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IN-SITU MEASUREMENT OF WALL THERMAL PERFORMANCE:

DATA INTERPRETATION AND APPARATUS DESIGN RECOMMENDATIONS

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ABSTRACT

Although the U-values of many building materials have been determined by laboratory testing, the *in-situ* thermal performance of walls, under either static or dynamic conditions, is not so well documented. This report examines the use of *field measurements* of heat flow and surface temperatures to determine the dynamic as well as static thermal performance of walls. The measurement strategies examined include both active devices, which generate their own heat fluxes on the wall surfaces, and passive devices, which rely on the weather to induce the required fluxes and temperature differences. Data obtained with both devices are analyzed with the Simplified Thermal Parameter (STP) model, which was designed to characterize a wall from flux and temperature measurements rather than from assumed material characteristics. The active measurement data are also analyzed with a modified version of the STP model that takes into account lateral heat losses. Some possible sources of error for both active and passive measurement strategies are also examined, and recommendations for both measurement strategies are given.

INTRODUCTION

A wall's thermal resistance (R-value) or its thermal conductance (U-value) are widely accepted parameters for characterizing its steady-state thermal performance. Techniques for determining the values of these parameters from in-situ measurements of temperatures and fluxes are available in the literature, which also includes numerous reports describing the difficulties involved with making these measurements.[1-3] On the other hand, no widely accepted technique exists for measuring or interpreting the data necessary to determine the dynamic thermal performance of a building's walls in-situ. Because the parameters conventionally used for characterizing dynamic performance (e.g. response factors),[4-6] are not easily extracted from heat flux and temperature measurements, it is difficult to establish criteria for either making or interpreting these measurements.

As a means of extracting information about the dynamic thermal performance of wall, two basic measurement strategies have been discussed in the literature, passive and active measurements.[7-10] The major difference between these strategies is that one uses time histories of naturally-occurring heat fluxes and surface temperatures (passive measurement strategy) and the other generates fluxes on a wall surface and measures the resulting temperature response (active measurement strategy). The advantages of an active measurement strategy are: 1) the measurements are theoretically independent of the weather, not relying on naturally induced fluxes or temperature differences to provide measurable results, and 2) the desired flux/temperature frequencies and amplitudes can be specified directly. The major disadvantage of such a strategy is its complexity; it requires precise control of heat fluxes or temperatures, implying a specially designed apparatus for that purpose. Passive measurement strategies are usually much simpler, requiring only two temperature sensors and one or two heat flux meters. The major disadvantage of passive strategies is that they do rely on specific weather conditions to provide measurable temperature differences and fluxes; in other words, measurements can be made only during certain time periods. On the other hand, the dynamic temperatures and fluxes measured with a passive system are ostensibly the same as those that we expect to find when making wall performance predictions. Thus, the measurement period can be chosen based on the presence of dynamic temperature and flux effects characteristic of those expected over the course of the year (i.e. the analysis automatically concentrates on naturally occurring dynamics).

The major issue in data interpretation is how to use heat flux and temperature data to generate a set of parameters that characterize the dynamic performance of a wall. Again, there are two basic aspects to this problem. The first is how to characterize the performance of a wall with a limited set of unique parameters. This problem is basically a modeling problem, the goal of which is obtain the minimum number of independent parameters required to characterize the wall. The second aspect of the data interpretation problem is how to generate the parameter values from the measured flux and temperature histories. This part of the problem is mathematical, involving the selection of appropriate algorithms and statistical testing. The link between these two aspects of the problem is that the degree to which the model parameters are independent affects the effort required to separate them mathematically.

The purpose of this report is to explore the issues involved in characterizing the dynamic performance of a wall from in-situ measurements, specifically: 1) to examine data from passive and active measurement strategies, 2) to demonstrate the application of a particular data interpretation technique based on the Simplified Thermal Parameter Theory,[11] and 3) to make recommendations for future dynamic characterization methodologies.

MEASUREMENTS

As a means of comparing active and passive measurement strategies, measurements made with an active measurement prototype, the Envelope Thermal Test Unit,[12] and passive measurements made in New Zealand [13] are examined.

Active Measurement Strategy

Active measurement strategies are little used for determining the thermal performance of walls. At Lawrence Berkeley Laboratory however, we have made several laboratory and field tests with a prototype device designed and built by our technical staff. The device, called the Envelope Thermal Test Unit (ETTU), has been used to test sections of stud walls in the laboratory, a stud wall in a single-family residence, and a thick concrete wall in a university building [Ref. 12].

ETTU is a microcomputer-controlled device that measures wall performance in-situ by heating the wall surfaces and simultaneously measuring the heat fluxes and surface temperatures on both sides of the wall. It consists of two thermal insulation blankets (extruded polystyrene) fitted with temperature sensors and wafer-thin electric resistance heaters front and back. These blankets, which are pressed against opposite sides of the test wall with wooden support structures, serve as surface temperature probes and large-area heat flux meters (see Figure 1). They are also used to specify the flux on the surface of the wall by controlling the power supplied to the electric-resistance heaters.

Using ETTU to evaluate the thermal performance of a wall involves driving the wall with prespecified fluxes on one side and measuring the resulting flux on the receiving side, as well as measuring the temperature responses on both sides. (The two ETTU blankets are functionally identical; the drive side is chosen by simply changing a parameter in the microcomputer program that controls the experiments and stores the data on floppy disk.) On the drive side, the heater on the wall surface (primary heater) is supplied with the electric power required to provide the desired heat flux.* To insure that the heat goes into the wall rather than being divided between the wall and the surroundings, the heater on the back side of the blanket (secondary heater) is also powered. The power to the secondary heater is controlled to minimize the temperature difference across the blanket, thus minimizing heat flow from the wall surface to the surroundings. On the receiving side of the wall, only the primary heater is powered, thus providing high-frequency, small-amplitude perturbations to the heat flux leaving the wall. The results of an ETTU test are time histories of surface temperatures and fluxes for a 0.6m (2 ft) square wall section.

For the tests described in this report, ETTU was programmed to provide a pink-noise spectrum of heat fluxes on the wall surface. The pink-noise spectrum is similar to the better-known white-noise spectrum, which contains all frequencies at equal amplitudes with random phase relationships. The pink noise spectrum weights the amplitude at each frequency by the inverse of that frequency, thereby weighting lower frequencies more (i.e. the lower frequencies have higher flux amplitudes). For the tests reported here, the fundamental frequency of the pink-noise spectrum was one cycle every twelve hours, specifically chosen to be a harmonic of the diurnal flux/temperature cycle.

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* The primary heater is actually two separately controllable heaters, one for the central measurement section, and one for the edge section.

The ETTU tests described in this report include a laboratory test of an insulated stud wall specimen, a field test of a residential insulated stud wall, and a field test of an insulated concrete wall. The wall specimen test was performed indoors on a built-up 1.8 m by 1.8 m (6 ft by 6 ft) wall section, made from plywood, extruded polystyrene, gypsum board, and wooden studs. The residential stud-wall test was made on an insulated wall between a house and its garage, both sides having gypsum board sheathing. The concrete wall test was on the thick exterior concrete wall of the mechanical room of a university building.

Passive Measurement Strategy

Considerably more experience has been reported on the use of passive measurement strategies for determining the thermal performance of building walls [Refs. 2,8]. As noted earlier, these tests require either one or two heat flux meters and a pair of temperature sensors. The data reported here, measurements made on the walls of two single family residences, comes from the Building Research Association of New Zealand. The data include indoor surface temperatures, outdoor surface temperatures, and indoor heat fluxes measured every 7.5 minutes for periods of approximately four days. In both cases, the fluxes were measured on a 0.6m (2 ft) square section with sensors mechanically pressed against the interior surfaces (see Figure 2).

DATA INTERPRETATION

For both passive and active measurement strategies, the usual goal of data interpretation is to obtain a set of parameters that can be used to either characterize a wall or to make predictions of wall performance. Although numerous techniques exist for characterizing or predicting the dynamic thermal performance of a wall from the thermal properties of its components, few techniques exist for doing this from measurements of surface heat fluxes and temperatures. To interpret the data in this report, we use a simplified model of wall heat transfer, the Simplified Thermal Parameter (STP) model developed at Lawrence Berkeley Laboratory [Ref. 11], and use a nonlinear search algorithm to obtain the parameter values.

The STP model characterizes a wall by its U-value, its time constant, and several coefficients. The U-value and time constant have the conventional definitions, whereas the coefficients multiply the thermal filters derived in an analytical solution of the one-dimensional heat transfer equation for a homogeneous wall. These filter coefficients are what distinguish a multi-layer wall from a homogeneous wall, and can be interpreted as describing the distribution of thermal mass within the wall. Each wall surface has its own coefficient, a large coefficient implying that a large fraction of the wall's thermal mass is near that surface, and a small or negative coefficient implying very little thermal mass at that surface (the coefficients are exactly one for a homogeneous wall, see reference 11).

To obtain the STPs of a wall from measured time histories of fluxes and temperatures, the time histories are first transformed into frequency representations using a fast fourier transform algorithm. Using the fourier transforms of the STP functions, the values of the parameters are determined by a nonlinear least-squares (Chi^2) minimization routine. This routine adjusts the values of the parameters within the STP functions (i.e. the U-value, time constant, and filter coefficients for each side of the wall) to minimize the deviation between the measured fluxes and the fluxes predicted from temperatures with the STP model. If flux data is available for only one side of a wall, the analysis can determine the filter coefficients for that side of the wall only. In this case, the deviation of the wall from homogeneity is represented by a single parameter.

Active Measurement Analysis

The results of the STP analysis of the ETTU tests are compared with the results of one-dimensional-heat-flow computer simulations of the walls. The simulations were performed using handbook values for the thermal conductivities and specific heats of the wall materials. The exact materials in the laboratory specimens were known, whereas the materials in the field test walls were surmised from building plans and from observation. Table 1 presents a comparison of the U-values and time constants determined with the simulations, with those obtained from measurements by STP analysis.

The filter coefficients from the STP analyses, a and b, are also presented in Table 1. The "a" coefficient refers to drive side of the wall, and the "b" coefficient refers to the receiving side. For the laboratory test, the plywood sheathing was on the drive side, whereas the in-situ stud wall was symmetric. The concrete wall was tested with the insulation on the drive side.

As is evident in Table 1, the results of the STP analysis are consistent with the computer simulations for the laboratory test, but less so for the in-situ tests. The results for the in-situ test of the stud wall are acceptable*, but those for the concrete wall show large discrepancies between the simulation and the STP analysis. These discrepancies may be explained by an important difference between the laboratory and field tests that is not apparent in Table 1, namely, that the average flux entering the wall was not equal to the average flux leaving the wall for the field tests. For both field tests, some fraction of the heat entering the wall on the drive side was evidently being removed from the measurement section by lateral conduction. This effect

* Note that the percentage error in the time constant is rather large, but that the absolute error is reasonably small.

TABLE 1: Comparison of STP Analyses and Simulated Wall Performance (Active Measurement Strategy)						
Wall	U-value [W/m^{2}K]		Time Constant [h]		Filter Coefficients [W/m^{2}K]	
	STP Analysis	Simulated	STP Analysis	Simulated	a (STP)	b (STP)
Insulated Stud (laboratory)	0.75	0.69	0.12	0.12	28.	21.
Insulated Stud (in-situ)	0.59	0.52	0.20	0.11	19.	9.7
Insulated Concrete (in-situ)	0.47	0.92	2.4	7.2	-1.0	19.

was especially evident for the concrete wall, for which only 50% of the heat entering on the drive side left on the receiving side. Lateral conduction was apparently minimal in the thin, carefully constructed laboratory wall, whereas the thicker less controlled field walls had conductive lateral heat flow paths. The in-situ stud wall may have had internal air gaps that can convect away heat, whereas the concrete wall was four times the thickness of the laboratory wall, and had highly conductive steel reinforcing rods. Because the STP analysis implicitly assumes that the heat leaving the wall is equal to that entering the wall, the lateral heat losses may well be the cause of the discrepancies between the simulations and the STP analyses for the in-situ tests.

As described above, the filter coefficients (a's and b's) in Table 1 are the parameters in the STP model that account for the non-uniform distribution of mass within most walls. This physical interpretation for the coefficients can be seen in Table 1. For example, in the laboratory test of the stud wall, a and b are very large, corresponding to the massive layers of plywood and gypsum board on the two surfaces. For the in-situ test of the stud wall, both a and b are much larger than 1, indicating that the surfaces of the wall are more massive than the center, as is most surely the case for a stud wall with fiberglass insulation and gypsum sheathing. However, we would expect that a and b would be equal for the in-situ stud-wall test, given that the wall was symmetrically constructed (gypsum board on both sides). These asymmetric results could be due to the lateral heat losses within the wall, or due to the difference between the heat flux spectrums on the two wall surfaces. For the insulated concrete wall, the trends are again correct: the insulated side of the wall had a small (negative) coefficient value, and the concrete side had a large coefficient value.

Modified Active Measurement Analysis

To account for the lateral heat flows induced by ETTU, we added a lateral heat-flow path into the STP analysis. The modification that we chose is an approximation, the correct solution being to rederive the Simplified Thermal Parameter functions assuming multidimensional heat flow. Nevertheless, we were able to define physical limits for the new parameter introduced; i.e., the average lateral heat flow is limited to the difference between the heat flows entering and leaving the wall. This lateral heat flow path adds one additional adjustable parameter into the analysis -- the lateral conductance. This lateral conductance is not meant to characterize the wall, but rather to correct for heat flow anomalies created by the measurement apparatus.

Analyzing the field-test data sets using the modified Simplified Thermal Parameter program did not significantly improve our comparisons with the computer simulations. The results of these comparisons, shown in Table 2, should be compared with the standard STP analysis results in

Table 1.

TABLE 2: Comparison of Modified STP Analyses and Simulated Wall Performance (Active Measurement Strategy)						
Wall	U-value [W/m^{2}K]		Time Constant [h]		Filter Coefficients [W/m^{2}K]	
	STP Analysis	Simulated	STP Analysis	Simulated	a (STP)	b (STP)
Insulated Stud (in-situ)	0.55	0.52	0.22	0.11	16.	10.
Insulated Concrete (in-situ)	0.41	0.92	3.6	7.2	-1.2	15.

Single-sided Active Measurement Analysis

To determine whether or not single-sided flux measurements can provide satisfactory estimates of the thermal parameters describing a wall, we performed one additional test using the unmodified STP analysis on active measurement data. Taking the data from the field test of the insulated stud wall, we used only the flux measurements on driven side of the wall. The parameter values thus obtained proved to be very similar to those obtained with two-sided analysis. The U-value was calculated to be 0.58 W/m^{2}K, the time constant 0.23 h, and the filter coefficient, a, 17.0 — all essentially equal to the values in determined by two-sided analysis as reported in Table 1 (the filter coefficient b cannot be determined with a single sided analysis). It is encouraging that this analysis yields the same results as the two-sided analysis, although we do not have any information about the other side of the wall (filter coefficient b), or how similar our results would have been had the wall not been symmetric.

Passive Measurement Analysis

The Simplified Thermal Parameter model was also used to analyze passive measurement data from the walls of two houses in the New Zealand studies. One wall was a standard fiberglass-insulated stud wall with a small air gap and brick facing on the exterior, and gypsum sheathing on the interior. The second wall was also an insulated stud wall, only it had weatherboard rather than an air gap and brick on the exterior.

Because the New Zealand data includes only the measured flux on the inside surface of the wall and the two surface temperatures, a one-sided STP analysis had to be performed. In Table 3, the results of the one-sided STP analysis on both walls are compared with the results of one-dimensional-heat-flow computer simulations and the results obtained by the Building Research Association in New Zealand. Because the exact material properties for the wall components were not available, we based the computer simulations on handbook properties for the described construction materials. For each wall we performed the analysis for three different time periods to check for consistency in the results.

Looking at the U-values in Table 3, we find that the STP analyses results are similar to those from the New Zealand analyses, but significantly different from the computer simulations. This outcome is not surprising, considering the uncertainty in the material properties used in the simulations. On the other hand, if we examine the STP analysis results for a given wall, we observe very little variation in the U-value determined for the three separate time periods -- standard deviations of 2% and 7% for the two walls. We can conclude from this consistency that the particular 24-hour time period chosen does not have a strong effect on the U-value determination.

TABLE 3: Comparison of STP Analyses, Simulated Wall Performance, and New Zealand Analyses (Passive Measurement Strategy)							
Wall	Test	U-value [W/m^2K]			Time Constant [h]		Filter Coefficient [W/m^2K]
		STP Analysis	Simulated	New Zealand*	STP Analysis	Simulated	a (STP)
Brick Faced Stud	1	0.54	0.45	0.59	1.8	1.4	1.1
	2	0.53	0.45	0.59	1.8	1.4	1.6
	3	0.52	0.45	0.59	0.22	1.4	9.9
Wooden Faced Stud	1	0.70	0.47	0.77	0.26	0.15	8.2
	2	0.72	0.47	0.77	0.44	0.15	7.4
	3	0.63	0.47	0.77	0.53	0.15	6.9

* Results obtained from steady-state analysis of entire test period.

Turning to the time constants and filter coefficients determined by the STP analysis (Table 3), we observe that these parameters are not as well-determined as the U-value. For both walls, an inverse correlation seems to exist between the values of the time constant and the filter coefficient (the larger the filter coefficient, the smaller the time constant). It appears that the search routine used in the STP analysis to determine the parameter values can arrive at different combinations that provide similar fits to the measured data, implying that the time constant and filter coefficient are not sufficiently independent. This inverse correlation suggests that either the single-sided analysis program or the single-sided analysis program in combination with passive measurements is unable to provide unique parameters that describe the dynamic performance of a wall.

Another possible cause for the poor determination of the time constants and filter coefficients from these passive measurements is the measurements themselves. If the frequency spectrums of the passive heat fluxes and temperatures do not contain measurable amplitudes in the frequency range that invokes dynamic effects in the wall, any analysis program will have difficulties determining dynamic parameters that describe the wall. To determine a wall's dynamic characteristics we must have information at low frequencies (DC is sufficient), and at frequencies close to the inverse time constant of that wall. At frequencies much lower than the inverse time constant, the time constant of the wall has little effect on the heat transfer, whereas at frequencies close to the inverse time constant of the wall, the effects of the time constant of the wall are most clearly discernible. At frequencies much higher than the inverse time constant, the wall's time constant once again has little effect on the heat transfer.

To determine whether or not the New Zealand measurements contain measurable fluxes and temperatures at the appropriate frequencies, we performed fast fourier transforms on the temperature and flux data. The resulting flux and temperature amplitudes are plotted in Figures 3-6. If we assume that the simulation time constants are reasonably close to the true values, we find that the inverse time constant frequencies are approximately 0.7 and 7 rad/hr for the two walls. For both walls, the flux amplitudes are between 0.1 and 0.6 W/m^2 near the inverse time constant of the wall (see Figures 3-4), however, for the second wall (see Figure 6), the temperature amplitudes near 7 rad/hr are less than 0.1 K. Although the flux amplitudes for both walls are within the measurable range, it is clear that the temperature measurements for the second wall are pushing the limits of measurement accuracies. These results indicate that the time constant determination for the second wall has a large uncertainty associated with the measurements.

DISCUSSION

In our analysis of both active and passive measurement data with the Simplified Thermal Parameter model, three important problem areas have been uncovered: 1) Active measurements seem to be plagued by lateral heat losses, 2) Passive measurements do not always contain enough information in the required frequency range, and 3) The parameters in the STP model do not seem to be mathematically independent.

With respect to the problem of lateral heat losses, we have established that active measurement systems are not, as originally conceived, independent of weather conditions. Rather, whenever an active system imposes an average flux that is very different from the weather-induced flux through the wall, the heat flux through the measurement section becomes nonuniform; as a consequence, data interpretation becomes quite difficult. Even when modifying the STP analysis to take lateral heat losses into account, the accuracy of the parameters determined was far from acceptable for the field test of a thick concrete wall.

The second problem area, that of obtaining measurable temperatures and fluxes in the required frequency range, can be further explored by means of fourier transforms of the passive and active wall fluxes. Examining the passive flux amplitudes versus frequency for the two New Zealand tests (Figures 3 and 4), we see that the majority of the dynamic flux is concentrated at approximately 12 rad/hr (or two cycles per hour), and at less than 1 rad/hr (corresponding to frequencies lower than 6 hours per cycle). As described earlier, to make an accurate determination of a wall's dynamic properties, dynamic fluxes at frequencies close to the inverse time constant of the wall are necessary. Although these spectrums appear to be well suited to measurements of walls with inverse time constants near 12 rad/hr or below 1 rad/hr, they are clearly not optimal for measuring all walls. For the particular tests that we have analyzed, the concentration of dynamic fluxes near 12 rad/hr corresponds to the cycling of the building's heating system, and the concentration of dynamic fluxes below 1 rad/hr corresponds to the natural weather-induced dynamics. In general, the inside flux amplitudes at low frequencies will depend on the weather conditions, whereas the inside flux amplitudes at the heater cycling frequencies are affected by many different factors, including: 1) the resistance and time constant of the wall, 2) the size of the building's heating system, 3) the dead band of the building's heating system, and 4) the severity of the weather conditions. From these two tests and from our general observations about the driving forces behind the flux spectrums, it appears that the accuracy or suitability of passive measurements is difficult to predict without having prior knowledge about the wall and the test conditions.

To compare naturally induced fluxes and temperatures with those generated by our active measurement system, we performed fast fourier transforms of the pink-noise fluxes for the in-situ test of a stud wall, and plotted the flux amplitudes against frequency (see Figure 7). Comparing Figures 3, 4 and 7, we see that the frequency spectrum of the naturally induced fluxes is significantly different from that generated by our active pink-noise system. In general, the flux amplitudes at all frequencies are much higher for the active test (the passive flux amplitudes are higher at around 12 rad/h, which corresponds to the heater cycling frequency). These higher amplitudes for the active test spectrum suggest that the signal-to-noise ratio is higher for the active measurements. Assuming that the uncertainties of the temperature and flux sensors remain constant, active measurements should thus provide more accurate determinations of dynamic properties.

The third problem area, the apparent interdependence of the dynamic parameters in the STP model, stems from the parameters chosen to characterize the distribution of thermal mass within a wall. Because the filter coefficients (a's and b's) in the STP model are not orthogonal to the time constant, at times the analysis will have difficulties separating the two parameters. These difficulties can arise when flux amplitudes near the inverse time constant are small, and are amplified when using single-sided rather than two-sided analysis, both of which were true for the passive measurements analyzed. Better measurement data would help to confirm the extent of this problem under normal circumstances, although theoretical work would be even more effective if it could develop an orthogonal parameter for quantifying the non-uniformity of thermal mass within walls.

One important issue that has not been addressed in this discussion is the effect of low-frequency (less than one cycle every 24 hours) weather fluctuations on active or passive measurement analysis. Because the STP analysis does not take into account the total amount of heat stored in a wall at the beginning and end of a test, frequencies lower than one cycle every 24 hours tend to bias the results. For example, if a low-frequency cycle causes the average temperature of the wall to be different at the beginning and end of the test, the heat stored in or removed from the thermal mass of the wall will not be accounted for by the STP analysis. One way to examine these effects is to use fourier transforms once again, this time to analyze weather data from different climate regions.[14,15] As an example, a sol-air-temperature frequency spectrum for Madison, Wisconsin in March is shown in Figure 8. If the low frequency weather fluctuations shown in Figure 8 are typical, it appears that low-frequency cycles, on the order of one cycle every two to seven days, have rather large amplitudes. Although this study is not complete, it suggests that the STP analysis procedure (or any future analysis procedure) should be modified to take into account the effects of fractional cycles.

CONCLUSIONS AND RECOMMENDATIONS

The most important conclusion to be drawn from the analyses described in this report is that the accuracy of both active and passive measurement strategies depends upon weather conditions. Active measurement strategies depend on the weather to provide DC heat fluxes through the wall large enough that the imposed active fluxes do not cause lateral heat fluxes in the wall. Passive measurement strategies depend on the weather to provide measurable DC heat fluxes, as well as measurable dynamic heat fluxes at frequencies near the inverse time constant of the wall being tested. In addition, both strategies can be affected by low-frequency weather fluctuations.

If active measurement strategies are to be used in the future, it is clear that they must be designed to take weather conditions into account. This could be accomplished by devising a way to set the mean surface flux generated by an active measurement system equal to the mean weather-induced flux to be expected under the prevailing weather conditions. Two possible techniques for achieving this are: 1) to use a passive heat flux sensor on the wall surface to control the DC heat flux of the active system, 2) to use a wall classification scheme along with the weather to specify the DC heat flux of the active system. This latter technique, wall classification, could also be used to optimize the frequency spectrum generated to analyze the wall. By concentrating heat fluxes at frequencies close to the inverse time constant of the wall being tested, a better signal-to-noise ratio could be assured. This less general, but potentially more accurate technique would use some easily available information about the wall to find the appropriate frequency range, no longer treating the wall as a black box. Walls could be put into several classes such as: light frame construction, light masonry, and heavy masonry. A sample classification scheme is shown in

Table 4, where the quoted time constants were obtained by computer simulations with handbook material properties.

TABLE 4: Classification of Walls by Thermal Time Constant			
Wall Type	Components	U-value [W/m^2K]	Time Constant [h]
Light Frame	gypsum insulation plywood	0.5	0.1
Light Masonry	cinderblock	3.	1.
	gypsum insulation brick	0.5	2.
Heavy Masonry	gypsum concrete insulation	0.7	7.
	gypsum cinderblock insulation plywood	0.4	6.

Our experiences with passive measurement analysis can also provide some general recommendations for in-situ dynamic performance determination. We saw that the inside surface flux spectrum was dominated by the cycling of the building's heating system at high frequencies, and by weather fluctuations at low frequencies. Realizing that in general the cycling of a building's heating system depends on building characteristics as well as the severity of the weather, we can conclude that passive heat flux measurements on the inside wall surface will often not provide the heat flux spectrum necessary to determine the dynamic performance of a wall. To expand our conclusions to outside surface flux measurements we can once again use fourier transforms of weather data to predict the flux spectrum to be expected during a passive test. The sol-air-temperature frequency spectrum for March in Madison, Wisconsin shown in Figure 8 shows the low-frequency amplitudes to be expected on the north wall of a building. However, the data sampling rate was only one point per hour. To perform this test for walls with short time constants, data at higher sampling frequencies would have to be used.

As we have already noted that passive measurements do not generally provide the information necessary for determining the dynamic thermal performance of a wall, and that active measurement strategies must be modified to take into account the effects of weather, one final recommendation remains. This recommendation, based on the experiences behind this report, is that the modelling research required to improve or replace our present data interpretation strategy should proceed in parallel with any future measurement efforts. Based on the knowledge gained in the efforts above, such research should be able to provide a model with independent parameters and a simpler data analysis technique, which could then be used to better evaluate both active and passive measurement strategies, as well as to analyze laboratory hot box data.

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14. Z. O. Cumali, Spectral Analysis of Coincident Weather Data for Application in Building Heating, Cooling Load and Energy Consumption Calculations, ASHRAE Transactions, No. 2159, ASHRAE Annual Meeting, Kansas City, MO, June 28 - July 1, 1970.

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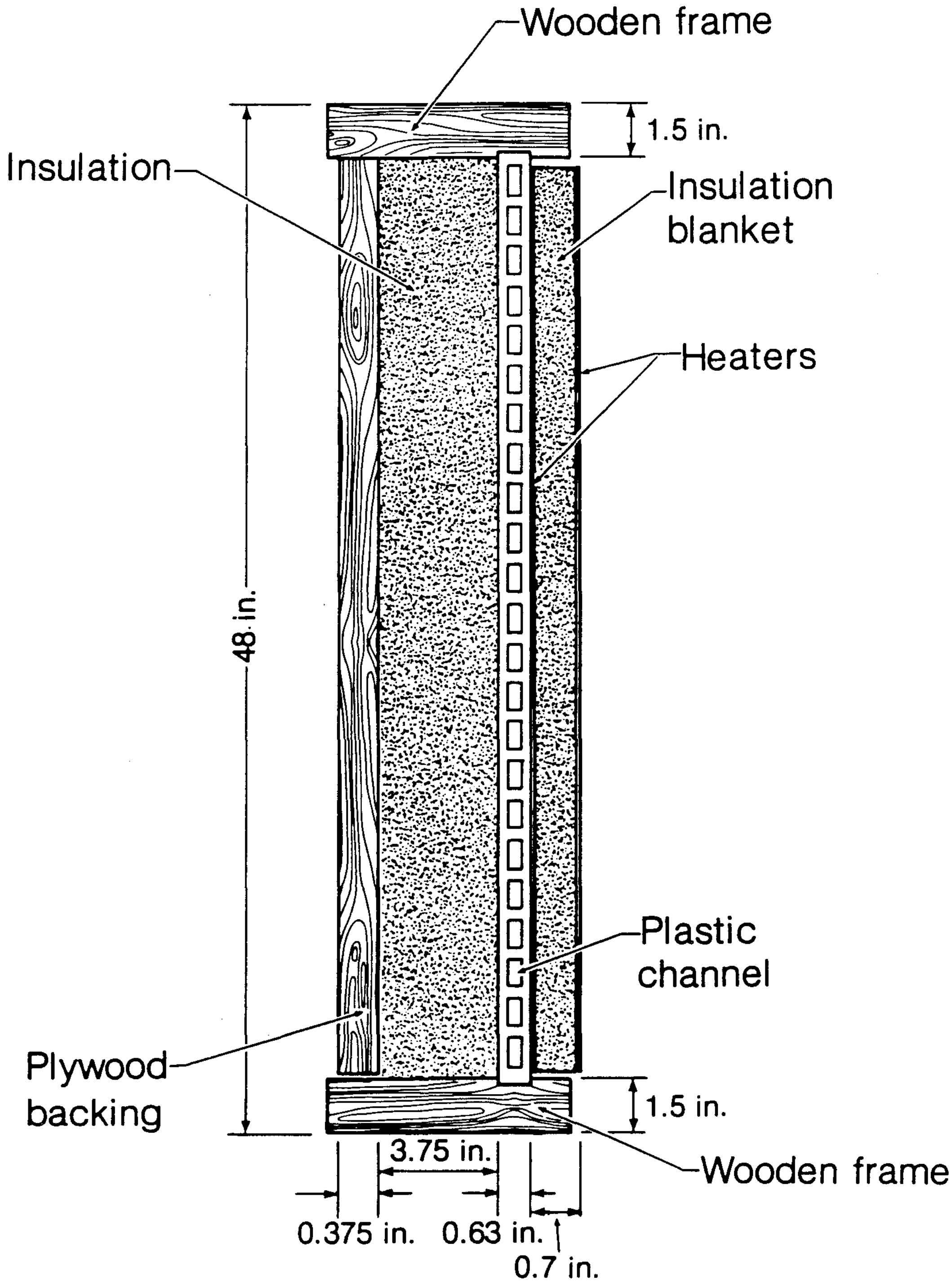


Figure 1. Cross-sectional view of Envelope Thermal Test Unit blanket within its support structure.

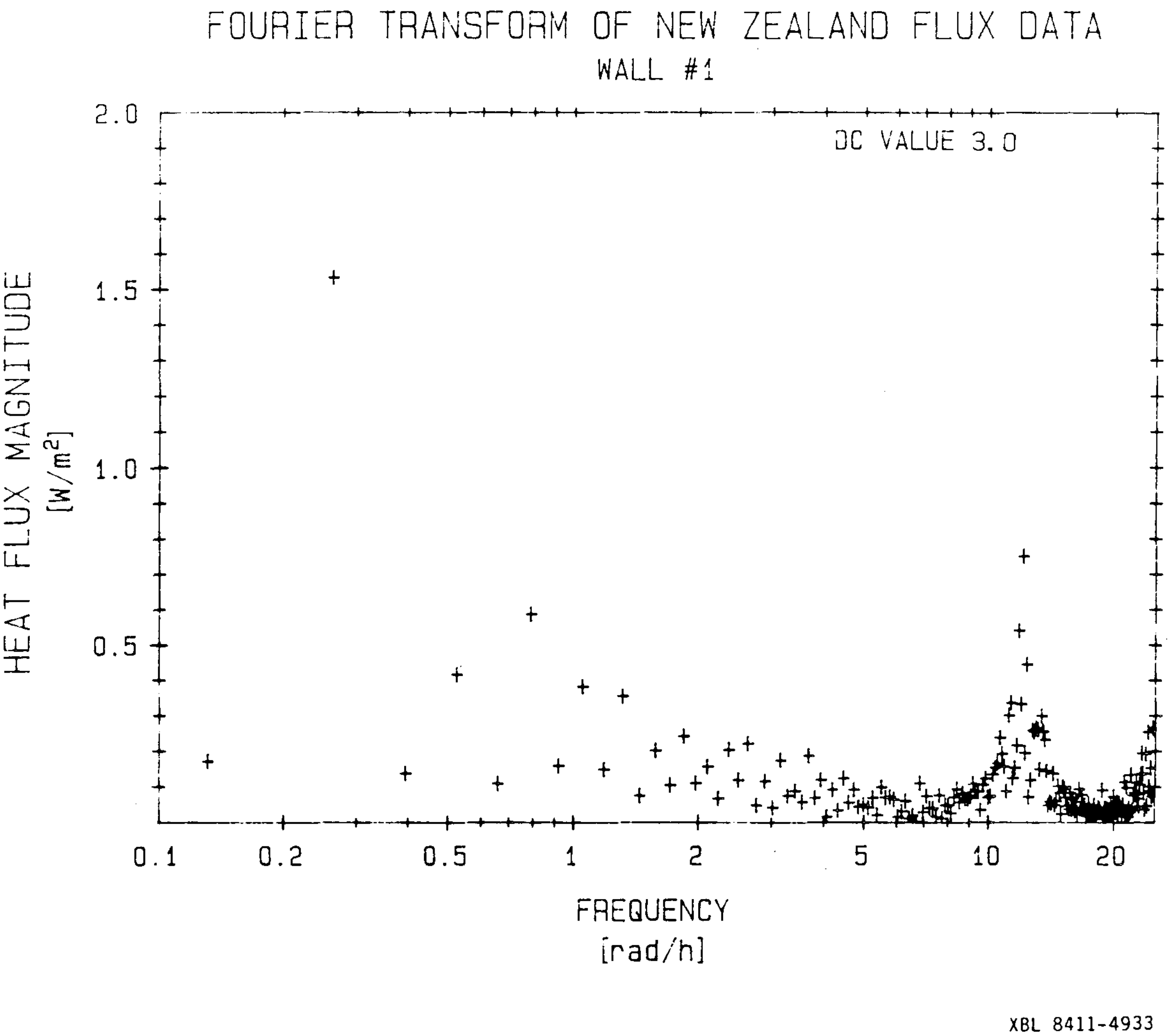
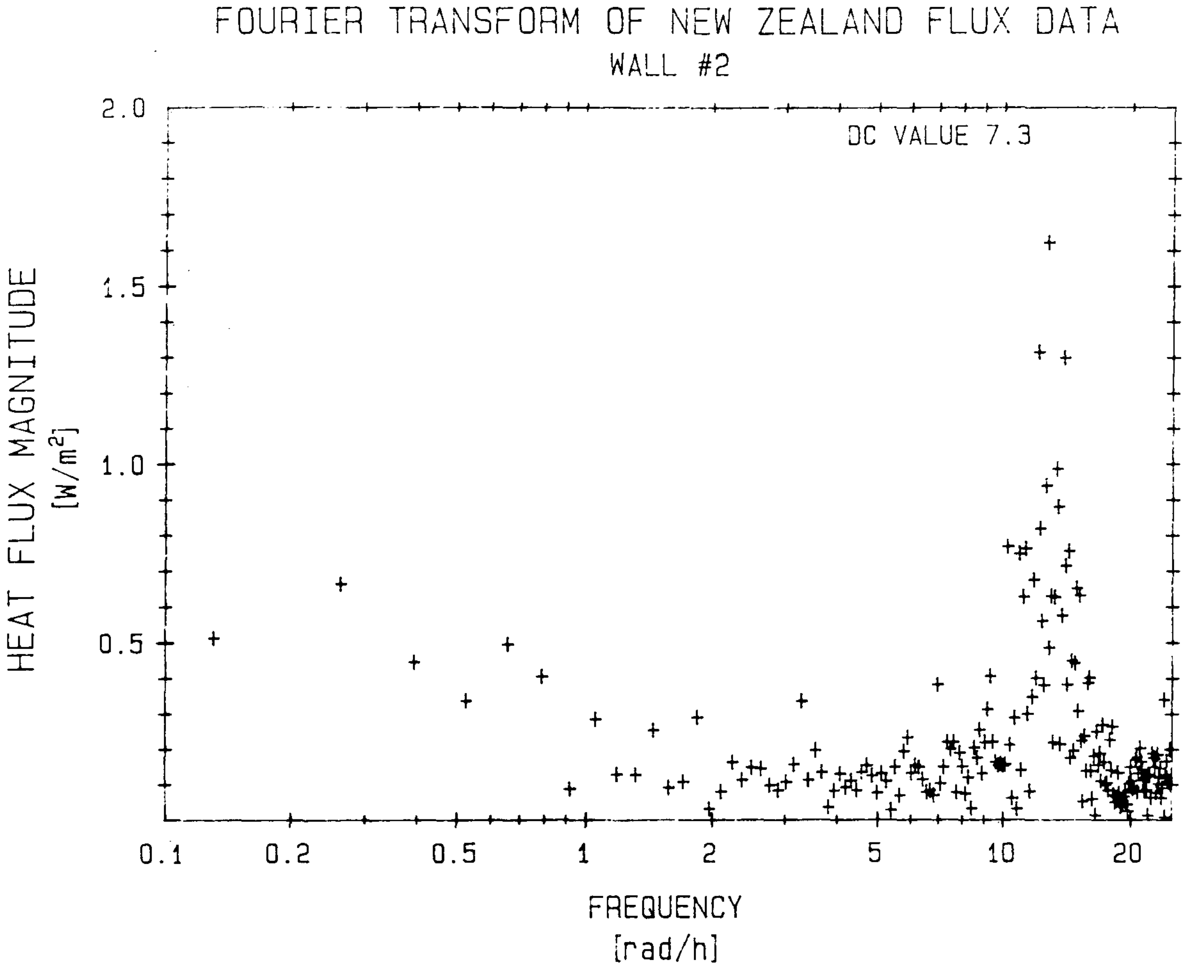


Figure 3. Fourier transform of New Zealand indoor heat fluxes for Wall #1 (DC-component of flux (average) = 3.0 W/m^2).



XBL 8411-4934

Figure 4. Fourier transform of New Zealand indoor heat fluxes for Wall #2 (DC-component of flux (average) = 7.3 W/m^2).

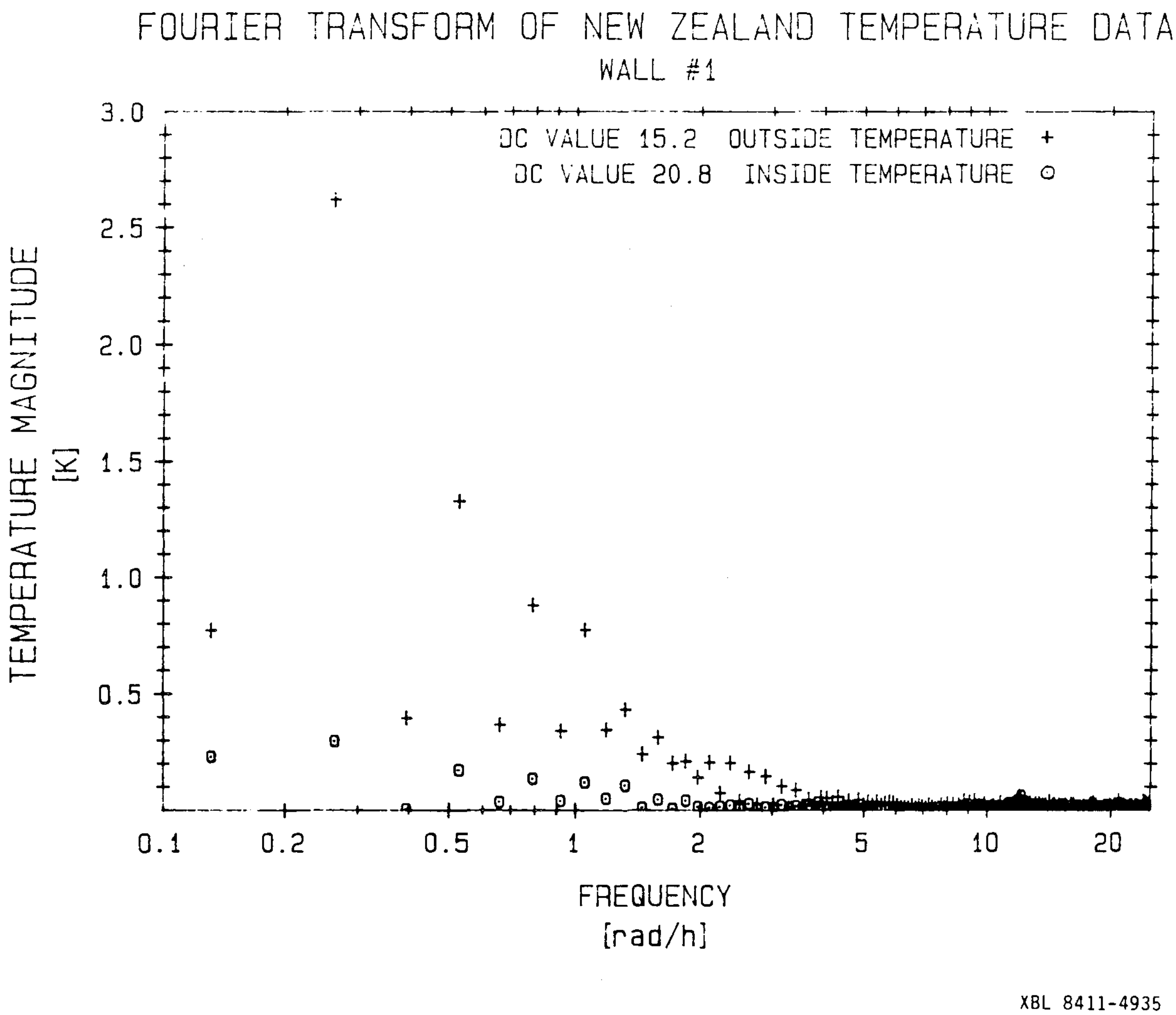


Figure 5. Fourier transform of New Zealand indoor and outdoor temperature data for Wall #1 (Outdoor average = 15.2°C, Indoor average = 20.8°C).

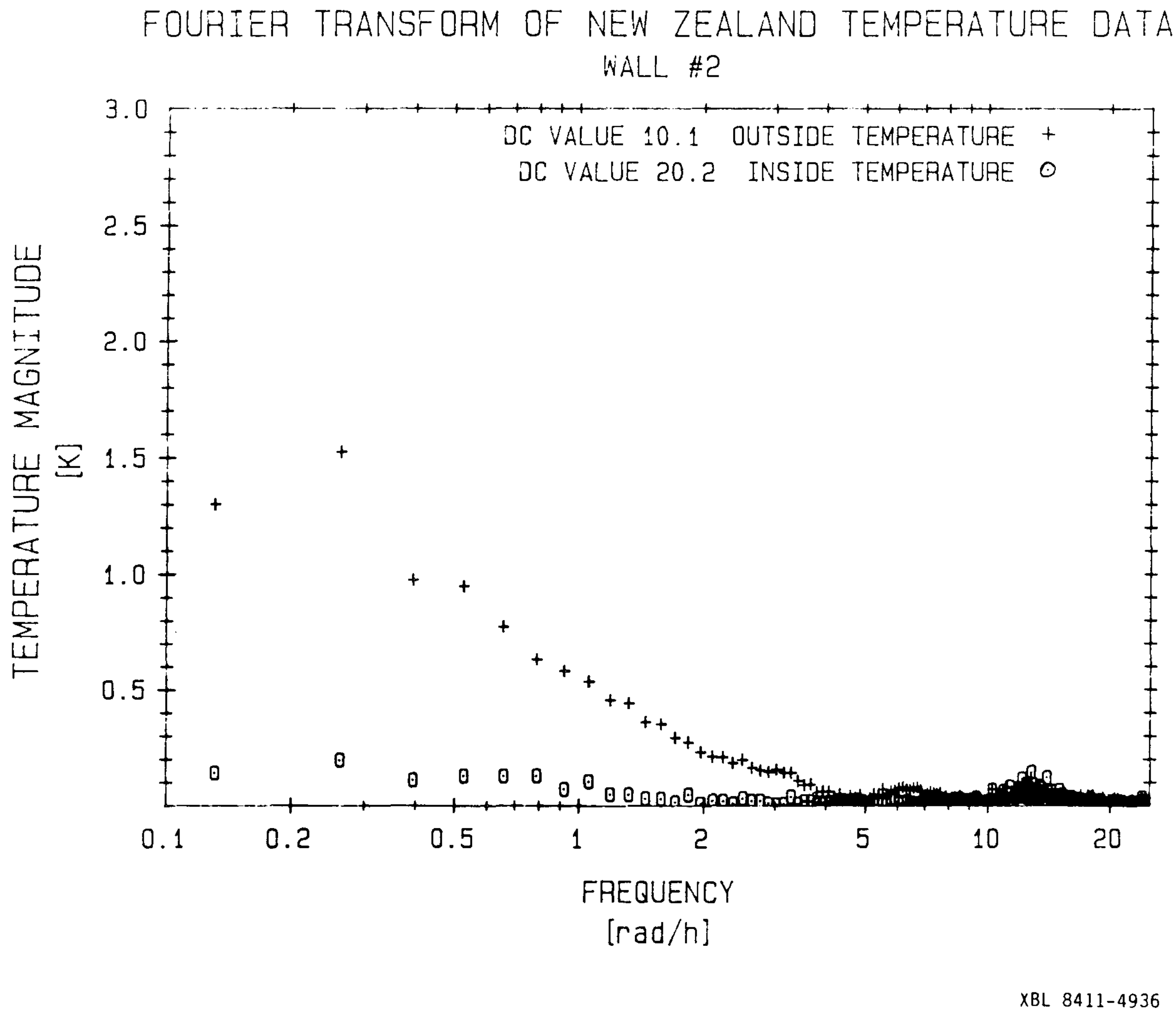


Figure 6. Fourier transform of New Zealand indoor and outdoor temperature data for Wall #2 (Outdoor average = 10.1°C, Indoor average = 20.2°C).

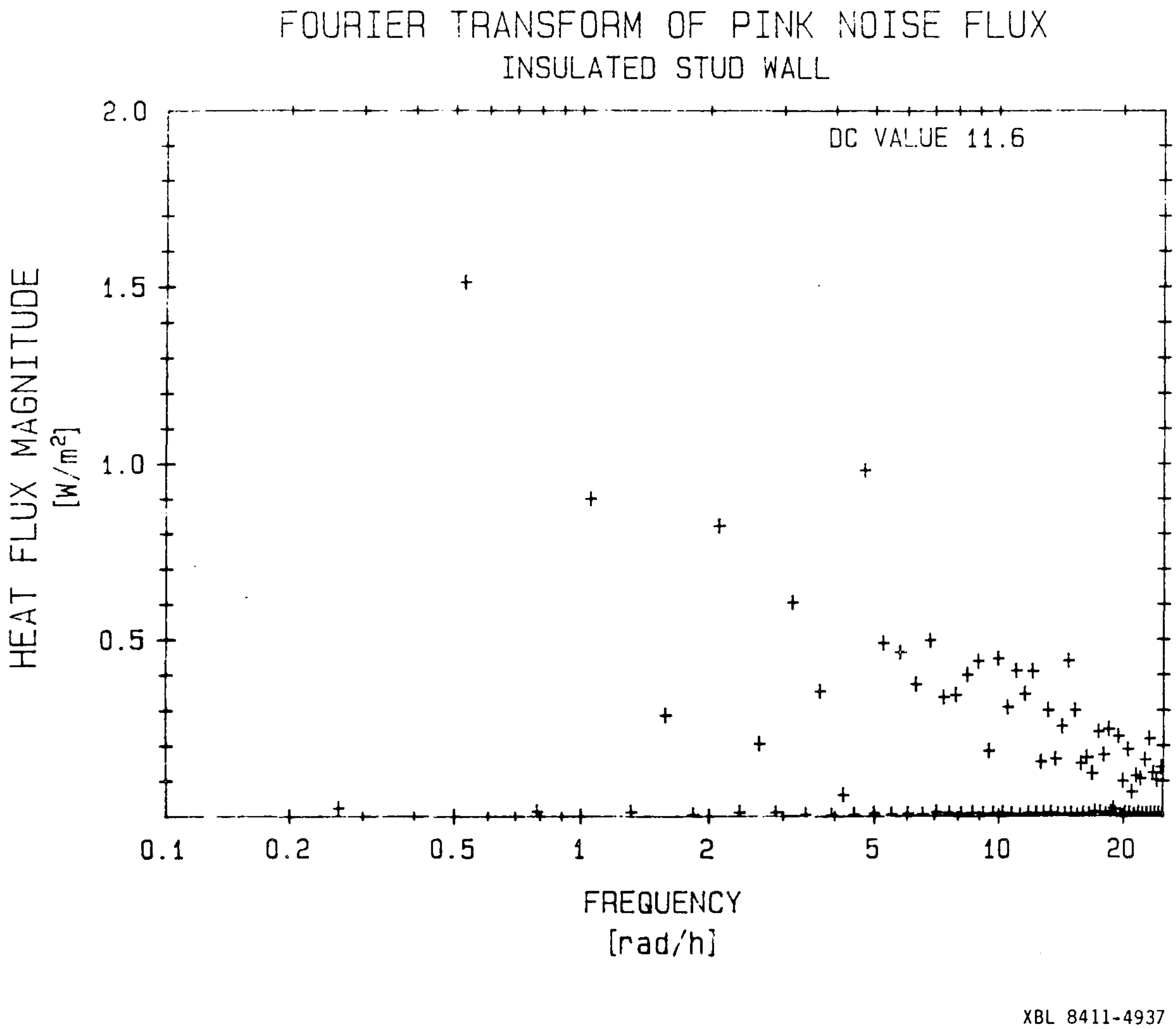


Figure 7. Fourier transform of pink-noise driveside heat fluxes for in-situ test of insulated stud wall (DC-component of flux (average) = 11.3 W/m^2).

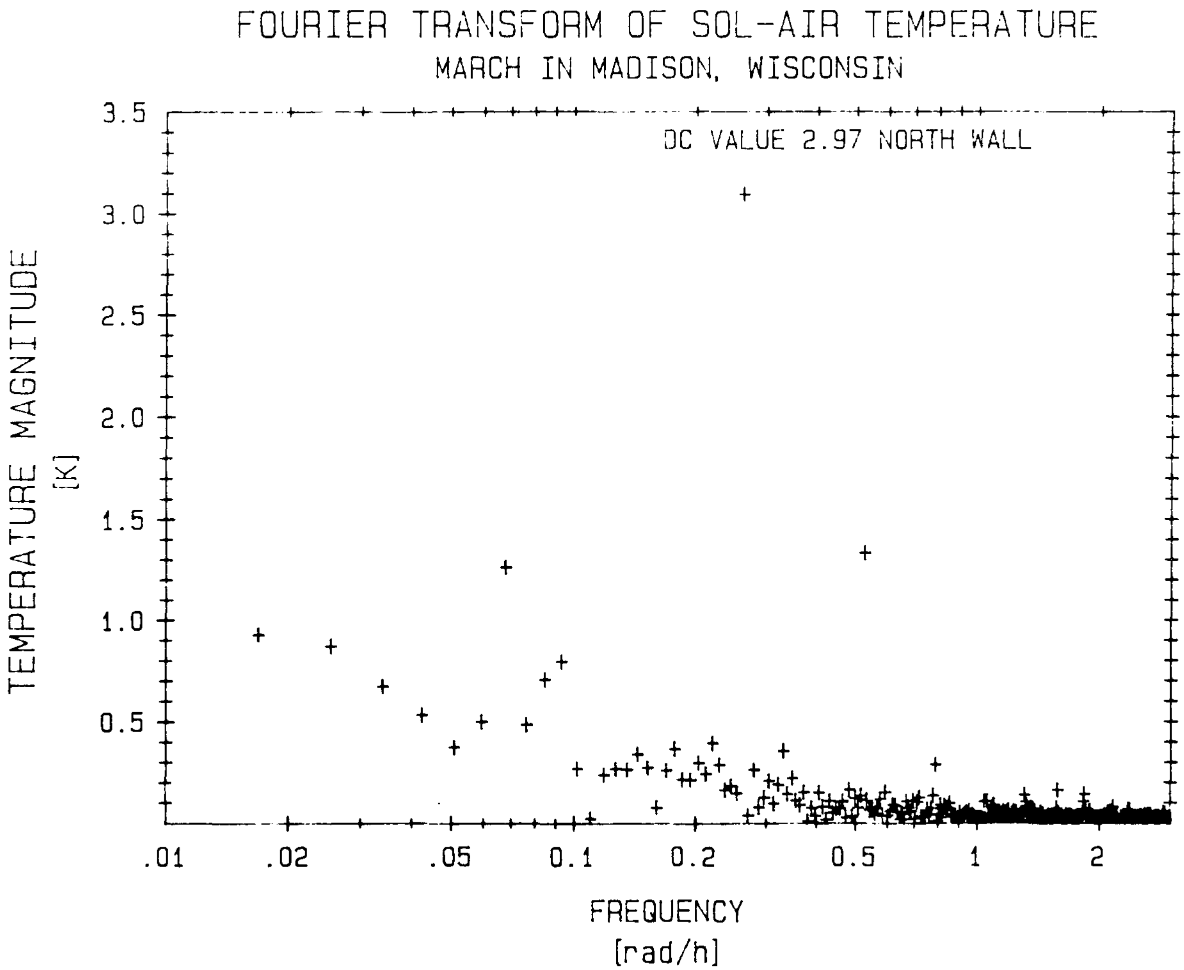


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Figure 8. Fourier transform of sol-air temperature on a north-facing wall for March in Madison, Wisconsin (average temperature = 2.97 ^{o}C).