

M_e = seasonal furnace efficiency (percent).

The interior temperature (T_i) in Equation (1) was estimated from monthly temperature measurements made throughout the house (see p. 36 in the Project Plan (2)). These measurements were averaged and assumed to be constant throughout the heating season. Solar gains (S) were taken from NBS-BSS 96, a National Bureau of Standards report (3) for the city in which the houses were located. Heat-loss coefficients due to infiltration (UA_i) and conduction (UA_c) were calculated from field measurements and ASHRAE tables.

Once the balance point (T_b) had been calculated, hourly degree days (HDD_b) were computed from hourly weather tapes from NOAA; these were used in Equation (2) to calculate the heat loss for each month. After monthly heat losses had been calculated, they were added together to provide yearly energy consumption for heating.

To compare the above calculation method with the traditional simplified calculations, the steady-state annual heat-loss formula from Manual J (4), referred to as the Standard Heat Loss Methodology (SHLM), was used with estimated infiltration rates and mechanical efficiencies rather than measured values:

$$Q = 24\ HDD_{65}\ (UA_c + UA_i)\ \ /M_e. \qquad (3)$$

In this formula, estimated values of 1.0 air change were used to calculate (UA_i) for unweatherized houses; 0.5 air change was used for weatherized houses. Mechanical efficiencies (Me) were 0.60 for oil furnaces, 0.70 for gas furnaces, 1.00 for electric baseboards or unvented space heaters, and 0.70 for unvented space heaters.

RESULTS

The results of both these calculations, or audits, were compared with annual heating energy consumption from furnace meters. Figure 1 shows compared results of the Standard Heat Loss Methodology (SHLM) audit with measured data. Figure 2 compares an instrumented audit with measured data. In order to insure accuracy, measured data were collected at the furnace weekly and correlated with degree days from weather tapes for the city and time in which the data were collected. Only fits that had an r^2 of 0.90 or better were considered acceptable.

Figure 1 shows the SHLM data shifted up from the diagonal (perfect fit line), meaning that the SHLM usually overcalculates. This shift is about 20% if one ignores the few cases in which calculated consumption was twice as high as measured consumption, perhaps a result of unaccountable behavior patterns or underestimated free heat. In Figure 2 the data show a better relationship to the perfect fit line, but the scatter is considerable. It is difficult to say that one method of calculation is better than the other for any one house. From this observation two questions arise: (1) How can calculations for individual houses be improved? (2) Are instrumented audits and balance-point calculations worth all the effort?

To investigate the possibility of improving calculation methods, it is worth examining figures 3 and 4. These figures show typical examples of energy consumption before and after weatherization on a single house. Energy consumption is broken down into infiltration losses, conductive losses, solar gains, and internal gains. Although shown on these figures, solar and internal gains are not additive because they were subtracted out when calculating the balance temperature (see Equation (1)). As these figures show, conductive losses were responsible for most of the energy losses. On the average across all 110 houses, infiltration losses before weatherization accounted for 19% of the load, while after weatherization they accounted for 29% of the load. Conductive losses, on the other hand, made up 81% of the losses before weatherization and 71% after. This shows the large effect that (UA_c) has on these calculations. Even if one considers energy flux rather than energy losses and adds solar and internal gains to the comparison, conduction represents 58% of the energy flux. Although most of the factors in these equations could be greatly improved by research, clearly the place to begin is with (UA_c). Thermography has pointed out some of the inaccuracies in calculated UA, and co-heating has promise as a way of measuring UA_c, but little work has been done on improving the accuracy with which UA is measured or predicted by auditors in the field.

The question of whether instrumented audits are worth the effort must be examined at two levels, first at the level of the individual house and then at the level of 100 or more houses. Our ability to calculate energy consumption for an individual house with these two methods is obviously still unsatisfactory. At the level of 100 or more houses, however, the instrumented audit improved the SHLM by about 20%. A closer examination of the data used in the SHLM and in instrumented audits would show that the same conductive heat loss coefficient (UA_c) was used in both equations. The improvement afforded by the instrumented audit was due to a 10% improvement in measured infiltration rates and mechanical efficiencies, and an improvement to the calculation method by using the balance temperature of the house and the monthly time step.

Because of the improvement to aggregate rather than individual building calculations, it seems reasonable to use this type of audit to collect data for forecasting while awaiting improvement to the calculation of UA_c before using it on individual houses. Regional data could even be collected on infiltration rates, mechanical system efficiencies, and conductive losses individually and then used in a regional formula to predict energy use. It also seems reasonable to add to such a data base solar gains per square foot for different orientations and internal gains associated with different appliances, equipment, and numbers of people.

ACKNOWLEDGEMENT

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

(3) Kusuda, T., and Ishii, K. Hourly Solar Radiation for Vertical and Horizontal Surfaces on Average Days in the United States and Canada, NBSS-96, National Bureau of Standards, April 1977.

(4) National Environmental Systems Contractors Assoc., Load Calculation for Residential Winter and Summer Air Conditioning: Manual J, NECA, 1975.

Table 1 - Data For Figures 1 and 2

House No.	Bal. Point Calculation	Measured Data	ASHRAE Calculation
ATL 2B	81.3	101.95	154.215
ATL 23B	101.3	95.16	116.736
ATL 29B	188.2	116.13	140.711
ATL 17A	22.5	37.54	21.462
ATL 22A	78.8	61.47	66.694
ATL 31A	121.61	47.98	89.996
ATL 32A	27.8	62.79	36.604
CHA 20B	37.2	55.37	81.787
CHA 23B	98.4	65.63	107.021
CHA 25B	47.7	58.24	51.668
CHA 2A	70.8	55.05	56.457
CHA 3A	63.4	42.59	59.260
CHA 8A	90.3	39.91	59.438
CHA 16A	45.7	43.19	75.825
CHA 18A	39.8	49.28	41.939
CHA 20A	27.5	39.26	49.408
CHA 23A	60.1	45.22	55.020
CHA 25A	34.3	36.02	35.883
CHA 33A	44.1	26.74	52.719
CHA 39A	33.1	27.73	48.098
CHA 44A	54.5	39.22	39.310
CHA 47A	22.0	6.46	32.825
CHA 49A	37.5	24.03	64.357
CSP 7B	113.5	115.16	142.635
CSP 44B	78.2	134.62	161.259
CSP 7A	64.8	70.87	91.104
CSP 11A	48.0	33.78	83.240
CSP 13A	31.1	67.35	56.634
CSP 14A	74.9	68.66	89.178
CSP 17A	73.4	63.97	92.673
CSP 20A	141.2	70.00	178.352
CSP 23A	66.8	125.65	123.901
CSP 24A	129.8	187.22	190.363
CSP 26A	77.9	86.69	107.838
CSP 31A	51.0	69.77	89.833
CSP 37A	37.1	65.16	91.564
CSP 41A	52.8	36.25	77.417
CSP 43A	26.0	66.63	74.738
CSP 44A	33.3	47.12	84.890
CSP 47A	62.6	75.80	79.192
CSP 49A	49.3	50.26	81.108
EAS 31B	256.9	94.80	291.098
EAS 33B	187.5	97.91	218.974
EAS 4A	279.3	101.27	301.516
EAS 12A	103.3	105.77	122.392
EAS 20A	115.6	28.37	74.596
EAS 22A	142.8	78.17	145.312
EAS 27A	91.4	48.17	101.798
EAS 31A	121.11	69.09	121.826
EAS 33A	96.2	88.90	98.319
EAS 39A	171.3	166.54	192.600
EAS 42A	111.5	27.81	74.109
EAS 44A	124.2	64.30	131.445
FAR 2A	27.4	49.17	69.820
FAR 10A	48.6	53.56	86.457
FAR 15A	37.6	76.83	125.072
FAR 17A	121.9	60.39	104.270
FAR 25A	60.6	76.83	87.129
FAR 30A	30.0	60.39	87.462
FAR 32A	86.5	74.55	109.610
FAR 35A	68.5	80.97	149.801
FAR 36A	26.6	54.52	61.821
MSP 20B	199.7	156.48	257.419
MSP 23B	622.0	347.16	573.974
MSP 33B	139.6	172.67	177.662
MSP 34B	264.0	134.04	330.430
MSP 40B	195.5	109.99	222.752
MSP 42B	276.2	173.01	265.357
MSP 44B	143.4	151.04	213.521
MSP 45B	304.3	182.40	327.745
MSP 46B	218.3	147.94	235.392
MSP 1A	146.4	158.91	151.881
MSP 2A	288.1	140.59	220.108
MSP 3A	144.6	80.16	149.946
MSP 4A	311.1	150.37	254.388
MSP 13A	213.3	186.42	189.182
MSP 20A	94.2	105.80	118.359
MSP 21A	278.6	130.35	220.724
MSP 23A	298.1	301.55	267.380
MSP 26A	135.4	103.35	151.134
MSP 33A	109.9	105.99	127.315
MSP 34A	175.8	117.04	198.129
MSP 42A	195.8	160.22	172.291
MSP 45A	140.1	160.95	147.402
MSP 46A	90.4	134.79	97.253
STL 38A	219.5	139.44	166.679
STL 42A	109.7	98.01	126.425
STL 55A	88.1	63.19	70.657
STL 92A	204.2	146.32	150.773
STL 93A	90.8	80.47	68.061
TAC 45B	172.9	110.85	152.225
TAC 49B	144.0	69.96	127.830
TAC 55B	90.6	98.46	156.692
TAC 4A	43.3	63.29	51.081
TAC 39A	23.9	41.58	43.257
TAC 45A	68.7	47.17	77.424
TAC 49A	77.5	50.37	84.635
TAC 55A	51.8	55.55	92.807
TAC 81A	25.9	69.87	19.383
TAC 83A	45.0	41.64	89.192
TAC 87A	34.1	42.00	39.816
TAC 41B	137.3	120.88	138.283
WAS 2A	53.8	38.65	58.815
WAS 7A	78.7	68.54	86.064
WAS 41A	56.0	45.72	64.724
WAS 53A	86.2	88.75	85.942

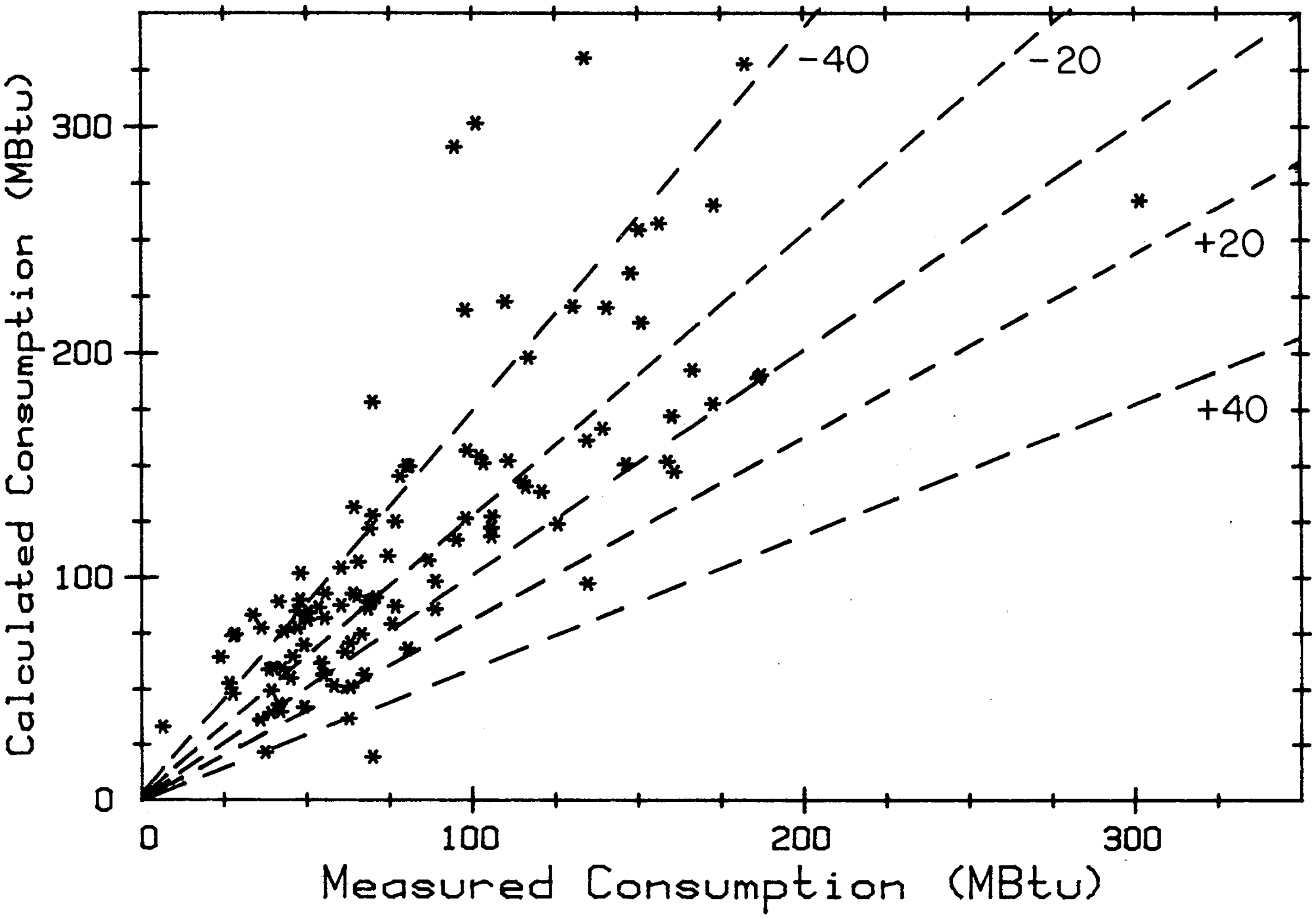

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FIGURE 1

CALCULATED vs MEASURED ANNUAL HEATING FUEL CONSUMPTION USING STANDARD HEAT LOSS METHODOLOGY

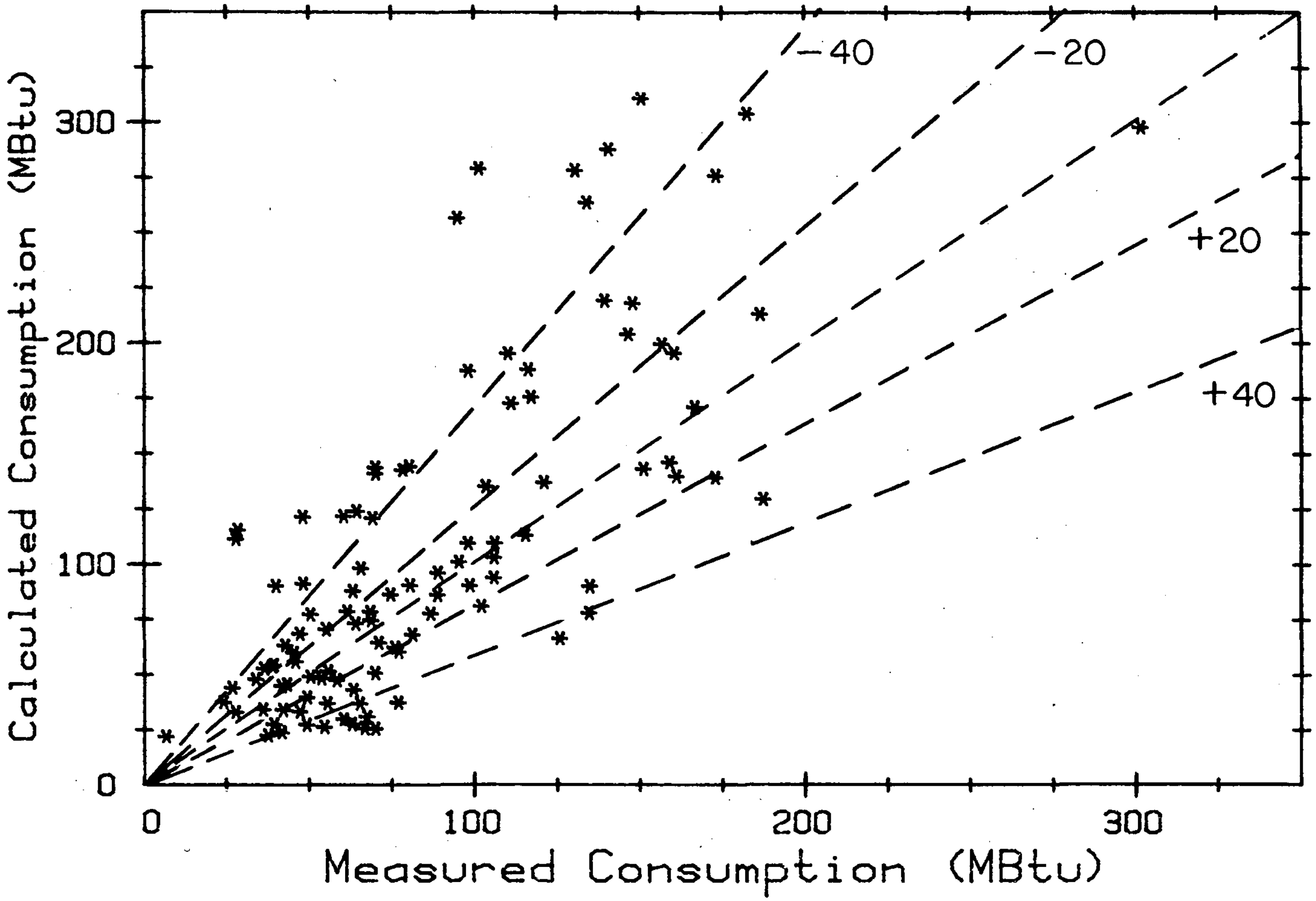

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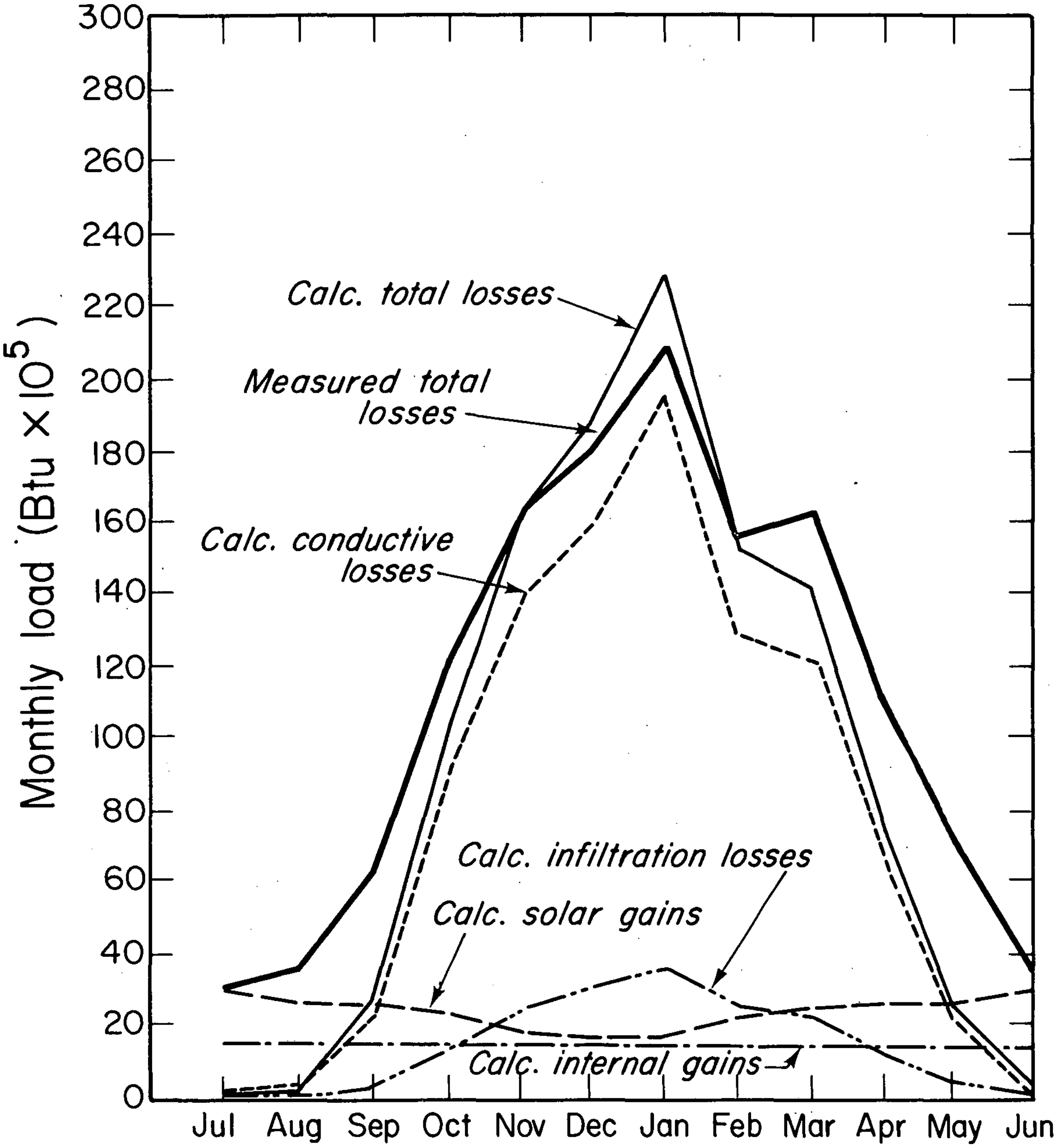
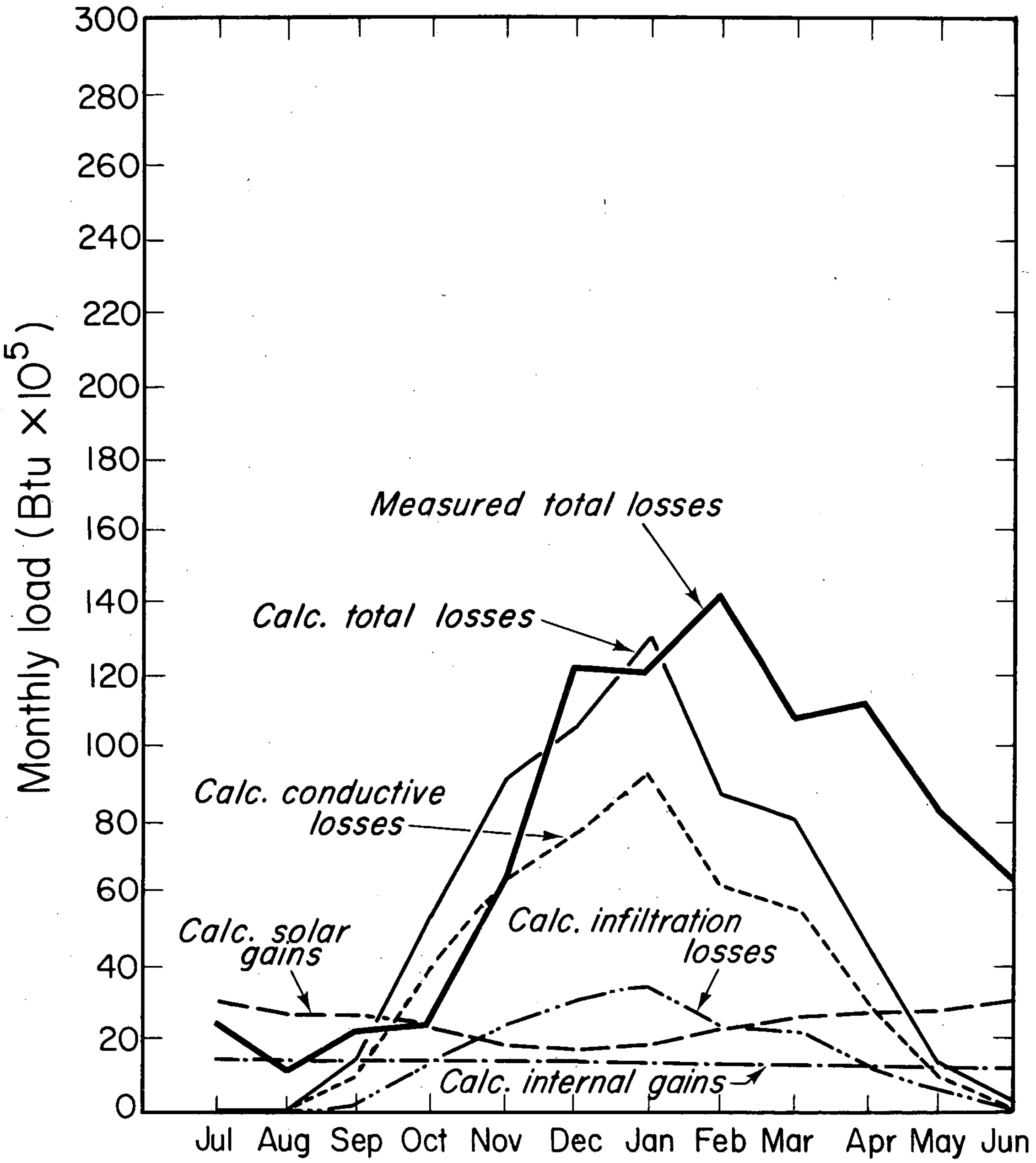
FIGURE 2

CALCULATED vs MEASURED ANNUAL HEATING FUEL CONSUMPTION
USING INSTRUMENTED AUDITS & BALANCE POINT CALCULATIONS



XBL 828 – 1062

Figure 3. Typical example of heat losses before weatherization in a detached one-story frame house in Colorado Springs.



XBL 828 — 1063

Figure 4. Typical example of heat losses after weatherization in a detached one-story frame house in Colorado Springs.

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