1990-20

Prediction of Long-Term Average Radon Concentrations in Houses Based on Short-Term Measurements

William E. Belanger, P.E.
U. S. Environmental Protection Agency
Region III
841 Chestnut Street
Philadelphia, PA 19107

Abstract

Previous studies have examined the relationship between short term screening tests and annual average radon concentrations, but have generally been limited by short term measurements conducted at only one location in the house or during only one season. This study examines the usefulness of short term measurements to estimate long-term averages when the short term measurements are made in living areas of the house and in the basement. The effect of season is also examined. This analysis is particularly useful in situations where there is not time to do an annual measurement, but multiple rooms can be easily tested. We used the raw data from five different researchers to cover the full annual cycle and multiple sampling locations. The result is a matrix of factors which can be used to estimate the annual average radon based on a test at any time of year. Separate factors are calculated for basement and first floor monitoring locations. We also examined the effect of sample duration on measurement precision.

Introduction

The Environmental protection Agency Published the Citizen's Guide to Radon in August of 1986. The Citizen's Guide outlines a two-step testing process which calls for an initial screening measurement followed by a longer term follow-up measurement. The screening measurement is to be done in the basement or lowest habitable level of the house with the doors and windows kept closed except for normal entry and egress. If radon in excess of four picoCuries per liter is detected by the screening test, additional tests of up to a year's duration are recommended. These follow up tests are made in each living level of the house. The basement is included in these follow up tests only if it is used as a bedroom or den or if people spend a significant amount of time there. The whole measurement process including the time needed for the test, purchase of detectors, sample analysis, mailing, and procrastination can take well in excess of a year.

Under some circumstances, a full year of monitoring is not practical or is not desired by the person conducting the test. In this circumstance it would be desirable to be able to compare the short term test with the concentration that would have been measured if a full year test had been conducted. It is also desirable to be able to compare short term tests with one another, for example when tests are performed in different seasons or in different locations in the house. We collected and analyzed a number of existing data bases. These data bases were selected because there were both short term and long term tests performed in the same house. In addition, houses where continuous monitoring has been conducted have been used to investigate the variations in testing precision which result from different sampling durations. The results suggest corrections can be made to short term data to provide an estimate of long term averages in houses. This paper uses radon measurements made in several thousand houses to derive factors which can be used to normalize short term radon data to whole house annual averages.

Use of a short term sample to estimate the annual average can be expected to introduce error into the radon measurement process. If the errors that are introduced are smaller than those inherent in the measurements, the additional errors would be unimportant. If, however, the errors introduced by short term sampling are larger than the measurement errors, then there will be the need for a policy decision on whether or not these errors are acceptable. That decision is beyond the scope of this paper, but we will attempt to quantify the errors.

Optimization should be an inherent part of this process. The decision on the acceptability of errors should not be based purely on the errors observed from simple comparison of short term measurements with annual averages. These short term samples will include variance due to seasonal differences, location differences and differences due to house conditions as well as "random" variations. Many of these sources of variance can be reduced by the prudent choice of sampling strategy and application of correction factors. When the estimate is as good as can be made from the available data, then the decision on whether or not the errors are acceptable should be made.

Experimental Methods

Five independent datasets were used in this analysis. These are the first year data from the EPA State surveys, Data collected by George Mason University for a survey in Northern Virginia, data collected by Pennsylvania in the Reading Prong, continuous radon monitoring at one location in each of four houses in Butte, Montana and continuous radon monitoring at several locations in a house in Media, Pennsylvania conducted under the auspices of Rutgers University. The original data was obtained in each case to allow a consistent analysis to be performed. Other studies where the raw data were not made available were not included in this analysis, though the conclusions drawn by the researchers were compared to our results and found to be similar.

No new radon measurements were made for this investigation. Because existing radon data was used, the author was limited to whatever analytical methods and quality assurance procedures were used by the person who collected the data. These ranged from carefully calibrated quasi-continuous radon monitors to radon test kits purchased on the open market. All radon measurements were assumed to be accurate, i.e there was no systematic bias. Precision was improved by eliminating measurements known to be of low precision. For example, alpha track detectors bought in the marketplace were assumed to have acceptable precision only above a 1-year average of one pCi/l (equivalent to 4 pCi/l for 3 months). This is well above the limit of detection for these detectors, and typically yields a coefficient of variation of about 20 percent. Charcoal detectors of many types were also included in this analysis. These were again assumed to be unbiased. This assumption is supported by the analysis of data collected by Mose. Short term samples using three different charcoal detectors were shown to be unbiased estimators of alpha track averages at the same location when the low radon concentrations were eliminated.

The parameter of interest in this investigation is the ratio of a short term measurement to a long-term average. This requires that the short-term to long-term ratio is not a function of radon concentration. This independence is shown by Perritt. There is a noticeable decrease in precision at low concentrations, which may account for a dependence being seen by others. The long term average chosen here as a baseline was the average of radon concentrations averaged over all floors of the house. This is not the same as the EPA follow up protocols which exclude space that is not actually lived in. This was done because the "lived in" status of floors of a house was generally not reported in the data, and because the utilization of rooms in a house is not a property of the house. A basement that is not lived in this year may have a couch and a television in it next year. All "livable" spaces were therefore assumed to be occupied.

EPA/State Survey

The EPA/State survey data used in this paper consists of a subset of the data where both long and short term measurements were made. Radon was measured in 908 homes in AZ, MA, MN, MO, ND and TN. Short term tests were made using two-day open face charcoal canisters and were analyzed by EPA's Eastern Environmental Radiation Facility in Montgomery, AL. Only one canister was placed in each home. These were placed in screening locations using closed house conditions. Closed house conditions and screening locations greatly reduce the variability in the short term radon measurement and also tend to produce somewhat higher radon concentrations. Most of the short term tests were conducted in winter and spring, with the majority in March. Because the canisters were placed only in screening locations, there were no short term measurements made in the first floor where the house had a basement. Similarly, it is not possible to use this dataset to evaluate the benefits of short term measurements on multiple levels of a home.

Annual radon concentrations were measured using commercial alpha track detectors. At least one detector was placed on every floor with a minimum of two detectors per house. The detectors were left in place for a full year. Over the full year of monitoring there was no attempt to achieve closed house conditions. The houses were operated by the residents as they normally would. The commercial alpha track detectors used were quality assured according to EPA protocols and were also spot checked by exposing some detectors to known radon concentrations in the EPA radon chamber. The quality of this data probably exceeds that which would result from a consumer purchase of similar detectors.

The EPA/State survey data is the most definitive indicator of long-term versus short term concentrations because it allows direct comparison of short term tests with whole house annual average concentrations. The main limitation of this data is the monthly distribution of the short-term tests. These are heavily biased toward the winter and spring, with very few summer and fall measurements. Figure 1 shows the ratio of short-term to annual whole house average when the short term measurement is made in the basement. Figure 2 shows the same ratio where the short term measurement is in the first floor. The confidence intervals are two standard deviations of the mean. It can be seen that the lack of samples in summer and fall make it difficult to draw seasonal information from this dataset alone.

George Mason University Data

About 1800 homes in northern Virginia were tested for radon in a program run by George Mason University in 1987 and 1988. Of these, 368 homes were tested for radon using both short term charcoal samplers and long term alpha track detectors. This work is further described by Mose[1]. The measurements were made using commercial charcoal and alpha track detectors. Charcoal samplers included diffusion barrier types exposed for seven days, open-face types exposed for two to three days, and bag types exposed for three to four days. All detectors were deployed according to the manufacturer's directions. There was no indication that there were significant differences in results between the charcoal monitors so they were treated as equivalent. The homeowner was instructed to maintain closed house conditions during the charcoal test. The short term detectors were deployed mostly in May, but many were deployed throughout the summer.

Four quarterly alpha track measurements were performed in each house. The homeowner was instructed to place the detector in the lowest livable room or the room closest to the soil. This causes the alpha track measurements to overpredict average radon in the house in most cases. The elimination of homes with annual average below one pCi/l and homes where the alpha track detectors were not placed according to instructions left 249 houses with both short and long term measurements. Closed house conditions were not maintained for the duration of the alpha track monitoring, so normal seasonal variations in radon are reflected in the data. These seasonal variations are somewhat smaller than those in other datasets, perhaps due to the use of air conditioning in the homes selected. Figure 3 shows the ratio of short term radon to the annual average at the same place in the house. Note that there is no significant bias overall. The seasonal trend is evident in the spring, summer and fall, but there are too few short term measurements in the winter. The data allow analysis of the ability of short term closed house measurements to predict long term averages at the same monitoring location. This is not the same as predicting the average throughout the house, though it is possible to adjust the data to compensate for this. Finally, the seasonal distribution of the George Mason short term tests covers part of the year not addressed well by the EPA/State surveys and, when combined with that data, allows seasonal variations in closed house screening tests to be examined.

The George Mason University data is also useful for determining seasonal variations using long-term measurements in the mid-atlantic and similar climates. The four seasonal alpha tracks in over 1000 houses provide an excellent indicator of seasonal variations at the detector locations. Figures 4 and 5 show the seasonal trends for basement and first floor locations.

Again, the error bars are two standard deviations of the mean. Note the similar seasonal trend, with a slightly, but not significantly, greater seasonal variation in first floor locations.

Pennsylvania Data

Pennsylvania Bureau of Radiation Protection measured radon in 1476 houses in the Reading Prong during the winter of 1986 using three-month commercial alpha track detectors. Closed house conditions were virtually assured by the season. Detectors were placed in varying locations, some in the basement and some in the first floor. These detectors provided a winter average measurement in screening locations. Radon concentrations are generally high enough that low exposure of the detectors is not a problem. The same houses were measured using annual alpha track detectors the following year. Where mitigation efforts took place between the two years, the data were excluded. Two or three detectors were used for each house. The detector locations included basements and first floors. Second floor measurements were reported only occasionally. This data was previously analyzed by Granlund[2].

These measurements provide information on the relationship of radon concentrations from floor to floor in the house and limited information on the effect of season. Figure 6 is a histogram of the ratio of basement to first floor radon. By comparing data from two years in the same house, it is possible to extract winter vs annual differences for comparison with other datasets, and these differences can be evaluated separately in the first floor and the basement. The variations introduced solely by short term testing cannot be isolated. Figure 7 gives confidence limits on the mean of the floor to floor and winter to annual ratios. Note the significantly greater seasonal variations in the first floor. Seasonal differences are also more pronounced than those in the George Mason University data, but consistent with the EPA/State survey.

New York State Data

Radon was measured in 2288 homes in New York State. Commercial alpha track detectors were used to monitor radon annually in the living area, for two months during the heating season in the living area, and annually in the basement if there was a basement in the house. For purposes of this paper, the data used was limited to those annual radon concentrations greater than 1 pCi/l or two-month concentration above 4 pCi/l. This was done to assure sufficient exposure of the alpha track detectors. This left 145 houses in which the ratio of heating season to annual average was calculated, and 536 houses for which the ratio of basement to upstairs annual radon was calculated. Since the shortest sample duration was two months, the variability introduced by shorter sample duration cannot be determined from this data. This data was reported by Perritt[3]. Figure 8 shows a histogram of the basement to first floor ratio. It is similar to the Pennsylvania data. Figure 9 shows a histogram of the heating season to annual average ratio. Note that there is less spread in the seasonal ratios than in the floor to floor ratios, though Figure 10 shows that the winter to annual ratio is similar in magnitude on average to the basement to first floor ratio.

Butte Data

Radon measurements were made in 68 houses in Butte, Montana from October 1981 to June, 1983. This dada was recently published by the Environmental Protection Agency[4]. Of these houses, only four had radon measurements made at intervals shorter than one week. These houses were intensely monitored with continuous radon and working level monitors. The data was intensely quality assured by EPA, in cooperation with the Montana Department of Health and Environmental Science. Measurements were performed in only one location in each house. It is possible to calculate a long-term average at that location, but not an average radon in the house. However, the data can be broken into intervals as long or as short as desired, and so can simulate a population of short-term "tests". By examining "tests" of various length, it is possible to find the effect if the duration of a short term test on the variability introduced by the shortness of the test. Since one house was tested under closed house conditions, it is also possible to see how closed house conditions affect the ability of a short term test to predict a long term concentrations. Since the summer season appears well-defined in the data, closed house conditions are examined in the other houses by excluding the summer season. This technique yielded comparable results.

It is also possible to examine seasonal differences from this data. This has been done for all 68 houses in an Environmental Protection Agency report[5]. The seasonal trends noted in uncontrolled Butte houses are somewhat stronger than those in the George Mason University alpha track data, but consistent with the other datasets. This could be due to climatic differences or due to the greater use of air conditioning by the survey participants in northern Virginia. The Butte data shows summer radon to be higher than winter radon in houses thought to be closed during the summer. This was not observed in any other dataset.

Media House

One house in Media, Pennsylvania was continuously monitored for radon from November to April of 1988-1989. The monitoring was performed as a part of a research project conducted under the auspices of Rutgers University. Radon monitors using passive scintillation cells were installed near the center of the basement and the first floor. A solid-state radon monitor was placed in a bedroom on the second floor and was read out weekly. Continuous records of meteorology were generated on site.

The data, like the Butte data, can be broken into a number of short term "tests". The effect of sampling duration can be examined similar to the Butte data. Only winter measurements were made, but data has the advantage of continuous measurements on three floors of the house. Very little data of this type appears to have been taken to date. Not only can floor-to floor differences be compared with those derived from the other datasets, but the effect of duration of test can be directly compared on several floors in the same house. These results are discussed below.

Results

The EPA/State survey provides seasonal short-term to whole house annual ratios for winter and spring. The George Mason University data contains useful seasonal information for summer and fall but lacks sufficient measurements to calculate a whole house average. The adjustment of the George Mason University data was done by normalizing to the EPA/State data. The spring season is contained in both datasets and so the George Mason University seasonal factors were adjusted to make the spring ratios the same as those from the EPA/State dataset. This adjustment is intended to yield "whole house averages" from other seasons of the George Mason data.

Both the Pennsylvania and New York data allow direct comparison of winter and annual data. Floor-to-floor differences can be examined in the New York and Pennsylvania data, but there is insufficient data to directly calculate whole house averages because of the lack of second floor measurements. It is not clear whether the houses had second floors that were not measured or if second floors did not exist. This leads to the dilemma whether to compensate for the lack of second floor data in calculating a household average. We have elected to make this small correction as if second floors existed in all houses because two story houses are the rule in this part of the country.

From the table below it can be seen that summer first floor radon measurements should yield a result close to the whole house average, while similar winter first floor measurements should be higher than the whole house average by a factor of 1.6. Summer basement measurements should yield results about 1.8 times the whole house annual average while basement winter measurements should be 2.4 times the whole house annual average. Note that this data is unbalanced. The overestimation in winter is not balanced by an underestimation in summer. The basement overestimation is not accompanied by a first floor underestimation. The author believes this is due to the inherent bias in the screening locations and in the closed house conditions used for the short term tests. The annual averages include periods of low radon concentration which were "designed out" of the short term tests by choice of sampling location and closed house conditions.

Note the similarity among seasonal effects between datasets. This table illustrates the mean effect of season as a source of variance. There is also a variation in the seasonal effects from house to house. This latter variability prevents an exact correction from being applied unless one has a knowledge of the seasonal variations in the particular house being measured. Of course, if one had this information, a short term radon test would be unnecessary. As estimate of the variation in seasonal trends can be obtained by examining Figure 9. Similar results, not presented here, were obtained for the other datasets.

	winter	spring	summer	fall
Basement Seasonal (closed house) to Whole House Annual				
EPA/State	2.9	2.1		
Geo. Mason	2.3	2.1	1.8	2.3
Pennsylvania	2.0			
Average	2.4	2.1	1.8	2.3
First Floor Seasonal (closed house) to Whole House Annual				
EPA/State	2.2	1.3		
Geo. Mason	1.6	1.3	1.1	1.5
Pennsylvania	1.5			
New York	1.2			
Average	1.6	1.3	1.1	1.5

Another source of variance is the inability of a short term sample to predict a long term concentration. This variance due to sampling time is best illustrated in Figure 11, which shows the variability within single houses. The figure is from Butte House 1, but the other continuously monitored houses give similar results. Since the distribution of the data does not conform to a regular distribution, the fifth and ninety-fifth percentiles are reported as confidence limits. For longer sampling times, there are not enough points to allow these percentiles to be chosen, so the extreme values are reported. This has the effect of showing an artificial reduction in variability that is probably not real. Note that the sampling variability can be considerably reduced by avoiding summer sampling, or by sampling under closed house conditions. Figure 12 demonstrates this reduction in variance. It can also be seen that the reduction in variance is accompanied by the introduction of a systematic overestimation in the radon concentration. If one wished the most accurate prediction, it would be prudent to remove this bias. On the other hand it may be decided that such a bias is desirable in that it reduces the chance of under-estimating the radon.

Figures 13 and 14 show the effect of sampling duration separately for basement and first floor samples. This chart is from the house in Media, Pennsylvania, and includes only one season of data. For a 90-day average, the high and low extremes are the same because there is only one 90-day average in the data. Note that in this house the basement radon is three times that on the first floor. If only the basement had been measured, the first floor concentration would have been overestimated by about a factor of two. The variability of the data seem to improve up to a duration of about a week, and then only very long samples offer further improvement.

Conclusions

We have shown that short term sampling can provide estimates of long term radon concentrations at the same location with little bias. However there is considerable variance associated with the ability of individual samples to predict a whole house average. The variance is partly due to the differences between houses, partly due to differences between floors in a house, partly due to the time when the short term sample was taken and also due to other random effects. If short term measurements are to be used to predict a long term whole house average, then this variance should be reduced to a minimum. Any procedure which can be incorporated into a sampling protocol which reduces the variance is desirable.

The variance can be reduced by a number of techniques. For example there is a systematic difference between the radon measured in the basements and first floors of houses. It is possible to compensate for the systematic difference by applying a correction based on our experience with large numbers of houses. However, this technique can only remove the effect based on the mean of the floor to floor differences. Further reduction in variance is possible if sampling is done simultaneously on more than one floor. By sampling in this way, it is no longer necessary to estimate the floor to floor differences based on a large number of houses. The differences become known, at least at the time of the sample. This further reduces the variance in the resulting prediction.

In addition the number of floors is not the same in all houses. A house with a second floor has twice the chance for non-basement radon exposures as a one story house. One would calculate a different whole house average for a two-story house than for a ranch house. The number of floors in a house are easily counted, so there is no reason to treat all houses as if they were of one design. The author therefore recommends sampling on each floor of the house as a means of minimizing the errors in the calculated average.

It may also be possible to use the simultaneous basement and first floor measurements as a confirmatory measurement. If floor to floor differences fall outside an expected range, then the measurements may be suspect. Basement to first floor ratios appear to fall mainly in a range from 1 to 4 from the New York and Pennsylvania data. Thus if one were to make short term measurements in a basement and on the first floor and the ratio were between one and four, the data would seem credible. In the data examined this ratio appears to fall outside these limits about 25 percent of the time. A ratio of .75 to 5 is satisfied about 85 percent of the time, so less "rejections' of tests can be obtained by using wider limits. The ratio between basement and first floor tests be used as a quality assurance tool with limits of 1 to 4 or .75 to 5 depending on the level of confidence desired.

By prudent choice of sample duration and house conditions, it is possible to minimize the variance due to sample time. It has been shown that closed house samples of about a week duration can predict average radon levels at the same location within about -25 to +40 percent (the bias due to closed house conditions.) This suggests that any sampling protocol should include closed house conditions and that the duration of short term samples be more than a day and preferably as long as a week.

Seasonal variations were also obvious in the data. These seasonal variations are a source of variance if a short term measurement is to be used to predict an annual average. Unlike floor to floor differences, seasonal variations in a particular house cannot be determined except by actually measuring the radon in more than one season. It will therefore be necessary to utilize seasonal trends from large numbers of houses to reduce this source of variance. It cannot be eliminated because of the differences between houses in their seasonal radon patterns, but at least the seasonal trends can be removed.

References

1. D. Mose, G. Mushrush and C. Chronsiak, "Reliability of Inexpensive Charcoal and Alpha Track Radon Monitors," Natural Hazards, 1990

2. C. Granlund and M. Kaufman, "Comparison of Three Month Screening Measurements with Yearlong Measurements Using Track Etch Detectors in the reading Prong," Pennsylvania Department of Environmental Resources (1987)

3. R. Perritt, T. Hartwell, L. Sheldon, B. Cox, C. Clayton, S. Jones, M. Smith and J. Rizzuto, "Radon 222 Levels in New York State Homes," Health Physics 58 no 2: 147. (1990).

4. "Radon Measurement Comparison Study," U. S. Environmental Protection Agency, EPA 520/1/89/034. (1990).

5. "Seasonal Variations of Radon and Radon Decay Product Concentrations in Single Family Homes," U. S. Environmental Protection Agency, EPA 520/1/86/015. (1986).

Prediction of Long-Term Average
Radon Concentrations in Houses
Based on Short-Term Measurements

William E. Belanger, P.E.
U. S. Environmental Protection Agency

Figure Captions

Figure 1 Ratio of Short Term Basement Radon to Annual Whole House Radon.

Figure 2 Ratio of Short Term First Floor Radon to Annual Whole House Radon.

Figure 3 Ratio of Short Term Radon to Annual Radon at the Same Location.

Figure 4 Seasonal Trends with Three Month Basement Tests.

Figure 5 Seasonal Trends with Three Month First Floor Tests.

Figure 6 Basement to First Floor Radon Ratios in Pennsylvania.

Figure 7 Confidence Limits on Average Floor to Floor and Winter to Annual Ratios in Pennsylvania.

Figure 8 Basement to First Floor Ratios in New York.

Figure 9 Heating Season to Annual Average Ratio in New York.

Figure 10 Confidence Limits on Average Seasonal and Floor to Floor Ratios in New York.

Figure 11 Variation due to Sampling Duration with Uncontrolled House Conditions.

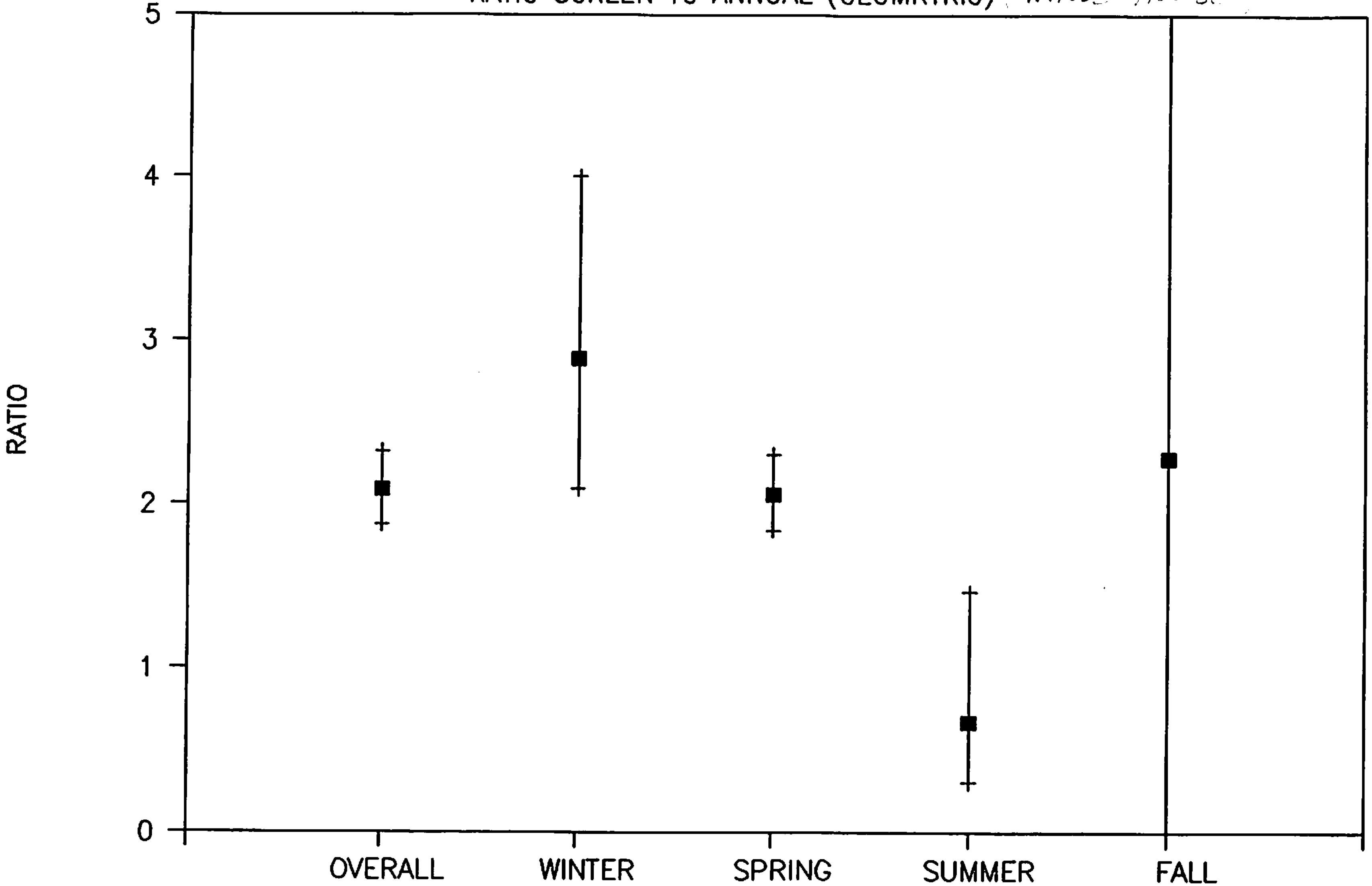
Figure 12 Variation due to Sampling Duration with Closed House Conditions.

Figure 13 Effect of Sampling Duration in the Basement (Winter Only).

Figure 14 Effect of Sampling Duration in the First Floor (Winter Only).

EPA/STATE SURVEY – BASEMENT

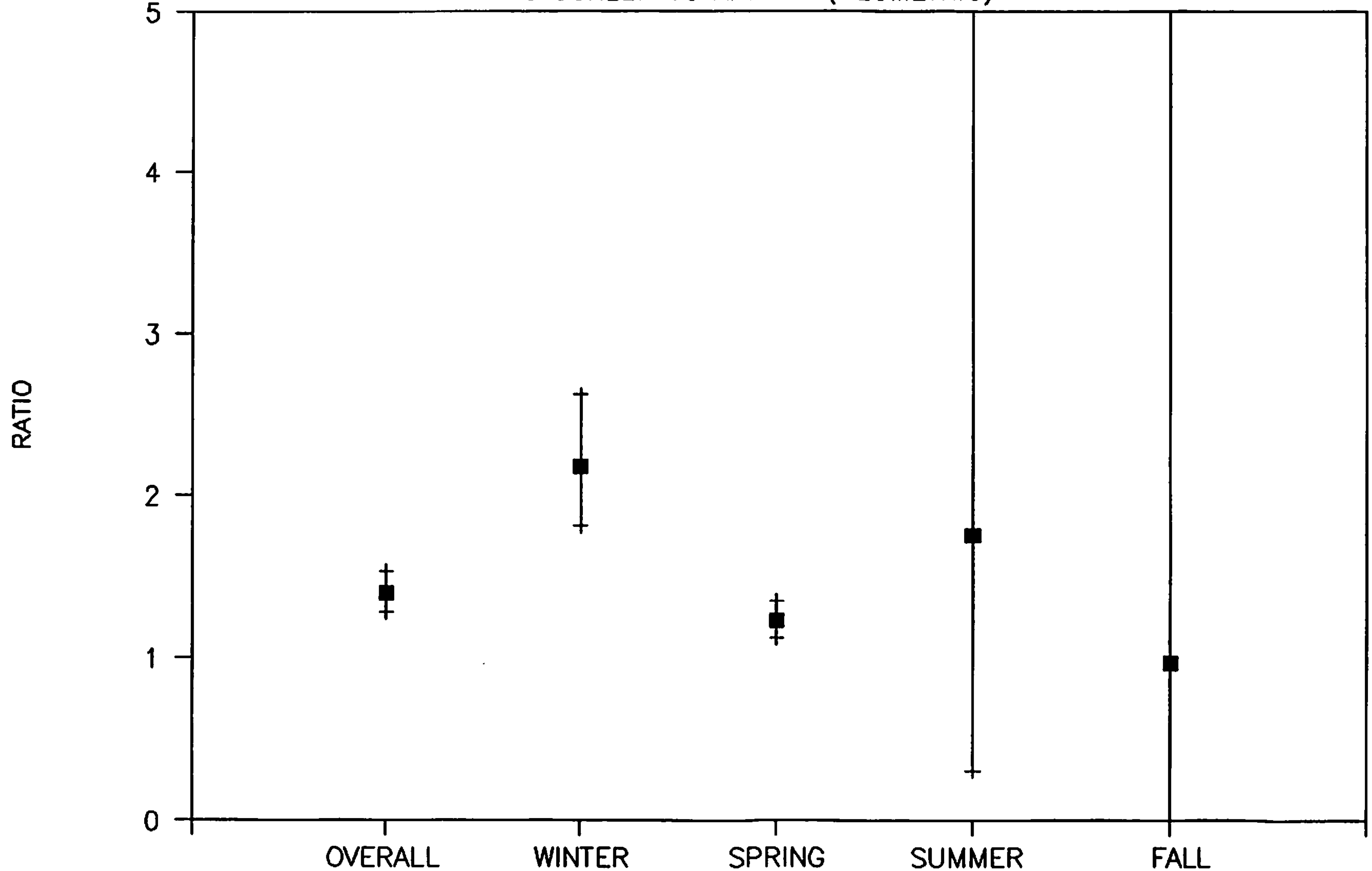
RATIO SCREEN TO ANNUAL (GEOMRTRIC) (WHOLE HOUSE



908 HOUSES

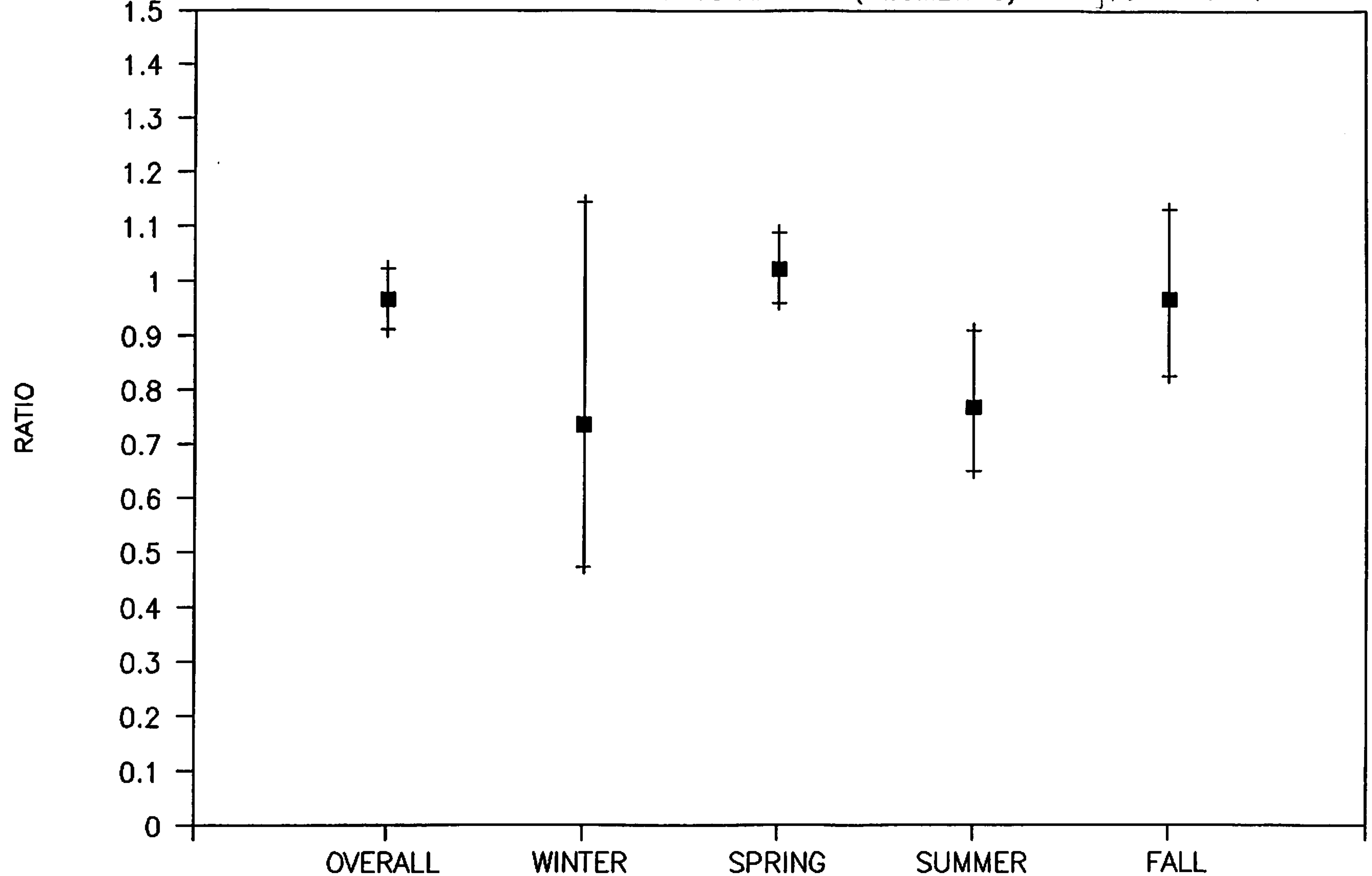
EPA/STATE SURVEY - FIRST FLOOR

RATIO SCREEN TO ANNUAL (GEOMETRIC)

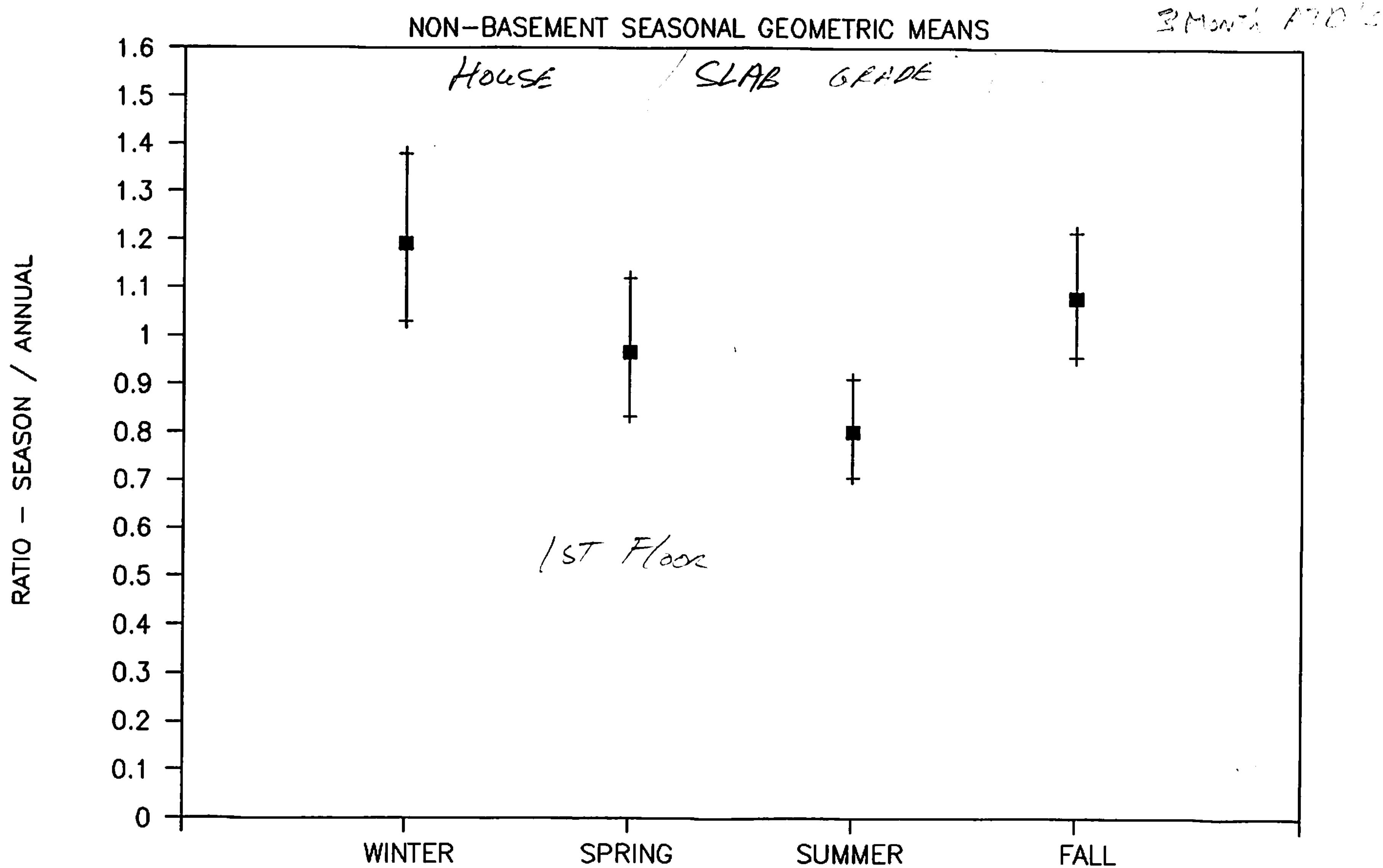


GEORGE MASON U. DATA

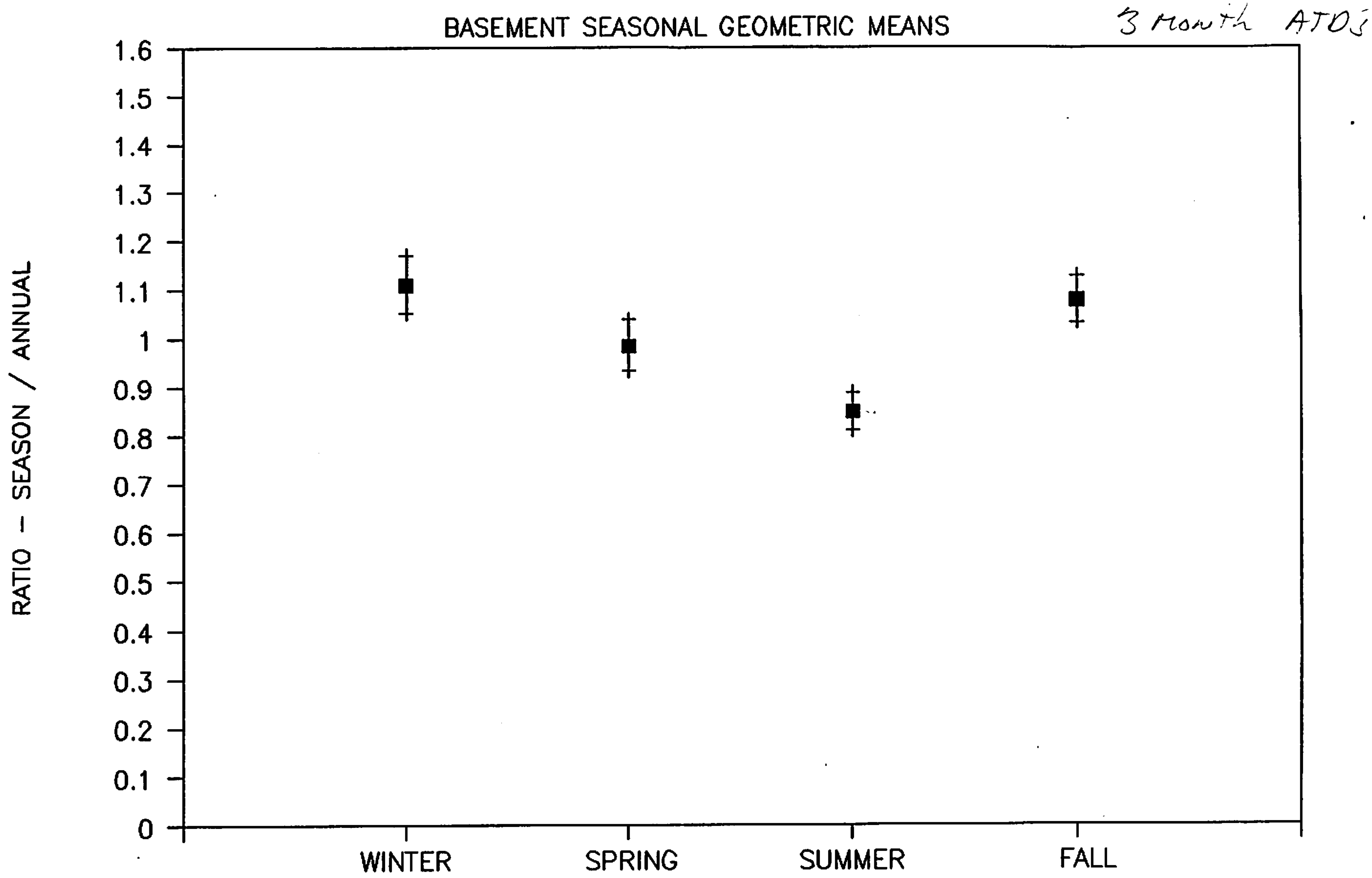
RATIO OF SCREEN TO ANNUAL (GEOMETRIC) SAME LOCATION



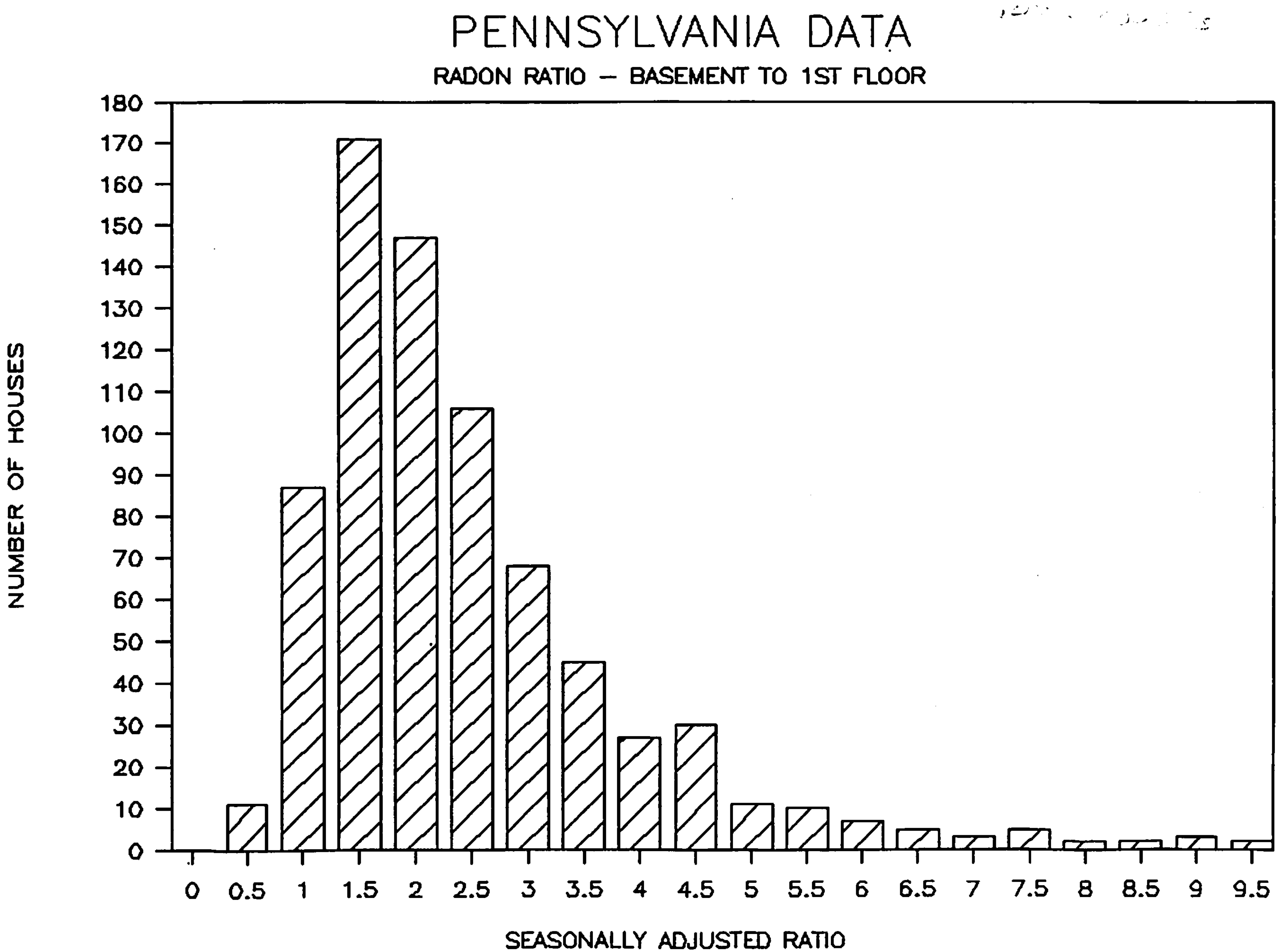
GEORGE MASON UNIV. DATA



GEORGE MASON UNIV. DATA



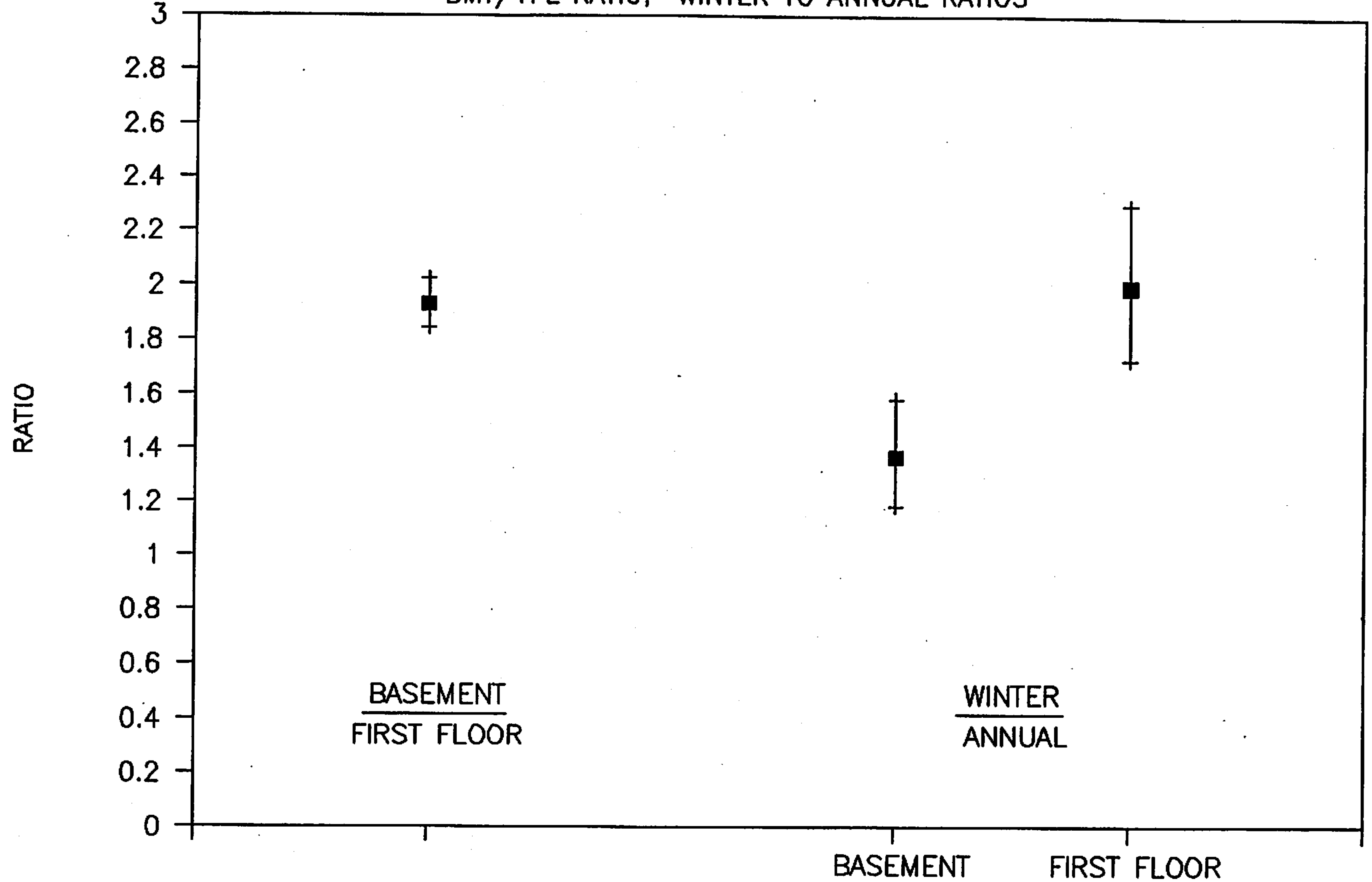
RATIO of 3 Mos BAS to YR Long BAS



PENNSYLVANIA DATA
RADON RATIO — BASEMENT TO 1ST FLOOR
NUMBER OF HOUSES
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
8.5
9
9.5
SEASONALLY ADJUSTED RATIO

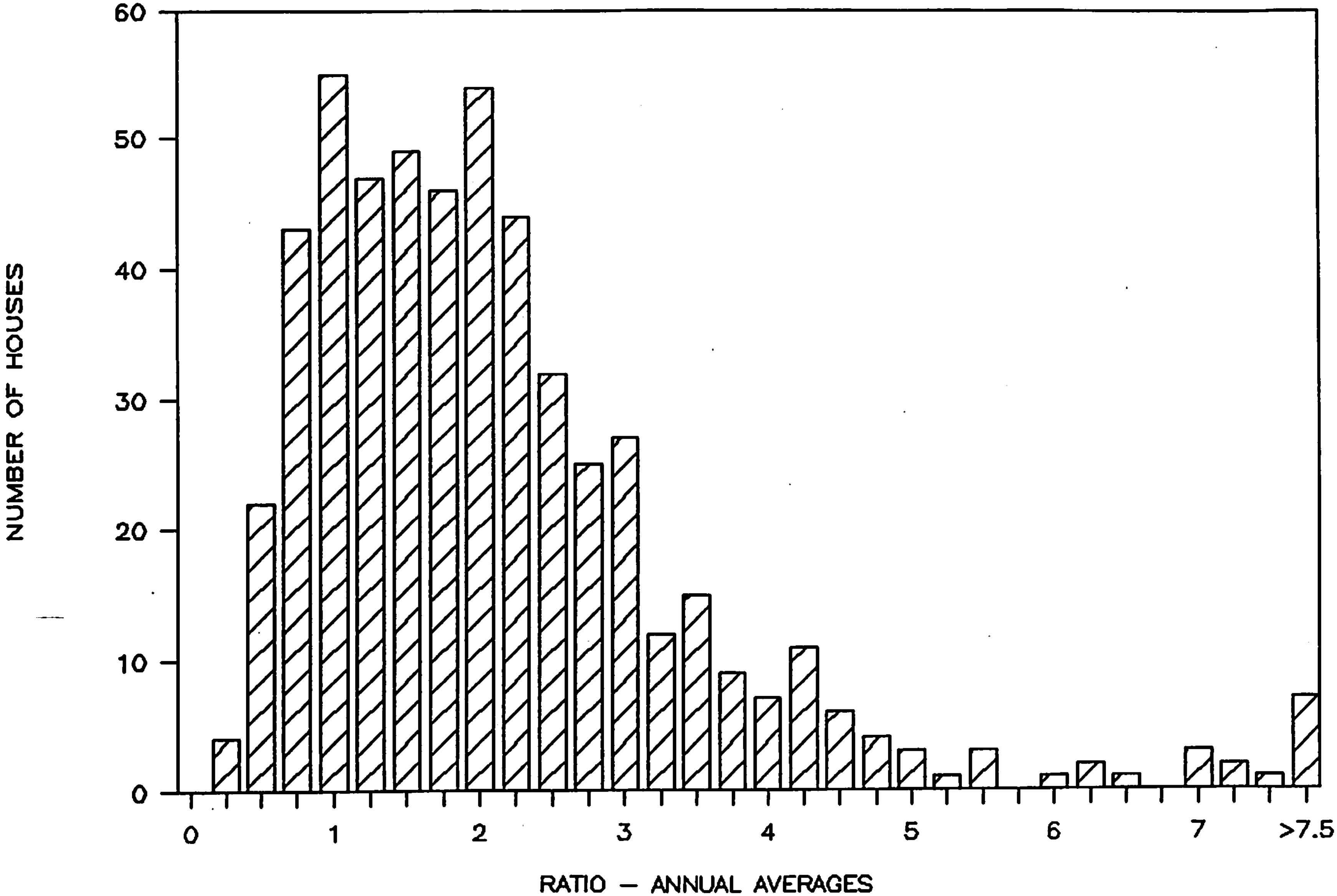
PENNSYLVANIA DATA

BMT/1FL RATIO, WINTER TO ANNUAL RATIOS



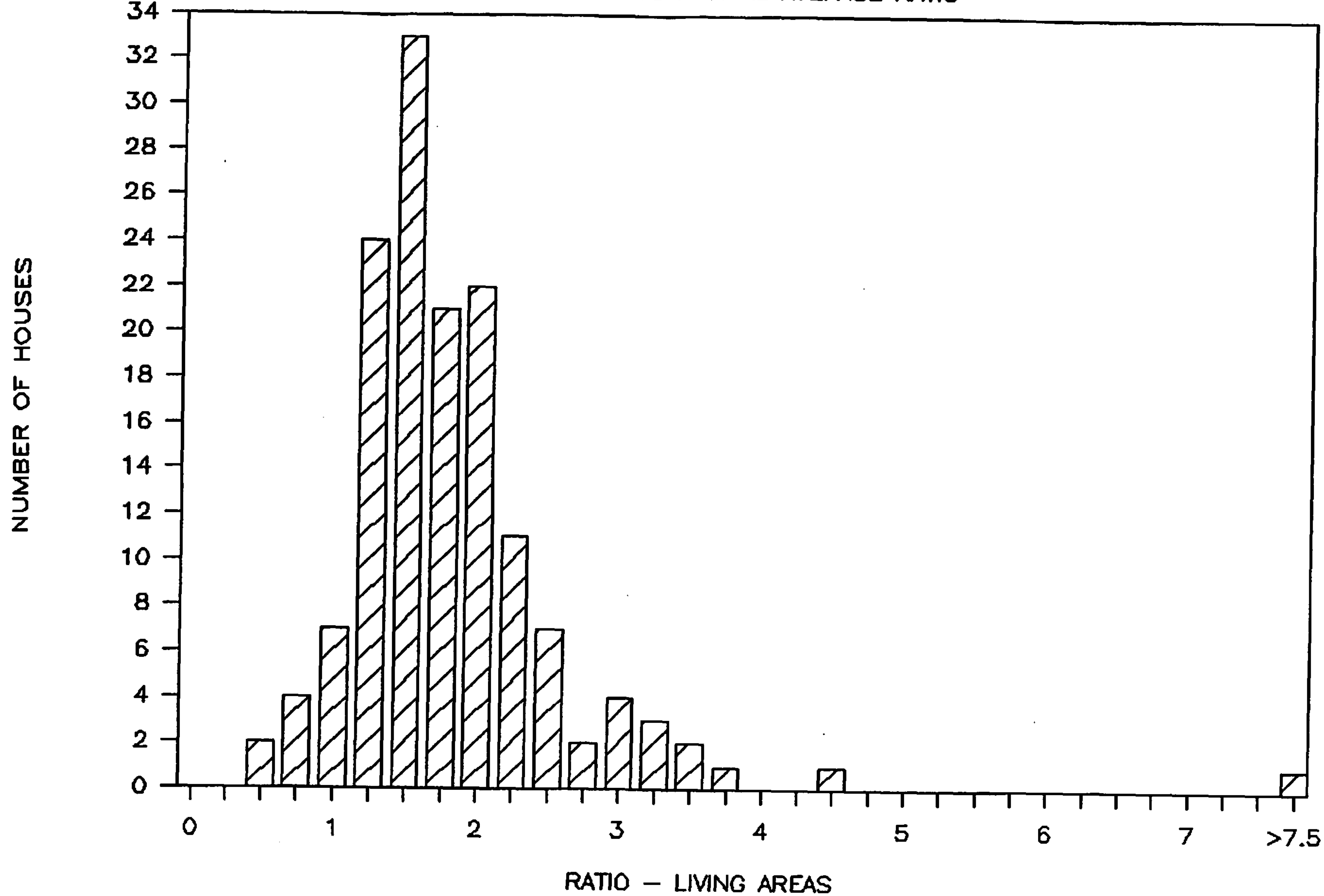
NEW YORK DATA

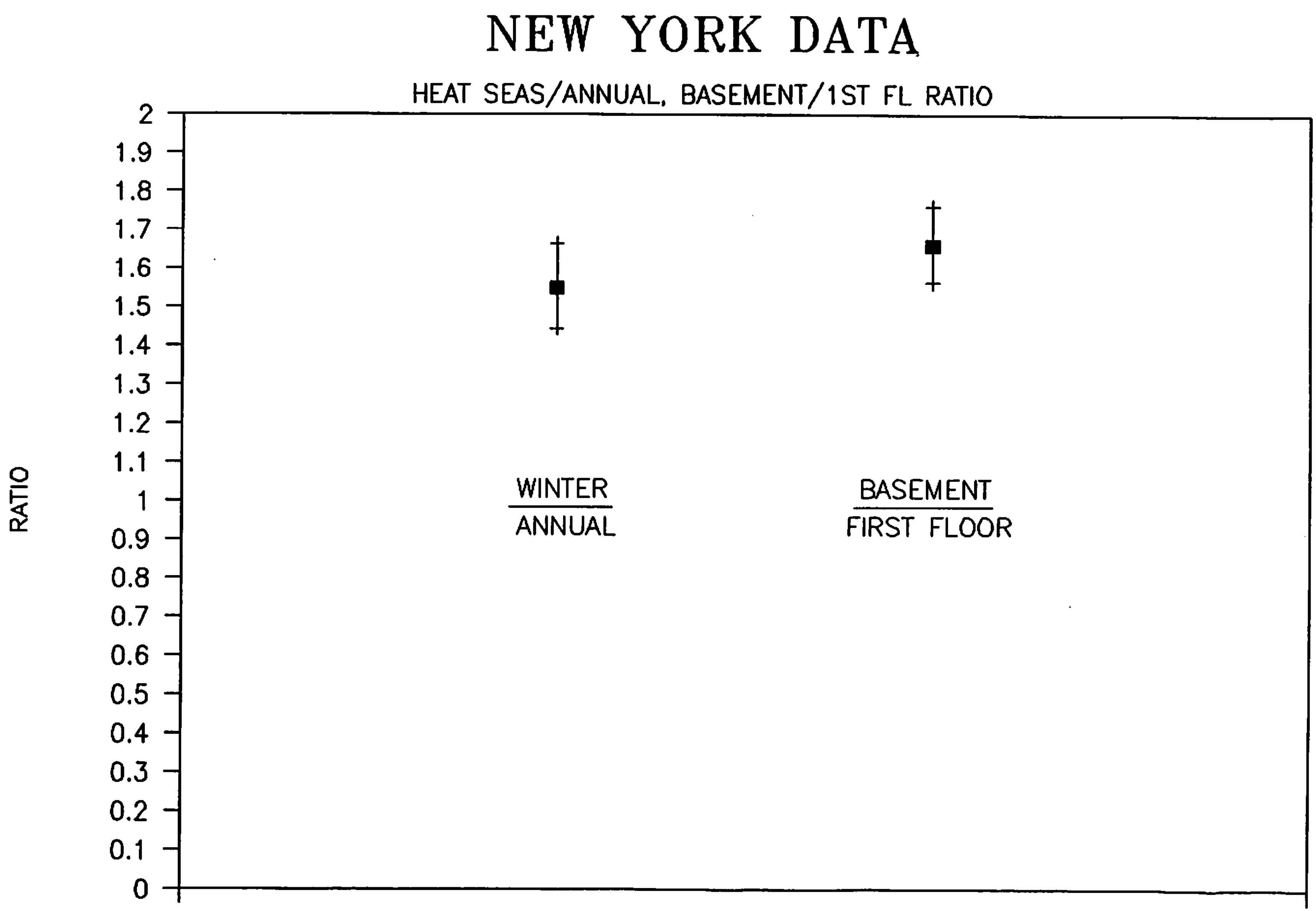
BASEMENT TO FIRST FLOOR RATIO



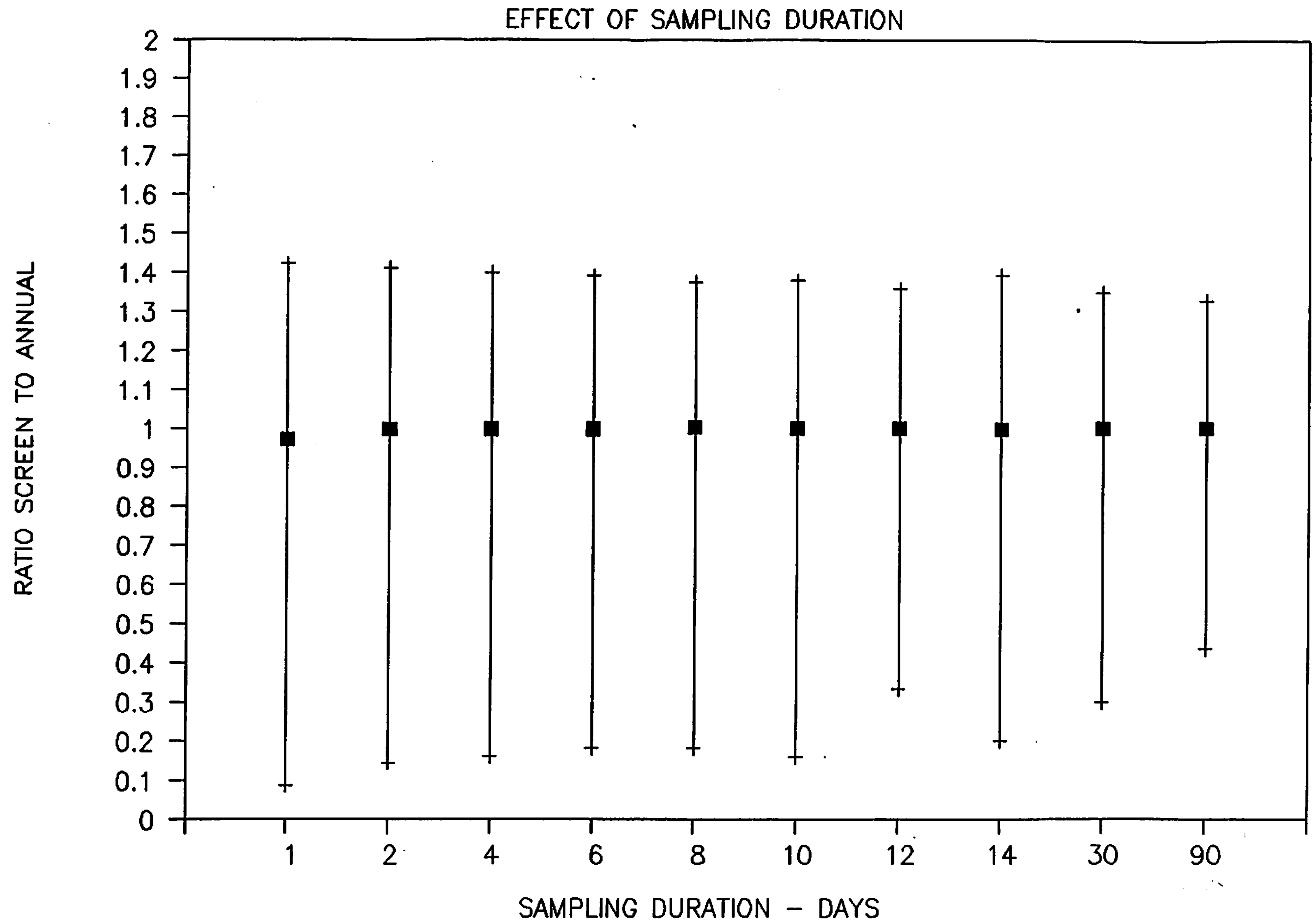
NEW YORK DATA

HEAT SEASON TO ANNUAL AVERAGE RATIO

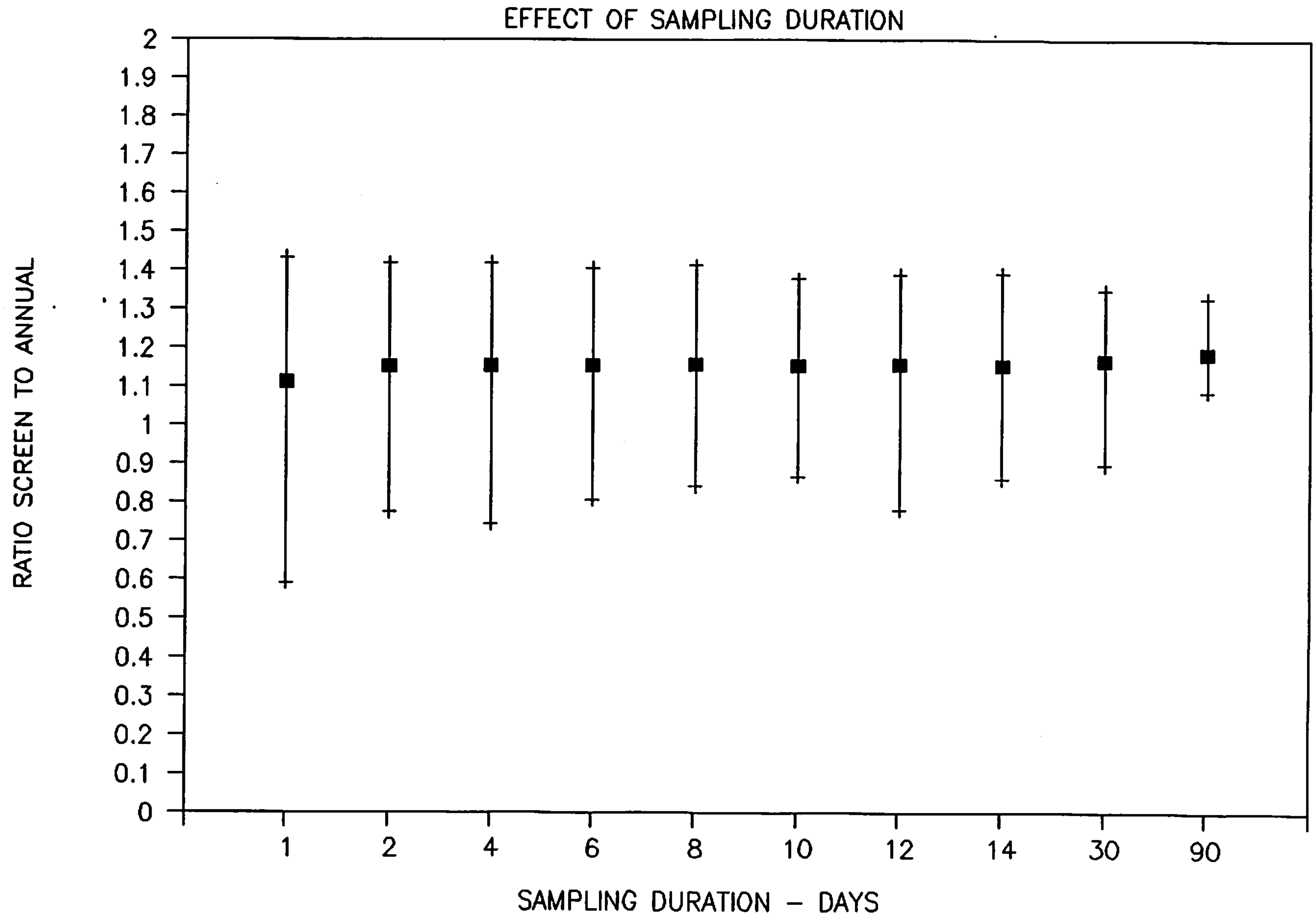



NEW YORK DATA
HEAT SEAS/ANNUAL, BASEMENT/1ST FL RATIO
RATIO
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
WINTER
ANNUAL
BASEMENT
FIRST FLOOR

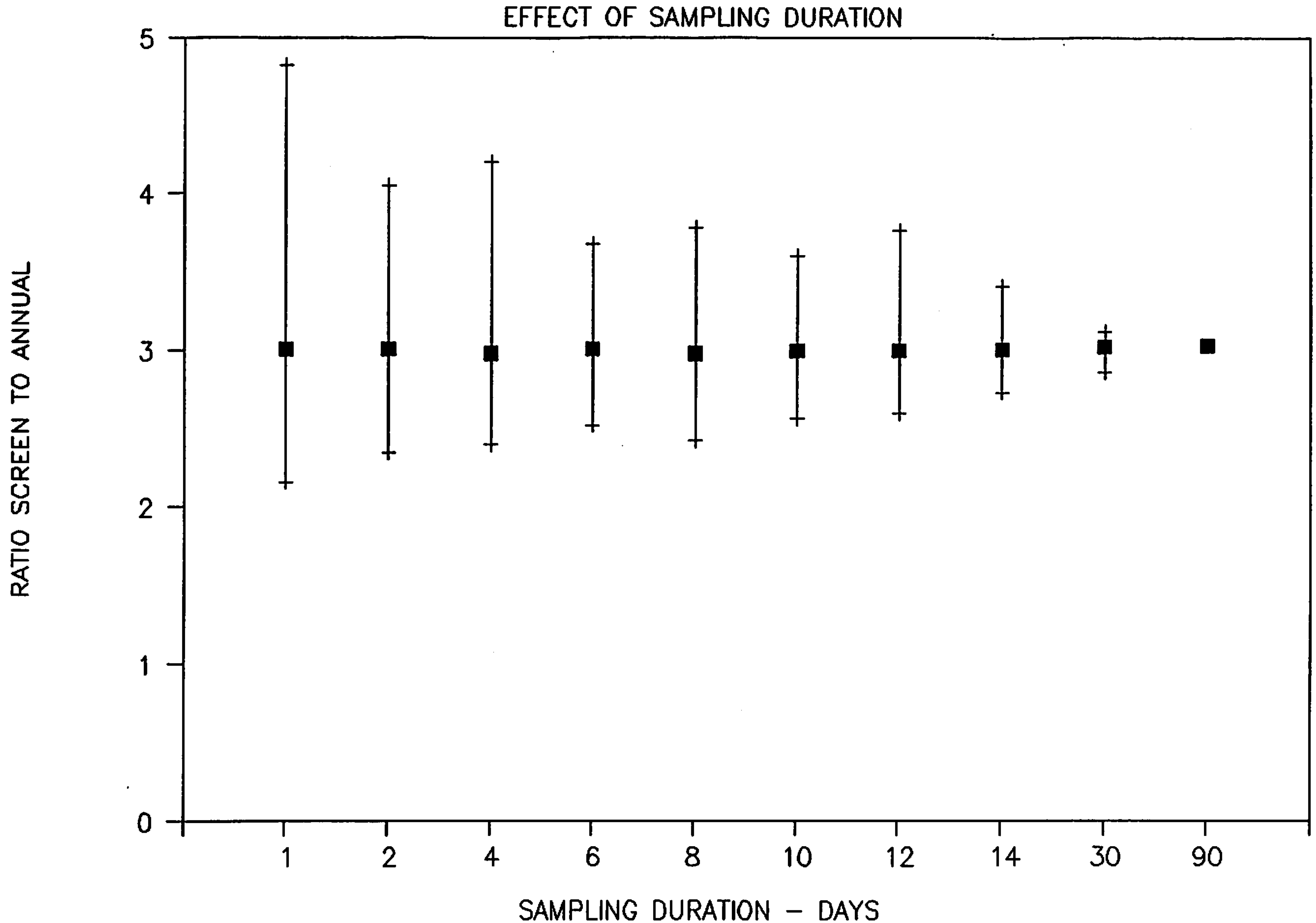
BUTTE HOUSE 1 – UNCONTROLLED



BUTTE HOUSE 1 – NON–SUMMER



MEDIA HOUSE – WINTER BASEMENT



MEDIA HOUSE – WINTER FIRST FLOOR