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REPORT ON AN APPARATUS FOR MEASURING THERMAL RESISTANCE OF EXPANDED POLYSTYRENE INSULATION.

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EXECUTIVE SUMMARY

An apparatus to measure the thermal resistance of expanded polystyrene (EPS) has been developed at IRC as one of two elements of inexpensive instrumentation proposed for the quality assurance programs of the EPS industry. The other is a flexural strength apparatus and has been reported in another document.

The apparatus reported here was used for testing 16 pairs of specimens selected from a set of EPS experimental products and the results were compared with those obtained on a Guarded Hot Plate (GHP) apparatus. The difference in each of these comparative tests varied from 0 to the maximum of 0.6 percent, while the mean difference was 0.03%. Yet the new equipment is approximately ten times less expensive than a GHP apparatus and much easier to operate. It is therefore expected that this new equipment will be used by Canadian manufacturers of EPS (and other thermal insulating boards) as a tool for control of the production quality.

INTRODUCTION

The need for a simple and inexpensive tester

Thermal resistance of insulating materials is usually determined either with a Guarded Hot Plate (GHP) or a Heat Flow Meter (HFM) apparatus. Commercial equipment in either category is available but is expensive. Moreover, this equipment often demands substantial skills to maintain its proper calibration which discourages a small manufacturing company from its use.

At the same time, to monitor variations in the moulding process, the technical committee of the EPS industry postulated measurements of thermal resistance and flexural strength of the EPS sampled at the selected mould locations*. Therefore, the steering committee of the joint SPI/NRC-IRC research program recommended that IRC develop inexpensive test equipment which could be used at the manufacturing site for the routine measurement of thermal resistance.

It has been known to the measurement community that the measurements of thermal resistance of insulating materials can be considerably simplified through the use of a thin heater apparatus. A thin heater, with low thermal

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*This approach is further discussed in the IRC report on flexural strength tester developed for quality control of EPS boards.

conductivity in the direction parallel to the heater surface, may, under specific test conditions, be used without the guard ring system of GHP apparatus. A new ASTM Standard C1114 summarizes this knowledge and presents two designs of a thin heater (TH) apparatus. Since these designs, in terms of geometry and dimensions, were not suitable for purposes outlined above, a new thin (foil) heater apparatus was designed and built at IRC. This report presents the apparatus and its evaluation for the routine testing of EPS products. The use of the equipment is limited to 30 cm x 30 cm specimens of thickness 25 mm (or less) tested at a mean specimen temperature close to the ambient.

The operating principle

The thermal resistance, R, of the specimen is calculated from the equation

$$R = \Delta T/Q \qquad (1)$$

where ΔT is the temperature difference and Q is the rate of heat flow across the bounding surfaces of a test specimen under steady state conditions.

Consider that a thin, rectangular and uniform heater is placed between two identical test specimens. With the thickness of the heater negligible in comparison with the other dimensions (width and length), losses from the heater edges may be disregarded. Thus, under the steady state conditions, one may expect that half of the heat generated by the heater will be transported across each test specimen. If R_h is the total electrical resistance of the heater, A its area and I the current, the heat flux through the test specimens under steady state conditions, will be

$$Q = I^2 . R_h / 2A \qquad (2)$$

For a heater with the total electrical resistance and area well defined, the measurement of the current, I, will give the rate of the heat flow through bounding specimen surfaces. If the temperature difference, ΔT, across the test specimens is measured independently of the electric current, I, equation (1) can be used to calculate the average thermal resistance of two test specimens. Usually, I is determined by measuring the voltage applied across the heater.

THE APPARATUS

The main components of the TH apparatus are:

1) a thin foil heater
2) two cold plates
3) a cooling bath
4) a power supply and
5) a personal computer and a data acquisition board

equipped with a programmable frequency generator.

These five components and their assembly are described in detail below.

The Foil Heater

The foil heater used in this construction measures 30 cm x 30 cm and consists of a thin film of Kapton on which the heater is built. (This heater was manufactured by Minco Corporation). The uniform layout of the heating element is shown in Figure 1. The total thickness of the assembly is 0.25 mm, and the total resistance of the heater, as measured at operating temperature of 35^{o}C, is 15.6 ohm.

The difference between temperatures of the heater and cold plate is measured with the help of four, gauge 36 copper-constantan thermocouples. These thermocouples are mounted in the central region of the heater and connected to four identical thermocouples placed on the cold plate to form a thermopile, see later text.

The Cold Plates

The cold plates are made from 30 cm x 30 cm x 6 mm copper sheet. One of the surfaces of each plate is machined flat, as required by ASTM C 177 test method. This flat surface carries grooves to accommodate thermocouples and thermistors, positioned and protected by an epoxy resin. Finally, the flat surface of the cold plates are coated with black paint, providing an infrared emittance of the surfaces, E of 0.89.

A flexible 8 mm o.d. copper tubing is bent into a counter flow pattern as shown in Figure 2 and soldered to the other surface of the plate. This copper tubing provides a path for the cold, constant temperature fluid circulated from the cooling bath.

The Cooling Bath

The temperature of the fluid circulated through the copper tubing is held constant within $\pm$ 0.01 K using a constant temperature bath, Model #rte-100a manufactured by Neslab Corporation. The rate of the fluid flow is 12 l/min.

The Power Supply

The circuit diagram for the power supply of the foil heater is shown in Figure 3. The main component of the power supply is a frequency-to-voltage converter. The programmable frequency is generated with the help of the control function of the data acquisition board installed in the personal computer. By adjusting the frequency supplied to the converter, the voltage applied by the power supply is controlled.

Data Acquisition and Control Interface Board

The board is a Metra Byte model DAS8-PGA with eight analog inputs and programmable gain covering nine ranges from 0-10 volt to 0-0.02 volt. This board is operated by the software and used to collect data on the voltage applied to the heater, the thermistor voltage, electric current and the voltage output from the differential thermopile. The board is IBM PC bus compatible and features a 12 bit successive approximation A/D converter. The board is equipped with programmable timer/counter which can be configured as a frequency generator for the output, steering the power supply unit.

The assembly

The test assembly is shown schematically in Figure 4. Two identical test specimens, approximately 30 cm x 30 cm x 25 mm, cut from the same test sample, are placed horizontally, on both sides of the heater. The heat flows vertically, both up and down, through the specimens.

The thermocouple leads from one side of the thin heater and one of the cold plates are connected in series as shown in Figure 5 to form a thermopile with four junctions. These thermocouples, after being mounted in their respective locations, had the calibration (resistance against temperature) checked against another thermocouple set calibrated by the NRC Institute for National Measurement Standards.

Figure 6 shows the block diagram of the apparatus. The power supply, controlled by the frequency to voltage converter is connected to the heater. The analog to digital converter of the board collects input from three controls:

1) the differential thermopile measuring the temperature difference across the specimen,
2) the thermistor measuring temperature of one of the cold plates,
3) the voltage across the foil heater.

THE METHOD

Both quantities needed to calculate thermal resistance, i.e. the thermopile output and the voltage across the foil heater are measured with the help of the data acquisition module of the board. The first is used for calculation of the temperature difference across the specimen, the latter for calculation of the power generated on the heater.

The TH apparatus is controlled in the following manner. The cold plates are held at constant temperature, near 13^{o}C, by circulating thermostated fluid from the cooling bath. The voltage output of the thermistor is measured with the help of the data acquisition module of the board and used for the calculation of the cold plate temperature.

The thermopile output is also measured using the data acquisition module and the temperature difference across the test specimens calculated. This differential is added to the cold plate temperature to determine the temperature of the heater surface and the information is supplied to the temperature control module of the board which generates the frequency corresponding to the power required to raise the temperature of the heater close to 35^{o}C. The frequency as fed into the power supply delivers the appropriate voltage to the heater which immediately alters the temperature of the heater. The process of measurement and control which is automated with the use of the software continues as a closed loop until the test assembly comes to a steady state. To reduce the period before the steady state is achieved, the software operates in both proportional and integral modes.

Additional measurements of thermocouple outputs across the cold plates are carried out in a differential mode, to make sure that the readings are close to 0 volt and to confirm that both the cold plates are at the same temperature.

Though the data acquisition system continuously monitors all the voltages mentioned above, the quantities relevant to the test procedure (see equations 1 and 2), viz. the thermopile output that corresponds to the temperature differential across the specimen and the voltage applied to the heater, are measured in the rate of twice per second and at the end of 1000 such readings an average value is recorded for each of them. The corresponding thermal resistance, calculated according to equations (1) and (2), is then displayed by the computer. When a series of the calculated thermal resistance shows no systematic changes and stays within a small(usually 0.2%) variation of the same value, one may assume that a steady state is reached. Usually, when dry 25 mm thick EPS specimens are tested the steady state is achieved within an hour, see Figure 7.

COMPARATIVE MEASUREMENTS

Measurements were performed on two sets of IRC-NRC transfer standards: medium density glass fiber specimens and expanded polystyrene. Furthermore, a pair of polyurethane specimens encapsulated with epoxy resin and carefully calibrated on the GHP apparatus was also used.

The test results are listed in Table 1. It can be seen that the data obtained from the thin heater apparatus agree in all cases with the data from GHP measurements at least within 0.8%.

In addition to these measurements, GHP and TH apparatus were compared using sixteen different experimental EPS batches. From each of these batches, a pair of specimens was selected and tested both on the GHP and TH apparatuses.

The results are listed in Table 2. The difference in each of these comparative tests varied from 0.02 to a maximum of 0.64%, while the mean value of all differences was 0.03%.

CONCLUDING REMARKS

The accuracy of the apparatus designed and built at NRC is comparable to that of a standard GHP equipment and better than that of an average HFM apparatus. Yet the new equipment is approximately ten times less expensive than a GHP apparatus, about six times less expensive than a HFM apparatus and much easier to operate than either. A special software was developed that controls the power supplied to the heater reducing the period necessary to achieve the steady state. In effect, this apparatus permits performing measurements much faster and with much higher precision than other commercially available equipment. It is therefore expected that this new equipment will be used by Canadian manufacturers of EPS (and other thermal insulating boards) as a tool for control of the production quality.

A very stringent criterion of low cost was set for the design of this apparatus leading to the selection of relatively inexpensive data acquisition and control interface board. The precision of the measurements may be further improved by using a more sophisticated, albeit more expensive board. It will also permit use of the TH apparatus for transient measurements as well as to study the effects introduced by the condensation of moisture and condensable blowing agents in cellular plastic thermal insulations.

ACKNOWLEDGEMENT

The authors are grateful to their colleague Mr. Gint Mitalas who designed the proportional/integral control of power supplied to the heater which reduces the stabilization time.

Table 1. Measured thermal resistances, R, versus R_{cal} which is calculated from temperature dependence of thermal resistances of the transfer standards or calibrated specimens (established from GHP tests).

Specimen #	Mean Temperature (°C)	R ($K.m^2/W$)	R_{cal} ($K.m^2/W$)	ΔR %
1	24.2	0.7141	0.7188	0.7
2	24.2	0.7120	0.7129	0.1
3	24.2	1.216	1.226	0.8

Table 2. Experimental data on expanded polystyrene test specimens at a mean specimen temperature of 24°C; R_{TH} and R_{GHP} are respectively the values for the thermal resistance as determined on the thin heater apparatus and on the GHP apparatus.

Specimen Code	R_{TH} ($K.m^2/W$)	R_{GHP} ($K.m^2/W$)	ΔR %
12C1AB	0.5335	0.5345	0.19
31B3AB	0.5554	0.5574	0.36
14C4CD	0.5696	0.5687	-0.19
33A2AB	0.5966	0.5958	-0.13
13C2AD	0.6199	0.6200	0.02
11C1BC	0.6333	0.6350	0.27
16A4AB	0.6828	0.6826	-0.03
15A1AB	0.6851	0.6838	-0.19
34B4AC	0.6861	0.6891	0.19
32C1AB	0.6934	0.6947	0.19
17C3AB	0.7009	0.7054	0.64
18B2AB	0.7147	0.7149	0.02
6A2BC	0.7866	0.7864	-0.02
5A3AB	0.8027	0.7984	-0.54
7B2AB	0.8053	0.8041	-0.15
8C3BC	0.8818	0.8810	-0.09

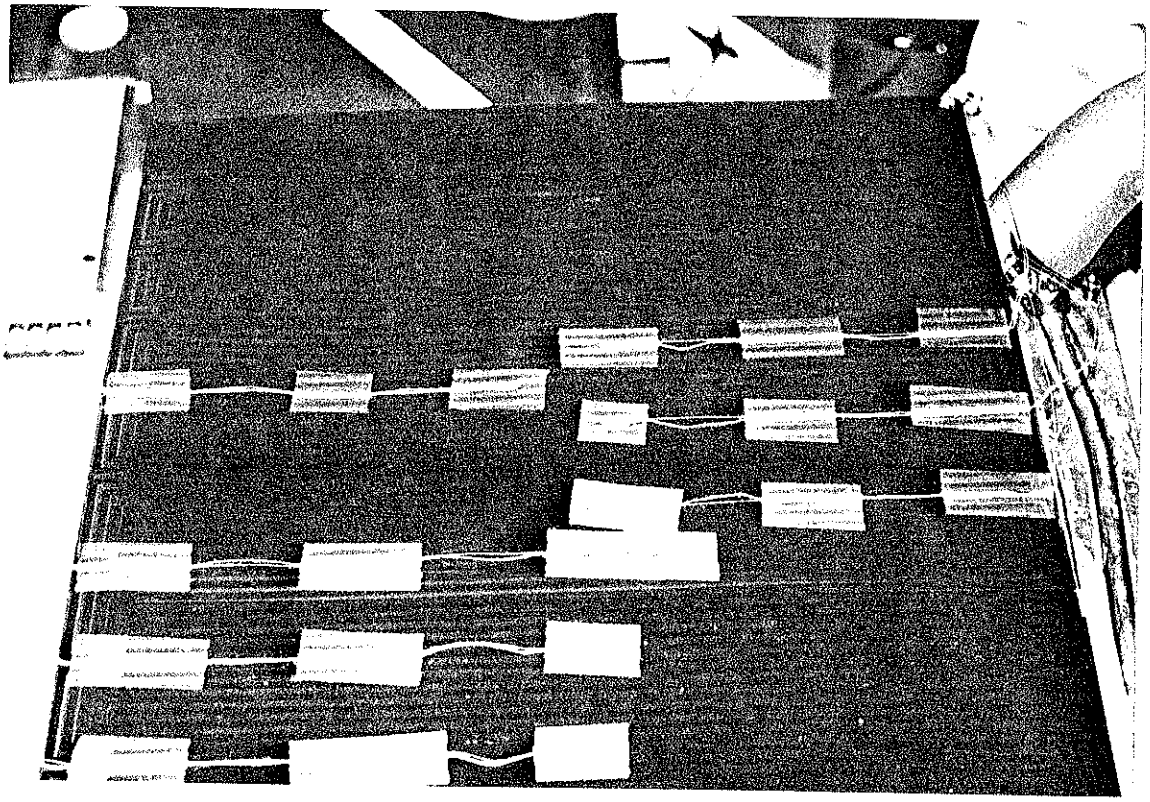


Figure 1. A photograph of the thin foil heater showing the uniform layout of the heating element.

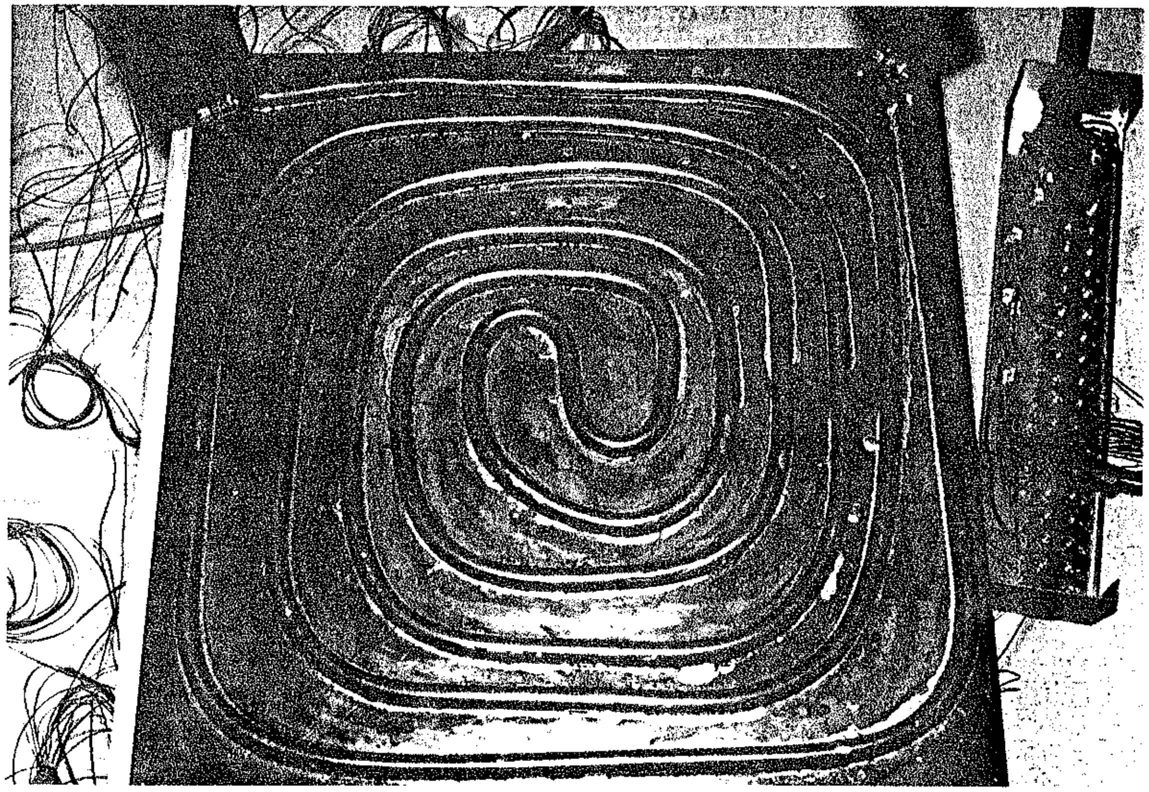
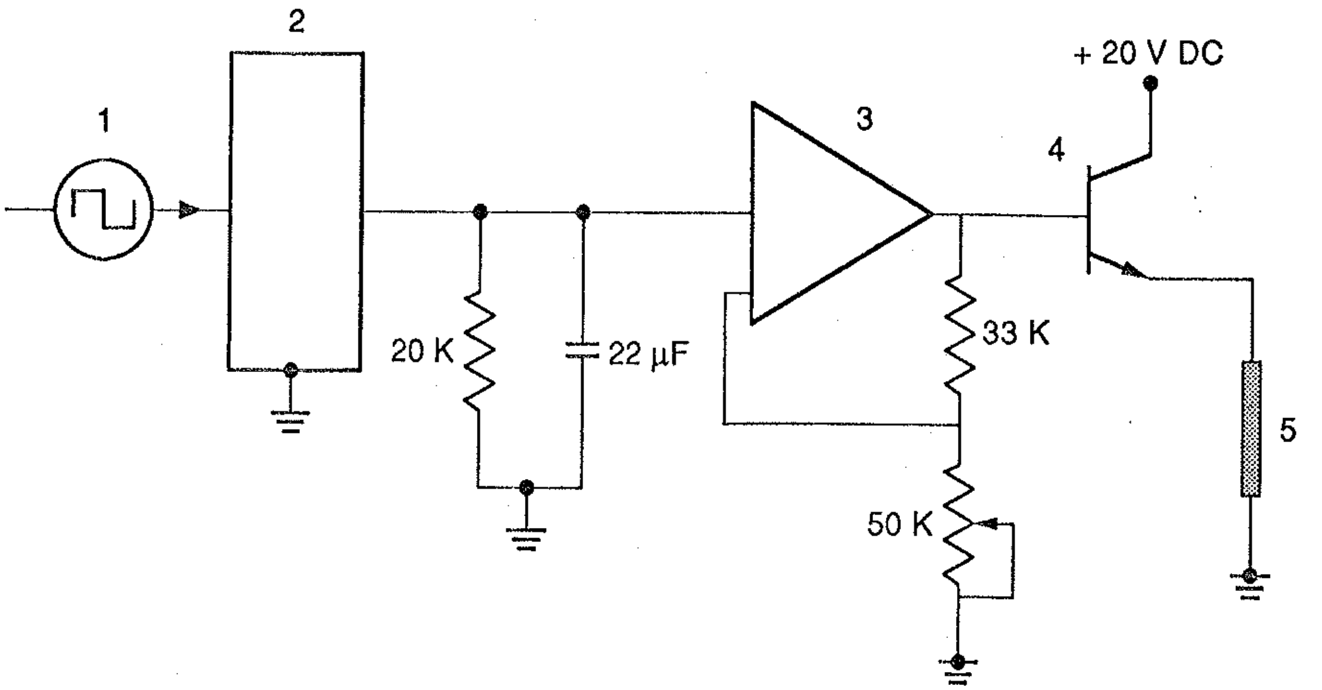


Figure 2. A photograph of the copper tubing on the cold plates showing the counter-flow pattern of the cooling fluid.



1. VARIABLE FREQUENCY FROM COMPUTER
2. ADVFC 32 FREQUENCY TO VOLTAGE CONVERTER
3. CA3140
4. MJE 800
5. FOIL HEATER

Figure 3. The circuit diagram for the power supply for the thin foil heater.

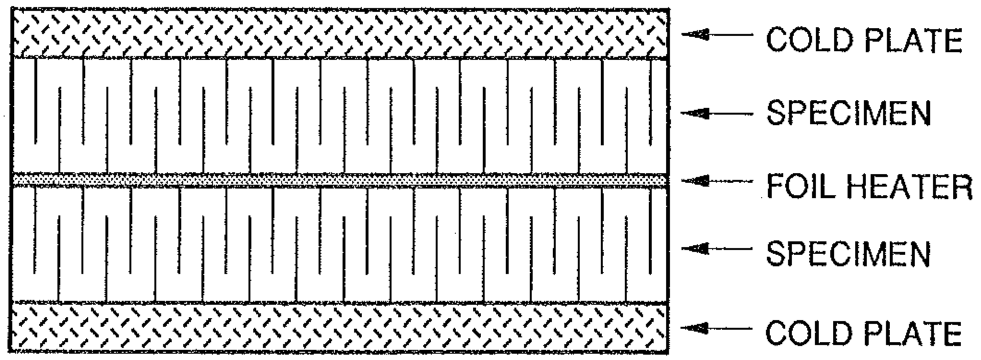


Figure 4. Schematic of the test assembly.

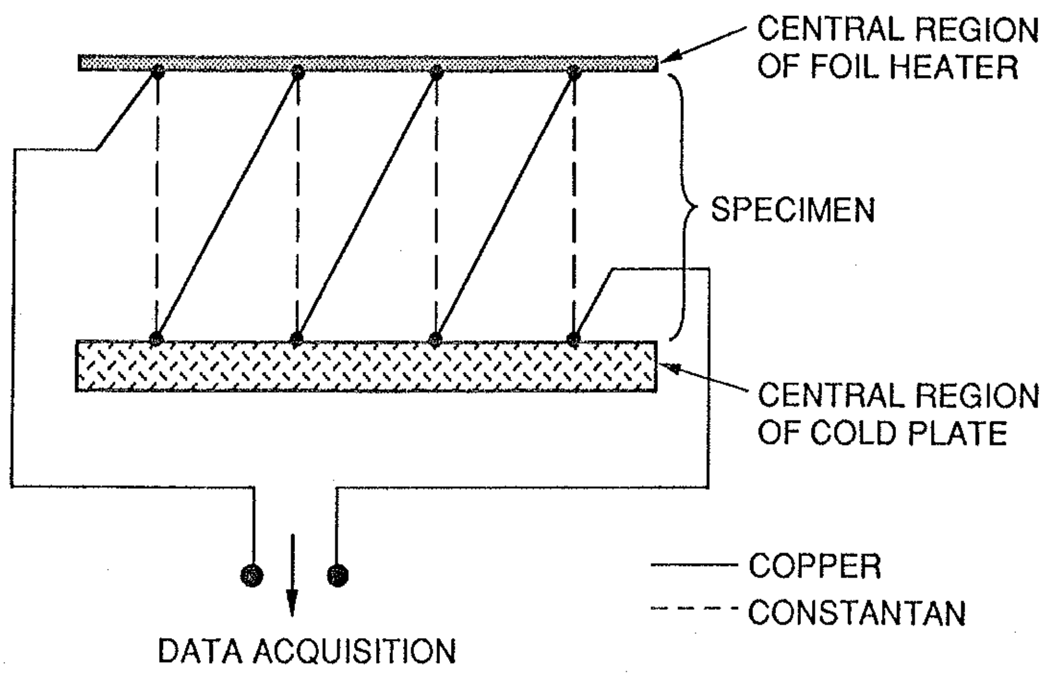
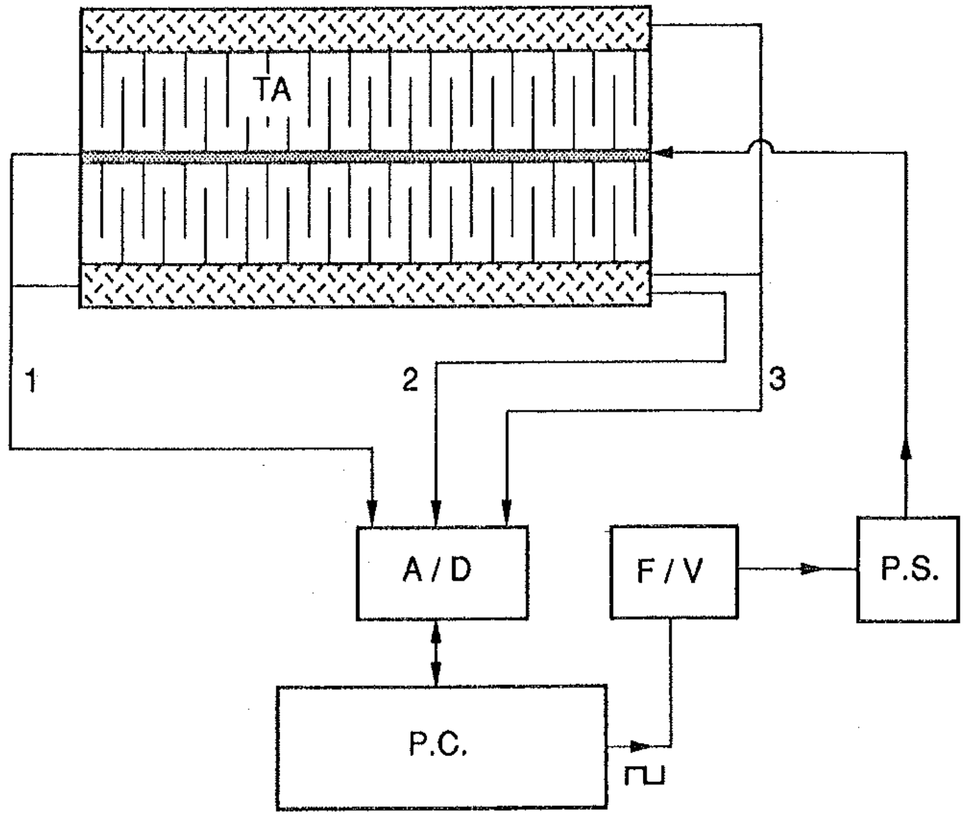


Figure 5. Schematic of the thermopile used for temperature differential measurement.



TA - TEST ASSEMBLY
A / D - DATA ACQUISION CARD
P.C. - COMPUTER
F / V - FREQUENCY-VOLTAGE CONVERTER
P.S. - POWER SUPPLY
1, 2, 3 - OUTPUT FROM THERMOPILE, THERMISTOR AND FOIL HEATER

Figure 6. Schematic of the measurement set-up.

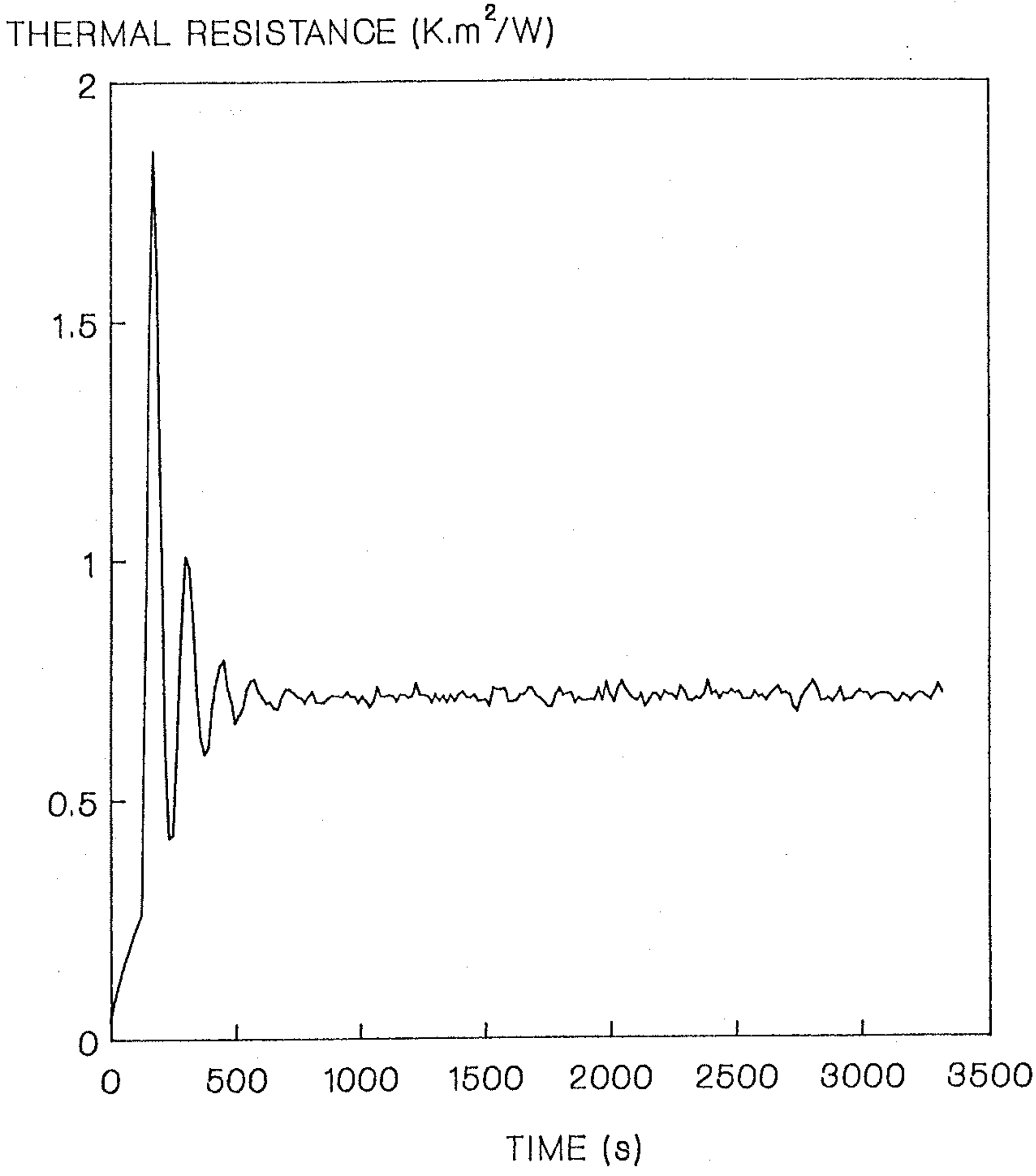


Figure 7. Variation in the calculated value of thermal resistance from the start of a measurement until the steady state is established.