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APPENDIX 7 TO MAIN REPORT

STUDY OF APPLE HILL
ENERGY EFFICIENT HOMES

TASK H - TIME CONSTANTS

Prepared for:

The POLICY DEVELOPMENT AND RESEARCH SECTOR

of

CANADA MORTGAGE AND HOUSING CORPORATION

BY

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1.0 INTRODUCTION

The rising cost of energy has resulted in increased demand for energy efficient housing. In response to this increased demand, house builders, sponsored and encouraged by various government agencies, have been trying to construct tighter, and more energy conserving houses. Typical insulation levels of houses, being constructed under the R-2000 and the SEEH program, are R40 for the ceiling, R20 for the walls, and R12 in the basement. Also, provisions are made for the installation of a continuous air vapour barrier to reduce air infiltration, and convective heat loss. There are a number of analytical models, such as HOTCAN, and CMHC-2, to predict energy performance based on design specifications. However, there is no guarantee, that, once constructed, the house will perform to these predictions. For this reason, there is a need to develop tests to determine the degree to which newly constructed houses meet performance specifications. Tests have been developed to measure air tightness and air change rates in houses. Thermographic scannning can be used to isolate areas of high heat loss. The problem for the prospective home buyer is that there is no one definitive test which can provide a measurement, or rating, of the thermal efficiency of a house. A test which has been proposed for this purpose involves the measurement of the thermal time constant of the house.

The time constant is a factor which relates the rate of heat flow and heat storage to changing temperature conditions inside and outside of the house. Embodied in this time constant are the following factors:

- conductive heat loss,
- convective heat loss,
- radiant heat loss and gain,
- thermal storage

In reality the structure and composition of a house is made up of almost an infinite number of time constants forming various pathways and mechanism for energy to flow. The proposed time constant test is based on the assumptions that:

- the flow of energy through these structural components is analogous to the flow of current through a large electrical network of resistors and capacitors, and
- this complex network can be represented by one "lumped" circuit with only one or two major time constants.

The purpose of this task, as part of the Apple Hill study, was to develop this theory further. This includes the development of a test procedure, complete with analysis techniques, as well as field testing, and evaluation. The results of this work are presented in this report.

2.0 THEORY

The thermal time constant test is best described using an electrical analogy. During the winter, houses are typically heated by a central, forced air furnace to maintain a constant indoor temperature. The energy required to do this is dependent on the thermal resistance and thermal capacity of the structure, as well as on the difference between inside and outside temperature. In the electrical sense, this condition is similar to the resistance and capacitance in an electrical circuit. In electronics, the furnace is analogous to a current source, while temperature can be represented by voltage.

A simple electrical schematic for this circuit is shown in Figure 2.1. This electrical analogy models the performance with two lumped RC circuits in series. The first RC network, (symbolized by G1 and C1), has a short time constant to model heat transfer in the air contained within the envelope of the house. The second circuit, G2 and C2, models the response of the thermal mass and the heat loss of the structure which possesses a significantly longer time constant than does the first network.

The transient response of the electrical network to a constant current source can be represented as:

$$(1)\quad Vt(t) = V1(0)\exp(-G1/C1)t + i(t)/G1(1-\exp(-G1/C1)t) + V2(0)\exp(-G2/C2)t + i(t)/G2(1-\exp(-G2/C2)t) + VE$$

This is analogous to the thermal response:

(2) T(t) = T1(0)exp(-t/t1*) +Q(t)/U1A1(1-exp(-t/t1*))

+T2(0)exp(-t/t2*) +Q(t)/U2A2(1-exp(-t/t2*)) +TE

where: t1* is the time constant C1/G1 and

t2* is the time constant C2/G2

Figure 2.2 illustrates the Temperature vs. time response of a house which is subject to, first, a step heat input of Q1 resulting in a heating curve, and then "no" heat input (during testing there was some heat input from the recording devices and a light bulb represented as Q2) which results in a cooling curve. Figure 2.2 also describes graphically the terms used below.

T(t) = inside temperature

T1(o) = initial difference between the structure temperature and the inside temperature.

T2(o) = initial temperature difference between the equivalent outside temperature and the structure temperature

TE = equivalent outdoor temperature

Tinf = Steady State Temperature

Q1 = heat input during heating cycle

Q2 = heat input during cooling cycle

G1/C1 = thermal conductance/thermal capacitance of air

G2/C2 = thermal conductance/thermal capacitance of structure

$t1^*$ = short time constant (air)

$t2^*$ = long time constant (structure)

To obtain reasonable test results, temperature readings should be made accurately (to within 0.1 degrees celcius). Also the ideal test conditions should be:

1/ constant outdoor temperature for a reasonable time before and during the test, to ensure steady state conditions,

2/ no energy input into the house other than by the controlled heat input. This includes solar and wind effects, thermal heat storage in the walls, people heat gain, hot water, lights etc.,

3/ constant infiltration during the testing,

4/ constant indoor temperature for a reasonable time before the test to ensure steady state conditions

The resulting thermal responses can be analysed at some point in time $t \gg t1^*$. At this point equation (2) reduces to:

$$(3) \quad T(t) = Q(t)/G1 + T2(0)\exp(-t/t2^*) + Q(t)/G2(1-\exp(-t/t2^*))+TE$$

$$= Q(t)/G1 + Q(t)/G2 + TE + T2(0)\exp(-t/t2^*)-(Q(t)/G2)(\exp-t/t2^*)$$

where: $U1A1 = G1$ and $U2A2 = G2$

if:

(4) $Tinf = TE + Q/G1 + Q/G2$

then:

(5) $T(t) - Tinf = (T2(0)-Q/G2)\exp(-t/t2^*)$

Taking the natural logarithm of both sides of equation (5), we get:

(6) $Ln(T(t) - Tinf) = Ln\ (T2(0)-Q(t)/G2) + (-t/t2^*)$

This is in the form of a linear equation:

(7) $Y = B + (-mx)$

where $m = 1/t2^*$

From the heat loss tests, T(t) is known, that is the inside temperature at any time t, thus if Tinf is assumed, a log-linear regression analysis on 'temperature difference vs. time' can be performed.

From the regression analysis the following parameters can be obtained:

$m = 1/t^*2$
$B = \ln\ (Tt2(0) - Q/G2)$
$A = \exp\ (B)$
r = correlation coefficient

Tinf and the number of points used in the linear regression analysis are continuously adjusted to obtain an optimum r. From these, the best estimate of t*2 can be selected. A computer program was designed to perform the above calculations. Detailed analysis is dicussed in Appendix "B", Regression analysis.

The same procedure was conducted for both heating and cooling curves.

From the general form of equation (4), the following can also be stated for both heating (H) and cooling (C) curves.

(8) Tinf (H) = R* Q1 + TE

(9) Tinf (C) = R* Q2 + TE

where R = 1/G1 + 1/G2

Since Tinf (C), Tinf (H), Q1 and Q2 are known, we have two equations and two unknowns (R and TE), solving for R we get

(10) R = (Tinf(H) -Tinf(C))/Q1-Q2)

Substituting back into equation (8) or (9) to obtain TE; we get;

(11) TE = Tinf(H) - R*Q1, or

(12) TE = Tinf(C) - R*Q2

An air change test is also performed just before the heat loss test in order to obtain an air change rate, which will be used to determine the heat loss due to infiltration.

Figure 2.1

ELECTRIC CURCUIT ANALOGY

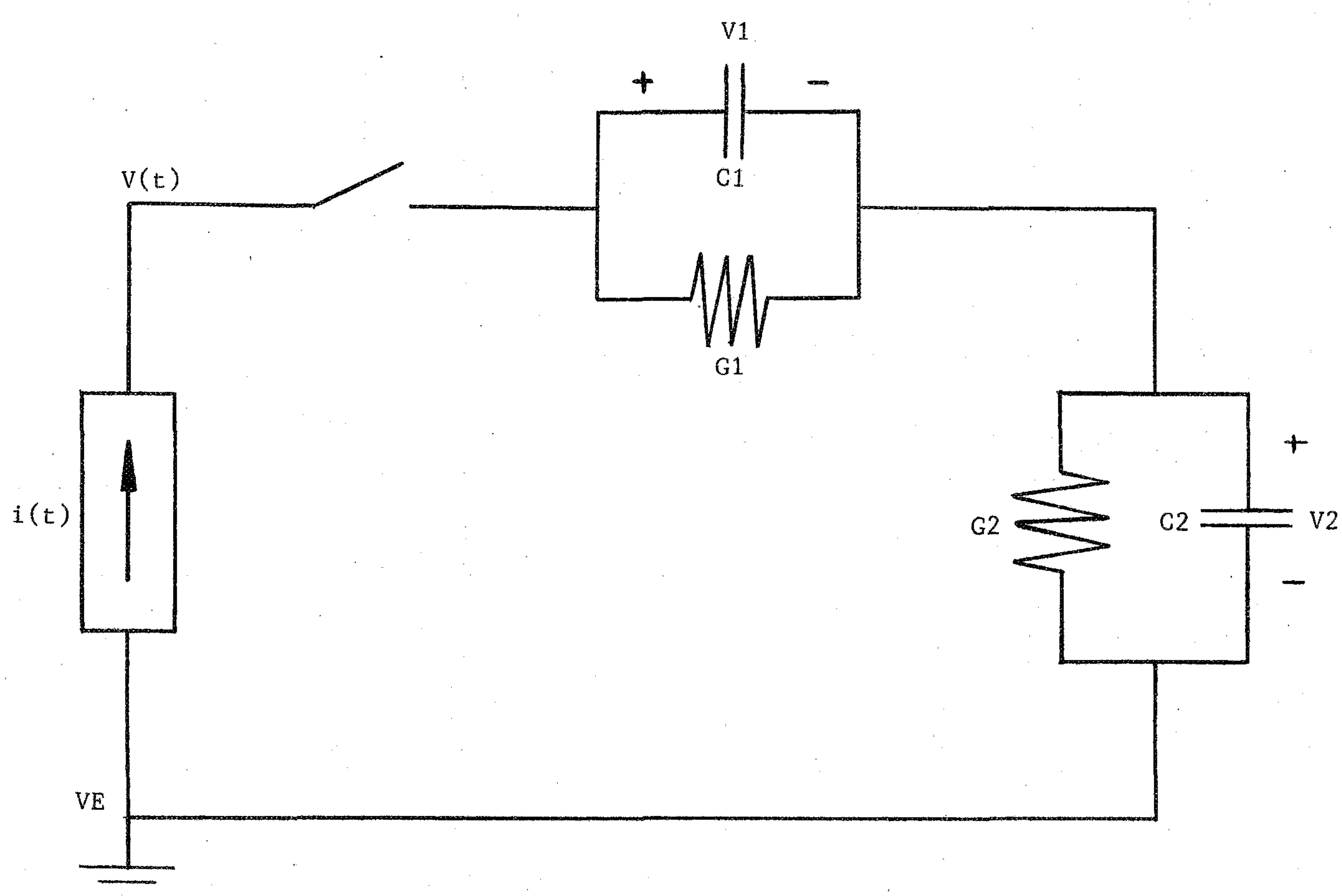
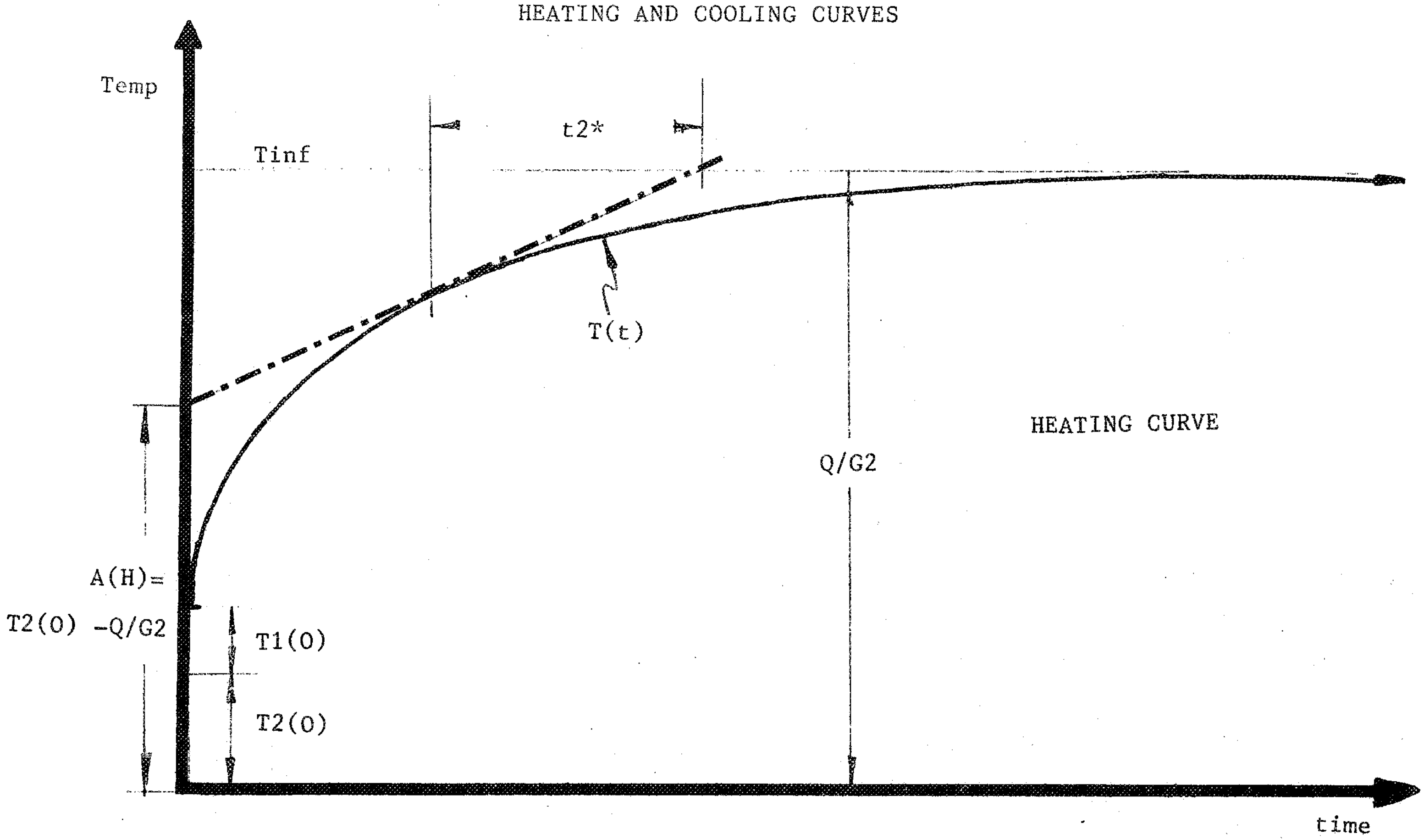
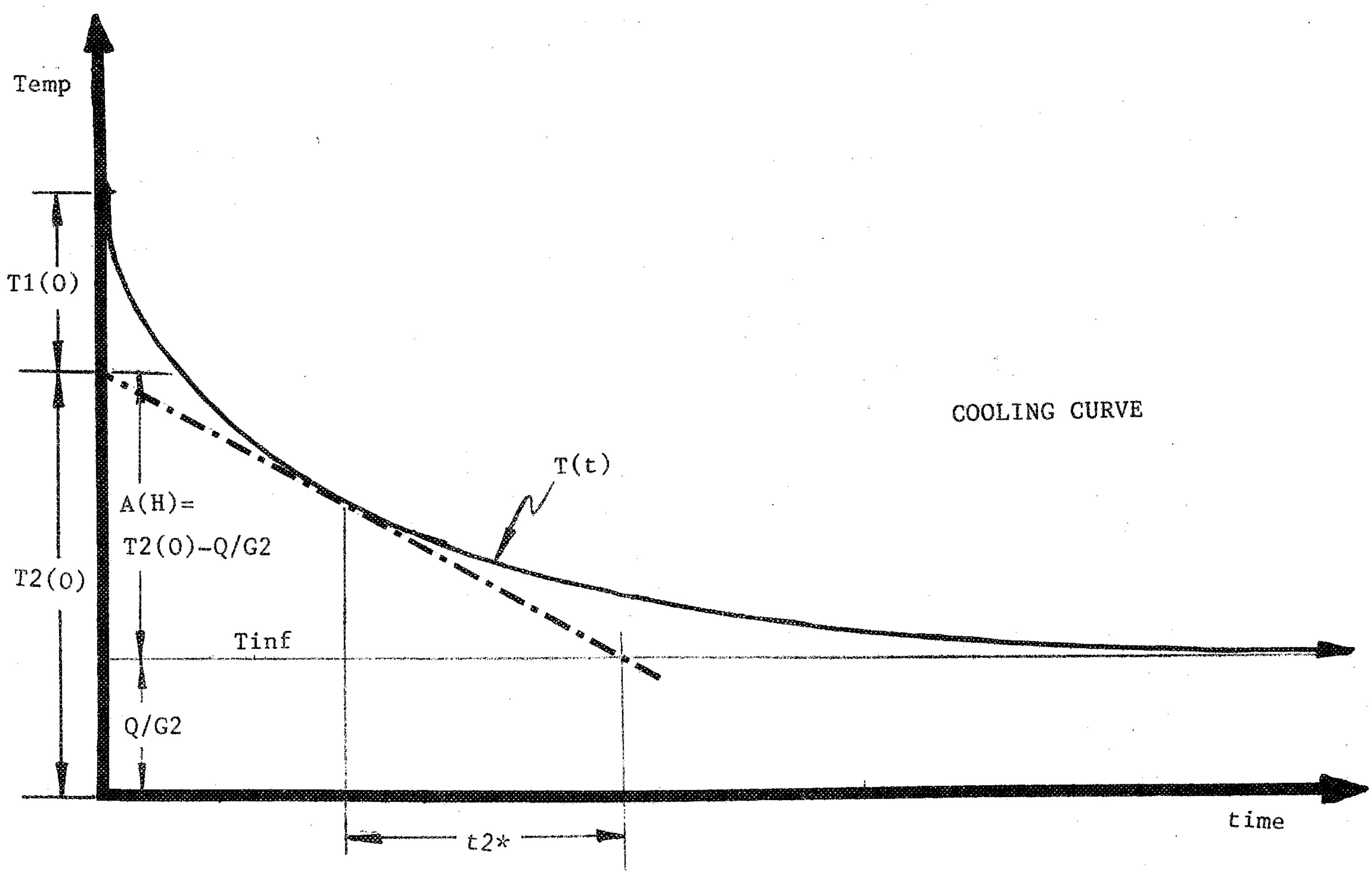


Figure 2.2
TEMPERATURE DISTRIBUTION FOR THE
HEATING AND COOLING CURVES





3.0 TIME CONTSTANT TEST - METHODOLGY

This section briefly describes the procedures for heat loss tests in residential homes. The time required on-site for this test is approximately 12 hours. The test is conducted overnight to minimize solar effects, in the following stages:

Preparation ....0.5 hrs.

Air Change Test.............1.0 hrs.

Heating Test................5.0 hrs.

Cooling Test................5.0 hrs.

Repacking...................0.5 hrs.

Description of each of these stages, and explanations of calculation procedures, are listed below.

3.1 PREPARATION

ARRIVAL TIME: 4:00-5:00 p.m.

1. Close all exterior doors, windows and vents.
2. Open all interior doors to provide proper air circulation.
3. Turn off all heat producing devices.

4. Determine the envelope area (m2) and volume (m3) of the house. (See Appendix 'A' for calculation procedures.)

5. Turn off all lights except one illuminating the chart recorder.

3.2 Air Change Test

1. Perform an Air Change test according to the procedures for air change testing, shown in Appendix A.

3.3 Heating and Cooling Tests¢

1. Install temperature sensors (thermocouples) on each floor of the house in an open and unobstructed area, making sure there is no direct heat source on the thermocouple. A final thermalcouple should be located outside.

2. Connect the thermocouples to the temperature recording device (A/D converter, strip chart recorder), and calibrate it to check for accuracy. (See Appendix 'A' for calibration details). Temperature readings for every five minutes are required.

3. Place electric fans throughout the house evenly spaced with a timer on each. (As a guide, place 5 fans in a larger, two storey house, 2 in the basement, 2 on the first floor, and 1 on the top floor). The timers should all be in synchronize. They must all turn on at 7:00 p.m. and turn off at 12:00 a.m., and must remain

off for a minimum of 5 hours, preferably until the technician arrives in the morning to collect the equipment. In a smaller house such as a Bungalow, use only 3 fans, placing 2 in the basement and 1 on the first floor.

4. Turn on the air circulating fans where one exists, making sure that any exhaust fan is not operating.

5. Determine the energy input rate with the heaters on, and the heaters off. (See Appendix 'A' for calculations).

3.4 Repacking

ARRIVAL TIME: 5:15-A.M ON.

1. Disconnect all equipment, and carefully store them back in their original containers.

2. Turn off the circulating fan.

3. Pack all of the equipment in your car, and lock the house door behind you.

4.0 Time Constant Test Results

A total 15 time constant tests were performed in the Apple Hill subdivision. A summary of the results from analysis of cooling curves from these tests is presented in Table 5.1. These tests were conducted, in most cases, on unoccupied houses. The source of heat for the heating cycle of this test was the furnace in all cases. Due to the oversized capacity of the furnaces, and limits on the thermostats used to control the furnaces during these tests, the heating cycles were usually too short to provide sufficient data for analysis. In most cases, the temperature of the house rose to greater than 30C in less than one hour of heating. Subsequent revisions in the test procedure have resulted in the use of electric heaters with lower heating capacity than the furnaces. However, all the houses in the subdivision were occupied before this change could be implemented. Consequently, analysis of heating curves is only available for five houses.

Time constants related to the cooling curves range from 338 to 1968 minutes, when the test is conducted for 4 to 6 hours. Six tests were conducted on the Russett model home in order to obtain a first approximation of the repeatibility of the test. A wide range of time constants were obtained. These large variations are probably the combined result of an inadequate test procedure, the sensitivity of analysis, the impact of ambient conditions, and the existence of more than one dominant time constant.

Improvements which should be incorporated into the test procedure include:

- use of portable electric heaters and fans,

- air change testing to allow convective and conductive heat loss to be separated,

- temperature sensors distributed thoughout the house, each providing resolution to 2 decimal places,

- heat input to the house capable of providing temperature savings greater than 10C in four hours,

- restricting testing to periods when ambient temperature is below freezing, and living space temperature is greater than 20C,

- monitoring ambient temperature, and wind speed, as well a solar radiation before and during testing.

From this preliminary evaluation of the time constant theory and testing procedures, it appears there is some basis upon which a test can be built to evaluate houses. However, more theoretical development and field testing is required in order to identify the dominant time constant characteristics in houses, and to evaluate the impact of test conditions, test procedures and analytical methods on the reliability and repeatability of the results.

TABLE 5.1
SUMMARY OF TIME CONSTANT TEST RESULTS

HOUSE NO.	MODEL	DATE	TEST NO.	TIME CONST. (MIN.)	TINF COOLING (C)	TIME CONST. (MIN.)	TINF HEATING (C)	TEMP. AMBIENT (C)
19	RUSSET		5	368	19.3			10.3
			6	1138	13.7			12.8
			7	447	22.6			12.8
			13	348	19.6			8.3
			14	1966	-2.1			5.3
			15	1282	9.2			6.7
23	CORTLAND		2	801	13.2			4.0
25	CORTLAND		10					2.0
			12	537	12.8			4.0
29	WILLOW		3	717	14.1	185	32.7	3.0
31	YORK		8	867	14.6			12.8
			9	447	22.6			12.8
			11					
35	FIRESIDE		4	1451	0.8	378	34.6	
39	BALDWIN		1	692	13.7	505	34.3	-1.3

APPENDIX 7-A

Area and Volume Calculation

Area Calculation:

The total envelope area of the heated space in a house is to be estimated; this includes;

the area of all 4 walls from the basement floor to the top ceiling

the area the basement floor

the area of the upper ceiling

Note: crawl spaces and adjoining unheated rooms such as garage is NOT to be included.

Example:
The house dimensions are: 25ft. wide by 40 ft. long.

The basement is 8 ft. high, the first floor and second floor are 9 ft. high each.

There is an adjoining unheated garage whose dimensions are 9 ft. x 25 ft. high each.

Area:

walls	:	25 x (8+9+9) x 2	= 1300 ft.2
walls	:	40 x (8+9+9) x 2	= 2080 ft.2
bsmt.fl	:	25 x 40	= 1000 ft.2
ceiling	:	25 x 40	= 1000 ft.2
garage	:	0	= 0 ft.2¢
			5380 ft.2

Metric Conversion: 5380 ft.2/10.76 ft.2/m2 = 499.7 m2

Volume:	house :	25 x 40 x (8+9+9) =	26000 ft.
	garage:	0 =	0 ft.

Metric Conversion: 26000 ft.3/35.33 ft.3/m3 = 735.9 m3

Recording Calibration

Strip Chart Recorder:

1. Turn on recorder, and place thermocouple leads in sockets (Indicate direction of temperature increase by breathing on the thermocouple, then observing which direction the pen moves.)

2. Turn heat switch on, and paper feed to 6 cm/hr.

3. Place scale to 2 mV Full Scale Deflection (FSD).

4. Short the positive and negative leads, and use 'zero' adjuster to move pen to desired location on the paper. (Repeat this for both channels).

5. Repeat Step 4 on 1 mV FSD.

6. Replace recorder to 2 mV FSD. .1m3

A/D CONVERTER

1. Turn on computer.
2. Load temperature sensing program.
3. Run temperature sensing program.

Heat Input Calculations

1. Turn on only the energy consuming devices that would normally be operating during a 'heating' test, that is, all heaters, timers, temperature recorder, air circulating fan, and the one light bulb illuminating the temperature recorder.

Locate the electricity meter, and time 25 revolutions of the rotating arm. Do this three times, to check accuracy, and take the average. (If any time measurement seems unreasonable, repeat this procedure).

Q1 = (number of revolutions) x 3600¢

138.9 x (time of 25 revolutions)

2. Turn off all energy consuming devices except for the timers, temperature recorder, air circulating fan and light bulb illuminating the recorder.

Time 1 revolution of the rotating arm on the electricity meter. Do this three times to check for accuracy and take the average. (if any time measurement seems unreasonable, repeat this procedure).

The heat input for the cooling curve can be calculated as:

Q2 = 3600

138.9 x (time of 1 revolution