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A study of the insulation properties of building materials and their application in Middle Eastern climates

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A STUDY OF THE INSULATION PROPERTIES OF BUILDING MATERIALS AND THEIR APPLICATION IN MIDDLE EASTERN CLIMATES

BY

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M.Phil Thesis

A Masters Thesis submitted in partial fulfilment of the requirements for the award of Master of Philosophy of the Loughborough University of Technology, England.

August 1980

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SYNOPSIS

The influence of climate on the thermal performance of buildings and the traditional selection of suitable materials is assessed and analysed in the context of the Saudi Arabian climate. Techniques used to artificially generate conditions of thermal comfort for the occupants are defined along with suggestions for reducing the energy consumption in buildings. A review is given of methods used to calculate the thermal properties of building materials, and comments made on the applicability of "steady state" and transient heat flow based calculations, when applied to materials likely to be used in Middle Eastern conditions. Theoretical models enabling the calculation of thermal conductivity for both homogeneous and composite materials are critically discussed. The measurement of the thermal conductivity of polymeric foam and building block composite laminates over a wide range of temperatures is described in the context of an adapted guarded hot plate apparatus, and theoretical models tested. A new, rapid, technique for determining the thermophysical characteristics of building materials is demonstrated.

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PART : 1

THE IMPORTANCE OF TRADITIONAL BUILDING TECHNIQUES AND THERMAL COMFORT

1.1 Introduction

In the developed countries, man's progress, and the growing mechanization and industrialization of society has resulted in most people spending by far the greater part of their lives in an artificial climate. This fact has caused an increased interest in the environmental conditions which should be set, and with the techniques under our control today We have the chance of creating almost any indoor climate. It is important to provide the emerging and developing countries, whose progress has been affected by their hot-humid or hot-dry climates, with adequate energy efficient systems, and appropriate building materials leading to greater indoor comfort. The aim of any engineer designing the services for an occupied space should be to enable the occupants of that space to pursue their normal activities in comfort. Thermal, acoustic and visual factors need to be considered as a whole and must be appropriate to the human activity, since the means of providing one component may influence the design of another. Ventilating plant may need acoustic treatment; acoustic treatment of a building may influence the thermal properties, and so on.

Man's dependance on thermal surroundings is the main reason for building houses. Native architecture around the world has often been of an energy conserving design with minimal environmental control. The thick walled clay houses in old parts of Central Saudi Arabia, the large wooden windows in the houses of Jeddah[1] West Saudi Arabia, (hot-humid area), the igloo of the Eskimos, and the high ceiling coupled with open courts of the Mediterranean villa[2] are but few examples. If we considered the Middle East area, we can find several sorts of old traditional houses, according to the area and the local climate of that area. In the Southern

Middle East (Saudi Arabia and the Arabian Gulf States), the houses of the region[3,4] have flat roofs and open courtyards, with thick white washed brick or mud walls, small windows and high-ceilinged rooms. This leads to cool indoor conditions as a relief from the scorching desert conditions outside. In Southern Iran, lowland Iraq and the Gulf region, underground rooms ventilated naturally from wind towers are often constructed in houses to protect the inhabitants from the fierce heat of summer. High rainfall has resulted in the construction of house types with pitched roofs in Western and Northern Turkey and along the Caspian Coast of Iran. In Iran such roofs are thatched, whereas in Turkey the red-tiled roof so characteristic of the Mediterranean region predominates.

Modern buildings, now so prevalent in Middle Eastern Cities, with their extensive use of concrete, steel and glass, often do not appear to be designed with any particular climatic regime in mind. Occasionally one finds tower blocks with balconies which shade the windows beneath from the mid-day sun, but mostly the internal climate of these large buildings is controlled, at considerable expense, by sophisticated air-conditioning units. Indeed the buzz and whine of air-conditioners during summer is a new urban noise characteristic of many Middle Eastern cities. In the large cities which are situated in dry inland locations, simple evaporative coolers have become tremendously popular over the last 20 years. These work on the principle that as water evaporates, energy is given up from the air, producing a cooler temperature. Relative humidity is increased, however, and so these coolers can only be utilized successfully where summer humidities of less than 30% prevail. In Riyadh and Mecca[5], there has been a tremendous increase in the sale of these coolers, and there have been more than 7 manufacturers producing over 42,000 units every

year for the last ten years, quite apart from the imported units. This is now beginning to give rise to concern owing to the very large quantities of water being consumed and to the maintenance, since dust and salt causes corrosion to the units.

In this part, of the thesis, traditional buildings in Saudi Arabia are classified. The use of traditional materials in these buildings is described along with the present day difficulties in obtaining and using such materials for construction. The older techniques of building houses are not practical today[4] because houses would take a long time to build and also they cost more money. The trend is to incorporate new building materials[6], with better insulation properties and to develop an artificial climate within them. This applies irrespective of whether buildings are for work, business, or leisure. It is for this reason that an investigation of new and more economical materials to replace the older ones is pursued in part 2 of this thesis. Also lessons should be learned from the functions of traditional buildings as they are useful in both thermal and ventilation design aspects, and influence the positioning and the thickness of the materials required.

The aspects of thermal comfort and the traditional technology in building are considered very carefully and their importance is indicated. Creating thermal comfort for a person is a primary purpose of many industries, including the building and insulation industry. This has an important role on the construction of buildings, the choice of materials and thus on the whole building industry. Studies on thermal comfort with their measurement and prediction are reviewed and outlined. The generalized comfort equations and charts for specifying comfortable

environments are presented. Thermal comfort in the U.K. is reviewed and compared with the limited number of studies in the Middle East. A more detailed review of thermal comfort and the factors influencing it is presented in Appendix C. This information is a very important tool in providing the engineer with the relevant knowledge as how to consider using the new building materials and advanced technology in the best possible way. The outcome will be more energy efficient buildings and greater thermal comfort.

1.2. Thermal Comfort

1.2.1. Definition of Thermal Comfort

Thermal comfort analysis involves the study of the effects of surroundings such as the climate, living space, and clothing on our thermal behaviour and feelings. Groups as well as individuals like to live and work in comfortable surroundings, without any heat stress or complaints. Comfort is a state of feeling, but has not any identifiable sense organ like the basic five senses summarized by many authors[7,8,9]. This dichotomy was recognized in the ASHRAE comfort standard 55-56, where thermal comfort is defined as "that state of mind which expresses satisfaction with the thermal environment"[10]. Most of the current predictive charts are based on comfort defined as a sensation "that is neither slightly warm or slightly cool". Most of the previous work has been limited to sedentary man, lightly clothed. This ASHRAE approach has proven sound since about 90% of man's indoor occupation and leisure time is spent at or near the sedentary activity level.

During physical activity, a change occurs in man's physiology. There is always some form of thermal regulation occurring during exercise within man's body. Judgements of temperature and comfort during activity have a basis different from those occurring during the sedentary condition. The same skin and body temperatures, if used as indices of comfort, will likely prove false during moderate to heavy activity[10]. Thermal neutrality for a person is defined as "the condition in which the subject would prefer neither warmer nor cooler surroundings".

Thus thermal neutrality is a necessary condition for thermal comfort, but it need not to be a sufficient condition.

Creating thermal comfort for a person is a primary purpose of the building and insulation industry as well as the heating air-conditioning industry. This has had a radical influence on the construction of buildings, the choice of materials etc., and thus on the whole building industry[11].

1.2.2. Assessment of Thermal Comfort

Thermal comfort can be best evaluated and explained by considering three basic models: the physiological, sociological and the physical approaches.

The physiological model is one which has to match the heat loss from a subject to the heat generation or metabolic rate and achieves this while maintaining a constant body core temperature of 37°C and a skin temperature of 33°C and sweat rate appropriate to that activity level. In hot environments[12], where temperatures are > 33°C, sweating and evaporation must take place to offset heat gains, and to prevent any thermal stress or strain. If temperatures are very high, so that the body cannot overcome them naturally, external cooling must take place to avoid the physiological strain. Heating and cooling systems are therefore convenient ways of helping the person to control his heat loss rather than actually warming him up or cooling him down. Responses of subjects can be predicted for many combinations of environmental variables inside and outside the neutral state by using the ASHRAE[10]

comfort chart shown in Figure 1.2.2. (1).

The sociological model is one which depends mainly on the behavioural response of an individual to his environment and surroundings. This response depends on many variables such as customs, religious values, cultural constraints, social and economical conditions.
For this reason it is difficult to fix one value for a comfortable constant thermal condition for all people, as in physiological model, but an allowance for flexibiltiy should prove more satisfactory. A designer who understands both the traditional situations and the life style of the people is more capable of providing them with the suitable solutions.

The physical model is one which considers the heat exchange between a body as the thermal system and the surrounding environment in which six parameters at least[13] have been considered. The activity level and type of clothing are two parameters specific to the individual body, wherever the other four parameters are the properties of the surrounding environment. These are air-temperature, mean radiant temperature, relative humidity and air velocity. Equations[11] have been developed to describe thermal comfort, taking into consideration all these parameters, which are fully explained and discussed in Appendix C.

1.2.3. Studies on Thermal Comfort

Many institutions and research centres have continuously supported active research programmes and field studies on thermal comfort for almost forty years. Observations have come from a wide variety of

climates and countries, ranging from extreme winters to extreme summers. Their main purposes are: to find a way of describing the thermal environment which correlates well with human responses, thus enabling reliable predictions to be made, and to define the range of conditions found to be pleasant or tolerable by the population concerned. In a review article in 1961, Nevins[10] showed that temperature criteria for thermal comfort have risen steadily since 1900, from (18 to 21°C) dry-bulb air-temperature (DBT) range to the (24 to 26°C) DBT in 1923 to 20°C ET in 1941. ET is defined as an arbitrary index which combines into a single value the effect of temperature, humidity and air movement on the sensation of warmth or cold felt by the human body. The numerical value is the temperature of still, saturated air which would induce an identical sensation. The increasing trend in both effective temperature (ET) and DBT probably results from the year-round use of lighter weight clothing by both men and women, and from changing living patterns, diets and comfort expectations. Dry-bulb temperature (DBT) is the simplest practical index of cold and warmth under ordinary room conditions and is obtained with a dry-bulb thermometer. When humidity affects the efficiency of the body's temperature regulation by sweating, the significance of DBT is limited. The studies of Koch, Jennings and Humphreys in 1960 showed that humidity had negligible effect on comfort until relative humidities of 60 percent and dry-bulb temperature of 18°C were reached. Below these levels, dry-bulb temperature (DBT) alone was the governing factor. The comfort limits selected for field application have usually been expressed in terms of dry-bulb and wet-bulb temperatures. The original effective temperature ET scale is still used on a numerical basis in predicting extreme discomfort from high temperature and humidity and man's heat tolerance while working at high humidities.

1.2.3.1. Field-Study Methods:

In field studies, the subjects continue their normal every day activities in their normal surroudnings. Such studies if carried out in different (summer or winter) environments can be very useful, if analysed properly. Estimates of the air-temperature, the mean-radiant temperature, the relative humidity and the air velocity are made. Clothing is not controlled in field studies, but has often been described item by item and recorded. Methods of estimating the metabolic rate have not often been recorded in the field studies of thermal comfort. Estimates of warmth are obtained by means of rating scales, which differ according to the climate and the study. The most commonly used have been the seven-category scales, such as the 'Bedford' scale[14] and the 'ASHRAE' scale[10].

Table 1.2.3.1.-1 The 'Bedford' scale and the 'ASHRAE' scale of warmth

The Bedford Scale	The 'ASHRAE' Scale
3 Much too warm	3 Hot
2 Too warm	2 Warm
1 Comfortably warm	1 Slightly warm
0 Comfortable	0 Neutral
-1 Comfortably cool	-1 Slightly cool
-2 Too cool	-2 Cool
-3 Much too cool	-3 Cold

Two survey designs have been used. The 'longitudinal' considers a few subjects for providing repeated assessments of warmth over a long period, so that their adjustments to changing conditions can be observed. The 'transverse' design considers a large number of respondents who are asked to make only one assessment.

1.2.3.2. Environmental Chamber Studies of Thermal Comfort

Studies of thermal comfort can be done in environmental chambers with full control of all the variables. P.O. Fanger[11] described the environmental chamber of the Technical University of Denmark, which was placed in operation in 1968. The chamber is 2.8 m wide by 5.6 m long with a ceiling height of 2.8 m. In the chamber all relevant combinations of air temperature, air humidity, mean radiant temperature and air velocity can be produced. Symmetric as well as asymmetric radiation fields can be produced. All parameters are automatically recorded with a digital system.

In thermal comfort studies it is important that the assessment of the thermal environment is not disturbed by discomfort arising from other environmental variables; which should be kept at a suitable neutral level. The average illumination level, 0.8 m above floor level, is 150 lux. The sound level is 45 dB (A), and the sound pressure level is 63 dB (lin). Dust concentration and odour level are kept suitably low by (a) the use of high efficiency dust filters and activated charcoal filters, and (b) keeping the air-change in the chamber at 40 hr^{-1}.

1.2.3.2.(1) Experimental Subjects

In environmental chamber studies, subjects should be in good health and take part in the experiment only if they have had a full night's sleep prior to each exposure, are free from fever, and have eaten a normal meal about one hour before the start of the exposure.

1.2.3.2.(2) Measurements

The condition in the chamber is held constant during each specified period. The air-temperature can be maintained at different levels with the mean radiant temperature equal to the air-temperature. Air velocity and relative humidity are also considered and set at different levels. Clothing is controlled in general, and the thermal resistance is determined (the clo-value) with full description of them item by item. For example the Kansas State University standard uniform (light clothing assembly) with a thermal resistance of 0.6 clo, comprised of cotton twill shirt and trousers, cotton under-shorts and cotton sweat socks (no shoes). The clo-values are measured on a thermal manikin (Seppanen et al 1972) at Kansas State University.

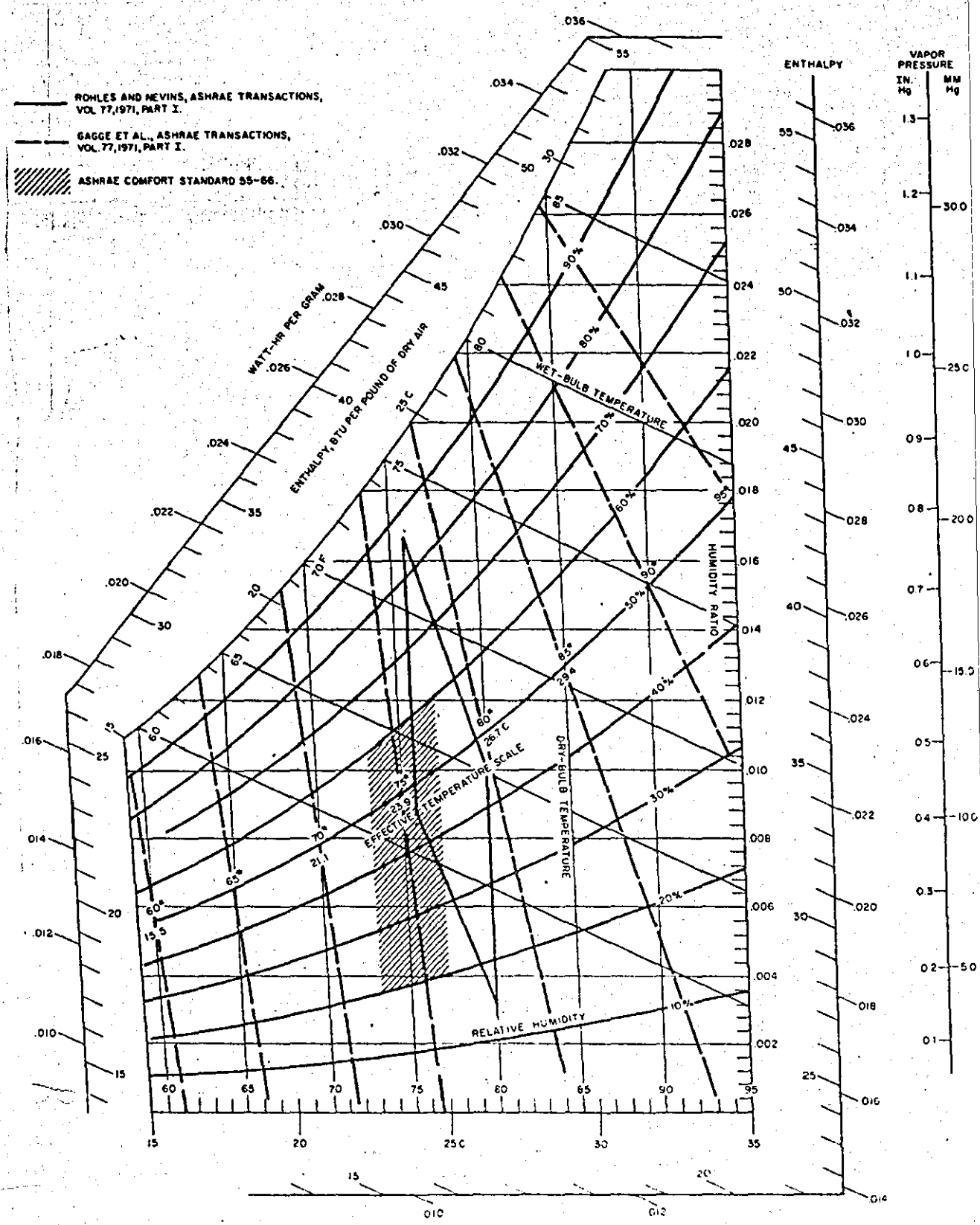
1.2.3.2.(3) Physiological Measurements:

The subjects wear a harness with 14 thermistors taped to the skin. The thermistors are distributed evenly over the body

surface as reported by Olesen et al (1972). Central body temperatures are registered every five minutes by means of a data recording system outside the chamber. Evaporative weight loss is measured by weighing the subject initially, after ½ hour in the chamber, and at the end of the exposure.

1.2.3.2.(4) Comfort Zone:

Throughout each exposure the subject indicates his thermal comfort sensation on a dial voting apparatus, whenever appropriate. The apparatus is connected to an indicator outside the chamber, and the ambient temperature (mean radiant temperature = air temperature) is adjusted to ensure that the subject's responses remain within the comfort zone marked on the dial; as close to exact thermal neutrality as possible.



(23)

Figure: 1.2.2.(1) The New ASHRAE Comfort Chart

1.2.4. The New ASHRAE Comfort Chart

In Fig. 1.2.2.(1)[10] the most recent applicable comfort envelope from the Kansas State University (KSU) - ASHRAE project is plotted on the coordinates of the ASHRAE psychrometric chart. The comfort zone recommended in ASHRAE Comfort Standard 55 - 66 is also drawn for comparison. The new ET lines are drawn over the two comfort zones. Fig. 1.2.2.(1) applies generally to altitudes from sea level to 2100 m and to the most common special case for indoor thermal environments in which mean radiant temperature is nearly equal to dry-bulb air temperature and air velocity is less than 45 fpm (0.23 m/sec). For this case the thermal environment is well specified by the two variables shown: dry-bulb air temperatures and the humidity ratio. The KSU-ASHRAE Comfort envelope applies for occupants wearing clothing of 0.6 - 0.8 clo insulation and contrasts with the 0.8 - 1.0 clo values assumed in the ASHRAE Comfort Standard 55-66. For the KSU data, their activity is classified as sedentary (1 met). In Standard 55-66, office work (slightly higher than sedentary) was the design activity. These small differences in level of activity and clothing insulation account for the 3°F (1.5°C) displacement of the KSU - ASHRAE envelope above the Standard 55-66 zone. A wide range of environmental applications are covered by the ASHRAE Comfort Standard 55-66. Offices, homes schools, shops, theatres, and many others can be approximated well with these specifications. The Standard specifies an environmental range for Comfort based on available research data and the field judgements of that Standard's sub-committee members as of 1966.

The design data given in KSU envelope define conditions which will maximize the thermal acceptability of the environment for a large group of adults, similarly clothed and active, and will minimize the fraction of potential complainers in the group occupying the space. Variation among individuals is expected. Young children and the aged will require some additional adjustment. Children below 12 years. of age may require 1°F (0.5°C) reduction in design temperature, and adults over 60 may require an increase of 1°F (0.5°C). In place of the old effective temperature (ET) lines, the new (ET)* loci are plotted in Fig. 1.2.2.(1). This chart is primarily useful in the usual comfort range for sedentary, lightly clothed people and secondarily at the higher temperatures where sedentary heat stress is involved. Although the ET* scale is derived on the basis of a one hour exposure, previous data shows no changes of engineering importance in response due to longer exposures unless the limits of heat stress ET* > 90°F (32°C) are approached.

The ET* lines show a moderate humidity effect on thermal comfort itself. Its effect on discomfort increases as both the thermal level of the environment and regulatory sweating increases. Man's total evaporative heat near the comfort range is only about 25% of the total heat loss. As the thermal level increases, evaporation becomes a larger portion of the heat loss and accounts for 100 percent of the heat loss, as the environmental temperature equals and rises above skin temperature of 35°C (or 95°F).

To summarize, the data in Fig. 1.2.2.(1) are useful for light clothing and for seated or sedentary activity. The ASHRAE Comfort

Standard 55-66 applies generally for average clothing and activity. The KSU-ASHRAE Comfort envelope is useful in evaluating the environment for lightly clothed subjects, resting and working at desk. The most commonly recommended design conditions for Comfort where the two zones overlap are therefore:

$$ET^* = 76^oF \text{ or } 24.5^oC$$

Dry-bulb air temperature = mean radiant temperature = 76^oF (24.5^oC)
Relative humidity = 40 percent (20-60 range)
Air velocity less than 45 fpm (0.23 m/sec)

1.2.5. The Fanger Comfort Equation[11]

Fanger's objective was to generalize the physiological basis of comfort so that for any activity comfort can be predicted analytically in terms of environmental parameters. His comfort equation is based on a rationally derived heat balance equation for the passive state during thermal equilibrium and on the two experimental observations that during a stat of comfort (defined by a neutral temperature sensation) a unique relation exists between the level of activity described by metabolism and both $\bar{t}_{sk}$ skin temperature (for comfort) and E_{rsw} sweat secretion (for comfort). During a state of comfort, his predictive equations for a comfortable $\bar{t}_{sk}$ and E_{rsw} are:

$$\bar{t}_{sk} = 35.7 - 0.0372\ M \text{ in } ^oC \text{ and } W/m^2 \quad (A)$$

$$E_{rsw} = 0.42\ (M-58.2) \text{ in } W/m^2 \quad (B)$$

For sedentary conditions (1 met, 58.2 W/m^2 or 50 K cal/hr m^2) the comfort values for $\bar{t}_{sk}$ and E_{rsw} are 93.2°F (34°C) and zero respectively. During exercise (M > 1 met), $\bar{t}_{sk}$ drops and E_{rsw} increases in accordance with current observations on exercising, clothed and unclothed subjects.

The heat balance equation:

$$S = M\,[(1 - E) - 0.0023\,(44 - \phi P_a) - 0.0014\,(34 - T_a)]$$

$$- 2.2\,(0.06 + 0.94\,w_{rsw})\,h_c\,(P_{sk} - \phi_a\,P_a)F_{pcl}$$

$$- h\,(\bar{t}_{sk} - t_o)\,F_{cl} \qquad W/m^2$$

at thermal equilibrium (S = o) is essentially a function of the following form:

$$f\,(M, W, clo, E, \bar{t}_{sk}, MRT, t_a, P_a) = o \qquad (C)$$

When Equation A and B are substituted in Equation (C), the resulting equation would be Fanger's Comfort Equation and would be a new function:

$$f'\,(M, W, Clo, \nu, MRT, t_a \text{ and } P_a) = o$$

From a comfort equation so derived, it is possible to predict any combination of environemtnal factors (i.e., t_a, MRT, ν, P_a) that produce a "comfortable" environment for a clothed (clo) person performing any selected activiy (M and W).

In the above equations the given terms are defined as follows;

Clo = Clo value

E = Rate of total evaporative heat loss, caused by the evaporation of body fluids.

E_{rsw} = Sweat Secretion.

ε = Mechanical Efficiency.

F_{cl} = Dimensionless factor which is a function of the insulation of the clothing worn.

F_{pcl} = Permeation Efficiency.

ϕ_a = Relative Humidity, as a fraction.

h = Combined heat transfer coefficient, equal to the sum of the Radiation(h_r) and Mean Convective heat transfer coefficient (h_c).

M = Rate of Metabolism, and is proportional to man's oxygen consumption.

MRT = Mean Radiant Temperature.

P_a = Saturated Vapour Pressure at the Ambient Air Temperature.

P_{sk} = Saturated Vapour Pressure at the Average Skin Temperature.

S = Rate of heat storage, and is proportional to the time rate of change in intrinsic body heat.

t_a = Ambient air temperature.

t_o = The average of the Mean Radiant and Ambient air temperature weighted by their respective heat transfer coefficients.

t_{sk} = Average Skin Temperature.

W = Mechanical work accomplished.

w_{rsw} = Total Skin Wettedness.

v = Ambient Air Movement.

1.2.6. Thermal Comfort in Middle East

In the Middle East area, there have been a few field studies of thermal comfort on a very limited scale, but none of these studies have been conducted in Saudi Arabia, and it is evident that more research work is needed to give a complete understanding of the thermal response in this vast area. Here are a few examples which can give a clear indication of the thermal comfort in certain parts of the Middle East.

The first example is a study by Crocott in which he refers to the practical experience of Anglo-Iranian Oil Company, who have installed large air cooling and air-conditioning systems in their staff accommodation and offices in the Gulf area, which in summer time is actually one of the hottest geographical locations in the world. Crocott recommends an indoor air temperature around 26°C at relative humidity (RH) between 25 and 60%.

The second example is a field study and observation of subjects in both hot humid and hot dry conditions by Webb (1964). These observations have been analysed in detail by J. F. Nicol[15]. The subjects were engaged in office work and the observations recorded were made in June-July 1962 in Baghdad, Iraq, where the weather was hot and dry. Clothing consisted of a light cotton shirt, lightweight trousers and light cotton undergarments, the subjects' homes were of modern design with walls of concrete blocks. At night the Iraqi subjects slept on the roof; four of them had fans, one had an evaporative cooling device, one had both and two had neither, and for one subject there is no information. Details of night clothing were not

obtained. The subjects made the environmental measurements themselves in their own homes, throughout the day and night. A total of 1284 observations were recorded by the nine subjects. The daytime mean temperature in Baghdad was 37°C. The air velocity on average was about 1 m/s, and Nicol showed that this provided a benefit approximately equivalent to a reduction of 3°C in the globe temperature. The neutral temperature was 33°C, but it would have been equivalent to about 30°C if the air velocity had been only slight.

In their survey of office workers in England, Humphreys and Nicol (1970)[16] found a mean air velocity of about 0.15 m/s. (A fuller description of thermal comfort in the U.K. is given in Appendix C). Fanger's (1970) predictions show a comfort optimum of 26.5°C at this air velocity, as shown in figure 20, assuming a metabolic rate of 58 W/m^2 (50 k cal/m^2 h) and a clothing insulation of 0.5 clo (approximately that for the Iraqi subjects). For the higher mean air velocity (1.0 m/s) of the present results, Fanger predicts an optimum of 28.4°C. Fanger's method further predicts that 70% of the population would be uncomfortable at 32°C. Other theoretical models (Humphreys, 1970; McIntyre, 1973) would also estimate an optimum temperature in the region of 28°C. These results show that acclimatized subjects can be comfortable at temperatures considered unacceptable in models developed for temperate regions.

Fanger's pointed that although acclimatized persons living in the tropics can better endure hot environments and have become used to accepting the discomfort due to heat, this seems to have only a slight influence, if any, on the thermal environment which they will actually prefer if given a choice. In this respect many of the office

workers in Jeddah and Riyadh[17], Saudi Arabia during the summer time where the outdoor mean temperatures exceed 40°C, and air velocities are very slight felt discomfort, but they expressed a full comfort as they started working in the air-conditioned offices. The mean air-temperature was found to be in the range of 27°C to 30°C, yet most of them voted 'comfortably cool' to 'comfortable' in the first two hours of work. Their mean voting changed to the state of 'comfortable' to 'comfortably warm' at the end.

In hot climate one can say that the respondents prefer to have a sensation rather cooler then neutral. Also there is a deliberate and effective use of air movement by using hand fans and electrical fans, to achieve thermal comfort. One of the Roorkee (India) observers has provided the following description (Sharma, 1967).

> "The room is full of warm air in the mornings.
> The windows are opened and the fans run at full
> speed to churn cool air into the room.
> Within half or three-quarters of an hour the
> air is cool enough for work to begin.
> Conditions remain comfortable with fans runn-
> ing throughout the forenoon".

The actual human response to a climatic regime is still very difficult to quantify with any accuracy, yet it is obviously of vital importance in a developing country when new industrial and urban development is being planned. Although some general works do exist, as yet little research appears to have been carried out on the thermal

comfort in the Middle East. Recently, interesting works[3] of a biomedical nature have appeared dealing with Libya and Kuwait, which have attempted to access all factors affecting human life, including local climate conditions.

One of the simplest methods for outlining comfort conditions for humans in differing climatic regimes is the use of climographs. With these diagrams, monthly plots are made of relative humidity against ~~wet~~ dry bulb temperature, and they do permit at least a rough classification of the major cities within the region in terms of their general suitability for human activity. From these graphs it can be seen that very few of the large cities possess what would be classified as an 'ideal' climate, except during only a few months per year. Indeed, some coastal stations, such as Bahrain, experience 'uncomfortable' conditions for most of the year, whilst interior stations, such as Tehran and Ankara, reveal marked extremes, with a raw winters and scorching summers. Only Shiraz possesses a climate which approximates the ideal climate range, and even here the temperatures of the summer months can sometimes produce uncomfortable conditions.

1.3. Traditional (Primitive) Buildings in Saudi Arabia

1.3.1. Introduction

Most of the older buildings in many parts of Saudi Arabia and the rest of the Middle East were built in a locally traditional manner. These houses provided for centuries good internal comfort conditions to their occupants, without the use of modern energy-consuming equipment such as air - conditioning, and materials such as steel and concrete. The primitive early architects and builders in that area exploited the limited materials available to them and worked them into a structural form that admirably met both the demands of the climate and the requirements of their particular culture. It is useful in the present context to study and analyse the functions of these traditional houses, and their relation with the climatic conditions as well as knowing the building materials locally available in that area.

Thus lessons learned from traditional technology may be blended with new techniques and new materials, reducing the total cost of modern construction with increased safety, internal comfort, and lower energy consumption. Ideally improvements should be achieved whilst keeping the traditions, resources and the structure of the society intact.

1.3.2. Classification of Buildings

In Saudi Arabia, where the area exceeds one million square miles, with both coastal areas, interior regions and mountainous regions, there are different types of primitive dwellings. They differ in accordance with the climatic conditions on the one hand, and according to the building materials locally available on the other. The following information was mostly obtained through the field surveys and personal experience.

1.3.2.1. Coastal Buildings

Along the western coast of the country, where the climate is characterised by high temperatures and little rainfall[18] and where at the same time there is often high humidity due to the prevalence of offshore winds, traditional houses[1] are built of the white to grey coral stones available along the sides of the Red Sea. These houses maintain good internal comfort conditions throughout most of the year. They consist of at least two floors, so that in the hot summer their occupants can use the lower floor rooms, as they are cooler. Hot air tends to flow upwards to the upper floor rooms. In the winter, the top floor rooms will be warmer, and hence most preferable to the occupants. These traditional houses (known as the Red Sea style) have elaborate balconies[1,19] - known as "roshan", pl. "rawasheen" enclosed with pierced timber screens on all exposed walls to allow through breezes as well as giving privacy and shade to the occupants. The other walls of such houses are thick to reduce heat penetration during the daylight hours, when the temperatures are very high, and are light coloured to reflect a large amount of the heat as

radiation. A good example of such primitive dwellings can still be found in Jeddah, the main port of Saudi Arabia on the Red Sea as shown in Figures 1 and 2.

In small villages and less developed areas along the Red Sea, both temperatures and humidity are high. Here where there is intense solar radiation and where there is very little diurnal variation in temperature, the critical parameters of comfort are shade and ventilation [20]. To reduce the heat-holding capacity of the walls and to maximise the air flow across the interior, primitive man in this area reduced the wall mass to a minimum. The roof thus became the dominant structural element in the form of a huge steeply sloping parasol, conical in shape, with a thatched roof, sitting on a cylinderically walled adope hut. The roofing materials employed were predominantly sticks with various plant fibres and vines for lashing them together, producing a roof of minimum mass to avoid heat build-up and subsequent radiation into the living space. Abu-Arish and Jizan[21] are good examples of an area where such structures may be found.

In the Eastern Province, along the east coast of the Arabian Gulf, primitive houses are built of mud bricks and coral stones[1] and protected from the intense heat, radiation and sand storms by surrounding the house with natural trees, mainly palm. Most of these houses were built with a central courtyard. This gave the occupants a cool refuge when the heat of the day penetrated the walls of the house. By moving from room to courtyard to roof people were able to achieve optimum comfort conditions without mechanical cooling[4].

1.3.2.2. Buildings of the Interior

Another type of thermal regime, where the humidity is very low, can be found in the interior and north of Saudi Arabia, where during summer, the day time temperatures are extremely high coupled with uncomfortably low temperatures late at night[18,22]. During winter the night temperatures are extremely low, with warm to cool days. Against such fluctutions, the desirable insulation material would be one with a high heat capacity. Such a material would absorb solar radiation during the daylight hours and slowly re-radiate it during the night. Thus the diurnal temperature curve inside the building would be flattened out into a much more comfortable profile, cooler in day time and warmer at night. Clay and Stone possess high heat capacities and since they are plentiful in many parts of Saudi Arabia, e.g. Riyadh, Medina, Tabouk, Hail and Qaseem, it is not surprising to find that primitive men around this area built their homes out of such materials. The primitive house of this area is built of baked mud bricks reinforced with plant fibres. The walls are very thick with a smooth mud plaster exterior, as shown in Figure (3). All roofs are flat, and are used for resting and sleeping during the comfortable summer nights when it seldom rains. The walls are load bearing and carry palm-trunk (or Athel-trunk) roof beams, which in turn support a mud slab reinforced with palm fronds. Door and window openings are high and reduced in size to hold down interior radiated heat and light levels which can be intense during the summer months. Most of such houses are painted or stuccoed white to reflect a maximum amount of radiant heat.

Primitive houses of both Mecca and Medina are built with granite stones available in the area and also with hand-made burnt clay bricks. They have very thick walls, and large wooden windows, to direct ventilation, as shown in Figures (4 and 5). Most of the houses have internal courts and small gardens. Alternatively, the house may be have ventilation openings to receive fresh air from the roof and that can be directed downward to the internal rooms on all floors.

1.3.3. Traditional Building Materials and Their Location

Stones, sun-dried mud bricks, burnt clay bricks and wood are the basic traditional building materials, used in Saudi Arabia. The common factor in selecting any of these materials are: their cost, transportation, the function of the building, the availability of an expert builder, and the social, economic and cultural conditions of the owner. The most important factors of all are the influences of the climate and the local materials which come from the ground surface formations, in each region.

In the Western region[23] the materials come from the coastal plains in the form of marine deposits[24] along the Red Sea and are cut as coral stones (Jeddah). To the east of these plains granite[25] and diorite stones were cut out of the igneous and metamorphic[26] rock formations. The clay deposits in the valleys of such areas were used for making hand made bricks burnt in primitive kilns. In the Central and Northern regions[23], "Najd Plateau" the traditional materials were sun-dried mud bricks. Limestones were cleaved and cut easily from the well stratified sedimentary rocks and were used in many houses of these regions. In the Eastern province along the Arabian Gulf, a form of coral rocks underlies the coastal waters[27, 28, 29], exposed in some places and in others covered by sand and silt. Coral stones were cut and used with the silt as local materials. A detailed description of the above materials and their location is given in Appendix 'D'.

1.3.4. Materials of Construction

1.3.4.1.Stone Construction

Most of the traditional buildings of Jeddah, Mecca , Taif, Al-Qatif, Oqair and to a lesser extent in houses of Riyadh, were built of various types of stones, according to the types of rocks in each area. Stones were used to build load - bearing walls, and partition walls. The thickness of such walls varies from 40 to 120 cm, according to the height of the building, roof span, type of mortar used, the type of cut, and the durability of the stones. Mortars used were silty clay, loam enriched with lime, and semi-hydraulic lime, in which small size siliceous limestone was mixed with clay and burnt together. Stones were cut and sawed manually, and roughly without standardization as shown in Figure 10, and sometimes collected near the building site, with many odd shapes and sizes. In general any thick wall, consisted of exterior and interior parts with flat cut facing stones, and the centre part consisted of odd shape stones. These stones had been fixed together using mortars and wedge like stone chips at the inner joints to give more stability. In many high buildings, small trunks of wood were used horizontally between stones to stop vertical cracks from developing, as well as tie stones, which were placed across the wall depth, securing both exterior and interior parts of the wall in place. The thickness of walls was reduced in some cases by using reinforcing struts or columns of rubble stones fixed behind and within the wall at short spans of 60 to 120 cm. This system was used also to construct non-load bearing walls, where thin coral stones slabs were fixed

together and plastered as shown in Figure (7).

In construction of doors, the lintels used were stones cut to form an arch on top of the open court doors and in the case of windows horizontal wood lintels were used. The traditional houses which have nice-cut regular size stones were left unplastered externally, whenever walls of irregular size stones were usually covered with a layer of 2-4 cm silty clay or lime plaster as shown in Figures (8 and 9). All houses were plastered internally.

1.3.4.2. Sun-dried Mud Brick Construction

Traditional buildings of Central and Northern Saudi Arabia such as in Dariyah, Riyadh, Hail and in other smaller towns were built of earth soil, which was shaped into large size bricks. Earth or clay which is composed of extremely small particles of complex alumino - silicates[25], is plentiful in these regions. The procedure was to dig a pit and collect the earth into a heap where water and straw were added to compose a wet and plastic mix. The mud was mixed throughly and left for a few days, and then more dry earth and straw was added to stabilize it. The stability of the mix was dependent mainly upon the proportions of the main ingredients of clay, sand, straw and water. Durability of the mix was increased by the straw distribution, which improved bond, and decreased thermal movements. Sand in the mix helped in reducing changes in volume of the mud bricks between the wet and dry condition. The mud mix was casted into bricks in standardized

wooden moulds or casted manually into irregular mud blocks with flat top and bottoms. These were left exposed to sun and air on top of a flat surface area covered with a thin layer of grass and straw. The drying period ranged from 1 to 2 weeks according to the size of these bricks, and according to how often they turned over. The traditional houses were built nearby these sites, where stone rubble foundations were laid down, and then sun-dried mud bricks set on top of each other.

The mortar used was soft mud with high clay content, and in semi-dry condition. Wall thickness varied from the base to the top according to the size of the house. An average thickness for a two-storey building was 80 - 100 cm at the base, and 30 - 50 cm at the roof level. Walls are usually plastered with 2 - 5 cm of thick mud - straw or mud - lime mixtures to protect the wall from rain penetration, and to give beauty to the house as shown in Figure (3). Special treatment was given to the construction of coloumns and opening sides, where stones and wood were used to reinforce the walls.

Earth was also used to cover the roof, where a mixture of mud mixed with lime, made a hard layer of 3 to 5 cm thick. This layer overlaid wooven mats and wooden roof, where the main palm beams or other imported beams supported smaller fronds laid diagonally. The roof maintained a small slope of 3 to 5 percent towards spouts to drain rainwater quickly away from the wall sides.

1.3.4.3. Burnt Clay Bricks Construction

A large number of traditional buildings in Mecca, West of Saudi Arabia, were built of burnt clay bricks. These bricks were used as walling materials, in building partition walls, roof parapets, load bearing walls and in some cases as roof slabs in the form of small arches and domes. The clay was selected and collected from the nearby valleys, placed in a shallow ditch, where water and tiny wood chips were added and mixed thoroughly[30]. This mixture which includes silt as well, was moved to an adjacent ditch, where the proper consistency was obtained. Wooden moulds of standardized size were used to give the clay bricks their shape. These moulds are quickly raised leaving the shaped bricks on a flat ground to dry primarily for a few days before being placed in covered kilns. Proper clay stacking, burning time, and heat control were improved by the brick makers in that area[30] through the years. Tiny wood chips helped in reducing brick weight, stopping cracks and improving the firing process. Brick colour was generally red, but other colours like yellow, blue and brown were produced, and were used in roof parapets giving multi colour patterns. These light weight bricks are good insulators where thermal conductivities of such types range from 0.20 to 0.50 W/mK , whenever common bricks[31] have an average conductivity of 1.15 W/mK .

1.3.5. Functions of the Traditional Buildings

Most of the traditional houses were built to provide their occupants with shelter and comfort. Since Saudi Arabia is located in a tropical area, astride the Tropic of Cancer, intense heat during the summer and cold nights during the winter are the main features of the Saudi climate. Climate, tradition and culture, have been reflected in the design and functions of the houses. Good house orientation, with narrow streets and alleys between, adequate wall thickness, suitable window openings, and flat roofs are but a few examples. Room design has achieved good ventilation by setting high ceilings, movable window shutters, cooling wind towers, courtyards and terraces.

These are the most important items in the design of the traditional buildings. Our aim is to explain them, and indicate their importance and drawbacks so that one can utilize the suitable functions together with the modern technical knowledge to achieve more accurate solutions and energy savings without altering comfort levels.

1.3.5.1. House Orientation and Location

House orientation was very important in traditional houses, where maximum comfort was the main objective. Houses along the Red Sea such as in Jeddah [1,19] and Yanbo were oriented towards the prevailing wind directions. These directions were north and west as shown in Figure 1, in which cooler air-breezes penetrated into living and bedrooms. In all locations north of the Equator, such as Saudi Arabia, southern walls are exposed to direct sun-rays all the day, whenever northern walls

are less exposed to the sun. There were minimum openings and sometimes no openings facing south in the hot-humid and hot-arid areas. House orientation for the courtyard house was not important, as no external windows were used.

In rural areas and oasis, houses were located between trees, and shrubs. Tall trees created natural shading[32] and protection against direct sun radiation, which reduced temperature effectively to more acceptable levels.

1.3.5.2.Number of Floors

Most of the traditional buildings in Saudi Arabia, and many parts of the Middle East were built of at least two to three floors. This created greater insulation and cooler environment within the house structure. During summer days lower rooms were cooler, as hot air escaped to top floor rooms. In addition there was a heat build up by the roof mass. Hence lower floors rooms were used during the day, and roof was used for sleeping. In winter the same picture happened and cold air flowed downwards into the lower floors. Top floor rooms were warmer and most utilized. Top floor and middle floor rooms in some cases were used for sleeping during winter.

1.3.5.3.Streets and Alleyways

The old cities of the Middle East such as Jeddah, Mecca and Baghdad[33] were characterised by their narrow streets and alleyways. Most of them have been enclosed by a city wall and this has restricted the construction of wider streets. The main purpose for narrow streets was to allow buildings to provide shade for each other. The narrow width of the street together with the multi-story buildings and massive overhangs protected facades from long hours of exposure to the sun. Streets like alleys, half dark and full of turnings[34] excluded wind and sandstorms, and created cooler climate in hot days. Straighter narrow streets increased wind speed, so that temperature was reduced and comfort increased.

1.3.5.4.Wall Thickness

Climate, type of wall constuction, either load bearing or non-load bearing, the number of floors, roof span and type of building materials influenced the thickness of traditional walls. Thickness varied from 40 to 120 cm as shown in Figure 11. Thick walls have a very high heat holding capacity, which stops heat penetration into the house during mid-day hot hours. These walls re-radiate the heat when temperatures drop, and keep adjacent rooms warmer, working as environmental regulators.

In hot humid areas traditional walls were very light, and mainly of timber framing as that will reduce thermal storage, and allow air breezes to cool the house.

1.3.5.5.Window Openings

Most of the courtyard houses have a very limited number of small windows in the external walls. The size does not exceed 30 x 60 cm, and they are located towards the top of rooms. This style was best known in the hot-dry regions as in Riyadh, Hail and Baghdad in Iraq[33]. In hot-humid areas such as Qatif, Damman and Oqair, windows were much larger as air breezes and air movement were needed to assist in sweat evaporation which is made more difficult by the generally high ambient temperature and humidity. In some cases these windows were shaded by a large wooden external screen, which was 50 - 70 cm away, and covered the total wall facade. Its main function was giving privacy, and shading the main windows from direct sun-rays. At the same time hot air enclosed between it and the wall flows upward and away from the building, causing a draft. This will cool the rooms sheltered by this system. In Jeddah and Mecca, windows were very large, and occupied the entire width and height of at least one wall in a room. Sometimes these windows were projected outside the main wall line in shape of balconies called "rawasheen" as mentioned in 3.2.1., and are shown in Figures (12 and 13).

The light weight of these wooden windows, resulted in negligible thermal storage. These windows provided shade, and allowed air movement to assist in sweat evaporation as well. The change in the direction of local winds between day and night is a feature most marked in the Mecca valleys and on the Jeddah sea coast. This feature had been fully exploited by the

orientation of openings across the breeze direction, and by selecting the freshest indoor and outdoor locations for sleeping, day time activity and rest.

1.3.5.6.Flat Roofs

All the traditional buidlings in Saudi Arabia and the southern parts of the Middle East were built with flat roofs. The roof was constructed of large wooden trunks 40 - 60 cm apart with smaller palm fronds laid diagonally above the amin beams, about 5 - 15 cm apart. This was covered with wooven mats, and 5 - 15 cm layer of hard - dry mud, hardened with lime. The roof was designed in this way to support foot-traffic and sleeping during the night, as well insulating the lower rooms from mid-day hot temperatures. Every house has a staircase which leads onto the roof, with a small room for storing the sleeping mats. A parapet 1.50 - 2.00 metres high surrounded the roof and in many cases, this was built of bricks in the shape of screens to allow through ventilation across the roof surface. Roofs may be divided into two or more parts to accommodate one or more families living in the same house.

1.3.5.7.Room Design

Rooms in traditional houses were spacious, although the ceiling beams had short spans. This was overcome by intermidiate coloumns, as shown in Figure (14). The height of the rooms was at least 3.50 metres, so that warm air could accumulate in the upper part. This air is replaced by cooler air at the

lower level through windows.

Windows played an important rule in ventilation and shading control. This was obtained by the sliding movement of the windows vertically upward or downwards, so that warm air in the room can be extracted outside the building.

In large houses ventilation was obtained through cooling towers, and all internal rooms were located around this wind tower. The tower is projected above the roof level, and across the prevailing wind direction, to catch every available breeze, and to conduct it downwards. This will cause draft and cool the concerned rooms, on the different floor levels.

Top floor rooms were located beside a roof terrace called "Kharjah" which was used to cool them. Also this terrace was used as a place for rest in the late afternoons and early hours of the night. This system was known along the Red Sea coast[35].

In the courtyard houses, rooms were located around the court. At night much of the heat gained by the courtyard during the day is lost to the sky by long-wave radiation, causing cooler environment to the surrounding rooms.

1.4. Conclusions and Consequences for Thermal Design

Building design has always been dictated by climatic conditions. Western style buildings often demand curtain wall construction and large glazed areas as shown in Figures (15 and 16) to admit sufficient daylight owing to the predominance of overcast skies. This style of buildings is not suited for the tropics where daytime temperatures are high and the sky generally clearer[36]. Torpical buildings demand protection from the sun in summer to avoid thermal discomfort.

In the design of buildings appropriate to a given climate, three distinct aspects have to be considered:-

a) the climate itself

b) the indoor conditions preferred by the residents, and

c) the achievement of those indoor conditions

As indicated before, although the climate of Saudi Arabia is well defined,[37, 38] in Appendix B, the effect of the climatic elements on the thermal performance of structures in Saudi Arabia is not known, thus emphasising the need for basic research in the area along the lines being currently studied. The thermal performances of most building structures in Saudi Arabia, particularly heavy-weight structures, are not controlled by instantaneous values of the relevant outdoor elements, but on a combination of instantaneous values integrated on a time basis. The time-lag thermal responses of heavy-weight structures is mainly dependent upon the mass of the structure. Light-weight materials transmit solar heat with little time-lag. To reduce the effect of heat load from the sun[39], it is necessary to reduce the penetration of solar

radiation by shielding all the windows exposed directly to sunlight as shown in Figures (17 and 18) and to minimise the exposure time to other structural elements of the house, such as the walls and roof.

The roof is particularly important, because it receives solar radiation for the most of the day[40]. This can be reduced for a short time by building a protective wall (parapet) at the edge of the roof, which shades it during early morning hours and during sunset time. At mid-day, the angle of incidence of the sun on the flat roof is very close to normal, and the roof is exposed to intense solar radiation especially during summer. One of the main thermal problems in roof design for Saudi Arabia involves controlling the penetration of solar radiation. This affects the temperature rise of the ceiling surface, which in turn affects the thermal comfort of the occupants. There are several solutions[41], but the choice of suitable roof covering material is most important and must be both economically and technically viable. In certain governmental buildings, white reflective ceramics have been used as covering materials[42]. This method is very costly, and so for most domestic buildings in Saudi Arabia, white coloured cement tiles are adopted to cover the roofs, but there is no legislation governing their use. Similarly light coloured paints or other reflecting materials such as expanded polystyrene, may be used to reduce the absorption of solar radiation. It has been found[43] that the temperatures in rooms covered with such reflective materials are noticably lower than those without. Since all buildings have flat roofs, and these roofs are used by the people living in them, particular care is required over design, construction and maintenance as well as differentiating between hot-dry or hot-humid climates. (Once again very little useful

recorded information is available as to the effects of insulation in Saudi Arabia).

Similar to the roof, the walls are exposed to solar radiation. Walls facing east and west receive a good amount of radiation, but if the angle of incidence is small (early morning and late afternoon) the intensity will be less than maximum[44]. The walls on the north face receive comparatively little radiation and are much easier to shield in contrast to the walls on the south which require long overhangs to shelter them. Thus it is good practice to increase the openings on the north side of the house and reduce or eliminate them on the south as shown in Figure 19.

For the reduction of heat transmission through windows numerous types of shading devices are now available, but the choice of the most suitable method for overall performance requires careful consideration, taking into account the efficiency of the system in controlling the entry of solar heat as well as the interference it may cause to interior daylighting and natural ventilation. External sun protection by using wooden shutters is much more efficient than shades or blinds used internally, since the sun's radiation is obstructed before it enters the opening being shaded. It is however important that the shading device itself does not become heated unnecessarily as some of this heat may be transmitted into the building by conductance through the walls or by convection to the surrounding air which may flow into the building. To reduce these deficiencies, the shading device should have a light-coloured finish on the surfaces exposed to the sun and its design should allow for free flow of air over all surfaces away from the window openings. Natural vegetation can often be used effectively as it provides

easy high shading efficiencies. This practice should be encouraged, as it proved itself in some of the carefully designed houses of Saudi Arabia, as shown in Figures (20 and 21). Table 1.4.-1 illustrates the greater efficiency of the external shading devices over the internal types[34].

Thick walls have greater influence in reducing daily indoor temperature variations than thin walls and light-weight structures, but the extent of this control will depend on the degree of the variation in heating and cooling effects of the outdoor environment. A combination of thin wall (light-weight) and thick wall construction may prove satisfactory in certain cases. For instance, thick walls may be used in the east, west and south walls of a house when these walls cannot be shaded , while the north wall could be of light-weight construction with sufficient opening for through ventilation.

Table 1.4.-1 Shading Effectiveness[34]

Coefficient = 100 % Transmission

Coefficient	
0	Clear window
9	Inside dark roller, half drawn
19	Inside dark roller, drawn; inside medium roller half drawn
25	Inside dark blind, drawn
29	Inside light roller, half drawn
34	6 mm heat absorbing glass; inside medium blind drawn
38	Inside medium roller, drawn
42	Dark grey heavy drapes
45	Inside white blind, drawn
40-50	Tree performing light shade
53	Light grey heavy drapes
57	Outside awning, two-thirds drawn
60	Inside white roller, drawn; off-white heavy drapes
72	Outside aluminium shading screen
75	Outside canvas awning (dark or medium)
75-80	Dense tree performing heavy shade
85	Outside white awning, drawn

1.5. Conclusions and Consequences for Ventilation Design

Air change and movement within buildings, or ventilation, is a vital aspect of design which must be considered. Acceptable electric light sources and electric fans etc. have not produced a situation where natural lighting and ventilation can be dispensed with although the former may be wasteful of energy. Two factors control natrual ventilation. One is the pressure variations due to wind. The other is the 'stack' effect which results from warm air in a building, rising and being displace by colder external air. In low buildings with small rooms it is easy to achieve acceptable levels of ventilation, and to control both wind and stack effects by means of windows with adjustable opening lights, as in England.

In Saudi Arabia, where the climate is more severe during the summer, both excessive temperature and dust cause problems in achieving adequate natural ventilation in many parts of the country, especially in the Eastern Province and the Central Zone. Thus the promotion and exploitation of natural ventilation needs careful design[45]. In areas where both temperatures and humidity are very high as in Jeddah and Dammam, ventilation by natural means can be provided, if the ventilation criteria exist. The principal factors which govern ventilation rates in various circumstances and provide criteria for the performance of ventilation systems are,

a) Air movement: some degree of air movement is essential for feelings of freshness and comfort. Desirable speeds vary with temperature and conditions. In domestic buildings and other similar situations a velocity of 0.10 - 0.33 m/s is

considered reasonable, but for temperatures over 30°C a velocity of 0.5 - 1.0 m/s is more acceptable.

b) Relative humidity: it is usually considered that relative humidities between 30% and 70% are acceptable from the point of view of comfort and health and little effort is normally made to control humidity except in air conditioned buildings. Relative humidities are high along the coastal areas, as shown in Table B.7.-6 often to uncomfortable limits, so one of the best ways to improve comfort is to increase ventilation rates. Relative humidity in the Interior of Saudi Arabia however is very low Table B.7.-6 and humidifiers are often used.

In houses along the coastal areas of Saudi Arabia, where both temperatures and humidity are above the generally accepted comfort levels in summer, and in most occupied houses during sunlight hours, there will be a sensible solar heat gain and a gain (mostly of latent heat) from the occupants. These factors will increase both the temperature and humidity, making the conditions in the building even more uncomfortable than outside. The essential design aims are to make suitable allowance for securing good air movement at living levels[45] during hot weather and to provide high rates of air change. P.O. Fanger[11] states that the necessary temperature for comfort is independent of the air velocity because when it is low or approaching zero free convection then controls the convective heat transfer process, and there is inflection for the comfort lines at 0.1 - 0.2 m/s. He concludes that an increase in air velocity from 0.1 to 0.3 m/s must thus be compensated for by an increase in temperature of 1.5 - 3°C. So if we considered a

person wearing light clothing (I_{cl} = 0.5 clo, where I_{cl} is the clothing index) and performing work with mdeium activity, relative humidity 50% and relative air velocity 0.1 m/s, he will be comfortable at an air temperature of 19.6°C. By maintaining the same conditions and only changing the air velocity to 0.5 m/s and 1.0 m/s respectively. the comfort temperatures for the same person will be 22° and 23.4°C. Fanger's comfort diagrams can be applied within the temperate climate zones for adults, independent of the sex. For the tropical climates, where the mean air temperature is much higher than those in temperate climates, higher air velocities will also promote an improved comfort level. It has been found in a study on climate and comfort in a humid tropical area[46] that the range of temperatures for a neutral assessment is 23.4 to 27.6°C and for a warm assessment 27.6 to 31.8°C. For most purposes the preferred temperature may be taken as the mid-point of the neutral range, that is 25.5°C, and it increases a total of about 3.5 deg. C as the velocity of air past the body increases. It is interesting to note that, although higher temperatures become tolerable as air movement increases, either naturally or artificially, the neutral range at the same time decreases. Thus, conditions for comfort become increasingly critical as air velocity increases.

In the context of the coastal areas of Saudi Arabia it is important to consider window openings and balconies, and whether they have been directed towards the main wind directions in the early design stage of the house. From the climatic considerations the most preferable directions are towards the north and the sea, where sea breezes can reduce the temperature to a great extent, as shown in Figure 22.

In areas where dust storms exist, utilising the natural winds for air movement inside the houses is not advisable and more research should be done to solve the ventilation problems in such circumstances. During clear days, natural ventilation can be used with adjustable louvres being adopted to control the direction of the airflow inside buildings. For high velocities in the living zone, inlets and outlets are required at low level, and the latter, in the case of louvres, should be set horizontally. If the external wind speed increases, then the air can be diverted away from the living zone, so that its velocity drops before reaching the occupants. The greatest amount of general air movement can be produced by changing the air flow direction within a room. This change will produce more turbulent mixing than when the flow pattern is straight, which means that the whole room will benefit from increased air movement rather than only a small part of it[34].

In modern buildings there is an increasing number of cases where natural ventilation does not give satisfactory conditions and mechanical ventilation must be employed. The main situations which call for this type of ventilation may be tabulated[47] as follows

1. Internal rooms
2. Large closely populated rooms where distribution of natural ventilation would be inadequate (BS CP3 Chapter 1 (c) Ventilation, suggests all rooms occupied by more than 50 people).
3. Rooms where the volume per occupant is too low for efficient natural ventilation. (BS CP3 Chapter 1 (c) Ventilation, suggests under 3.5 m^3 per person).
4. In cases where specially close control of environment is required particularly in relation to relative humidity and dust particles

in the air.

5. Where natural ventilation is impractical due to external atmospheric pollution or noise.

6. In tall buildings where wind and stack effects would render natural ventilation impracticable.

7. Where extraction ventilation (or an excess of extraction over input) may be required to deal with fumes or smells from cooking or other special processes.

Table 1.5.-1 Recommended minimum rates of fresh air supply to buildings for human habitation[47]

Types of Buildings	Recommended minimum rates of fresh air supply to buildings
Assembly halls	28 m^3 per hour per person
Canteens	28 m^3 per hour per person
Factories and Workshops	
Work rooms	22.6 m^3 per hour per person
Lavatories and WC's	2 air changes per hour
Hospital Operating Theatres and X-ray Rooms	10 air changes per hour
Wards	3 air changes per hour
Houses and Flats	
Bathrooms and WC's	2 air changes per hour
Halls and passages	1 air change per hour
Kitchens	56 m^3 per hour
Living rooms and Bedrooms	
8.5 m^3 per person	20.5 m^3 per hour per person
11.5 m^3 per person	18.5 m^3 per hour per person
14 m^3 per person	12 m^3 per hour per person
Pantries and Larders	2 air changes per hour
Places of Entertainment	28 m^3 per hour per person
Restaurants	28 m^3 per hour per person
Schools	
Occupied Rooms (Classrooms, Laboratories, Practical Rooms etc.	
2.8 m^3 per person	42 m^3 per hour per person
5.56 m^3 per person	28 m^3 per hour per person
8.5 m^3 per person	20.5 m^3 per hour per person
14 m^3 per person	12 m^3 per hour per person
Cloakrooms	3 air changes per hour
Corridors, Lavatories and WC's	2 air changes per hour

Source: British Standards Institution CP3 Chapter 1 (c)

PART : 2

EXPERIMENTAL STUDY

"THE THERMAL PROPERTIES OF BUILDING BLOCK/ POLYSTYRENE FOAM COMPOSITE LAMINATES"

2.1. Introduction

Regulations and incentives have been introduced in most of the developed world[48] to promote savings in energy consumption in many fields. This includes the developement of new building materials as well as the use of insulation materials with existing structures, and a fuller understanding of heat flow through these structures is required. Theories on the conduction of heat are outlined and discussed here in this thesis, since a substantial part of the total amount of heat exchanged between the interior and exterior of a building is transferred by conduction. Heat conduction in both homogeneous and composite materials is reviewed for the purpose of measuring their thermal conductivities. The materials tested are common as building and insulation materials. These are "Thermalite" (aerated solid cement blocks) and "Styrofoam" 1B board insulation (extruded polystyrene). A guarded hot plate apparatus is used to determine the thermal conductivity of the above two homogeneous materials. For each material, two identical samples are tested, placed on either side of a heating unit which is surrounded by a guard ring to ensure no net loss of heat from the heater edges. The heat flow through each sample is then half the energy flow to the heating unit. The temperature of the central hot plate and the two cold plates is determined with thermocouples embedded in the surfaces of the plates.

"Thermalite" and "Styrofoam" are combined in two layers to form the composite material. It is suggested that such a composite will provide both the structural strength required ("Thermalite") and the excellent insulation properties ("Styrofoam"). This is to replace the thick walls used in traditional houses, thus increasing the space and maintaining the

same comfort levels. The same guarded hot plate apparatus is used in conjunction with heat flow sensables to calculate the thermal conductivity of this composite material. The use of these sensables reduced the time required to obtain 'k' values. The rapidity and ease of obtaing these measurements should represent a substantial saving in research time for the investigation of the thermal properties of composites with varying secondary phase (foam) concentrations.

2.2. Literature Review

2.2.1. Historical

Many problems in building research and building design require a complete understanding of the heat-transfer processes which take place between a structure and the surrounding environment. Heat transfer is defined in the literature as the transmission of energy from one region to another as a result of a temperature difference between them. The modes of heat transfer are: radiation, conduction and convection. In most situations, heat energy flows, not only by one, but by several of these modes acting simultaneously. When one mechanism dominates quantitatively, useful approximate solutions are obtained by neglecting all but the dominant mechanism. The heat-transfer at the external surface of a building is mainly by radiation and convection, whenever the heat flow through the walls and the roof is transferred mainly by conduction.

Radiation is the transport of energy from a material into the surrounding space by electromagnetic-waves, due to temperature gradient. The energy transmitted in this way is termed radiant heat. Its intensity depends on the temperature and the nature of the surface. The equation governing the radiant heat transfer is:

$$q = F \sigma \varepsilon \, (T_1^{\,4} - T_2^{\,4})$$

where

q = heat transfer rate or heat flux; (Watts/m^2)

F = geometric form factor between the source and receiver

σ = Stefan-Boltzmann constant; (W/m^2S)

ε = emmissivity of the radiator (source)

T_1 = absolute temperature of the source

T_2 = absolute temperature of the receiver.

Conduction is a process by which heat flows within a medium (solid, liquid, or gaseous or between different mediums in direct physical contact. The energy is transmitted by direct molecular communication without appreciable displacement of the molecules. Energy is also diffused through the material by these thermal communications.

If conduction occurs in a fluid in motion, the diffusion of thermal energy will be affected by the relative motion or the elastic impact within the fluid. Conduction processes affected by relative motion are called convection processes. Convection is most important as the mechanism of energy transfer between a solid surface and a gas, and is given by the following equation:

$$q = h\,(T_1 - T_2)$$

where

q = the heat transfer rate; (W/m^2)

h = the convective heat ransfer coefficient; $(W/m^2\,{}^{\circ}K)$

$(T_1 - T_2)$ = the temperature difference between the surface and the gas

In this review only the conductive heat transfer mode will be considered, since a substantial proportion of the total amount of heat exchanged between the interior and exterior of a building is transferred by conduction. The subject of heat conduction in solids and its related mathematical theories was first developed

more than one and half centuries ago. This is due principally to the French scientest Jean Baptise Joseph Fourier (1768-1830) and was introduced by him in his book "Théorie analytique de la chaleur"[49]. Others such as Lambert and Biot had developed some more or less correct ideas on the subject, but they did not explain it to the same degree, clarity and order as Fourier did.

Fourier treated many cases of heat conduction in solids. His work was extended and applied to more complicated problems by Laplace and Poisson at the same early period. Most of the later workers in the subject such as Lamé, Sir W. Thomson (Lord Kelvin), Riemann and many others did the same. Riemann in particular illustrated Fourier work in a very understandable and readable form[50].

From the forties to the seventies of this century, many workers such as Carslaw and Jaeger [51], Jakob[52], Schneider[53], Ozisik[72] and many others approached the mathematical solutions of heat conduction problems in an elegant way.

The conduction of heat process had been classified in the literature as steady and unsteady states. The steady state means that the conditions of the material such as temperature and density at all points of the conduction region are independent of time. The unsteady state implies a change with time, usually only of the temperature, and it is devided into two types, periodic and transient. The periodic conduction happens as a result of temperature variations with time, such as the conduction of heat energy through building walls due to solar effects. The transient conduction takes place, when this variation is irregular and not

periodic.

The solution of a conduction problem involves the functional dependence of temperature upon location in the conduction region and upon time in unsteady state circumstances. This means finding a temperature distribution which is consistent with the boundary conditions and any specified conditions internal to the region, such as rate of heat flow.

The rate of heat conduction through a solid material is proportional to the temperature difference across the material and to the area perpendicular to heat flow and inversely proportional to the length of the path of heat flow between the two temperature levels. This relation was established by Fourier and is analogous to the relation for the conduction of electricity, called Ohm's law. The constant of proportionality in Fourier's law, is called the thermal conductivity "k" and is a property of the conducting material and of its state. Thermal conductivity is defined[54] as a property of a homogeneous body measured by the ratio of steady state heat flux (time rate of heat flow per unit area) to the temperature gradient (temperature difference per unit length of heat flow path) in the direction prependicular to the area. It is expressed [55] as the heat flow in watts per square metre of surface area for a temperature difference of $1^{o}C$ per metre thickness.

Thermal conductivity measurements prior to the Second World War, were mainly conducted by National Standards Laboratories, and some limited number of centres at Universities or Government establishments. This trend changed from the early forties, when

more scientists and engineers of all disciplines were also involved. The reported differences in values of measured thermal conductivities of a particular material by an order of magnitude, necessitated unified standards and international conferences to discuss the matter.

Some of the published standards, were revised several times. The most common for the measurement of thermal conductivity of building and insulating materials in slab form are the British Standard 874: 1973 [56] with its new ammendment, published in 1979[57], and the American Standard C 177-71, revised in 1976 as C177-76[58].

Other test procedures and methods were applied in special and different cases, and refinements in this field were encouraged.

Many workers helped with their ideas and contributions to develop understanding in the field of thermal conductivity. Examples are Powell, who developed the Thermal Comparator[59] methods, Ziebland and his work on the thermal transmission properties of polymer composites[60], Pratt's excellent survey of heat transmission in low conductivity materials[61], Harmathy and his work on variable-state methods of measuring the thermal properties of solids[62], Woodside, Donaldson, Pratt and their work on edge heat loss analysis. The most authoritive and collective recent work on thermal conductivity is that of Tye[59,61].

Other advancements and contributions to this field were discussed in the specialized meetings and conferences. The first conference for the measurement of thermal conductivity was held

at the Battelle Institute in Columbus, Ohio in 1961.

Other meetings took place in Canada, The United States of America, and Europe. The first International Conference on Thermal Conductivity was held at the National Physical Laboratory, Teddington, England, in 1964. Many other conferences have since been organized to discuss and understand all the fundamental principles of accurate temperature measurement , heat loss considerations, the progress in this field, and the thermal conductivities of any new materials.

The following information should be given in case of any investigation concerning thermal conductivity: the material, its source, any fabrication treatments, chemical analysis, a detailed, microstructure or general form, density, porosity, grain size, pore size, diameter and length of fibres, homogeneity and preferred orientation. The method used should be explained in detail together with the error analysis, the experimental procedures and whether it differs or complies with the existing standards.

A selection of thermal-conductivity data and other thermal properties is given in Appendix (A-4). Thermal conductivity measurements were conducted for both homogeneous and composite materials in plane slab forms, and a literature review concerning the theories and measurements of thermal conductivities of materials will be revised in the following section.

2.2.2. Thermal Conductivity of Homogeneous Materials

2.2.2.1. Definitions

The literature on thermal conductivity of homogeneous materials is large, and extensive, due to the wide range of these materials. This includes metals, alloys, oxides, liquids, building materials and insulating materials. They have different testing methods and several types apparatus to cover their wide range of thermal conductivities. The aim is to limit this review to the range of solid building and insulating materials, because of their importance to the building industry and the cause of energy conservation.

A homogeneous solid is defined as that material, when a point within it is heated, the heat spreads out equally well in all directions[51]. That means the value of thermal conductivity is unaffected by variations in sample thickness or area within the range of temperature normally used[54]. Most of the heat insulating materials may be considered as homogeneous materials, even though they are mixtures of gases and solid bodies. This is a valid statement if every geometrically indentical portion which contains gases and solid bodies has the same apparent thermal conductivity[58]. Cellular materials, such as Cork which is naturally occurring, foamed and expanded plastics are considered homogeneous. Cellular polystyrene thermal insulation is an organic foam composed principally of polymerized styrene resin processed to form a homogeneous rigid mass of cells[54]. These cells are closed, and hence they are air and vapour-tight. Lightweight concretes combining structural strength with heat insulating properties are also produced in cellular form. They are compose of cement, sand and pulverised fuel ash with air-voids, and they are considered to be homogeneous.

2.2.2.2. Nomenclature:

a = thermal diffusivity; (m^2/s)

A = area, cross sectional area; (m^2)

c = specific heat; (J/Kg^oK)

C = constant, thermal conductance $= \frac{1}{R}$; (W/m^2K)

I = electric current flow rate; (Amp.)

k = thermal conductivity; (W/m^oK)

K = thermal conductance; ($W/^oK$)

L = thickness of the material; (m)

q = rate of heat flow; (W) or (J/S)

$\ddot{q}$ = rate of heat flow per unit area or heat flux; (W/m^2)

$\ddot{q}_o$ = constant density of flux imposed at abscissa x = o;

$\bar{q}$ = rate of heat generation per unit volume; (W/m^3)

R = thermal resistance = 1/k; (S/W)

R_e = electrical resistance; (ohm)

$T_{(x,t)}$ = temperature at abscissa x, and at time t; (K)

T_c = constant temperature imposed at abscissa X = L;

T_o = initial constant temperature ;

t = time; (S)

U = overall unit conductance, or overall transmittance ($W/m^2\,^oK$)

x,y,z,= cartesian coordinates;

r,θ,z = cylindrical coordinates;

X = distance, measured from the input face; (m)

Δ = difference between values;

n = coordinate in the direction of heat flow;

ρ = mass density;(Kg/m^3)

2.2.2.3. Theory

Experience has shown that when different parts of a solid body are at different temperatures, heat flows from the hotter to the colder portions by a process of electronic and atomic energy transfer known as "conduction".

lattice vibs.

To prove this statement imagine two parallel planes, distance x apart, with area A in an isotropic body and each at constant temperature as T_1 and T_2. A quantity of heat Q will flow in time t, this will be given by

$$Q = k \frac{T_1 - T_2}{x} A t \qquad \text{..... (1-H)}$$

$$q = \frac{dQ}{dt} = k \frac{T_1 - T_2}{x} A \qquad \text{..... (2-H)}$$

The limiting value of $\frac{T_2 - T_1}{x}$ or $\frac{\partial T}{\partial x}$ is known as the temperature gradient at any point.

$\frac{\partial T}{\partial x}$ is negative in the direction of heat flow, and the rate of heat flow across an isothermal surface in a positive direction is

$$q = - k A \frac{\partial T}{\partial x} \qquad \text{..... (3-H)}$$

and in terms of heat flux

$$\bar{q} = \frac{q}{A} = - k \frac{\partial T}{\partial x} \qquad \text{..... (4-H)}$$

The general equation of heat flux across any surface is:-

$$\ddot{q} = - k \frac{\partial T}{\partial n} \qquad \text{.....} \quad (5\text{-H})$$

Equations (1-H) and (5-H) are the fundamental hypothesis of heat conduction, which was proved by Fourier[49] and resulted in the general equation of conduction of heat or Fourier conduction equation:

$$\frac{\partial T}{\partial t} = a \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \qquad \text{.....}$$

The following mathematical derivation and analysis has been given previously in several papers (63 to 67) using a notation somewhat different from the present one.

Consider a small cube element of edges Δx, Δy and Δz of an isotropic material subjected to a conduction process as shown in Figure 2.2.2. (1)

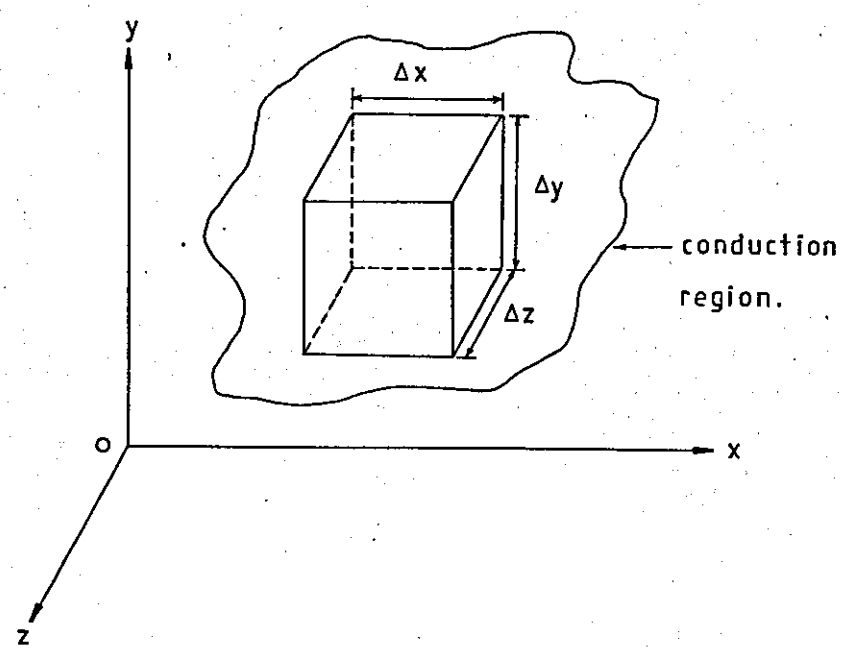


Figure 2.2.2.(1) Elementary cube in an isotropic medium subjected to a heat flow.

Let T represents the temperature at the centre of the cube; then, since the temperature will be variable throughout the material, we could express its value on any face of the cube as being greater or less than T by a very small amount, which could be neglicted.

Take the faces $\Delta y \ \Delta z$, the magnitude of the very small amount of temperature is given as

$$\frac{1}{2} \quad \frac{\partial T}{\partial x} \quad \Delta x$$

because $\frac{\partial T}{\partial x}$ measures the change of temperature per unit length along ox, and $\frac{1}{2} \ \Delta x$ is the length from the centre of the element to the faces $\Delta y \ \Delta z$.

Hence, the temperature of the left and right hand faces $\Delta y \ \Delta z$ will be

$$T_L = T - \frac{1}{2} \quad \frac{\partial T}{\partial x} \quad \Delta x \qquad \text{.....} \quad (6\text{-H})$$

$$T_R = T + \frac{1}{2} \quad \frac{\partial T}{\partial x} \quad \Delta x \qquad \text{.....} \quad (7\text{-H})$$

By using equation 3-H, $q = - k A \frac{\partial T}{\partial x}$ and substituting the values of T_L and T_R we obtain.

$$q_L = - k A \frac{\partial T_L}{\partial x}$$

$$= - k \ \Delta y \ \Delta z \ \frac{\partial}{\partial x} \left(T - \frac{1}{2} \frac{\partial T}{\partial x} \Delta x\right) \qquad \text{.....} \quad (8\text{-H})$$

for the flow of heat per second in the positive x direction through the left hand face

$$q_R = -k A \frac{\partial T_R}{\partial x}$$

$$= -k \Delta y \Delta z \frac{\partial}{\partial x} (T + \frac{1}{2} \frac{\partial T}{\partial x} \Delta x) \quad \ldots\ldots\ldots\ldots \quad (9\text{-H})$$

for the flow of heat per second in the positive x direction through the right-hand face.

The net rate of gain in the element $\Delta x \ \Delta y \ \Delta z$ due to conduction in the x direction only can be obtained by subtracting the quantities $q_L - q_R$, hence

$$q_L - q_R = -k \Delta y \Delta z \frac{\partial}{\partial x} (T - \frac{1}{2} \frac{\partial T}{\partial x} \Delta x) - [-k \Delta y \Delta z \frac{\partial}{\partial x} (T + \frac{1}{2} \frac{\partial T}{\partial x} \Delta x)]$$

$$= k \frac{\partial^2 T}{\partial x^2} \Delta x \ \Delta y \Delta z$$

Similar relations are written for the other two pairs of faces in the y and z directions:

$$k \frac{\partial^2 T}{\partial y^2} \Delta y \Delta x \Delta z \quad \text{and} \quad k \frac{\partial^2 T}{\partial z^2} \Delta z \Delta x \Delta y$$

The sum of the differences of these three pairs of relations represents the difference between the total in flow and total out flow of heat, or the amount by which the heat of the element is being increased per second,

$$k \frac{\partial^2 T}{\partial x^2} \Delta x \, \Delta y \, \Delta z + k \frac{\partial^2 T}{\partial y^2} \Delta x \, \Delta y \, \Delta z + k \frac{\partial^2 T}{\partial z^2} \Delta x \, \Delta y \, \Delta z \qquad \text{..... (10-H)}$$

The amount by which the heat of the element is being increased per second is also equal to the product of its mass, specific heat, and the time rate of change of temperature:

$$(\rho \, \Delta x \, \Delta y \, \Delta z) \; c \; \frac{\partial T}{\partial t} \qquad \text{..... (11-H)}$$

(10-H) must equal (11-H), Hence, we may write

$$k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \quad c\rho \; \frac{\partial T}{\partial t}$$

and since $\frac{k}{c\rho}$ = a, thermal diffusivity, hence

$$\frac{\partial T}{\partial t} = a \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \qquad \text{..... (12-H)}$$

Is Fourier conduction equation, which applies to three dimensional unsteady-state conduction in an isotropic region of uniform thermal conductivity.

If the conditions for equation (12-H) are met and the conduction occurs in steady state, the time derivative is zero and hence, the result is Laplace equation:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = o$$

This can be written as

$$\nabla^2 T = o \qquad \text{..... (13-H)}$$

If the steady state homogeneous region of uniform thermal conductivity is subjected to a distributed source of energy. The strength of the generation process, $\bar{q} = q/AL$, may vary over the region. The resulting equation is called Poisson's equation.

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\bar{q}}{k} = o \qquad \text{..... (14-H)}$$

The above equations are in terms of a cartesian coordinate system.

The temperature distribution, $T_{(x,t)}$, within an infinite slab of thickness L, is given by the solution of the one dimensional equation[51] of linear heat flow with specified boundary conditions;

$$a \frac{\partial^2 T_{(x,t)}}{\partial x^2} = \frac{\partial T_{(x,t)}}{\partial t} \qquad o < x < L \qquad \text{.....(15-H)}$$

where $a = k/\rho c$ is assumed to be independent of position, time and temperature. The boundary condition at the input face, $x = o$ will be an input flux $\ddot{q} = - k \frac{\partial T}{\partial x}$ (4-H).

The temperature of the output face will be held constant.

The temperature of the slab will be uniform and equal to the output face temperature at time zero. These boundary conditions can be written as;

$$\ddot{q}_{(o,t)} = -k \frac{\partial T_{(o,t)}}{\partial x} = o \qquad t < o \quad \ldots\ldots\ldots\ldots \quad (16\text{-H})$$

$$\ddot{q}_{(o,t)} = -k \frac{\partial T_{(o,t)}}{\partial x} = \ddot{q}_o \qquad t > o$$

$$T_{(L,t)} = o, \qquad t \geqslant o \quad \ldots\ldots\ldots\ldots \quad (17\text{-H})$$

$$T_{(x,t)} = o \qquad t \leqslant o \quad \ldots\ldots\ldots\ldots \quad (18\text{-H})$$

The solution for the homogeneous single layer has been given by Carslaw and Jaeger[51] as;

$$T_{(x,t)} = \frac{\ddot{q}_o (L - X)}{k} - \frac{8\, \ddot{q}_o L}{k \pi^2} \sum_{n=o}^{\infty}$$

$$\sum_{n=o}^{\infty} \frac{\exp[-(2n+1)^2 \pi^2 a t/4 L^2] \cos (2n+1)\pi x/2L}{(2n+1)^2}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots \quad (19\text{-H})$$

At the input face $x = o$, and for large values of time the series can be truncated at one term to give;

$$T_{(o,t)} = \frac{\ddot{q}_o L}{k} \left[1 - \frac{8}{\pi 2} \exp\left(- \frac{\pi^2 a t}{4 L^2}\right)\right] \ldots\ldots\ldots\ldots \quad (20\text{-H})$$

2.2.2.4.Theoretical Model

For the experimental configuration given in Figure 2.4.3. (1), where the heat source for the infinite slab (sample) is in contact with the slab and has heat capacity itself, the conditions used in deriving equation (19-H) are not exactly fulfilled as it has been assumed that the heat flux comes from a source with no heat capacity. As the heat capacity of the electrically energised heater is an appreciable fraction of the heat capacity of the sample it is necessary to use a double

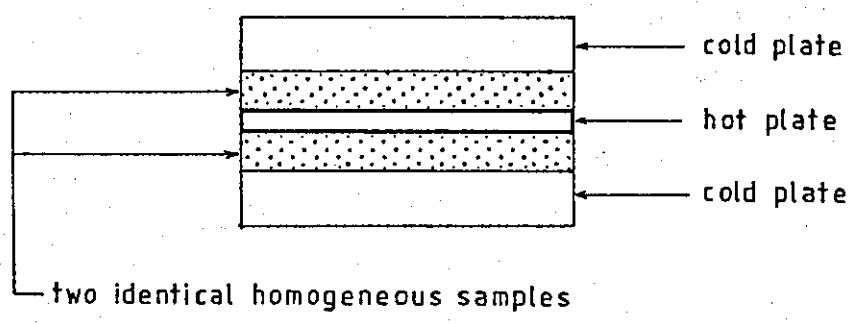


Figure 2.2.2.(2) Basic experimental arrangements for testing homogeneous samples.

layer infinite slab for a model[68]. Figure 2.2.2.(3) represents the theoretical model which agrees with the experimental arrangements shown in Figure 2.4.3. (1).

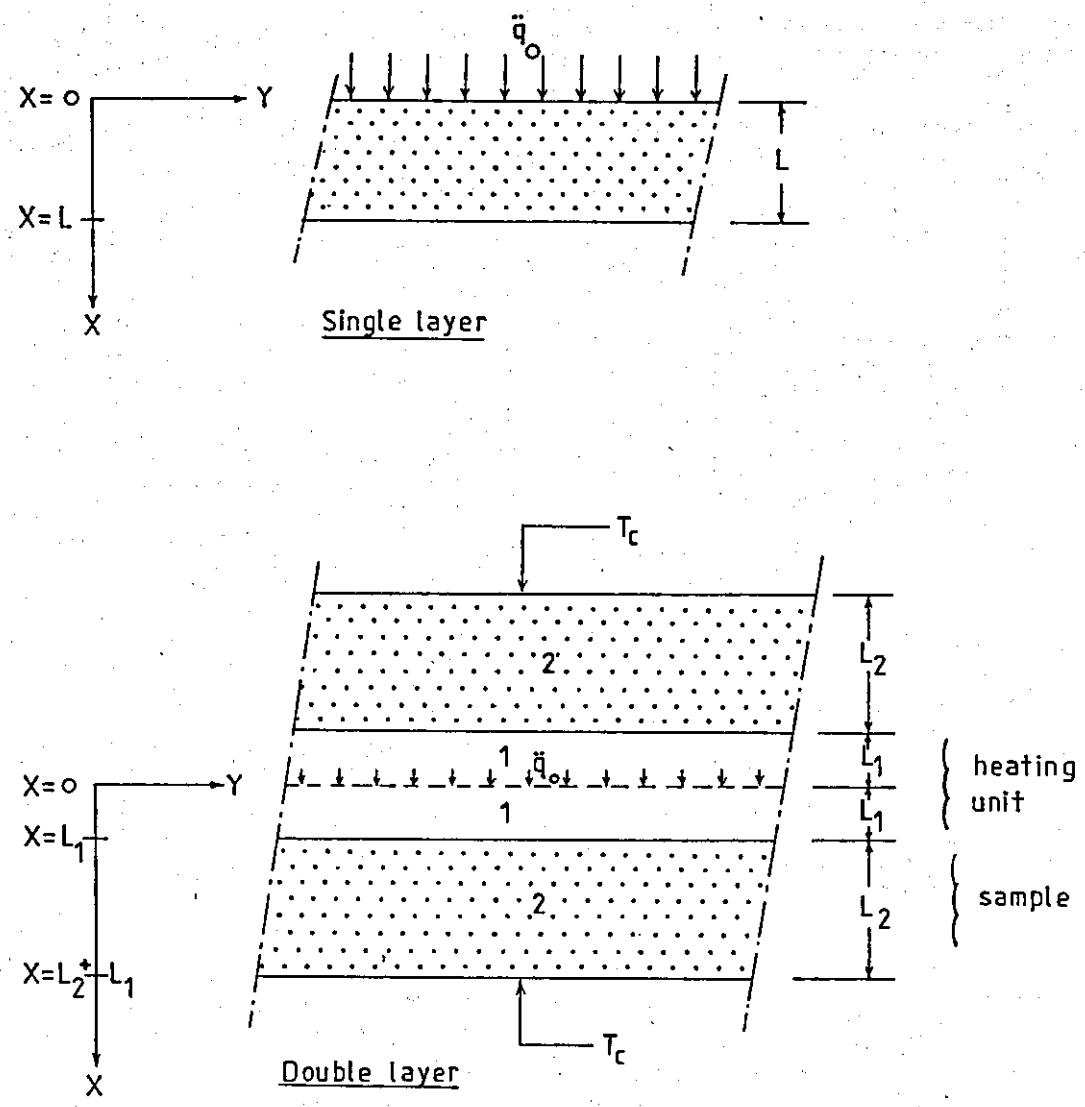


Figure 2.2.2.(3) Theoretical model.

For an infinite slab composed of two layers, 1 and 2, each of uniform thickness, an additional pair of boundary conditions are required, namely, the flux and temperature must be continuous at the interface.

Temperatures $T_1\ (x,t)$ in layer 1, and $T_2\ (x,\ t)$ in layer 2 represent the solution of equation (15.H) which can be written as;

$$a_l \frac{\partial^2 T_l(x,t)}{\partial x^2} = \frac{\partial T_l(x,t)}{\partial t} \quad (l = 1,2)$$

at abscissa $x = L$, $T_{1(L,t)} = T_c$

at abscissa $x = L_1$, $T_{1(L_1,t)} = T_{2(L_1,t)}$ ..... (21-H)

$$k_1 \left[\frac{\partial T_{1(x,t)}}{\partial x} \right]_{x = L_1} = k_2 \left[\frac{\partial T_{2(x,t)}}{\partial x} \right]_{x = L_1} \quad \text{.....} \quad (22\text{-H})$$

$$k_1 \left[\frac{\partial T_{1(x,t)}}{\partial x} \right]_{x = o} = \ddot{q}_o \quad \text{.....} \quad (23\text{-H})$$

at time $t = o$, $T_{1(x,o)} = T_{2(x,o)} = T_o$

The solution of equation (21-H) by means of Laplace transformations gives the value of $T_{1(L_1,\ t)}$ at the interface between the heating unit (1) and sample (2) Hence;

$$T_{1(L_1,t)} = T_i + \sum_{n=1}^{\infty} A(n) \exp[-\beta(n).t] \quad \text{..(24-H)}$$

in which

$$T_i = \frac{\ddot{q}_o L_2}{k_2} + T_c$$

T_i = temperature of the plate whose abscissa is $x = L_1$ under constant conditions.

$$A(n) = -2\left\{\frac{\ddot{q}_o L_2 \sin\sqrt{\frac{\beta(n)}{a_2}}\, L_2 + k_2\sqrt{\frac{\beta(n)}{a_2}}\, L_2\,(T_c - T_o)\cos\sqrt{\frac{\beta(n)}{a_2}}\, L_1}{L_2\sqrt{\frac{\beta(n)}{a_2}}\, L_2 \cdot \sqrt{\frac{\beta(n)}{a_2}}\, L_1\left[\frac{k_1}{L_1}\sin^2\sqrt{\frac{\beta(n)}{a_1}}\, L_1 + \frac{k_2}{L_2}\cos^2\sqrt{\frac{\beta(n)}{a_1}}\, L_2\right]}\right.$$

$$\left. \times \quad \cos\sqrt{\frac{\beta(n)}{a_1}}\, L_2 \cdot \sin\sqrt{\frac{\beta(n)}{a_1}}\, L_1\right\}$$

When $T_c = T_o$, the expression given by Halteman and Gerrish[68] for $\beta(n)$, (nth solution of the equation) is;

$$\tan\sqrt{\frac{\beta(n)}{a_1}}\, L_2 \cdot \tan\sqrt{\frac{\beta(n)}{a_1}}\, L_1 = \frac{k_2\sqrt{a_1}}{k_1\sqrt{a_2}}$$

After a long enough period of time, τ ; temperatures will be steady and we can find the value of $T_{1(L_1,t)}$ using only the 1st term in equation (24-H) with very little error.

Hence equation (24-H) becomes;

$$T_{1(L_1,t)} = T_i + A(1)\ \exp[-\beta(1).t] \quad \ldots\ldots\ldots\ldots \quad (25\text{-}H)$$

$$t \geq \tau$$

2.2.2.5. Determination of Time (τ):

Let us consider the difference in temperatures between two moments in time t and (t + d).

From equation (25-H);

$$T_{1(L_1,t)} = T_i + A(1)\, e^{-\beta(1)t} \text{ at time } t$$

and

$$T_{1(L_1,t+d)} = T_i + A(1)\, e^{-\beta(1)t+d} \text{ at time } (t+d)$$

$$\Delta T_{1(t)} = T_{1(L_1,t+d)} - T_{1(L_1,t)}$$

$$= [T_i + A(1).e^{-\beta(1)\ t+d}] - [T_i + A(1).e^{-\beta(1)t}]$$

$$= A(1).e^{-\beta(1)\ t+d} - A(1).e^{-\beta(1)\ t}$$

$$= A(1)[e^{-\beta(1)t}.e^{-\beta(1)d} - e^{-\beta(1)t}]$$

$$= A(1).e^{-\beta(1)t}[e^{-\beta(1)d} - 1]$$

$$\text{Log } \Delta T_{1(t)} = \text{Log}[A(1)\{e^{-\beta(1)d} - 1\}] + \text{Log } e^{-\beta(1)t}$$

$$= \text{Log}[A(1)\{e^{-\beta(1)d} - 1\}] - \beta(1)\ t$$

If d remains constant, the value of τ can be determined when the experimental curve Log $\Delta T_{1(t)}$ in terms of time becomes linear.

2.2.2.6. Determination of the Thermal Conductivity "k"

The representative curve of equation (25-H) which has the form $T_{(t)} = T_i + A(1) \cdot e^{-B(1)t}$ should come as close as possible to the experimental curve $T_{1(L_1,t)} = f(t)$ in which $t \geqslant \tau$;

T_i is known and in the case of one homogeneous sample of thickness L, T_i is the hot face temperature of the sample. The thermal conductivity "k" can then be determined by means of the formula;

$$k = \frac{\ddot{q}_o \cdot L}{T_i - T_c}$$ (reached under constant conditions).

2.2.3. Thermal Conductivity of Composite Materials

2.2.3.1. Definitions

In the last decade the extent of use of composite materials in the field of civil engineering increased tremendously. The most common materials are concrete, fibre reinforced resin, fibre reinfored cemet and glass fibre reinforced plastic (polyester) (g.r.p.)

The term composite already indicates the presence of more than one constituent material. Concrete is one of the oldest known composite materials for construction. It consists of a non-homogeneous,anisotropic medium, composed of particles of aggregate held together by hydrated cement paste. The thermal conductivity [69] of concrete is defined as the average thermal conductivity of a region (large compared with the average aggregate particle interspacing) instead of at a single point. In general, a composite material is composed of two constituents, matrix and fibres[70]. The fibres are embedded in the matrix. The matrix may be a resin (polyester or epoxide), a hardened cement paste (Portland or high alumina cement), a mortar or concrete, or a gypsum plaster. The fibre may be glass, steel wire, asbestos, polypropylene, nylon, etc. The contact between the matrix and fibres is established by the controlled application of pressure and temperature during the moulding process. Insulating materials based on mineral fibres may be considered a special kind of composite in which the enclosed air represents the continuous matrix. This indicates that the matrix (air or gas) is in direct

contact with the fibrous solid, which differs from the other composites.

Laminated layers are another form of composite . They have very wide range of applications in construction and insulation industry. As an example, polystyrene and polyurethane foams combined with other building materials produce composites that can function as water/vapour barriers as well as thermal insulants[71]

The literature on thermal conduction phenomena in heterogeneous media is extensive largely because of the technological importance of one of its applications, viz thermal insulation. The process of conduction in composites will be explained in the next section.

2.2.3.2. Nomenclature

a	=	thermal diffusivity;	(m^2/s)
A	=	area;	(m^2)
f	=	structural factor;	
$\phi(D)$	=	fibre distribution (orientation function);	
k	=	thermal conductivity;	(W/m K)
q	=	rate of heat flow;	(W)
$\ddot{q}$	=	heat flux = q/A;	(W/m^2)
R	=	thermal resistance = 1/k;	
t	=	time;	
T	=	temperature;	
V	=	volume;	
X,Y	=	dimensionless terms;	

Suffices:

c	=	continuous phase;
C	=	composite;
d	=	discontinuous phase;
F	=	fibre reinforcement;
L	=	longitudinal (along fibre axis)
M	=	matrix;
T	=	transverse (normal to fibre axis)

2.2.3.3. Theories of Conduction in Heterogeneous Systems

The specific heat of a composite laminate is simply the volume weighted sum of the specific heats of the constituents. The determination of the thermal conductivity of a composite k_c, from those of its constituents is more complex, and can only be predicted accurately by a knowledge of the conductivities of the constituents and their geometrical arrangement. An exact mathematical treatment of a composite thermal conductivity would require knowledge of the position of each individual fibre or (secondary phase) in the matrix ϕ (D). The respective volume concentration of the matrix $(1-V_F)$ and of the fibres (V_F), as well as their respective conductivities (k_M and k_F). Therefore most models are simplified according to the following assumptions:

a) The composite is an ideal and void-free material.

b) The fibres (reinforcement) are evenly dispersed in the matrix.

c) The fibres and matrix are thermally isotropic

d) Thermal contact resistance between matrix and fibres is negligibly low.

e) Twisting of fibre bundles is ignored.

A number of trials have been made to obtain equations that express k_c in terms of the conductivities of its constituent materials and their fractional volumes. The simplest models for theoretical prediction represent the constituent materials as separate resistances in the form of slabs arranged either in series or in parallel to the direction of heat flux. The series

arrangement has the maximum resistance to heat flow, and hence the minimum thermal conductivity, given by:

$$k_c = \frac{k_M \; k_F}{V_F \; k_M + (1-V_F) \; k_F} \qquad (1\text{-}C)$$

in which V_F is the volume fraction of the fibres (foam). The parallel arrangement has the minimum resistance to heat flow, and the maximum conductivity.

$$k_c = V_F \; k_F + (1-V_F) \; k_M \qquad (2\text{-}C)$$

In practice, the value of thermal conductivity of a composite k_c composed of two consituent materials (phases) lie somewhere between the extreme values predicted by equations (1-c) and 2-C). A number of formulae have been proposed to predict k_c values on the basis of a simple model.

The first model considers a cube of unit volume. This is shown in Figure 2.2.3. (1). The mathematical analysis of the model have been given by Ziebland[60], and resulted in the following formula:

$$k_c = k_M^{(1-V_F)} \; k_F^{V_F} \qquad (3\text{-}c)$$

in which

k_M = Thermal conductiviy of the matrix.

$(1-V_F)$ = Unit volume fraction of the matrix.

k_F = Thermal conductivity of the fibres.

V_F = Unit volume fraction of the fibres.

Ziebland introduced the dimensionless terms X and Y in which

$$X = k_M/k_F \qquad (4\text{-}C)$$

$$Y = k_c/k_F \qquad (5\text{-}C)$$

which led to the general relationship

$$Y = F[X, V_F, \phi\ (D)] \qquad (6\text{-}C)$$

In terms of X and Y, equations (1-C), (2-C) and (3-C) have been expressed respectively as follow :

$$Y = \frac{X}{V_F\ (X-1) + 1} \qquad (7\text{-}C)$$

which represents the weighted harmonic mean of the conductivity of constituent materials.

and $$Y = V_F + X(1-V_F) \qquad (8\text{-}C)$$

which represents the weighted arithmetic mean of k_F and k_M

also $$Y = X^{(1-V_F)} \qquad (9\text{-}C)$$

represents the weighted geometric mean of k_F and k_M

Ziebland showed that an examination of equations (7-C) and (8-C) for the two extreme distributions of the matrix materials resulted in

$$\frac{dY}{dX} = \frac{dk_c}{dk_M} = (1 - V_F)\ X = 1 \qquad (10\text{-}C)$$

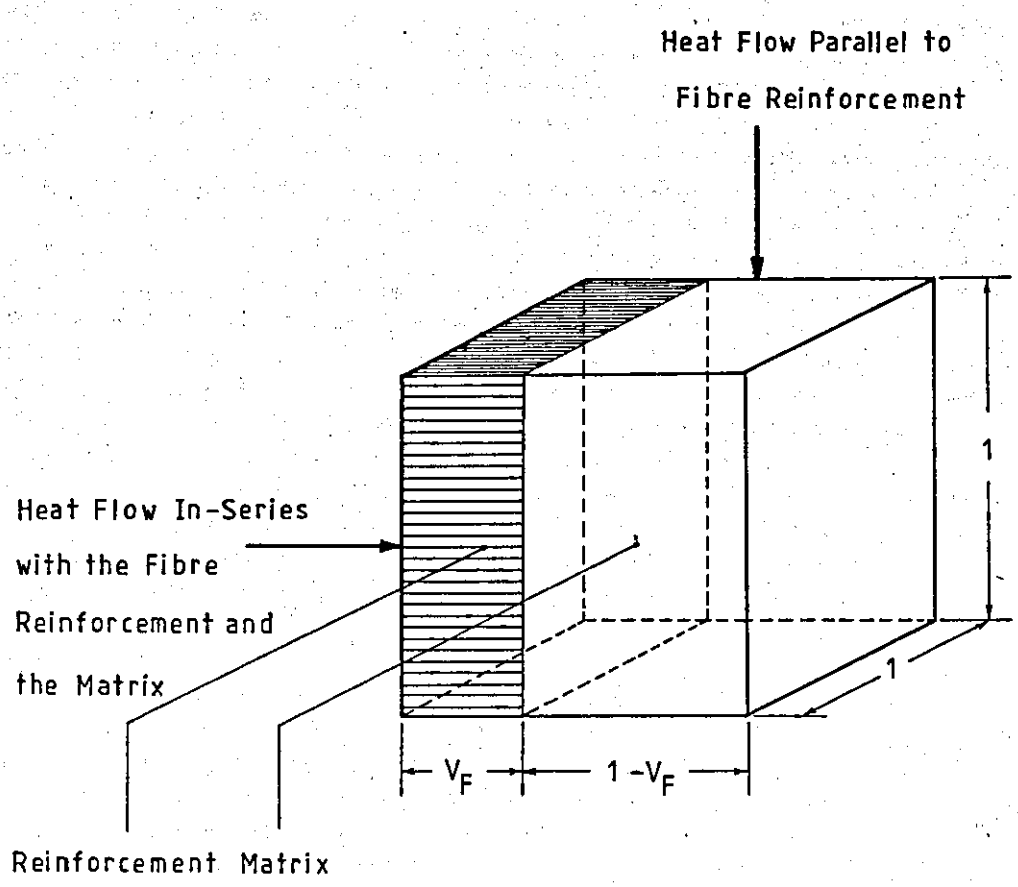


Figure 2.2.3.(1) , Model (1)

Unit Cube Model of Heat Flow through a Composite Laminate[60].

and if this relationship satisfies the conditions for maximum and minimum conductivity, any conductivity relation for other fibre distribution ϕ (D) will satisfy it.

Differentation of (3-C) with respect to X confirmed that the condition expressed by (10-C) had been fulfilled.

Also by substituting the limiting values of $V_F = 1$ and $V_F = 0$ in equation (3-C) the result is $k_c = k_F$, and $k_c = k_M$ respectively which agrees very well with the assumptions.

The same equations (1-C), (2-C) and (3-C) have been used[61] to predict the thermal conductivities of granular materials composed of two phases solid and fluid. The assumptions used in deriving them were the same as those used in deriving the first model for fibre reinforced composites.

The second model considers a unit volume cube of laminate, composed of a matrix and fibre reinforcement. The analysis of this model was given by Knappe and Martinez - Freire[74,75], by grouping the fibre reinforcement into two prisms having square cross sections and corresponding to the warp and weft directions. The model is shown in Figure 2.2.3. (2).

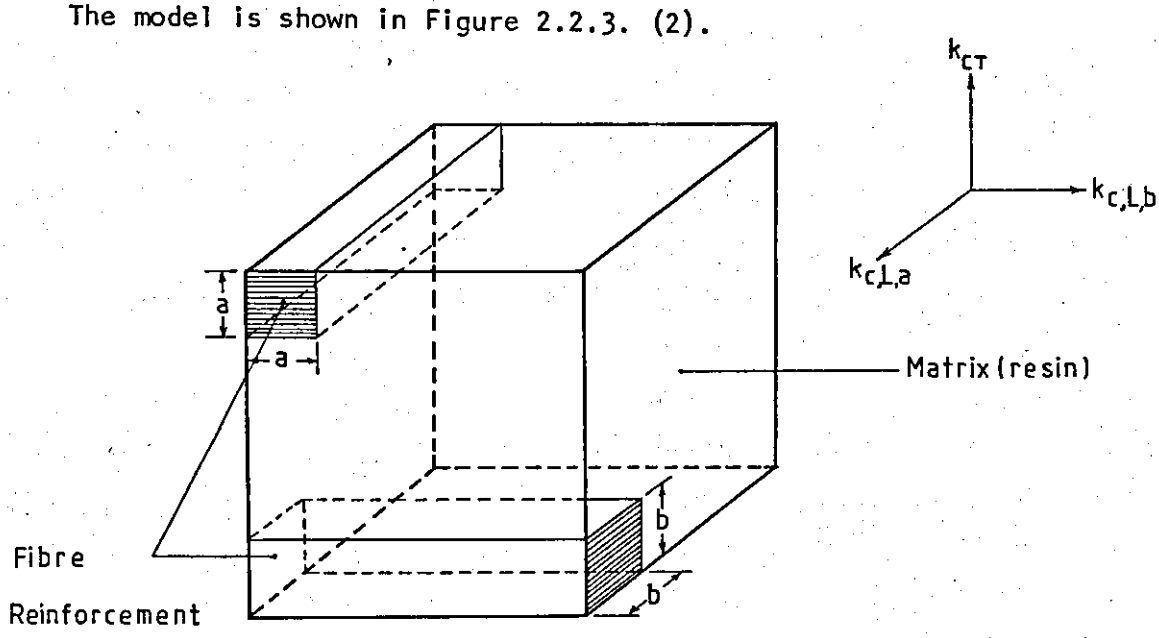


Figure 2.2.3.(2), Model (2)

Unit Cube Model of Heat Flow through a Composite Laminate in which the Fibre Reinforcement are arranged to the Warp and Weft directions.

The thermal conductivities of the composite were determined in three directions along a, b and transversly by dividing the model into a series of prismatic sections connected in parallel as resistances. The conductivity in the transverse direction is given by:

$$k_c = \frac{ab}{\frac{a+b}{k_F} + \frac{1-(a+b)}{k_F}} + \frac{b\ (1-a)}{\frac{b}{k_F} + \frac{1-b}{k_M}} + \frac{a\ (1-b)}{\frac{a}{k_F} + \frac{1-a}{k_M}}$$

$$+ (1-a)\ (1-b)\ k_M \qquad (11\text{-}C)$$

where a and b are the sides of the square cross-section prisms in each direction. By equating the thermal conductivity of fibres to that of matrix, the validity of equation (11-C) have been proved, i.e. when $k_F = k_M$, $k_c = k_M$ in the above equation.

The third model has been introduced by Wyllie and Southwick[76] for calculating the electrical conductivity of a medium of conductive particles saturated with a conducting electrolyte. the thermal conductivity of a composite model combining the series and parallel distributions and analogous to the above system was given by the following equation:

$$k_c = \frac{a\ k_F\ k_M}{k_F\ (1-d) + d\ k_M} + b\ k_F + c\ k_M \qquad (12\text{-}C)$$

where $(a + b + c) = 1$, when $k_F = k_M$

and $(ad + b) = 1 - V_F$

The quantities of a, b, c and d were calculated by assuming the

limiting values of k_F and k_M.

The fourth model has been introduced by Maxwell for calculating the electrical conductivity of a composite, Eucken[77] applied it to the calculation of the thermal conductivity of a granular material in which the fluid (air) forms the continuous phase. This was given by

$$\frac{k_c}{k_F} = \frac{1+2\ (1-V_F)}{1-(1-V_F)} \quad \frac{[(1-k_F/k_M)\ /\ (1+2\ k_F/k_M)]}{[(1-k_F/k_M)\ /\ (1+2\ k_F/k_M)]} \qquad (13\text{-}C)$$

in which k_c, k_F, and k_M represent the thermal conductivities of the composite medium, the fluid phase (air) and solid (matrix) respectively, with V_F the volume fraction of fluid (air), or porosity. Equation (13-C) have been applied to a cellular porous material by interchanging k_F and k_M, and putting $V_F = 1 - V_F$.

The fifth model was based on the results of Maxwell's dilute dispersion equation and was proposed by Lichteneker[78] to be valid for a two phase composite material of any geometry. The relation have been given by:

$$[\ V_F\ (k_F-k_c)/(k_F+f\ k_c)\ ] + [\ V_M\ (k_M-k_c)/(k_M+f\ k_c)\ ] = o \qquad (14\text{-}C)$$

in which f = a specific structural factor and is identical to ϕ(D)

When f = o, equation (1-C) the in-series solution result.

When f = ∞, equation (2-C) the in-parallel solution result.

2.3. Aims and Justification of the Present Work

At this time , the cost of cooling down or heating up of homes, schools, factories and offices is rising steadily. This trend is most likely to continue as the energy available to us from the traditional sources, i.e. the fossil fuels is being rapidly exhausted, and what used to be called the easy oil era[79] has elapsed. A great deal of effort has been made to remedy the situation and suggestions have been introduced and discussed in many recent publications (references 79 to 82), papers and articles[83, 84] concerning building for energy conservation. They recommended active research to develop other alternative sources of energy such as solar power, to replace the fossil fuels and also to reduce the present energy consumption by improving the features of thermal design of buildings, and naturally controlling their enclosed spaces. This requires introducing new thermal insulating materials and a better understanding of the thermal behaviour of a structure.

The scope for proper building design to withstand the severe climatic conditions of the Middle East, especially Saudi Arabia, has been discussed in detail in Part 1. This was described clearly by outlining the many examples of traditional techniques employed in the proper selection of site, materials, space utilization and the type of construction which resulted in higher comfort levels.

During the last three to four decades, two main factors have helped in creating the present unsuitable buildings in which none of the traditional techniques have been used. These are firstly the introduction of completely new building materials usch as concrete and cement blocks, coupled with imported western style construction. Houses have been built

with reinforced concrete skeletons and with roof thicknesses not exceeding 0.12 to 0.15 m. Walls were non-load bearing with a minimal thickness and no insulation. The second factor is the introduction of air-conditioning equipment and refrigeration systems to maintain the comfort requirements. Hence the valuable aspects of the old traditional technology have been neglected and forgotten.

Air-conditioning and heating equipment are energy consuming, and the evaporative (desert) coolers are water consuming, in an arid land. The traditional materials described in Part1, are unsuitable because of their expense and the longer time it takes to build with them. Some traditional solutions to thermal comfort such as compact houses with narrow streets and alley-ways are difficult to apply, since they restrict the free flow of modern transport and services.

The aims here are to find solutions to some of the above problems by investigating more suitable insulating materials. The practical use of cellular plastic as an insulation material in conjunction with the present cement block walls and concrete roofs is investigated. This is to replace the thick walls used in traditional houses, thus increasing the space and maintaining the same comfort levels. Methods of measuring thermal conductivities of both homogeneous and composite materials are investigated in the experimental study.

2.4. Experimental Detail

2.4.1. Sample Preparation

Three types of materials were used for thermal conductivity investigations, namely "Thermalite" aerated cement blocks[85], extruded polystyrene "Styrofoam" insulation[86], and a combination of the two as a composite material. The diameter of the samples required for the thermal conductivity measurement was 152 mm. Two samples in all were required for each test. They were made to be identical geometrically and in the same physical state, and of such size as to completely cover the heating unit surfaces. Cold plates were designed to cover completely the other sides of the samples. The samples were made to meet conditions stated in the standard test methods BS : 874[56] and ASTM C177-76[58], which includes the following:

- The portion of the sample over the test area must be typical of the whole sample in every aspect.
- The remainder of the sample must not, on average, distort the heat flow in that part of the sample adjacent to the metering area.
- The sample must be free of low thermal resistance paths that create thermal short circuits between the test surfaces.
- The heat flux throught the samples must be directly proportional to the temperature difference across the samples.
- The surfaces of the test samples shall be made plane by appropriate means so that intimate contact between

the samples and the plates can be effected.

"Thermalite" samples were obtained from standard "Thermalite" solid blocks which were about 440 x 215 mm and 100 mm thick. This was done initially by cutting each block into two equal halves, across its longitudinal dimension using a band saw. Then each half was cut into two, three, or four slices across the 100 mm thick side. Each slice was then planed roughly using a metal hand file, and by rubbing surfaces with each another, until an approximate thickness was obtained. This was nearly 6 mm more than the actual thickness required. Using a compass, a cricle whose diameter was 156 mm was drawn on each slice, and a circular plate was produced by cutting over the marked circle using a jig saw.

The flatness of the sample surfaces is the most significant factor in the accuracy of measurement. This is because the samples should be in complete contact with the high conductivity heating unit and cold plates over the entire surface area. If this is not achieved, air gaps between the samples and the plates will give incorrect values of thermal conductivity, according to the extent and thickness of the air layers.

The solution was to cut the surfaces and make them parallel by face-cutting in a lathe. The deviation from flatness should not exceed 0.2 mm[56] or 0.025% and the faces shall be parallel over the total surface area to within 1% of the sample thickness[58].

The extent of the deviation across the full area was judged by a straight edge and feeler gauge[57], and all the projecting

granules were removed.

The ratio between the dimensions perpendicular and parallel to the direction of heat flow should average 6 to 1[87], and for the purpose of this research a wide range of ratios were used as indicated in table 2.4.1.-1. In all, six different thicknesses were used, with maximum thickness of 41.6 mm and minimum of 16.8 mm.

Extruded polystyrene samples were obtained from board sizes 2438 x 600 mm for 20 mm thickness and 2438 x 622 mm for 50, 75 and 100 mm thicknesses. The commercial name for it is "Styrofoam" 1 B permanent building insulation. Initially circles of 154 mm diameter were marked by a compass. Circular samples were cut easily using the jig saw, which produced circular plate samples of 152 mm diameter. The samples were not compressed in any way so as to cause any air gaps or variations across the surface area, and the thickness was measured at six places by means of vernier callipers reading to 0.01 mm and the mean recorded. Any samples with more than 0.15 mm variation in thickness were replaced.

Three different thicknesses of foam were used, and the thicker range of samples were excluded because of the difficulties in assembling them for the test. Samples used are shown in Table 2.4.1.-1.

Composite samples were obtained by using "Thermalite" and extruded polystyrene samples.

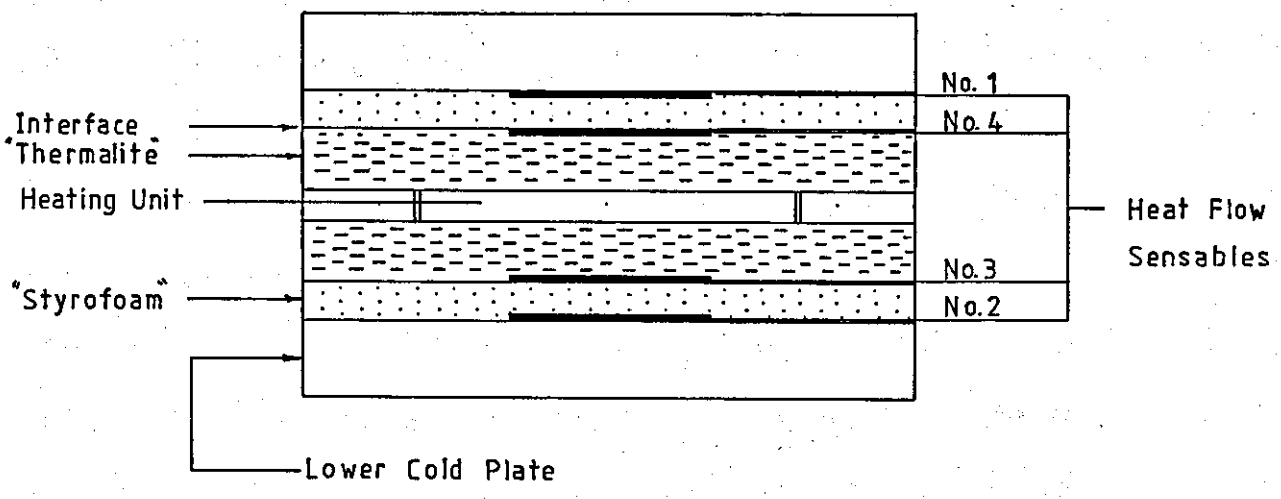
In terms of the theoretical models described in Section 2.2.3.3. the "Thermalite" samples were equivalent to the matrix and polystyrene foam samples were equivalent to the secondary phase or fibre content. The general conditions of sample preparation mentioned before were met. For the heat flow measurements, a 2-in (50 mm) square area was marked in the centre of the test samples. The square area was then engraved to a depth of 3.5 mm (using hand tools in the case of the "Thermalite" sample). A heat flow sensable was fixed in this engraved square area, using cement powder and "Sellotape" to prevent any air bubbles, so that its surface was exactly at the same level as that of the sample. In the case of the extruded polystyrene sample, the square groove was made by pressing a pre-heated (200°C) stainless steel 2-in (50 mm) square shaped plate into the sample for a very short time to cause an impression 3.5 mm deep. This enabled the heat flow sensable to be fitted without affecting the physical characteristics of the sample. The sensable was also fixed in place with "Sellotape". The surface of the heat flow sensable in the "Thermalite" sample formed part of the interface of the composite laminate and no air gaps were permitted. The surface of the foam sample containing the heat flow sensable was in direct contact with the cold plate. The arrangement of the composite samples is shown in Figure 2.4.1. Several combinations of "Thermalite" (matrix or primary phase) and polystyrene (or secondary phase) were prepared and tested as indicated in Table 2.4.1.-1. The thickness of each sample was measured at six places by means of Vernier callipers in the same way as for the other samples.

Table 2.4.1.-1. indicates the three types of samples: Thermalite ST, Extruded Polystyrene SP, and Composite SC, their numbers, thicknesses L, and ratio between the dimensions perpendicular and parallel to the direction of the heat flow R.

Table 2.4.1-1.

Sample	Thickness, L in m	Ratio , R Diameter/Thickness
"Thermalite"		
ST 1	4.16×10^{-2}	3.65 to 1
ST 2	3.20×10^{-2}	4.75 to 1
ST 3	2.60×10^{-2}	5.85 to 1
ST 4	2.34×10^{-2}	6.50 to 1
ST 5	2.12×10^{-2}	7.17 to 1
ST 6	1.68×10^{-2}	9.05 to 1
ST6x2	$2 \times 1.68 \times 10^{-2}$	4.52 to 1
"Styrofoam"		
SP 1	5.05×10^{-2}	3 to 1
SP 2	$2 \times 2.07 \times 10^{-2}$	3.67 to 1
SP 3	2.05×10^{-2}	7.41 to 1
"Composite Laminate"		
SC 1	5.26×10^{-2}	2.89 to 1
SC 2	4.40×10^{-2}	3.45 to 1
SC 3	3.74×10^{-2}	4.06 to 1
SC 4	6.48×10^{-2}	2.35 to 1

Figure, 2.4.1



Composite Sample , and Heat Flow Sensables Arrangement

2.4.2. Sample Characterization

Thermalite samples were taken from standard "Thermalite" aerated concrete building blocks. The work face dimensions of each block were 440 x 215 mm and 100 mm thick. The basic ingredients of the blocks were cement, graded sand and pulverised fuel ash from power stations. During manufacture, aluminium powder in suspension, water and a dispersing agent are added to the basic materials. They are thoroughly mixed and the mixture is then poured into moulds which vary in size between 0.77 and 3.5 m^3, depending upon the factory. The moulds are partially filled and are then placed in rising and stiffening chambers. It is at this stage that the aluminium powder reacts with the free lime in the cement to release hydrogen which is quickly replaced by air and which provides the aeration, resulting in a light micro-cellular structure. After cutting into various block sizes, the material is transported to high pressure steam autoclaves where it is cured, rendering the finished product physically and chemically stable. The total manufacturing and curing process takes approximately 24 hours. The properties of the blocks from which the samples were obtained by cutting were given by the manufacturer and are listed in Table 2.4.2.-1[85]. The blocks were left for three months in the laboratory at an ambient temperature of 18 to 22°C. Samples were then prepared as previously described , and the thickness of each sample measured at six places by means of Vernier callipers reading to 0.01 mm, and the mean recorded, prior to the test.

All samples were conditioned to a constant mass in a ventilated oven at an average temperature of 20°C. Their mass

was determined both before and after the conditioning and the percentage loss was calculated. The samples were placed promptly in the apparatus, and care was taken to prevent any loss of material or any moisture gain. Proper insulation such as loose-fill cork granules were placed in a box surrounding both the apparatus and samples to prevent heat losses from their outer edges and also to stop any moisture condensation on the cold plates. The mean ambient temperature during the test was recorded for the purpose of correcting the hot and cold face temperatures of the samples. The moisture content of the samples at the time of the test was calculated as well as their dry density according to B.S: 874[56] and ASTM C 177 - 76 [58]. This was done by measurements made at the end of the test under conditions of test-temperature equilibrium and after drying the samples in an oven at 110°C for 24 hours. The samples were then cooled in a desiccator over P_2O_5, in a constant temperature room (20 ± 0.5°C), and their dry density was calculated.

All samples tested were subjected to 24 hours constant heat flux and measurements were taken every half an hour for the first four hours, then every hour for another eight hours, and a final reading after 24 hours.

Extruded polystyrene samples were prepared as before from "Styrofoam" IB board thermal insulation. This is a closed cell polystyrene foam manufactured by an extrusion process developed by the Dow Chemical Company[86]. It is light blue in colour, and its physical and mechanical properties are given by the manufacturer and reproduced in Table 2.4.2.-2.

The thickness of each sample was measured at six places using Vernier callipers reading to 0.01 mm, and the mean recorded. All samples were conditioned prior to the test to a constant mass. This was achieved by placing them in a ventilated oven with an average temperature of 20°C for at least 16 hours. The percentage loss in mass was calculated, from the masses before and after conditioning.

The same procedure was followed as in case of the "Thermalite" samples. Directly after the end of the test, the moisture contents of the samples were determined as well as their thickness at six points.

Absolute dry density was difficult to determine, because the samples would melt when in prolonged direct contact with high temperature heat sources (110°C). The maximum recommended continuous temperature by the manufacturer is (75°C). For this reason the heat flux produced by the heating unit, was kept to well below this temperature.

The same conditioning methods were applied for the composite samples. Since the "steady state" condition was not reached quickly within the first six hours, the test was run for 36 hours. Ambient temperature was recorded during the test for the purpose of calculating accurately the hot and cold face temperatures of the composite samples. The interface temperature was measured by the built-in thermocouples incorporated with the heat flow sensables.

Table 2.4.2.-1.[85]

Physical and Mechanical Properties of "Thermalite" Standard Blocks, which complies with BS 2028, 1364 : 1968

Physical and Mechanical Properties	Values
Density (dry)	730 kg/m^3
Thermal coefficient of linear expn.	8.1×10^{-6} per ^oC
Specific heat capacity	1.05 KJ/kg^oC (between 20 to 100^oC)
Thermal conductivity (k value)	0.21 W/mK at 3% moisture content by volume in accordance with BRE best fit curve.
Measured 'k' value	0.184 W/mK at 3% moisture content by volume
Compressive strength	3.5 N/mm^2 in accordance with BS 2028, 1364 : 1968, Precast concrete blocks, Appendix C.
Combustibility	Non-combustible (BS 476)
Modulus of elasticity	2.8×10^3 N/mm^2
Vapour resistivity	Mean = 56 MN s/gm

Table 2.4.2.-2.[86]

Physical and Mechanical Properties of "Styrofoam" IB

Physical and Mechanical Properties	Value
Density	28 kg/m^3
Thermal coefficient of linear expansion	7.0×10^{-5} m/m ^oC
Thermal conductivity 'k' value at 10^oC mean temperature	0.034 W/mK
Compressive strength at 5% compression	0.25 MN/m^2
Water absorption	0.05% Volume
Capillarity	None
Water vapour permeability	7 micro g m/Nh
Fire rating	Combustible, if subject to an intense fire source, it may be burn rapidly, releasing dense smoke. So it should be covered with 13 mm plaster or plasterboard.

2.4.3. Thermal Conductivity Measurements

2.4.3.1. Apparatus

2.4.3.1-1 General

The general arrangement of the equipment as a whole is shown schematically in Figures 2.4.3. (1) and 2.4.3.(2). It consisted of an experimental box containing a pair of identical samples of such size as to completely cover the heating unit surfaces on both sides. These were held together by two cold plates kept at the same temperature by a constant temperature fluid, and with the same surface dimensions as that of the heating unit. Each face of the heating unit was fitted with thermocouples which set in grooves. The same number of thermocouples were permanently and similarly placed at corresponding positions in the facing cold plates.

The experimental box was filled with loose-fill material to reduce heat losses from the outer edges of the heating unit and the specimens, and to prevent water condensation at the cold plates.

The general design of the equipment was based on the general guide lines set out in the revised BS 874[56,57] and on ASTM, Standard method of test C 177-76[58].

2.4.3.1.-2 Heating Unit:

The heating unit was a round plate consisting of a central section and a guard section. The central section consisted of a central heater and central surface plates. The guard section

consisted of a guard heater and guard surface plates. The surface plates were made of copper which has a high thermal conductivity. The working surfaces were smoothly finished to a true plane. The two faces of the heating unit were substantially at the same uniform temperature. The heating unit had a gap of 2.5 mm between the central surface plates and the guard surface plates.

The test area was calculated by taking measurements to the centres of the separations that surrounded the central heater. The resistance of the heating unit and both the central section and guard section are shown in Figures 2.4.3. (3), 2.4.3. (4) and 2.4.3. (5) respectively. The overall dimensions of the heater are shown in Figure 2.4.3. (6).

2.4.3.1.-3. Power Supply Unit

The heating unit was heated by using a stabilized power supply unit. This unit could be operated as either a constant voltage or constant current supply, the mode being selected by a simple link. The output level was monitored precisely on two large clear meters which were switched to read both voltage and current at the same time. Separate switching of the mains input and direct current (D.C.) output was provided enabling the supply to be adjusted in circuit and left in 'stand-by' prior to supplying the load thus providing the best possible regulation without delay caused by a warm-up period. Protection against over-load and short circuit was by adjustable current limiting and adjustable over-voltage protection. The output of this unit was

as follows;

Voltage	0 - 30 Volts
Current	0 - 5 Amperes

For dimensions and specification of this unit see Appendix A .

2.4.3.1.-4. Cooling Unit

This consisted of two circular plates. The units (heat sinks)were fabricated from copper which has high thermal conductivity and were smoothly finished to a true plane. They had surface dimensions the same as those of the heating unit including the guard heater. Thermostated, refrigerated water (with anti-freeze) was circulated through a labyrinth of channels in each sink to maintain a uniform temperature lower than that of the heating unit. The water supply to both heat sinks came from a tank equipped with a pump, so that the pressure of the water circulating through the apparatus was kept constant and a steady flow-rate was obtained. All air bubbles were flushed out of the sinks by keeping the pump fully immersed under the water level inside the tank. The overall dimensions of the cold plates are shown in Figure 2.4.3.(7).

2.4.3.1.-5. Sensable Heat Flow Sensors

The sensable [88] was wafer-thin and generated its own millivolt output signal that was proportional to the amount of heat flowing through the gauge at that time. It was sensitive to all types of heat transfer. The best operation of these instruments was obtained when they were firmly attached to the surface under measurement. For the experiment where convective heat transfer measurements were being made, it was permissible to tape the instrument to the sample surface by means of "Sellotape" These instruments were calibrated and assigend a sensitivity value in terms of millivolts/BTU/ft^2-hr. Four units (each 50mm x 50mm) were located between the identical composite samples and the heat flow was recorded using a precise heat flow digital sensimeter as shown in Figure 2.4.3. (2).

2.4.3.1.-6. Measurement of Temperatures

Thermocouples were used for the purpose of measuring temperatures, with connections arranged so that they were read as a differentially connected thermopile. These thermocouples were type T (copper-constantan) with three wire sizes [89], number 28 AWG (American Wire Gauge) [90] (0.321 mm) for the sensable heat flow sensors, number 24 SWG (0.559 mm) for the hot plate and number 16 SWG (1.62 mm) for both upper and lower cold plates.

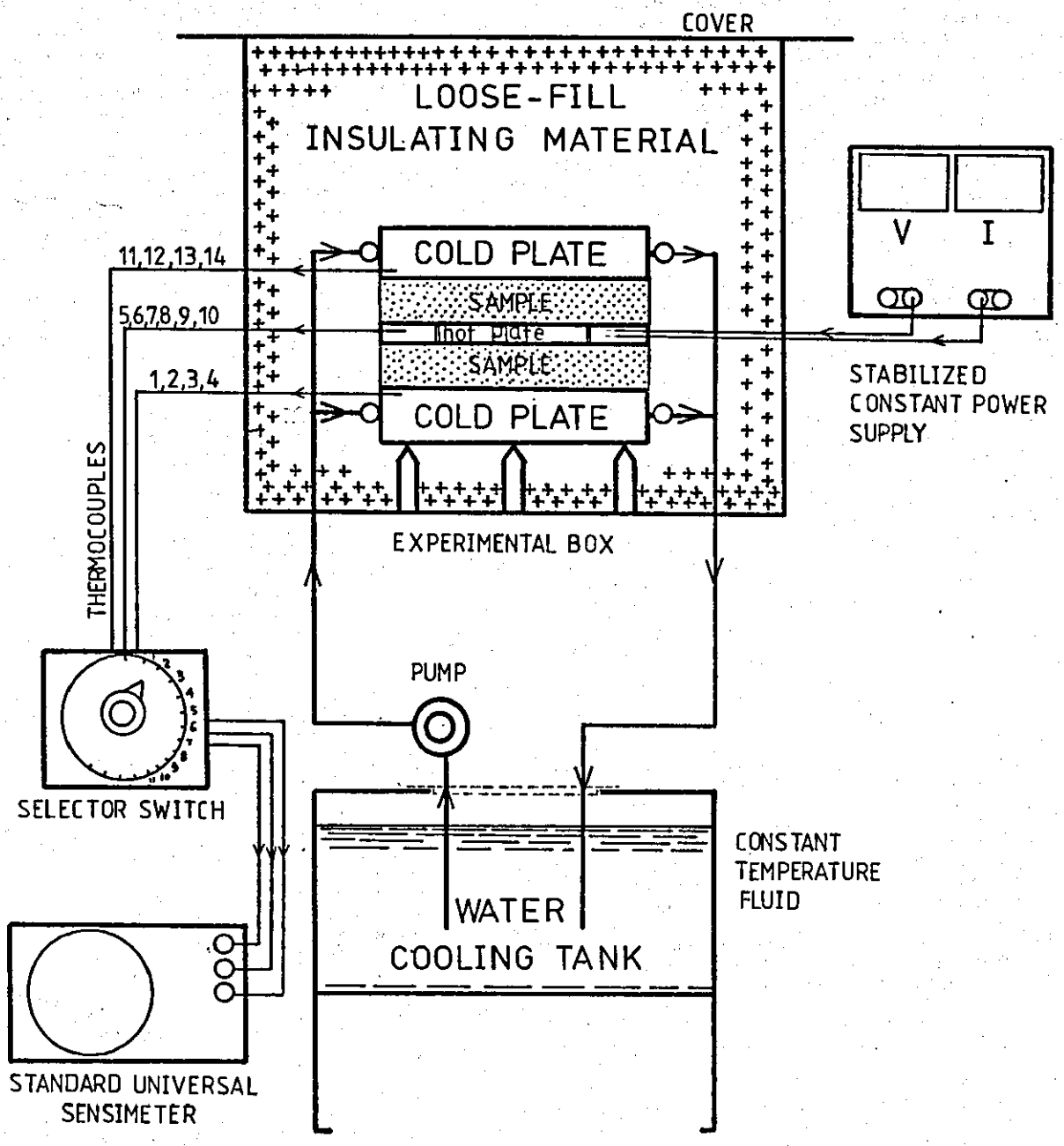
For measuring the surface temperature of the central section of the heating unit, the central surface plates were

were provided with (6) thermocouples set in grooves. There were (4) thermocouples permanently and similarly installed at corresponding positions in each of the facing upper and lower cold plates. Thermocouples were connected to a measuring system controlled by a selector switch to read between 1 and 14.

The heat flow sensors with their built-in thermocouples were used to determine the temperatures between the composite materials. These thermocouples were also connected to another measuring system controlled by a selector switch reading from 1' to 4'. Heat flow measurements were recorded at the same time by using a digital sensimeter which read directly in Watts/cm^2.

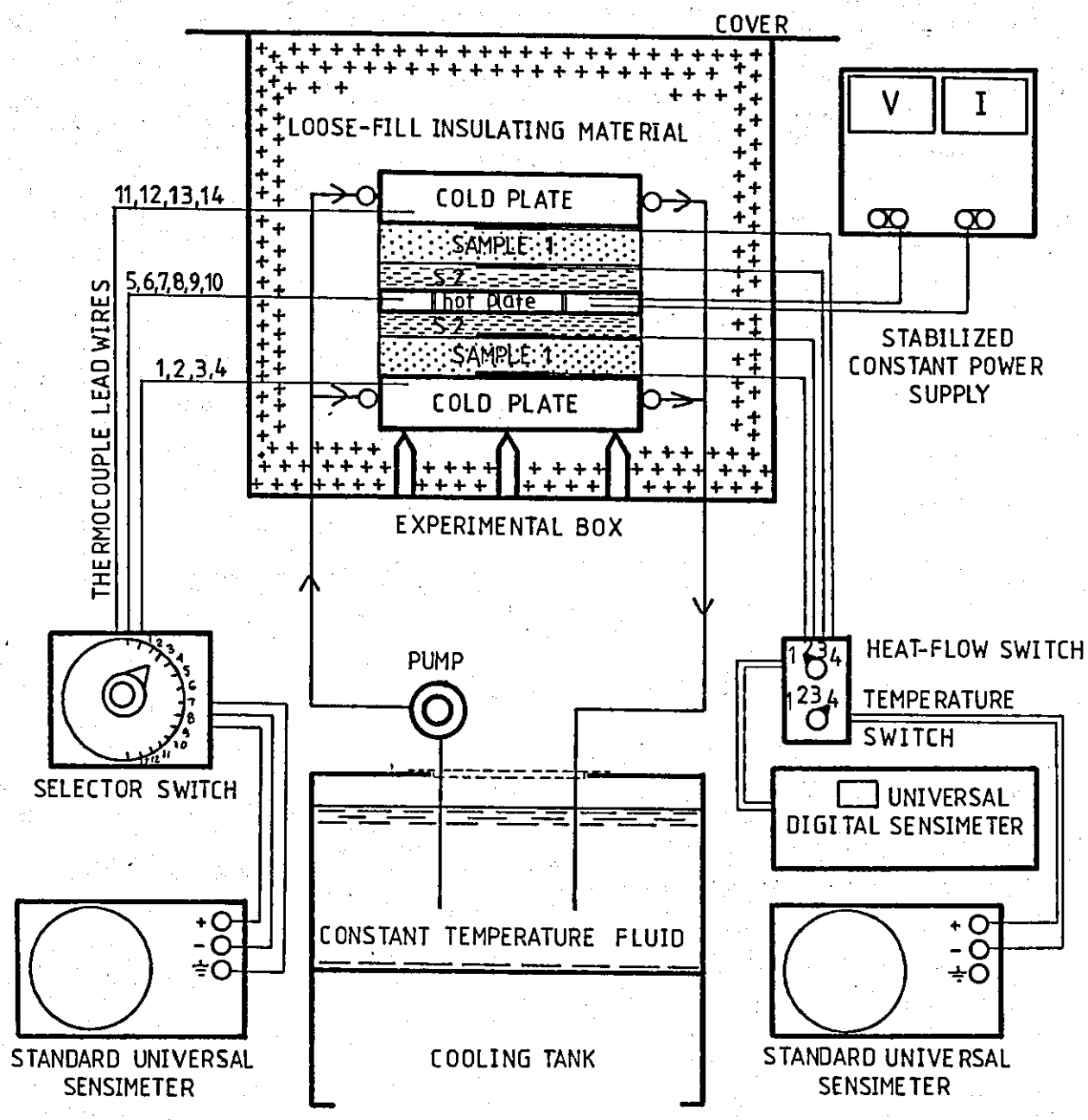
The reference junction of the thermocouples given at 0^oC [91] was corrected for the recorded ambient temperature during the test.

FIGURE, 2.4.3.(1)



EXPERIMENTAL ARRANGEMENTS FOR TESTING HOMOGENEOUS MATERIALS

FIGURE, 2.4.3.(2)



EXPERIMENTAL ARRANGEMENTS FOR TESTING COMPOSITE MATERIALS

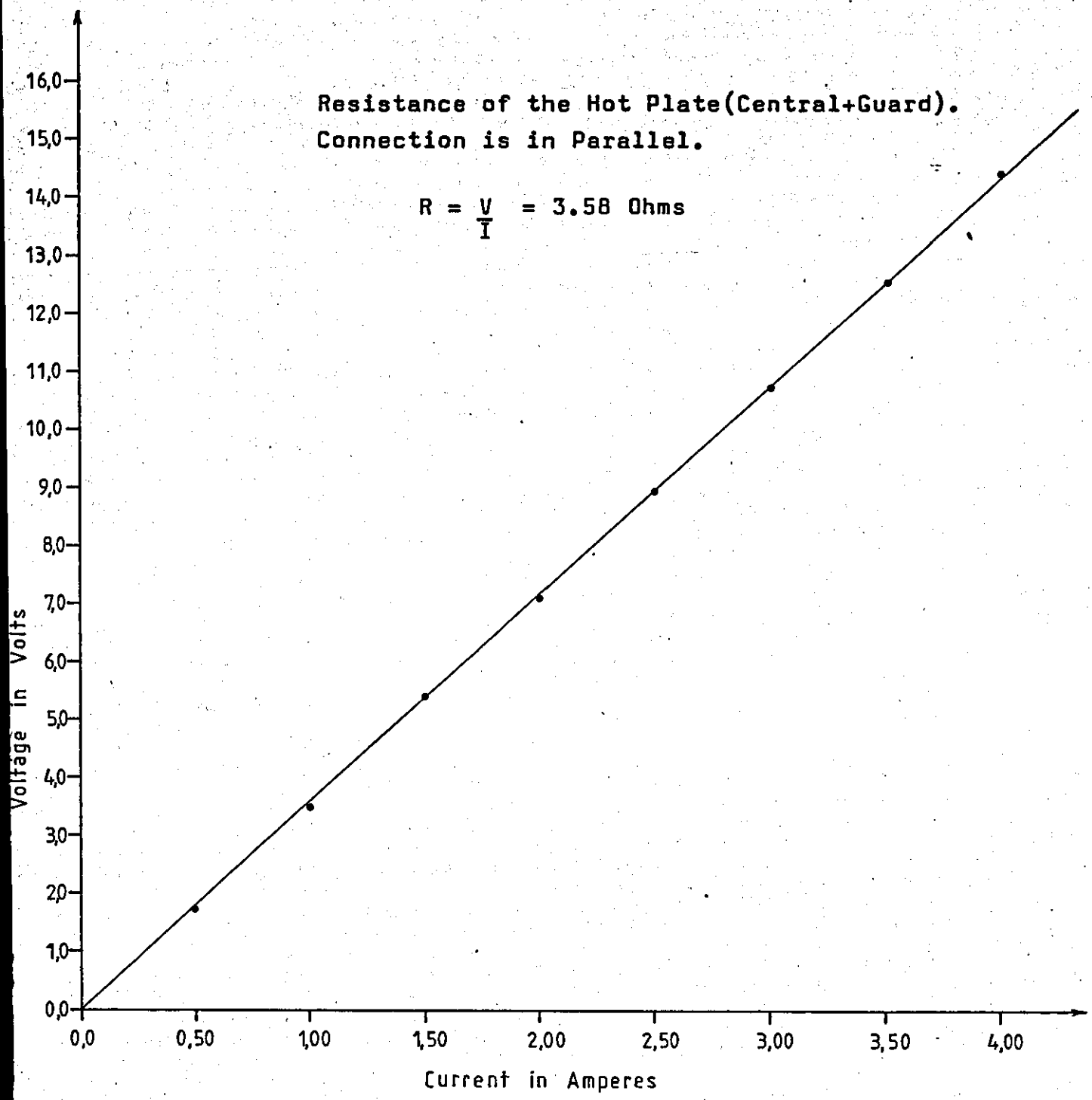


Figure 2.4.3.(3) Resistance of the Heating Unit ; Voltage Vs. the corresponding Current.

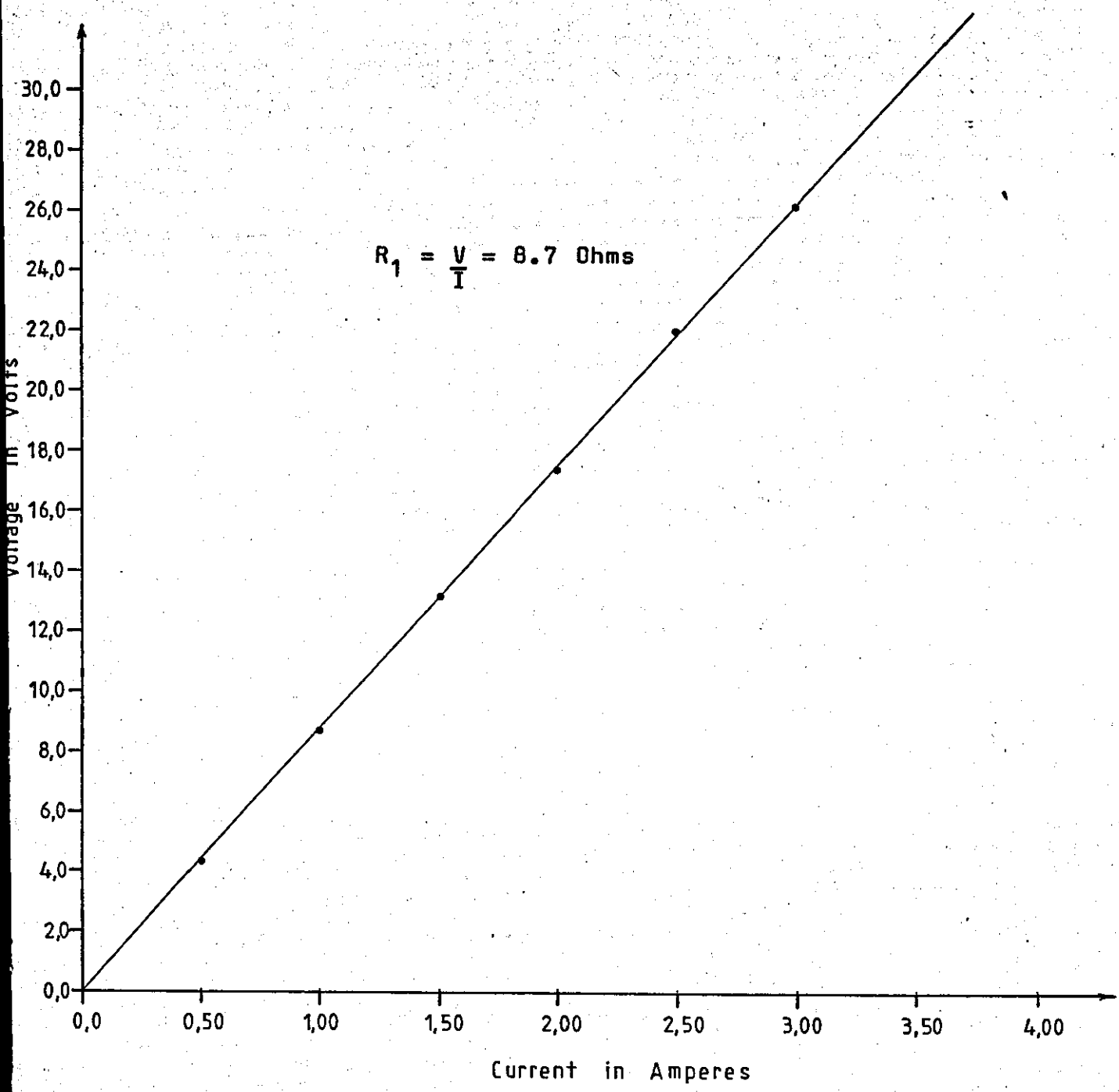


Figure 2.4.3.(4) Resistance of the Central Hot Plate ; Voltage Vs. the corresponding Current.

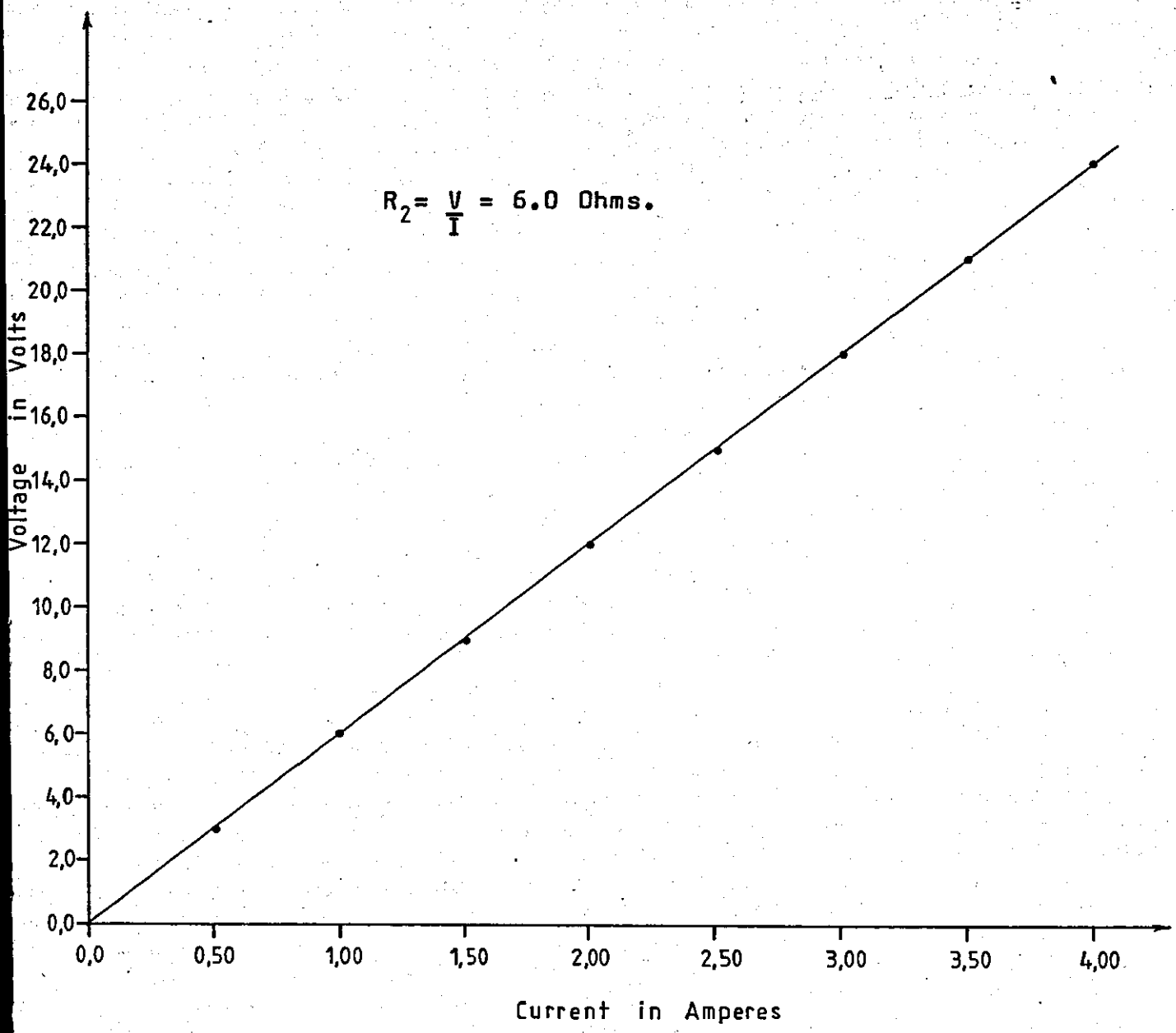


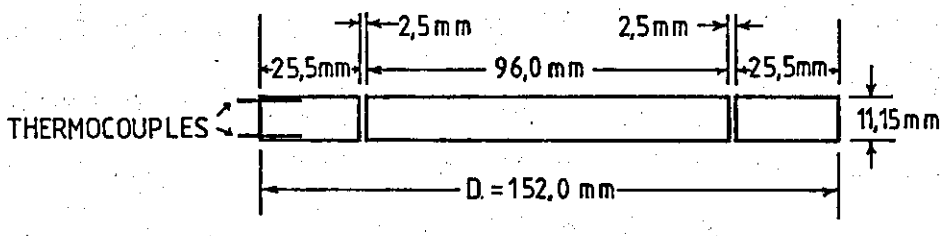
Figure 2.4.3.(5) Resistance of the External Guard Plate(Ring) ; Voltage Vs. the corresponding Current.

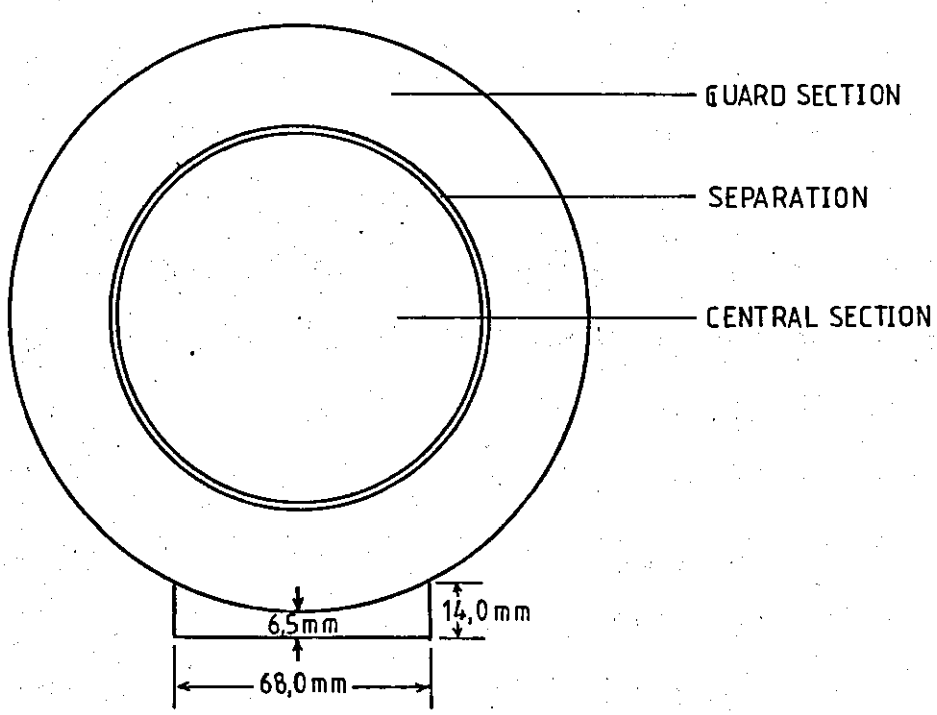
FIGURE 2.4.3.(6)

OVERALL DIMENSIONS OF THE HEATING UNIT

THERMOCOUPLES USED ARE TYPE : T, COPPER-CONSTANTAN,

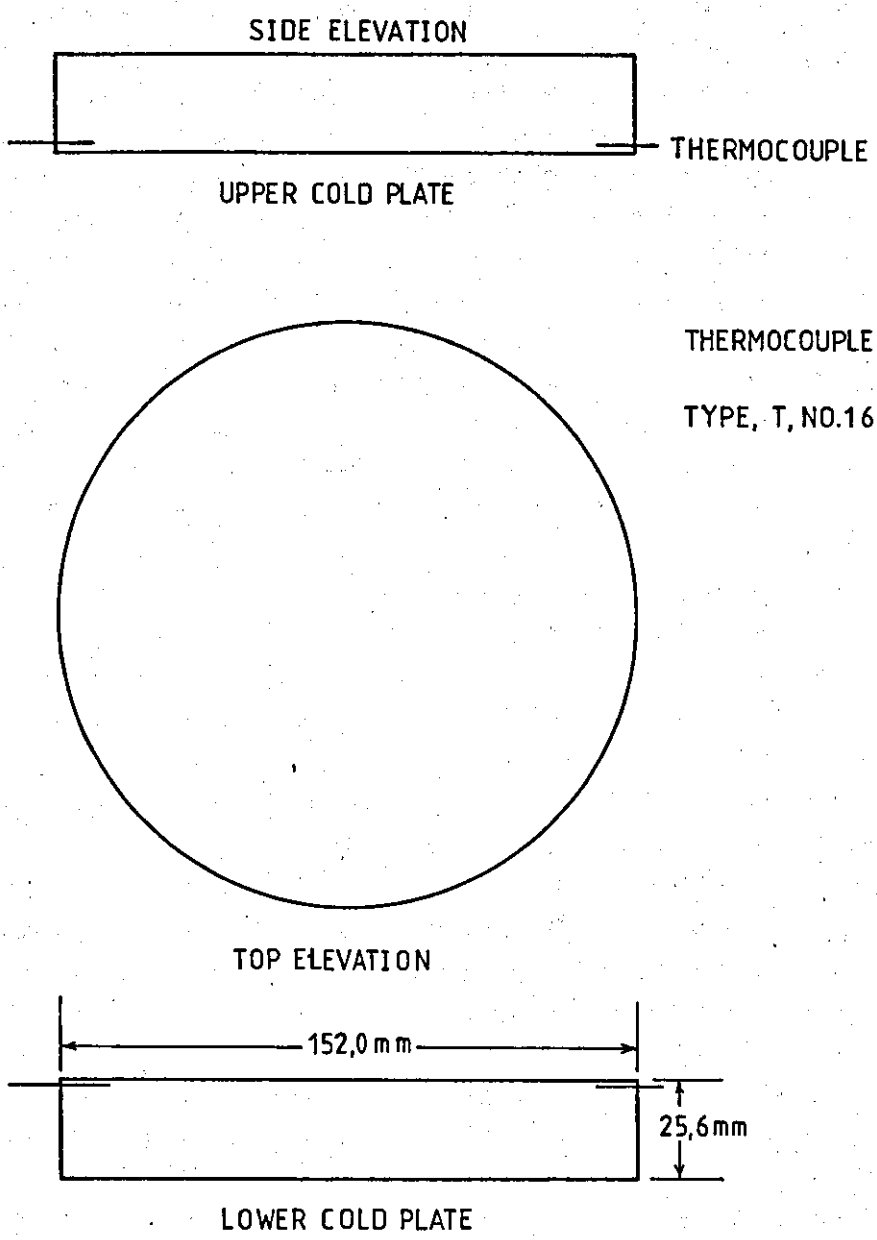
NO. 24 SWG (0.559 mm).





FIGURE, 2.4.3.(7)

OVERALL DIMENSIONS OF THE COLD PLATES



2.4.3.2. Testing Procedure

(I) Testing Homogeneous Materials

The sketch plan, Figure 2.4.3. (1), indicates the experimental arrangements for the test.

I.1 Preparation

I.1.1. Prepare two identical samples and insert each of them between the hot plate and cold plates.

I.1.2. Fill the surrounding experimental box with loose-fill insulating material, and cover the box.

I.1.3. Fill the cooling tank with water and anti-freeze liquid (1:1) till the fluid level covers both the inlet and the outlet of the centrifugal pump.

I.1.4. Connect the output of the "Stabilized Constant Power Supply" unit with the heating unit (hot plate) leads.

I.1.5. Attach the "Main Selector Switch" leads to the binding posts of the "Standard Universal Sensimeter", see Figure 2.4.3.2. (1).

I.1.6. Set the "Range Full Scale" dial to the millivolt input required for full scale meter reading (if full scale is to read up to 5.00 mV, set dial at 5).

I.1.7. Turn 'Function' pointer knob to "0" adjust setting. Turn the '0 Adjust' knob for a zero reading on the indicator.

I.1.8. Turn 'Function' pointer knob to "F.S." adjust setting. Turn the 'Full Scale Adjust' knob for a full scale reading on the indicator.

Notes:

i. When the 'Range Full Scale' knob is changed always check zero and full scale and adjust if necessary.

ii. 'Full Scale Adjust' should be adjusted once a day and/or after each change in range setting.

I.2. Testing

I.2.1. With the mains supply connected to the 'Cooling Tank', "Mains" and "Cooling" switches set to "On", both the pump and the refrigerator will start to circulate and cool the liquid in the tank and in the cooling plates.

I.2.2. With the mains supply connected to the 'Stabilized Power Supply' unit. "Input" and "Output" switches set to "On" and the output 'Voltage Adjust' controls set to maximum, set the "Current Limit" control to indicate the required current and reduce the 'Voltage' controls till the "Limit" (Red Light) just illuminates.

I.2.3. The ouput level can be monitored precisely on the two large clear meters which are switched to read both voltage and current at the same time.

I.2.4. At regular intervals, select the point you want to measure at the "Main Selector Switch" by turning the knob indicator towards the number on the switch (1 to 14). In the 'Standard Universal Sensimeter' turn 'Function' pointer knob to "Read" and read the indicator directly in the engineering units you are using (millivolts).

Each reading on the indicator corresponds to one selected point on the selector switch and gives the millivolts equivalent to temperatures on the cold and hot faces of the sample.

I.2.5. If 'Function' knob must be turned to "Reverse" to obtain a reading, this indicates reverse polarity on the input terminals.

I.2.6. After each set of readings, record the room temperature, and turn 'Function' pointer knob to off position.

I.2.7. Run the test, following the same procedure each time

I.2.8. Stop the test after 24 hours (readings are constant, when reaching the steady-state condition).

II Testing Composite Materials

The sketch plan, Figure 2.4.3. (2), indicates the experimental arrangements for the test.

II.1 Preparation

II.1.1 Prepare two identical composite samples, each composed of two layers.

II.1.2. Insert two heat flow 'Sensables' for each composite sample, one between the layers, and the other between the cold plate and the sample.

II.1.3. Follow the same steps 1.1.1. to 1.1.8. as for homogeneous samples.

II.1.4. Attach the 'Sensables Switch' leads to the 'Receptacle' on the rear of digital Sensimeter unit, and the built-in thermocouples leads to another 'Universal Sensimeter'

II.1.5. Connect the unit to the mains (115 volts A.C., 60 Hz power, converted with and adaptor).

II.1.6. Turn the power "On" and allow about 30 minutes for warm up.

II.1.7. Turn the 'Function' switch to '0 Adjust'. Adjust the '0' knob for a reading of 000 on the digital display.

II.1.8. Determine the mV output from the 'Sensable' at its full scale output (such as 445.18 mV at 500 BTU/Ft^2-hr)

II.1.9. Set the 'Gauge Factor' knob to show [4] 45

II.1.10 Turn the 'Function' switch to "F.S. Adj.", adjust the "F.S." knob for a 500 display on the digital display.

II.2. Testing

II.2.1. Follow the same steps as in 1.2.1 to 1.2.6.

II.2.2. Turn the 'Function' switch to "Read" in the 'Digital Sensimeter'.

II.2.3. Turn the 'Sensable Selector Switch' knob indicator towards the wanted number on the switch (1' to 4')

II.2.4. The digital display shall now show the measured heat flux directly in BTU/ft^2-hr - from the desired. heat flow sensable.

II.2.5. Follow steps 1.2.4. to 1.2.6. with the other 'Universal Sensimeter' to obtain the interfaces and cold plate temperatures.

II.2.6. Run the test, following the same procedure each time.

II.2.7. Stop the test after 36 hours, readings should cover the first and last 12 hour periods.

2.5. Results of The Experimental Study

2.5.1. Introduction

The standard apparatus for the determination of thermal conductivity 'k' has been described in Part 2.4. The essential features of this apparatus are shown schematically in Figures 2.4.3. (6) and 2.4.3. (7). When a "steady state" temperature equilibrium has been established across the test samples, "k" may be calculated from the power input to the test area, the area of the sample, the temperature difference between the hot and cold surfaces of the samples and their thickness. All the data has been recorded according to the Table HS for homogeneous materials, and Tables 1CS and 2CS for composite materials, which are shown in Appendix A1. The formula from which the thermal conductivity is calculated has been derived in Part 2.2. assuming that one dimensional heat flow occurs between the test area and the cold plates.

Errors due to heat losses at the edges of the samples and due to the temperature difference between the test area and guard ring have been discussed by many authors such as Woodside [95], Pratt[96] and Siu[97]. To eliminate errors arising from the temperature differences between the test area and guard ring, the guard ring was maintained at the same temperature as the test area so that no heat exchange could occur between the two. Another source of error [98] arises from measuring the temperature of the samples, indirectly by using sensors built into the surfaces of both hot and cold plates. These errors were considered to be

negligible for the series of tests conducted. The greatest source of error for a given material involves the heat loss from the edges. This can be determined by testing a few sets of samples of the same material, identical except for their thickness. The true thermal conductivity of the samples can then be found using these measurements. The values of thermal conductivity obtained under constant conditions are stated in Figures 2.5.3.— 1 to 2.5.3.— 14 and Figures 2.5.4.— 1 to 2.5.4.— 11.

2.5.2. Operating Conditions

The ambient temperature of the laboratory was recorded, and at time t = o, the test was started by switching on the heating unit and the refrigerator. The variation in the temperatures on both the hot and cold sides of the sample was measured at regular intervals until a degree of stability was obtained. This was judged by the constant difference in temperatures across the sample thickness for at least three intervals (each interval is one hour). The test was run for at least 24 hours in case of homogeneous samples, and for 36 hours in case of composite samples. Three identical tests were carried out on each sample to eliminate any single errors in temperature measurements.

2.5.3. Results Obtained For Homogeneous Materials

To determine the thermal conductivity of homogeneous materials, tests were carried out on two materials, "Thermalite"

and extruded polystyrene. Their normal dry room weights and conditioned weights were determined prior to the tests. Tests were carried out using various thicknesses and after the end of each test, their weights were determined. Also the oven-dry weight of each sample was determined after leaving them for 16 hours in an oven with a temperature range of 105 - 110°C.

2.5.3.1 "Thermalite" Samples

Seven different samples were used to obtain results of the thermal properties of "Thermalite" blocks. The samples were given identification letters and numbers according to their thicknesses and the imposed time rate of heat flow per unit area(heat flux) at the hot face. Table 2.5.3. - 1 summarizes this data. It shows the range of thickness, L, in metre and volume, V in m^3 with the imposed heat flux for all the samples. The samples prior to each test were measured at six places by means of vernier callipers to 0.01 mm, and the mean thickness was recorded. The deviation from flatness was found to be less than 0.1 mm, and the faces were parallel over the total surface area to less than 1% of the sample thickness. This was conformed to the existing BS 874 and ASTM C177-76 standards. The samples were conditioned to a constant mass in a ventilated oven as explained in 2.4.2, and the mass loss during conditioning M_r in % was determined. This was found to be less than 0.125% by weight, and was calculated from the following relation:

$$M_r = \frac{M_1 - M_2}{M_2} \times 100$$

where M_1 = Average mass of material in samples before conditioning

M_2 = Average mass of material in samples after conditioning.

The results for each individual sample are shown in Table 2.5.3. - 2.

Samples were placed carefully in the apparatus, and care was taken to prevent any loss of material or any moisture gain. This was achieved by surrounding the apparatus with external wooden box, filled with proper loose - fill cork granules as an insulation material. The box was covered with an insulating asbestos - cement board. The bulk densities of the conditioned samples as tested were calculated from the relation.

$$\rho = \frac{M_2}{V} \qquad (kg/m^3)$$

where V = Average sample volume, as tested in m^3

M_2 = As defined before.

The values are given in Table 2.5.3. - 4. and the mean bulk density was found to be 727.91 kg/m^3 with a standard deviation for all the samples of $\pm$ 1.769 kg/m^3. The bulk density given by the manufacturers[85] in Table 2.4.2. - 1 is 730 kg/m^3. This differs by a very small quantity of only 0.29% by weight and agrees very well with the calculated values.

The test was started at time t = o, and for each sample a suitable heat flux was chosen to obtain a temperature gradient across its faces not less than 15° C. Table HS was used to record all the information obtained from each test, such as the reference

temperature, the thermocouple readings of both the hot and cold faces of the samples, and the time interval. Other information including the power supply and current were monitored and recorded as well in the same Table. Readings from the test were obtained for the first 12 hours, and another two readings for the last 24 hours, before stopping the test. For each heat flux, the test was repeated three times maintaining the same conditions. All the readings were then calculated and the thermal conductivity of each test was determined. The results of these tests are shown in the Figures 2.5.3. (1) to 2.5.3. (7). Figure 2.5.3. (1) shows the results obtained for sample ST 1, where the mean thickness of the sample is 4.16×10^{-2} m. It shows the plot of thermal conductivity "k" in W/m K versus the corresponding time interval in hours for each of the three different heat fluxes as indicated in Table 2.5.3. - 1. A representative 'K' value was obtained after 6 hours for a heat flux of 405.0 W/m^2 (I = 2.0 Amp.) This was 0.2287 W/m K. For a heat flux of 227.3 W/m^2 (I = 1.5 Amp.) 'K' was 0.2170 W/m K reached after 4.0 hours. The last 'k' value was obtained after 3.0 hours for a heat flux of 148.0 W/m^2 (I = 1.2 Amp.) and its value was 0.2030 W/m K. The variation in 'k' values was due to heat losses from the sides of the samples as a result of the different temperature gradients across the sample faces, and the difference between the mean temperature of the room during the test and the mean temperature of the samples. Figure 2.5.3. (2) represents the results obtained with sample ST 2 (L = 3.20×10^{-2}m). The required time to obtain the 'steady state' conditions, with the relevant 'k' values are as follow:

$t = 4.0$ hours, $k = 0.220$ W/m K, $\ddot{q} = 405.0$ W/m^2

$t = 3.5$ hours, $k = 0.200$ W/m K, $\ddot{q} = 227.3$ W/m^2

$t = 3.0$ hours, $k = 0.186$ W/m K, $\ddot{q} = 148.0$ W/m^2

These results indicate that provided the same heat flux is used in the case of both samples ST 1 and ST 2, 'K' values differ by up to 8%. This is due to the different thicknesses of the samples.

Other samples gave different values of thermal conductivity and followed the same pattern of decreasing values with decreasing heat flux and thickness. The summary of the results is shown in Table 2.5.3. - 5 to 2.5.3. - 11. These show the thermal properties obtained at four different intervals 4, 6, 12 and 24 hours. Table 2.5.3. - 10 shows the values of the thermal properties of sample ST 6 ($L = 1.68 \times 10^{-2}$m), and Table 2.5.3. - 11 shows the same for sample ST6 x 2 which consists of two ST6 samples in direct contact forming a sample with double the thickness. The difference between their thermal conductivities increased from 7% in the case of higher heat flux (405.0 W/m^2) to 11.5% in the case of the lower heat flux (148.0 W/m^2).

The values of mass regain during the tests were obtained by weighing each sample after the test directly, and then drying them in an oven for 24 hours at 110°C. The samples were cooled as explained in 2.4.2. and then re-weighed. The mass regain during the test M_w in % was calculated from the following relation

$$M_w = \frac{M_4 - M_3}{M_3} \times 100$$

where

M_4 = Average mass of material in samples after the test.

M_3 = Average mass of material in samples after drying and second conditioning.

The mass regain for any sample during the test was not greater than 1% by weight. The results for each individual sample are shown in Table 2.5.3. - 3.

2.5.3.2. "Styrofoam" (Extruded Polystyrene) Samples

Three different samples were used to obtain values of thermal properties on "Styrofoam" IB board insulation. The samples were given identification letters and numbers according to their thicknesses and the imposed heat flux at the hot face. Table 2.5.3. - 12 summarizes this data. It shows the range of thickness, L in metres, volume, v in m^3 and the three imposed heat fluxes, 145.5, 99.2 and 63.9 W/m^2 respectively. The thickness of each sample was measured at six different places. The deviation from flatness was found to be less than 0.2 mm, and the faces were parallel over the total surface area to less than 1% of the sample thickness. This conforms to the existing standards: BS 874 and ASTM C177 - 76 as indicated before. The samples were conditioned in a ventilated oven at 20°C for at least 16 hours and the % loss in mass M_r was calculated. This was found to be less than 0.1%

by weight. The results for each individual sample are shown in Table 2.5.3. - 13.

Samples were placed carefully in the apparatus, and care was taken to prevent any extra pressure on them which might change their thickness. In all the tests, loose-fill cork granules were used to insulate both the samples and apparatus. The bulk densities of the conditioned samples as tested, were calculated as for the "Thermalite" samples, and are shown in Table 2.5.3.-15. Their densities were 29.35, 28.66 and 29.00 kg/m^3 for samples SP 1, SP 2, SP 3 respectively. Their mean bulk density was found to be 29.00 kg/m^3 with a standard deviation of $\pm$ 0.345 kg/m^3. The bulk density given by the manufacturers [86] in Table 2.4.2 - 2 is 28.0 kg/m^3. This differs by a small quantity of 3.5% by weight from the calculated values. The test was started at time t = o, and for each of the three samples, a suitable heat flux was chosen to obtain a temperature gradient across their faces not less than 15°C. The maximum recommended continuous operating temperature set by the manufacturers[86] is 75°C. For this reason, the maximum temperature of the hot face was limited to 60°C, so as not to cause any partial melting of the samples. The experimental data is recorded in Table HS as before, and the thermal conductivities at the relevant intervals are calculated in the same Table. The results of the tests are shown in Figures 2.5.3. (8) to 2.5.3. (14). Figure 2.5.3. (8) shows the results obtained for sample SP 1 - 5, where the mean thickness of the sample is 5.05×10^{-2} m. It shows the plot of thermal conductivity 'k' in W/m K versus the corresponding time interval in hours for 24 hours, the total

duration of the test. The graph represents the average values of the three tests conducted using the same heat flux of 99.19 W/m^2 (I = 1.0 Amp.) A representative 'k' value was obtained after 6 hours, of 0.0778 W/m K. The average 'k' was 0.0745 W/m K, which differs by 4.2% from the first value. Figure 2.5.3. (9) shows the results of the test on sample SP1-6 (L = 5.05×10^{-2}m) with a heat flux of 63.92 W/m^2 (I = 0.80 Amp.). The "steady state" condition was reached after 6 hours, with a 'k' value of 0.0695 W/m K. The average 'k' was found to be 0.0670 W/m K, which is 3.6% lower than the first value. The difference in thermal conductivities between the two samples SP1-5 and SP1-6 is 10%, this is due to a difference of 10 deg. C between their mean temperatures. The mean temperature of sample SP1-5 was 25.6°C and for sample SP1-6 was 15.6°C. The summary of the thermal properties of both samples at four different time intervals 4, 6, 12 and 24 hours is shown in Table 2.5.3. - 16. Figures 2.5.3. (10) and 2.5.3. (11) show the results obtained with samples SP2-5 and SP2-6 respectively. Their thickness was 4.14×10^{-2}m. Sample SP2-5 with a heat flux of 99.19 W/m K reached the "steady state" condition after 6 hours, with a 'k' value of 0.0672 W/m K. The average 'k' during the test was found to be 0.066 W/m K, which differs by 1.78% from the first value. The mean temperature of the test was 23.55°C. Sample SP2-6 with a heat flux of 63.92 W/m^2, reached its "steady state" after 5.50 hours, with 'k' equal to 0.0606 W/m K, and a mean temperature of 13.5°C. The difference in 'K' values between the two samples SP2-5 and SP2-6 was 8.2% due to a temperature difference between their means of 10.05°C. The thermal properties of both samples are summarized in Table

2.5.3. - 17. Figures 2.5.3. (12) to 2.5.3. (15) show the results obtained with samples SP3-4, SP3-5 and SP3-6 with a heat flux of 145.48, 99.19 amd 63.92 W/m^2 respectively. The required time to obtain the "steady state" conditions, with the relevant 'k' values and the mean temperatures of these samples are as follow :

$t = 6.0$ hours, $k = 0.0536$ W/m K, $19.96^{o}C$

$t = 6.0$ hours, $k = 0.0512$ W/m K, $11.87^{o}C$

$t = 5.0$ hours, $k = 0.0485$ W/m K, $6.24^{o}C$

The difference between the values of thermal conductivity of the first two samples was 4.47%, and between the last two samples was 5.27%. The summary of the last three sample results is shown in Table 2.5.3. - 18. By using the same heat flux for any of the three samples SP1-5, SP2-5 and SP3-5, values of 'k' decreased with decreasing thickness, coupled with decreasing mean temperatures.

2.5.4.. Results Obtained For Composite Materials

Four different composite samples were used to obtain results for thermal conductivities using a combination of "Thermalite" blocks and "Styrofoam" (extruded polystyrene) board insulation. The samples each consisted of a layer of "Thermalite" and a layer of extruded polystyrene of various thicknesses. They were given identification letters and numbers according to their thicknesses and the imposed time rate of heat flow per unit area, at the hot face. Table 2.5.4. - 1 summarizes this data. It shows the range of thickness L_c, in metre, volume V_c, in m^3, foam

thickness L_F, and matrix thickness L_M, and their volumes considering V_c = 1 unit. The imposed heat flux is also indicated at the same table. The experimental arrangement is shown in Figure 2.4.3. (2). The weight of each sample was determined before and after the experiment in the same way as described above for homogeneous materials. These were found to be more or less the same without any significant variations. Heat flow "sensables" were placed between the layers and between the sample and the cold plates to record the rate of heat flow directly, as explained in 2.4.1. The thermocouples in the "Sensables" gave the interface temperatures between the layers of the composite samples. The total number of tests was eleven, each being repeated three times to confirm the results. The data for each test is recorded in Tables 1CS and 2CS, shown in Appendix A. Each test started at time t = o, and the ambient temperature was recorded. Other values such as the temperatures of the interface, cold and hot faces of the sample were evaluated after correction to the ambient temperature at the reference junction of the thermocouples. The power supply and current were monitored and recorded. Readings from the test were obtained for the first and the last 12 hours, as each test was run for a period of 36 hours. All the readings were then calculated and the thermal conductivity of each sample was determined. The results of these tests are shown in the Figures 2.5.4. (1) to 2.5.4. (11).

Figures 2.5.4. (1) to 2.5.4. (3) show the results of the three sets of tests carried out on one composite sample SC1

consisting of two layers; extruded polystyrene (L_F = 0.0206 m) and "Thermalite" (L_M = 0.0320 m). The overall thickness of the sample L_c = 0.0526 m. The "Thermalite" layer was in contact with the heating unit. Each test was conducted for a period of 36 hours. Readings were obtained each half an hour for the first four hours, then each hour for the next 8 hours. After 24 hours from the start of the test, readings were obtained again each hour to the end of the test (36.0 hours). Figure 2.5.4. (1) shows 'k' values as a funtion of time t, for sample SC1-4, with an imposed heat flux of 143.83 W/m^2 as indicated in Table 2.5.4.-1 The continuous line represents the average 'k' values obtained from three tests using the equation

$$k_A = \frac{q\ L_c}{A(T_1-T_2)}$$

where the composite sample was considered to be one material, and k_A was the overall (bulk) thermal conductivity of the composite sample. The discontinuous line represents the average 'k' values obtained from the same three tests by using equation (5-c) where the thermal conductivities of both the "Thermalite" k_M and the extruded polystyrene k_F were considered. k_c was given by:

$$k_c = \frac{k_M\ k_F}{V_F\ k_M+(1-V_F)\ k_F}$$

in which the heat flux was across the surfaces of the two layers of material in-series. The mean k_A was found to be 0.123 W/m K, whenever the mean k_c was 0.1273 W/m K. The difference between

these two means is - 3.45%. The results obtained for sample SC1-4 are shown in Table 2.5.4. - 6. Figure 2.5.4. (2) and Table 2.5.4.-7 show the results obtained for sample SC1-5 with an imposed heat flux of 99.19 W/m^2. The mean k_A was 0.1156 W/m K, and k_c was found to be 0.1171 W/m K. The difference between k_A and k_c is - 1.25%. Figure 2.5.4. (3) and Table 2.5.4. - 8 show the results obtained for sample SC1-6 with an imposed heat flux of 63.92 W/m^2. The mean k_A and k_c were found to be 0.1034 W/m K and 0.1012 W/m K respectively. The average values of k_A at each interval are indicated by the circles and the continuous line. The average values of k_c are indicated by the squares and the discontinuous line. The difference between them after 24 hours to the end of the test is found to be + 2.14%. Table 2.5.4 - 2 summarizes the results for samples SC1-4, SC1-5, and SC1-6, at the indicated intervals. The ambient temperatures during the tests ranged from 20.20°C to 22.0°C. Average temperatures with thermal conductivities of both the matrix ("Thermalite") and the foam "Styrofoam" (extruded polystyrene) are also indicated.

Figures 2.5.4. (4) to 2.5.4. (6) show the thermal conductivity values as a function of time for the composite samples SC2-3, SC2-4 and SC2-5 respectively. The samples consisted of two layers, extruded polystyrene (L_F = 0.0206 m) and "Thermalite" (L_M = 0.0234 m). The overall thickness of the sample was L_c = 0.044 m. Each test was conducted for a period of 30 hours, and the results are tabulated in 2.5.4. - 9 to 2.5.4. - 11. The following mean values of thermal conductivities with the % difference are obtained for the period 24 - 30 hours; all 'k' values are in

W/m K;

SC2-3, k_A = 0.1149, k_c = 0.1174, - 2.12%

SC2-4, k_A = 0.1044, k_c = 0.1077, - 3.20%

SC2-5, k_A = 0.1024, k_c = 0.1053, - 2.83%

Table 2.5.4. - 3 shows the summary of the results obtained with the above samples SC2. Figure 2.5.4. (7) to 2.5.4. (9) show the results obtained for the composite samples SC3-4, SC3-5 and SC3-6 respectively. The thickness of the extruded polystyrene layer was 0.026 m and the "Thermalite" layer was 0.0168 m. The heat flux for each sample is shown in Table 2.5.4. - 1. k_A and k_c were calculated as explained before and are represented by the continuous and discontinuous lines respectively. The results are also tabulated in Tables 2.5.4. - 12 to 2.5.4. - 14. The following mean values of thermal conductivities with the % difference are obtained for the 24 - 30 hours period, all 'k' values are in W/m K;

SC3-4, k_A = 0.0907, k_c = 0.0924, - 1.87%

SC3-5, k_A = 0.0876, k_c = 0.0898, - 2.53%

SC3-6, k_A = 0.0787, k_c = 0.0757, + 3.90%

Table 2.5.4. shows the summary of the results obtained at the selected intervals for the above samples SC3.

Figures 2.5.4. (10) and 2.5.4. (11) show the results of thermal conductivities of samples SC4-5 and SC4-6 as a function of time. The thickness of the extruded polystyrene layer was 0.0414 m and the "Thermalite" layer was 0.0234 m. The tests were

conducted for 36 hours. The mean 'k' values for both samples for the period 24-30 hours are found to be as follows; all 'k' values are given in W/m K;

SC4-5: $k_A = 0.1060$, $k_c = 0.1036$, +2.28%

SC4-6: $k_A = 0.0947$, $k_c = 0.0919$, +3.02%

The above values are calculated and shown in Tables 2.5.4. -15 and 2.5.4. - 16. The summary of the results at the selected intervals is shown in Table 2.5.4. - 5.

Figures 2.5.4. $(\bar{1})$ to 2.5.4. $(\bar{11})$ show the heat flux in W/m^2 as a function of time for the composite samples SC1-4 to SC4-6 respectively. These values were obtained from the heat flow sensables described in 2.4.3.1. - 5. The thermal conductivity at any interval was calculated simply from the relation:

$$\bar{k}_c = \frac{\ddot{q}\, L_c}{(T_1 - T_2)}$$

where $\ddot{q}$ was the heat flux value at that interval, and was obtained by using the digital sensimeter. $\bar{k}_c$ was calculated for all the samples and the results are tabulated with the other results in Tables 2.5.4. - 6 to 2.5.4. - 16. It is noticable that the values of thermal conductivities obtained by the heat flow "Sensables" do not vary as greatly as the other values. The difference between the steady state values of 'k_A' and the values of $\bar{k}_c$ are as high as 30% (Table 2.5.4. - 15) for the higher mean temperatures of the samples. These differences are less for the lower mean temperatures. The following values are obtained from the above

tables for a mean sample temperature of 21.75 ± 1.5°C, with the volume of matrix V_M, decreasing

Sample	V_M	k_A, W/m.K	$\bar{k}_c$, W/m K	Difference, %
SC1-4	0.608	0.1230	0.0978	20.50
SC2-4	0.532	0.1044	0.0870	16.63
SC3-4	0.449	0.0907	0.0794	12.41

It is clear that the overall thermal conductivities of the composite samples obtained by the "steady state" equation are higher than those obtained by the heat flow sensables, due to the heat loss from the edges of the samples. The values of $\bar{k}_c$ are more consistent and do not vary by more than 4% for each sample, even though the mean temperatures of the samples varied by more than 20°C. Tables 2.5.4. - 6 to 2.5.4. - 16 show all the results obtained from the three different methods to predict the thermal conductivity of the composite samples.

2.6. Discussion of Results

2.6.1. General

The guarded hot plate used for the measurement of the thermal conductivity of "Thermalite" and extruded polystyrene samples as homogeneous materials has been designed and operated according to the standard specifications laid down by the British Standard Institution (1973) and the American Society for Testing Materials (1976). The test was carried out on both homogeneous and composite samples. A composite or layered sample is defined in article 4.5.1. (ASTM C177-76) as that sample, which if sliced parallel to the faces, has one or more slices with a significantly different apparent thermal conductivity The ASTM C177-76 only covers the testing of homogeneous materials, but here the same apparatus has been used in conjunction with the heat flow sensables to test composite samples in two layers. The overall thermal conductivities of the samples have been measured and calculated empirically and compared with the results obtained by calculating the theoretical composite thermal conductivities from the unit cube model of in-series heat flux through a layered composite material explained in section 2.2.3.3. Also by using the heat flow sensables, the heat flux through these composites has been obtained accurately and the thermal conductivity calculated and compared with the other two methods of arriving at a value of 'k'. The accuracy of these measurements depends on the accuracy of the apparatus, the flatness of the samples, the temperatures and the heat flow measurements. The thickness of the sample plays an important role in the accuracy of the

measurements as it influences the edge heat losses. Samples with several thicknesses have been tested and the results compared and contrasted.

2.6.2. Accuracy of The Measurements

In the last two decades, it has become apparent that the "Guarded Hot-plate Method" for the measurement of the thermal conductivities of materials, does not give "k" values of samples to the required accuracy. A comparison of the measured thermal conductivity of different samples of the same product can show variations of up to several percent. Tests on concrete blocks using the "Plain Hot-plate Apparatus" can show variations in 'k' values of up to 80%[87]. This has led the British Standard Institution to revise its existing standard BS 874: 1973[56] and an ammendment was published on 31 August 1979[57]. It has been agreed that more attention should be given to the preparation and conditioning of the samples coupled with the use of more suitable test equipment which should cover the range of values to be determined.

2.6.2.1. Sample Preparation

The diameter of the samples required for the thermal conductivity measurement was 152 mm. Two samples were required for each test. They were assumed to be identical, homogeneous and of constant thickness over the entire area of the heating unit.

In the preparation of these samples the flatness of the surfaces was the most important factor affecting the accuracy of measurements Both B.S. 874 and ASTM 177-76 limit the deviation in flatness to less than 0.2 mm, or the faces are to be made flat to within 0.025 % and parallel over the total surface area to within 1% of the sample mean thickness. Samples were prepared as described in 2.4.1. according to these standards, and the extent of their deviation from flatness across the full area was judged by a straight edge and feeler gauge. The thickness was determined by means of Vernier callipers reading to 0.01 mm. The deviation from flatness for all the "Thermalite" samples was found to be less than 0.1 mm, and in the case of extruded polystyrene samples it was less than 0.2 mm. This was achieved by cutting the sample surfaces and edges using a precise lathe. The reason for keeping the sample surfaces flat and parallel was due to the fact that each surface should be isothermal and in intimate contact with the heating and cooling units, in order to satisfy the fundamental hypothesis of heat conduction[49] in solids given by equation (1-H) and (5-H) explained in section 2.2.2.3. In a review by Laming[99], it is explained that two surfaces 'in contact' only touch at a number of scattered points where the total area in fact is very much less than the nominal area of contact. If the surfaces are metallic, and if there is a heat flux across the 'contact' much of it will flow through these small metallic bridges. Some, however, will cross the gap between the relatively large areas not in contact. In the first case, resistance arises from the constriction of the flow lines on either of the contact points, and there is no temperature discontinuity at the contact itself.

In the second case, the resistance is due to the fluid film (air or water) between the surfaces, and is strictly proportional to the difference between fluid and metal resistivities since it arises from replacement of metal (solid) by fluid. The total thermal conductance per unit area of nominal contact may therefore be written

$$C_t = C_s + C_f$$

where: C_s is the metallic or solid path conductance.

and C_f is the parallel conductance through the interface film.

Thermal conductance is defined by the equation

$$\text{Conductance } C = \frac{q}{\Delta T} = \frac{W}{K}$$

$$\text{Conductance/unit area} = \frac{q}{A\Delta T} = \frac{\ddot{q}}{\Delta T} = \frac{W}{m^2\ K}$$

ΔT is the contact temperature drop.

The thickness of the fluid film (air or water) depends on the overall flatness of the sample and plate surfaces. If this is not reduced, there will be a tendency to measure a temperature difference across the sample which is too large by a factor which depends on the thickness of this film at the point of measurement and on the position of the thermocouple with respect to the surfaces nominally in contact. If the surfaces of the heating unit, cooling units and samples are flat to 0.2 mm, there could be a fluid film (air layer) 0.4 mm thick over much of the area between the 'contacting' surfaces. It was found in similar investigations[87] that non- flatness introduces a systematic

error, which always produces a low value of thermal conductivity. The magnitude of the discrepancy increases as the conductivity increases and will also increase as the sample thickness is reduced. The magnitude of these errors could be as high as 9% for a 50 mm thick sample flat to 0.20 mm which has an average true 'k' value of 0.20 W/m K, and where both the heating and cooling units are also flat to 0.20 mm. The errors here were reduced to less than 1% in the case of "Thermalite" samples, and to less than 2% in the case of "Styrofoam" (extruded polystyrene) and composite samples. This was achieved by the careful preparation of the samples and repeating the test on three samples each time. In Figures 2.5.3. (1) to 2.5.3. (14) for the homogeneous samples and in Figures 2.5.4. (1) to 2.5.4. (11) for the composite samples, the variations between all the points for any test after reaching the steady state condition are minimal.

2.6.2.2.The Apparatus and Measurement of Data

This was explained in detail in 2.4.3. The precision attained was due to the working surfaces of both the heating and cooling units which were smoothly finished to a true plane. The maximum departure of the surface from a plane did not exceed 0.02%. The units were constructed from copper which has high thermal conductivity. It has been found by many authors including Donaldson [98] that the errors for a copper plate are, in all instances, smaller than those for an aluminium plate. Hence,

from the design point of view, copper was the better material. The two faces of the heating unit were substantially at the same uniform temperature, as can be judged by the output of the evenly distributed thermocouples. The heating unit had a gap of 2.5 mm between the central surface plates and the guard surface plates. The error due to any temperature differences across this gap was greatly reduced by balancing the temperature between the two parts. The thickness of the heating unit was 11.15 mm, which is less than 1/13 th of its overall diameter. This was achieved by the use of close windings which helped in obtaining a uniform temperature as mentioned above, and assisted in the reduction of the errors. The cold plates were kept at the same uniform temperature by circulating a refrigerated fluid which consisted of equal volumes of water and anti-freeze liquid. All air bubbles were flushed out of the cooling units by keeping the pump inlet and outlet fully immersed under the fluid level. During each test the temperatures of both the lower and upper cold plates were found to be exactly the same, so any errors which could have arisen from this were insignificant.

Errors in q, rate of heat flow, arise from changes in mains supply and component temperature change , due to ambient temperature change or internal temperature change . These errors were estimated at 0.06%. The observed error or parallax error made in reading the position of the pointer with reference to the scale was estimated to be 1.25%. The digital sensimeter and universal sensimeter were accurate to 0.2% full scale and errors due to observation were approximately 0.7%. The other errors

were in the measurement of the thickness of the samples and their diameter which was measured to the nearest 0.1 mm, which represented an error of 0.6% in the thickness or 0.15% in the area. Combining thse errors by the square root of the sum of the squares of the errors the overall error in 'k' is 1.6% due to the both Apparatus and measurements.

2.6.3. Homogeneous Materials:

The most familiar method of measuring the thermal conductivity of homogeneous insulating materials in the "steady state" condition is the "Guarded-Hot Plate Method". The apparatus and testing procedure have been discussed in 2.4.3. The difficulties of this method are due to the extended time it takes to reach the "steady state" condition and the heat losses from the sample edges. To discuss the first difficulty consider the assumptions used in deriving equation (4-H). The equation was derived by considering two parallel planes, distance x-apart, with area A, in an isotropic body and each at constant temperature T_1 and T_2. A quantity of heat will flow in time t, and that was given by

$$Q = k \frac{T_1 - T_2}{x} A t$$

and $$q = \frac{dQ}{dt} = k \frac{T_1 - T_2}{x} A$$

and $$\frac{q}{A} = - k \left(\frac{T_2 - T_1}{x}\right)$$

hence

$$\ddot{q} = - k \frac{\partial T}{\partial x} \qquad (4\text{-H})$$

where $-\frac{\partial T}{\partial x}$ is the temperature gradient in the direction of heat flow.

The general equation of conduction of heat was derived in 2.2.2.3.

$$\frac{\partial T}{\partial t} = a\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \qquad (12\text{-H})$$

It applies to three dimensional un-steady state conduction in an isotropic region of uniform thermal conductivity. The above equation can be written as

$$\nabla^2 T = \frac{1}{a}\frac{\partial T}{\partial t}$$

In the steady-state, the time derivative is zero, and hence, the result is Laplace equation

$$\nabla^2 T = 0 \qquad (13\text{-H})$$

Using the same assumptions for deriving equation (4-H) assume that the two parallel planes are the surfaces of a flat plate, thickness L, with the edges insulated. The plate has a uniform and constant temperature throughout, say zero degrees.

At time $t = o$, the temperature of face 1 ($x = o$), or the input face is raised to T_1, whenever the output face ($x = L$) is kept at the zero temperature. The temperature distribution, $T_{(x,t)}$ within the above plate is given by the solution of the one dimensional equation[51] of linear heat flow with specified boundary conditions, hence equation (12-H) can be written as follows:

$$T_{(x,t)} = o \qquad o < x < L \qquad t \leqslant o$$

$$\frac{\partial T_{(x,t)}}{\partial t} = a \frac{\partial^2 T_{(x,t)}}{\partial x^2} \qquad o < x < L \qquad t > o \qquad (15\text{-H})$$

At the output face,

$$T_{(L,t)} = o \qquad x = L \qquad t \geqslant o$$

And at the input face, there is a heat flux due to T_1, which is given by equation (4-H), hence

$$\ddot{q} = -k \frac{\partial T_{(o,t)}}{\partial x} = o \qquad x = o, \qquad t < o$$

$$\ddot{q} = -k \frac{\partial T_{(o,t)}}{\partial x} = \ddot{q}_o \qquad x = o, \qquad t > o$$

The plate (sample) will get to the steady state when

$$t \longrightarrow \infty \qquad \text{and} \quad \frac{\partial T}{\partial t} = o$$

and the steady state solution will be given by

$$\ddot{q}_o = -k \frac{T_1}{L} \qquad (S)$$

The complete solution for the homogeneous single layer has been given by Carslaw and Jaeger [51] as indicated in equation (19-H). This equation can be rewritten in terms of $\ddot{q}_o$ at the input face ($x = o$) where $T = T_1$, hence,

$$\ddot{q}_o = \frac{k\,T_1}{L - \frac{8L}{\pi^2} \sum_{n=o}^{\infty} \left(\frac{\exp\left[-(2n+1)^2 \pi^2 \frac{at}{4L^2}\right]}{(2n+1)^2} \right)} \qquad (R)$$

After a long enough time, the infinte sum $\sum_{n=o}^{\infty}$ can be replaced by its first term with a very small error, depending on the accuracy required, hence

$$\ddot{q}_o = \frac{k\,T_1}{L\left[1 - \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 at}{4L^2}\right)\right]} \qquad (\bar{R})$$

Suppose the experimental error is 2%, then the difference between (S) and ($\bar{R}$) will be as follow:

$$\frac{8}{\pi^2} \exp\left(-\frac{\pi^2 at}{4L^2}\right) \leqslant 0.02$$

The steady state will be reached when $t \longrightarrow \tau$

or $$\tau \geqslant \frac{1.502\,L^2}{a}$$

where 'a' is the thermal diffusivity of the sample and is given by the following relation

$$a = \frac{k}{\rho C}$$

The thermal diffusivities are calculated for both the "Thermalite" and "Styrofoam" (extruded polystyrene) from their mean densities

and specific heats, and the results are as follow:

"Thermalite" samples, $a = \dfrac{0.184}{728.0 \times (1.05\times10^{3})} = 0.024\times10^{-5}\ m^2/sec$

"Styrofoam samples, $a = \dfrac{0.04}{29.0 \times (0.3\times4186.8)} = 0.11\times10^{-5}\ m^2/sec$

The time required to get to the steady state for each sample is calculated and shown in Table 2.6.3. - 1. This table also includes the time obtained from Figures 2.5.3. (1) to 2.5.3. (14)

The second difficulty in obtaining the thermal conductivity of homogeneous materials is due to the affect of heat loss from the edges of the samples. The thickness of the sample with its mean temperature controls the level of these losses, and consequently the magnitude of the errors in the measured thermal conductivities. It is noted that the sample thickness shall be not greater than one-fifth of the length for materials which have dry densities less than 1800 kg/m^3 according to the revised BS 874[57]. This is recommended for the 300 mm square guarded hot plate and plain hot plate apparatus, which differs from the circular plates used for this study. Also it is recommended in ASTM C177-76[58] that in order to limit the heat losses from the outer edges of samples the ambient temperature, T_a surrounding the apparatus should be adjusted such that

$$\frac{T_m - T_a}{T_1 - T_2} \leq 0.1$$

where T_m is the mean temperature of the samples, $T_m = (T_1+T_2)/2$, and T_1 and T_2 are the temperatures of the hot and cold plates, respectively. The percentage error associated with this limit was not given. This necessitated testing many samples with different thicknesses, and varying the mean temperatures to find the optimum thickness for the apparatus at hand. Seven different thicknesses were used for "Thermalite" samples, and the results are shown in Figures 2.5.3. (1) to 2.5.3. (7). These results are grouped in Figures 2.6.3. (1) to 2.6.3. (4) in which the thermal conductivities of all samples are plotted versus the corresponding time intervals for the given heat flux. In these graphs, it is clear that the 'k' values for samples ST3, ST5 and ST6 are close to each other. The ratios of diameter to thickness for these samples are (5.85:1), (7.17:1), and (9.05:1) respectively. Figure 2.6.3. (1) shows that 'k' values for ST3-1, ST5-1 and ST6-1 are 0.2102, 0.2089 and 0.2089 respectively. Their mean 'k' value is 0.2093 W/m K, with a standard deviation of 0.00075. Figure 2.6.3. (2). shows 'k' values for ST5-2, ST3-2, and ST6-2, their mean 'k' value is 0.199 W/m K with a standard deviation of 0.00253, Figure 2.6.3. (3) shows for the same samples a mean 'k' value of 0.1854 W/m K with S.D. = 0.00398. If the relation $\xi = \left(\frac{T_m - T_a}{T_1 - T_2}\right) \leq 0.1$ given by ASTM is considered, 'k' obtained for ST5-1 ($\xi = 0.0898$) and ST6-1 ($\xi = -0.0113$) is 0.2089 W/m K. Also 'k' values obtained for ST4-2 ($\xi = -0.0628$), ST5-2 ($\xi = -0.1403$) and ST3-2 ($\xi = -0.0147$) are 0.2040, 0.2020 and 0.1980 W/m K respectively.

Analysing these values as shown in Table 2.6.3. -2 and Figure 2.6.3. (5), the following thermal conductivity values are obtained for each sample providing $\xi = o$ $(T_m = T_a)$ ST3: k = 0.2019, ST4: k = 0.2072, ST5: k = 0.2062, and ST6: k = 0.2071 W/mK. This indicates that for samples with their thicknesses less than one-sixth the diameter and their mean temperatures equivalent to the ambient temperatures, thermal conductivity values are accurate with insignificant heat losses. The average thermal conductivity obtained for "Thermalite" samples according to this criteria is found to be 0.2056 W/m K with a standard deviation of 0.0025. Considering $\xi = -0.1$, the mean thermal conductivity is 0.2017 W/m K with a standard deviation of 0.0025. The difference between these two values is 1.89% which agrees very well with the accuracy of the apparatus It is clear that the heat losses from the edges of samples ST1, ST2 and ST6 x 2 is quite high, and the differences from the true 'k' value ($\xi = o$) are 7.34%, 5.47% and 5.47% respectively. In case of ($\xi = -0.1$) the differences are: 7.39%, 5.12% and 5.52% respectively.

The low values of 'k' obtained for samples shown in Figures 2.6.3. (3) and 2.6.3. (4) are probably due to the formation of a frost film layer between the sample surfaces and the cold plates, as described in 2.6.2.1. The mean 'k' value for samples ST3-3, ST6-3 and ST5-3 is 0.1854 with S.D. = 0.004. This is 9.82% and 8.08% less than the true 'k' value for $\xi = o$ and $\xi = -o.1$ respectively.

The thermal conductance 'C' of a "Thermalite" block 100 mm thick is obtained from the relation $C = \frac{k}{L}$,

hence $C = 2.056\ W/m^2K$ $(\xi = o)$

and $C = 2.017\ W/m^2K$ $(\xi = -o.1)$

The thermal conductance values are calculated for all the "Thermalite" samples as shown in Table 2.6.3.-3. The correlation coefficient and the slope are calculated for each sample. The relation between the thermal conductance and the mean temperature is found to be linear and decreases with increasing thickness as shown in Figure 2.6.3. (6). The values of thermal conductance for mean temperatures of 40, 20, 10, and 0^oC are obtained from the above figure, and are plotted versus sample thicknesses. This is shown in Figure 2.6.3. (7).

The results obtained from the "Thermalite" samples dictated the use of samples which had a thickness to diameter ratio less than 1 to 6. Three different thicknesses were used in the case of the extruded polystyrene samples. One of them was within the above ratio (L/d = 1 to 7.41), two were greater than this ratio. The reason for this was to find the effect due to heat losses from the edges of the samples. Figures 2.5.3. (8) to 2.5.3. (14) show the values of thermal conductivity plotted against the time intervals during the tests. The variations between 'k' values in the first period before reaching the 'steady state' condition were due to the different initial conditions of the tests. These were kept as similar to each other as possible. The 'k' values in these periods are calculated from the "steady state" solution $k = \frac{q\,L}{A(T_1 - T_2)}$, so the values obtained before reaching the

"steady state" are not the true values. When repeating the test three times using the same heat flux, all the values of 'k' obtained after reaching the "steady state" condition were more or less the same. Figures 2.5.3. (12) to 2.5.3. (14) represent results for samples SP3-4, SP3-5 and SP3-6, these results are plotted in Figure 2.6.3. (8). The 'k' values obtained for the above samples are 0.0530, 0.0510, and 0.0483 W/m K respectively. 'k' values for samples SP1-5 and SP1-6 are 0.0755 and 0.0674 W/m K. 'k' values for samples SP2-5 and SP2-6 are 0.0667 and 0.0612 W/m K respectivley. It is clear that each thickness of the material has a different thermal conductivity, and the lower 'k' values are obtained with the minimum thickness (L = 0.0205 m). According to ASTM C177-76, to restrict the edge heat losses the following relation should be met:

$$\xi = \frac{T_m - T_a}{T_1 - T_2} \leq 0.1$$

Thermal conductivity values are calculated for several 'ξ' values, to analyse the results on the same bases. These calculations are shown in Table 2.6.3.-4. The true 'k' value for sample SP3 is 0.0532 W/mK when $\xi = \frac{T_m - T_a}{T_1 - T_2} = o$, and the true 'k' = 0.0522 W/mK ($\xi = -o.1$). Sample SP1 (L = 0.0505 m) has a 'k' value of 0.0729 W/mK ($\xi = o$) which is considered to be apparent because of the extreme thickness, and k = 0.0682 W/mK ($\xi = -o.1$). These are 27.02% and 23.46% higher than the true values. Sample SP2 (L = 0.0414 m) has apparent 'k' values of 0.0664 W/mK ($\xi = o$) and 0.0636 W/mK ($\xi = -o.1$).

They are 19.88% and 17.92% higher than the true values. Figure 2.6.3. (9) shows the relation between the thermal conductivity and the ratio $\varsigma = \frac{T_m - T_a}{T_1 - T_2}$. The slope of SP3 is found to be 0.00954, which is smaller than the other samples. The thermal conductances of the samples are calculated and the correlation coefficient between each sample and its mean temperature is found. These are shown in Table 2.6.3.-5. The relation between the thermal conductance and the mean temperature is found to be linear and decreases with increasing thickness as shown in Figure 2.6.3. (10). The values of thermal conductance of extruded polystyrene samples for mean temperatures of 40, 25 10 and $0^{o}C$ are obtained from Figure 2.6.3. (10) and are plotted against the sample thicknesses. This is shown in Figure 2.6.3. (11).

The thermal conductance 'C' of an extruded polystyrene board insulation, 50 mm thick is obtained from the true 'k' value as

$$C = 1.064 \ W/m^2K \quad (\varsigma = o.o)$$

$$C = 1.044 \ W/m^2K \quad (\varsigma = -o.1)$$

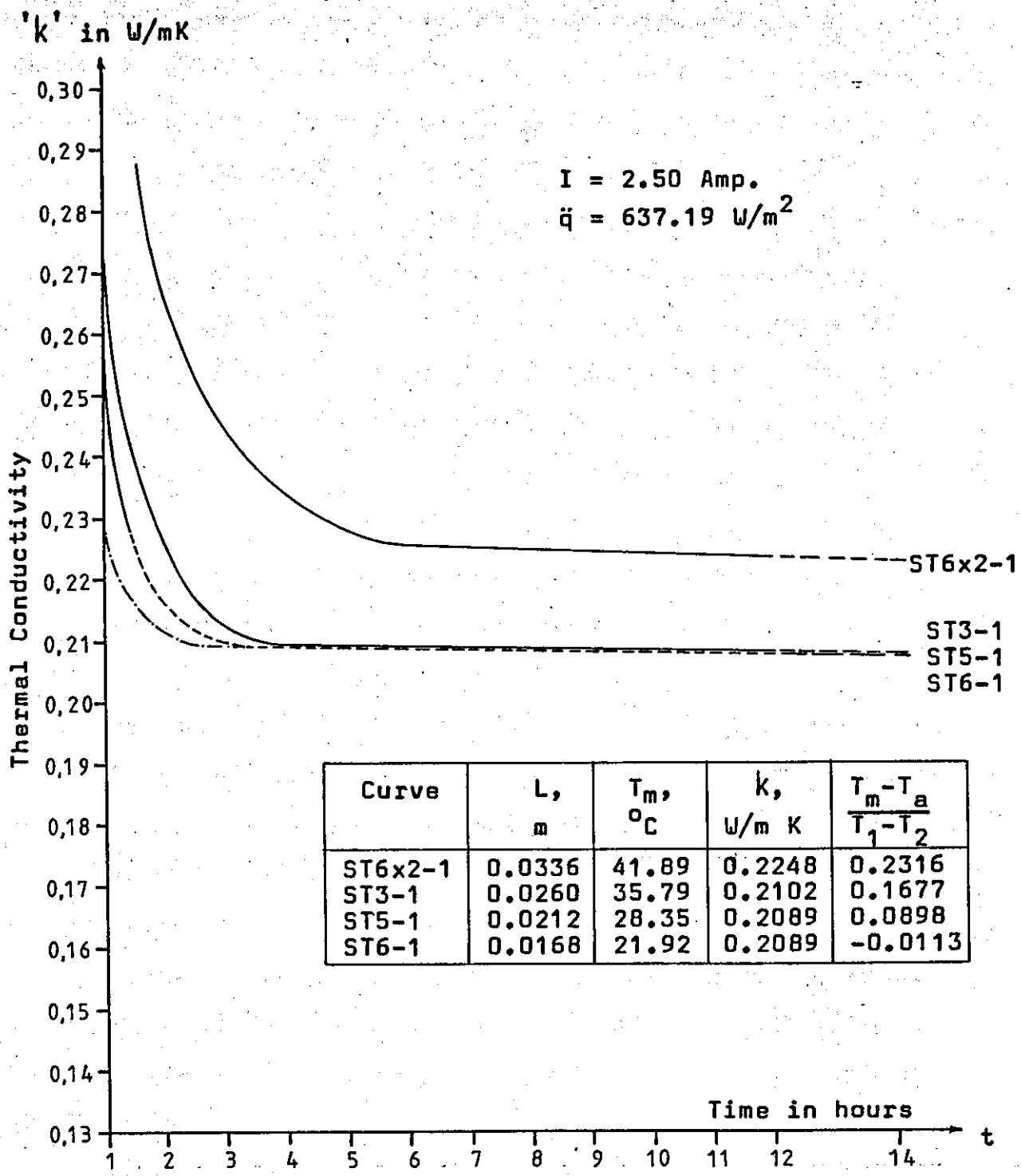
and for 100 mm thick board, the values are as follow:

$$C = 0.532 \ W/m^2K \quad (\varsigma = o.o)$$

$$C = 0.522 \ W/m^2K \quad (\varsigma = -o.1)$$

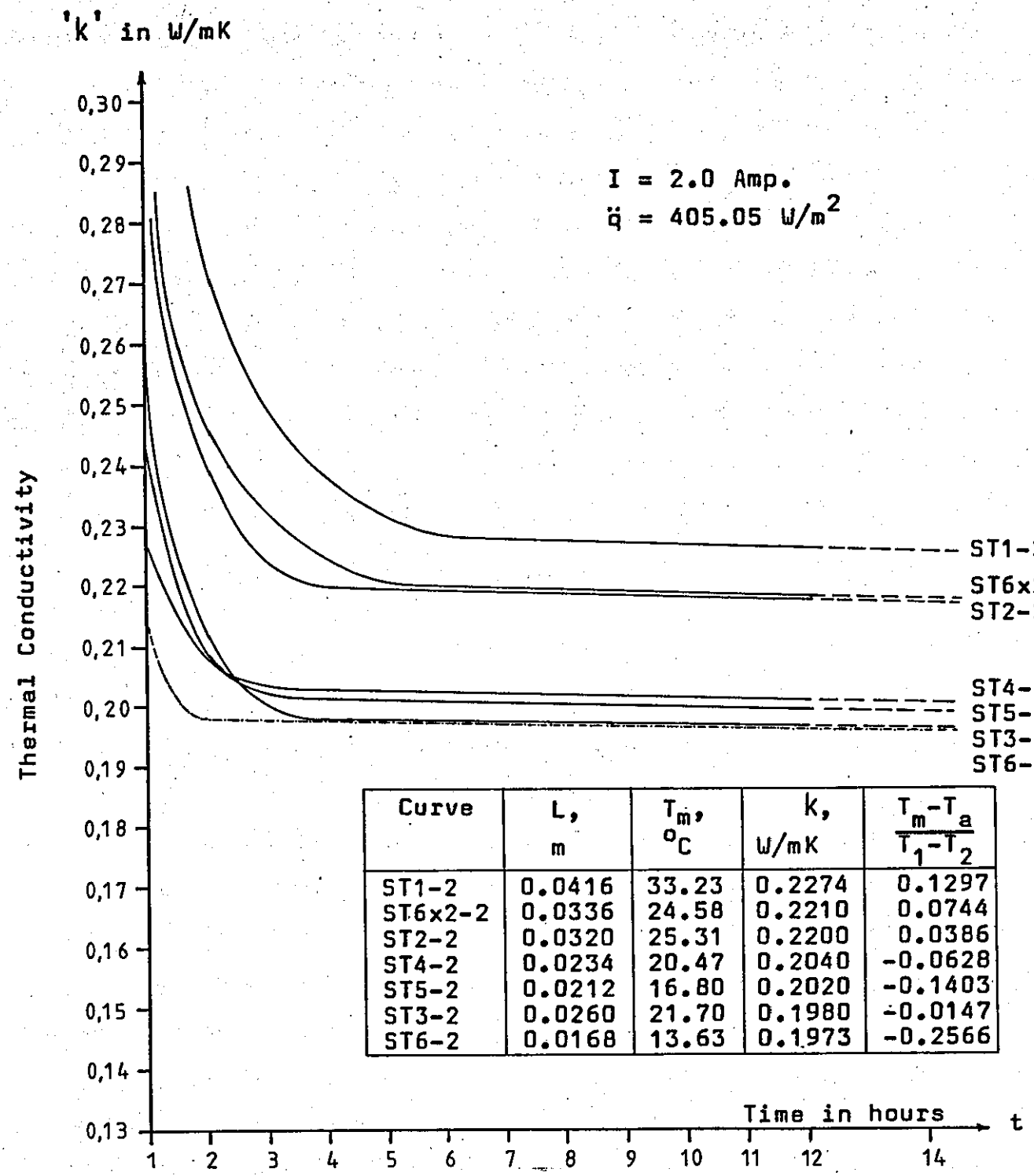
Table 2.6.3-1. Comparison between the time required to reach the steady-state, and time obtained during the test for both "Thermalite" samples ST, and "Styrofoam" (extruded polystyrene) samples

Sample No.	L, m	Time to reach the steady state, $t \geqslant \tau$					
		Calculated values	Experimental values ('k' vs. time t)				
		hr.-min.	-	-1	-2	-3	-4
ST1-	0.0416	3-00	-	-	6-00	4-00	3-00
ST2-	0.0320	1-47	-	-	4-00	3-30	3-00
ST3-	0.0260	1-10	-	4-00	4-00	3-00	2-30
ST4-	0.0234	0-57	4-00	-	3-00	-	-
ST5-	0.0212	0-47	-	3-30	3-30	3-30	-
ST6-	0.0168	0-30	-	2-30	2-00	2-00	-
ST6x2-	0.0336	0-58	-	6-30	5-30	3-00	3-00
			-4	-5	-6		
SP1-	0.0505	2-00	-	6-00	6-00		
SP2-	0.0414	1-21	-	6-00	5-30		
SP3-	0.0205	0-20	6-00	6-00	5-00		



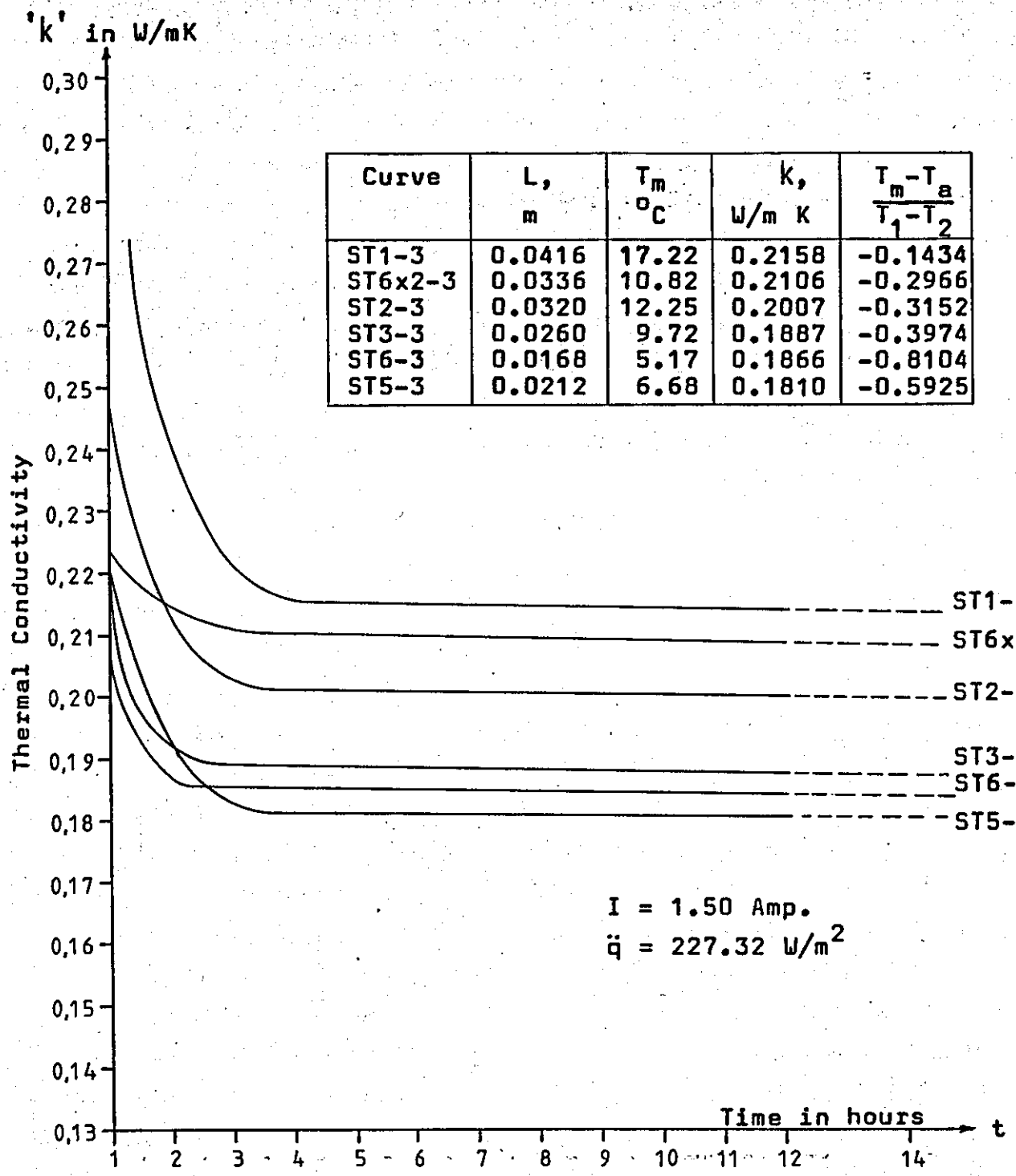
Curve	L, m	T_m, °C	k, W/m K	$\frac{T_m-T_a}{T_1-T_2}$
ST6x2-1	0.0336	41.89	0.2248	0.2316
ST3-1	0.0260	35.79	0.2102	0.1677
ST5-1	0.0212	28.35	0.2089	0.0898
ST6-1	0.0168	21.92	0.2089	-0.0113

Figure 2.6.3.(1) Thermal Conductivity Vs. Time of Test for 'Thermalite' Samples in the 'Steady State.'



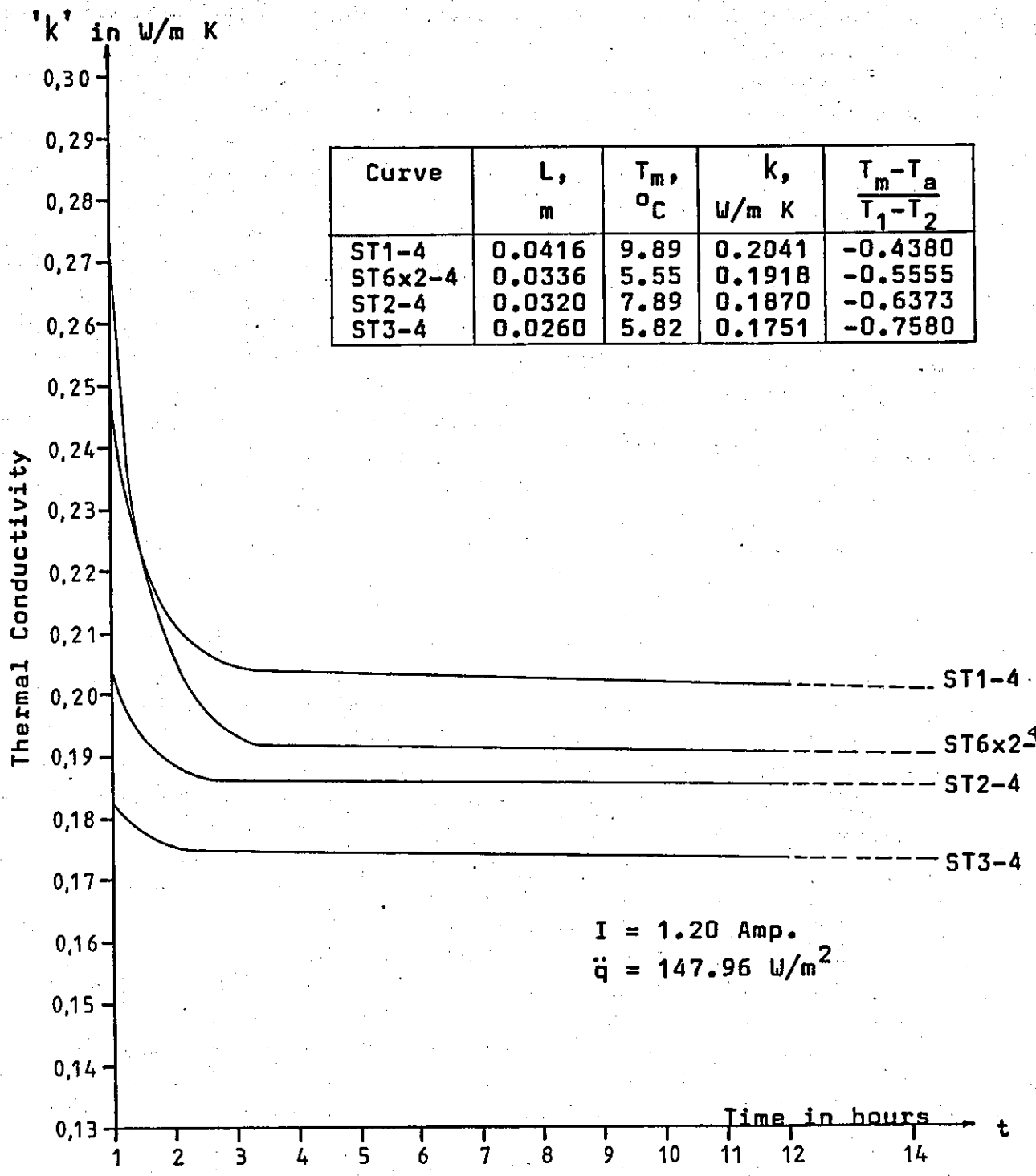
Curve	L, m	T_m, °C	k, W/mK	$\frac{T_m-T_a}{T_1-T_2}$
ST1-2	0.0416	33.23	0.2274	0.1297
ST6x2-2	0.0336	24.58	0.2210	0.0744
ST2-2	0.0320	25.31	0.2200	0.0386
ST4-2	0.0234	20.47	0.2040	-0.0628
ST5-2	0.0212	16.80	0.2020	-0.1403
ST3-2	0.0260	21.70	0.1980	-0.0147
ST6-2	0.0168	13.63	0.1973	-0.2566

Figure 2.6.3.(2) Thermal Conductivity Vs. Time of Test for 'Thermalite' Samples in the 'Steady State'.



Curve	L, m	T_m °C	k, W/m K	$\frac{T_m-T_a}{T_1-T_2}$
ST1-3	0.0416	17.22	0.2158	-0.1434
ST6x2-3	0.0336	10.82	0.2106	-0.2966
ST2-3	0.0320	12.25	0.2007	-0.3152
ST3-3	0.0260	9.72	0.1887	-0.3974
ST6-3	0.0168	5.17	0.1866	-0.8104
ST5-3	0.0212	6.68	0.1810	-0.5925

Figure 2.6.3.(3) Thermal Conductivity Vs. Time of Test for 'Thermalite Samples' in the 'Steady State'.



Curve	L, m	T_m, °C	k, W/m K	$\frac{T_m-T_a}{T_1-T_2}$
ST1-4	0.0416	9.89	0.2041	-0.4380
ST6x2-4	0.0336	5.55	0.1918	-0.5555
ST2-4	0.0320	7.89	0.1870	-0.6373
ST3-4	0.0260	5.82	0.1751	-0.7580

Figure 2.6.3.(4) Thermal Conductivity Vs. Time of Test for 'Thermalite Samples' in the 'Steady State'.

Table 2.6.3. - 2 Calculation of the Relation $\xi = \frac{T_m - T_a}{T_1 - T_2}$ and its relation with The Thermal Conductivity of "Thermalite" Samples.

Sample No.	T_m, °C	T_a, °C	T_1, °C	T_2, °C	$\frac{T_m - T_a}{T_1 - T_2}$	k, W/m K	Correlation and (slope)	'k' Obtained for the given points
ST1-2	33.23	23.40	71.13	-4.66	0.1297	0.2274	0.9998	0.0 = 0.2219
ST1-3	17.22	23.50	29.11	-4.67	-0.1434	0.2158	(0.0410)	-0.1 = 0.2178
ST1-4	9.89	23.20	25.09	-5.30	-0.4380	0.2041		-1.0 = 0.1809
ST2-2	25.31	23.00	55.22	-4.61	0.0386	0.2200	0.9975	0.0 = 0.2175
ST2-3	12.25	23.70	30.41	-5.91	-0.3152	0.2007	(0.0489)	-0.1 = 0.2126
ST2-4	7.89	23.60	20.22	-4.43	-0.6373	0.1870		-1.0 = 0.1685
ST3-1	35.79	22.40	75.70	-4.12	0.1677	0.2102	0.9864	0.0 = 0.2019
ST3-2	21.70	22.50	48.85	-5.45	-0.0147	0.1980	(0.0355)	-0.1 = 0.1983
ST3-3	9.72	22.20	25.42	-5.98	-0.3974	0.1887		-1.0 = 0.1664
ST3-4	5.82	22.60	16.89	-5.25	-0.7580	0.1751		
ST4	47.70	23.00	97.25	-1.78	0.2494	0.2204	1.00	0.0 = 0.2072
ST4-2	20.47	23.50	44.58	-3.63	-0.0628	0.2040	(0.0525)	-0.1 = 0.2020
								-1.0 = 0.1547
ST5-1	28.35	22.50	60.92	-4.21	0.0898	0.2089	0.9952	0.0 = 0.2062
ST5-2	16.80	22.70	37.83	-4.23	-0.1403	0.2020	(0.0417)	-0.1 = 0.2021
ST5-3	6.68	22.50	20.04	-6.66	-0.5925	0.1810		-1.0 = 0.1645
ST6-1	21.92	22.50	47.60	-3.75	-0.0113	0.2089	0.9707	0.0 = 0.2071
ST6-2	13.63	22.50	30.92	-3.65	-0.2566	0.1973	(0.02644)	-0.1 = 0.02044
ST6-3	5.17	21.80	15.44	-5.08	-0.8104	0.1866		-1.0 = 0.1806
ST6x 2-1	41.89	19.70	89.80	-6.02	0.2316	0.2248	0.9682	0.0 = 0.2175
ST6x 2-2	24.58	19.90	56.04	-6.87	0.0744	0.2210	(0.0401)	-0.1 = 0.2135
ST6x 2-3	10.82	21.60	28.99	-7.35	-0.2966	0.2106		-1.0 = 0.1774
ST6x 2-4	5.55	19.90	18.47	-7.36	-0.5555	0.1918		

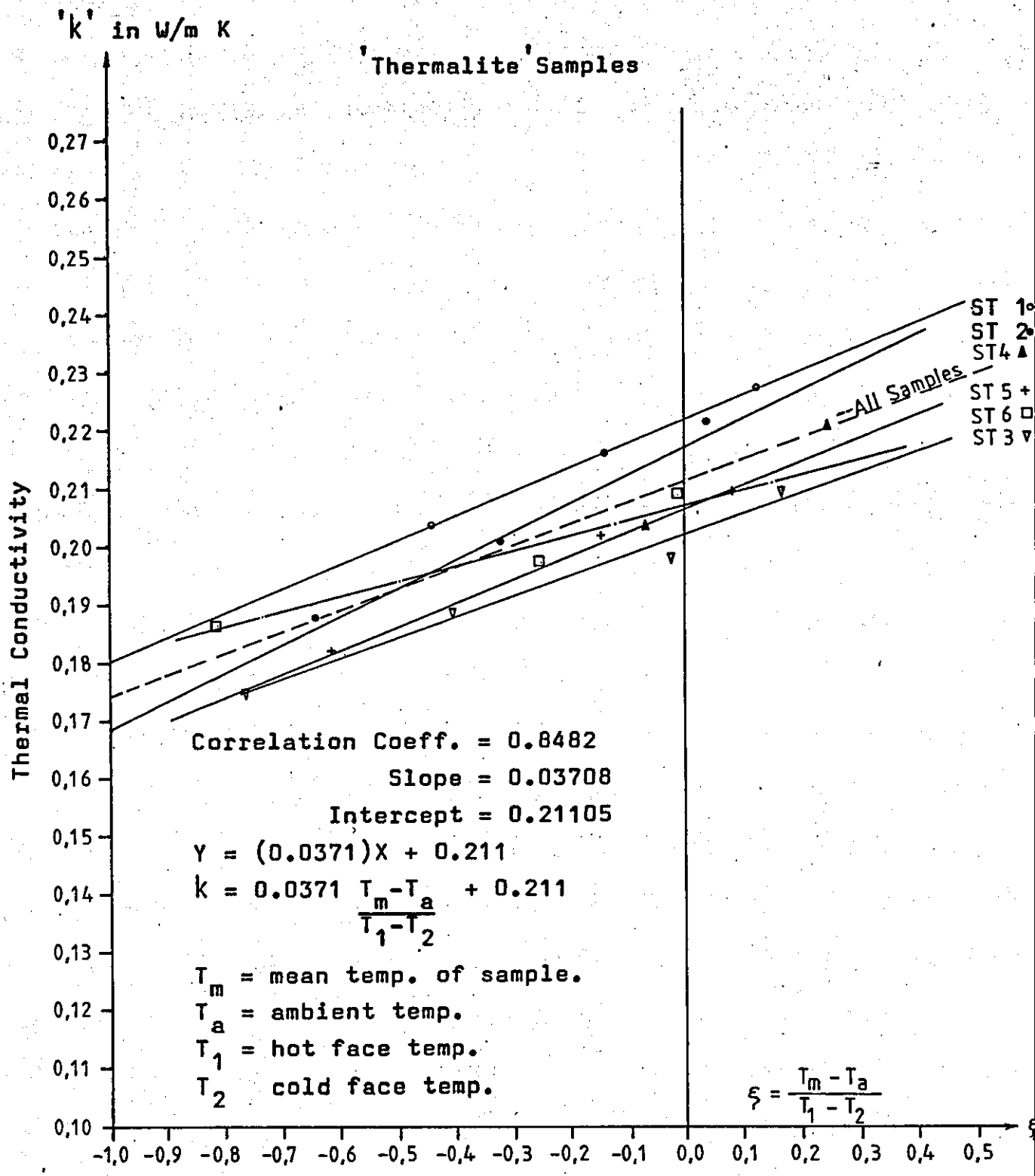


Figure 2.6.3.(5) Thermal Conductivity Vs. the ξ ratio of 'Thermalite' Samples in the 'Steady State' obtained from Table 2.6.3-2.

Table 2.6.3. - 3. Thermal Conductance of "Thermalite" Samples with the Correlation and Slope obtained for each sample

Sample No.	T_m, ^oC	Mean k, W/m K	Thermal Conductance $C = \frac{k}{L}$, W/m^2 K	Correlation and(slope)	"C" obtained for the given T
ST1-2 ST2-3 ST2-4	33.23 17.22 9.89	0.2274 0.2158 0.2041	5.4663 5.1875 4.9062	0.9772 (0.0229)	40 = 5.643 20 = 5.184 0 = 4.7255
ST2-2 ST2-3 ST2-4	25.31 12.25 7.89	0.2200 0.2007 0.1870	6.875 6.2718 5.8437	0.9833 (0.0562)	40 = 7.727 20 = 6.603 0 = 5.478
ST3-1 ST3-2 ST3-3 ST3-4	35.79 21.70 9.72 5.82	0.2102 0.1980 0.1887 0.1751	8.0846 7.6154 7.2577 6.7346	0.9625 (0.0407)	40 = 8.3072 20 = 7.494 0 = 6.681
ST4 ST4-2	47.70 20.47	0.2204 0.2040	9.4188 8.7180	1.00 (0.0257)	40 = 9.221 20 = 8.706 0 = 8.191
ST5-1 ST5-2 ST5-3	28.35 16.80 6.68	0.2089 0.2020 0.1810	9.8540 9.5283 8.5377	0.9486 (0.05998)	40 =10.669 20 = 9.470 0 = 8.270
ST6-1 ST6-2 ST6-3	21.92 13.63 5.17	0.2089' 0.1973 0.1866	12.4345 11.7440 11.1071	0.9996 (0.07923)	40 =13.8557 20 =12.271 0 =10.6864
ST6x 2-1 ST6x 2-2 ST6x 2-3 ST6x 2-4	41.89 24.58 10.82 5.55	0.2248 0.2210 0.2106 0.1918	6.6905 6.5774 6.2678 5.7083	0.8700 (0.02355)	40 = 6.765 20 = 6.294 0 = 5.823

All Samples	Correlation Coefficient	= 0.1022	40 = 8.1395
			30 = 7.959
	Slope	=(0.01802)	20 = 7.779
			10 = 7.599
	Intercept	= 7.4188	0 = 7.4188

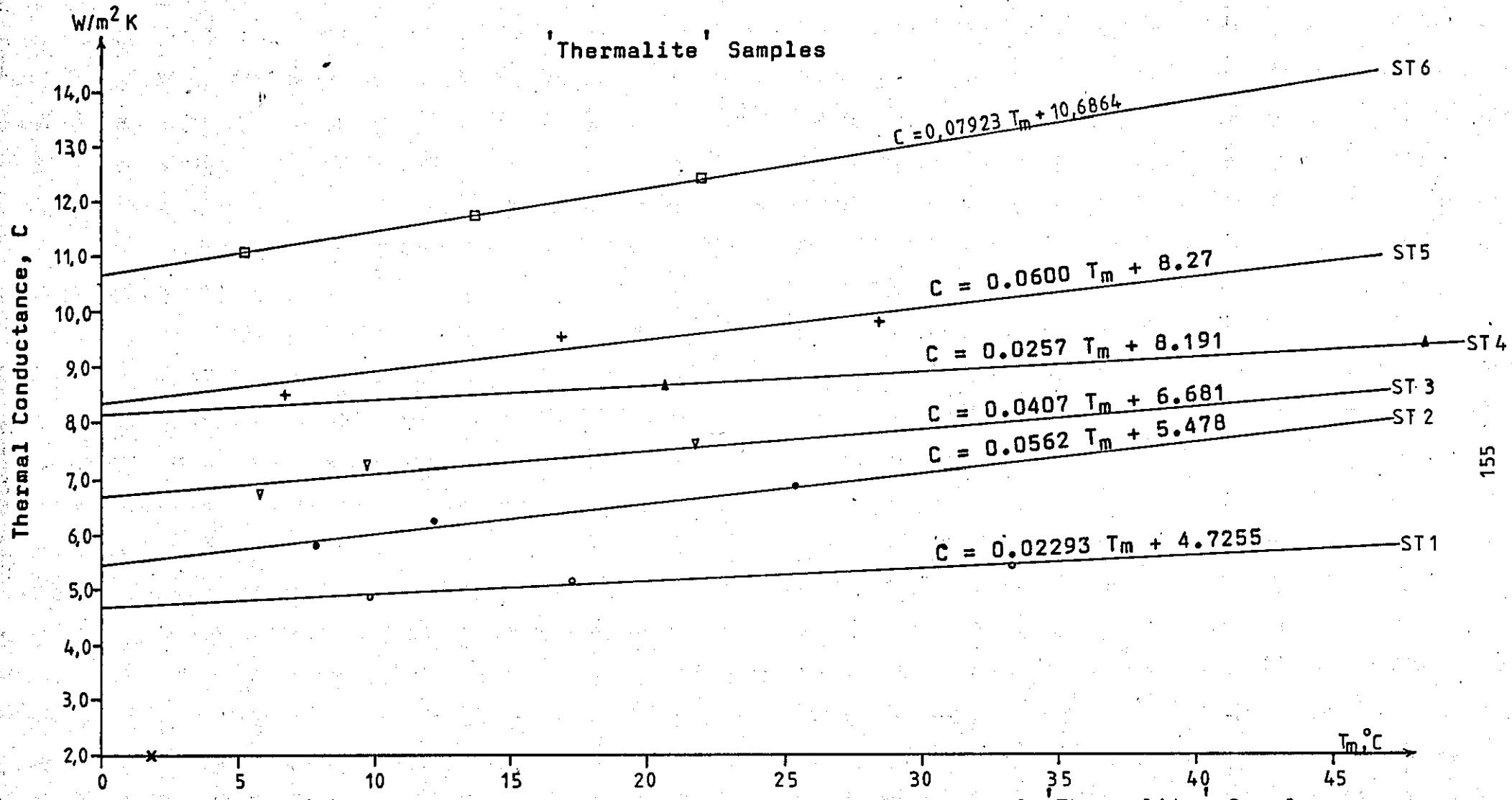


Figure 2.6.3.(6) Thermal Conductance C, Vs. Mean Temperature of 'Thermalite' Samples obtained from Table 2.6.3-3.

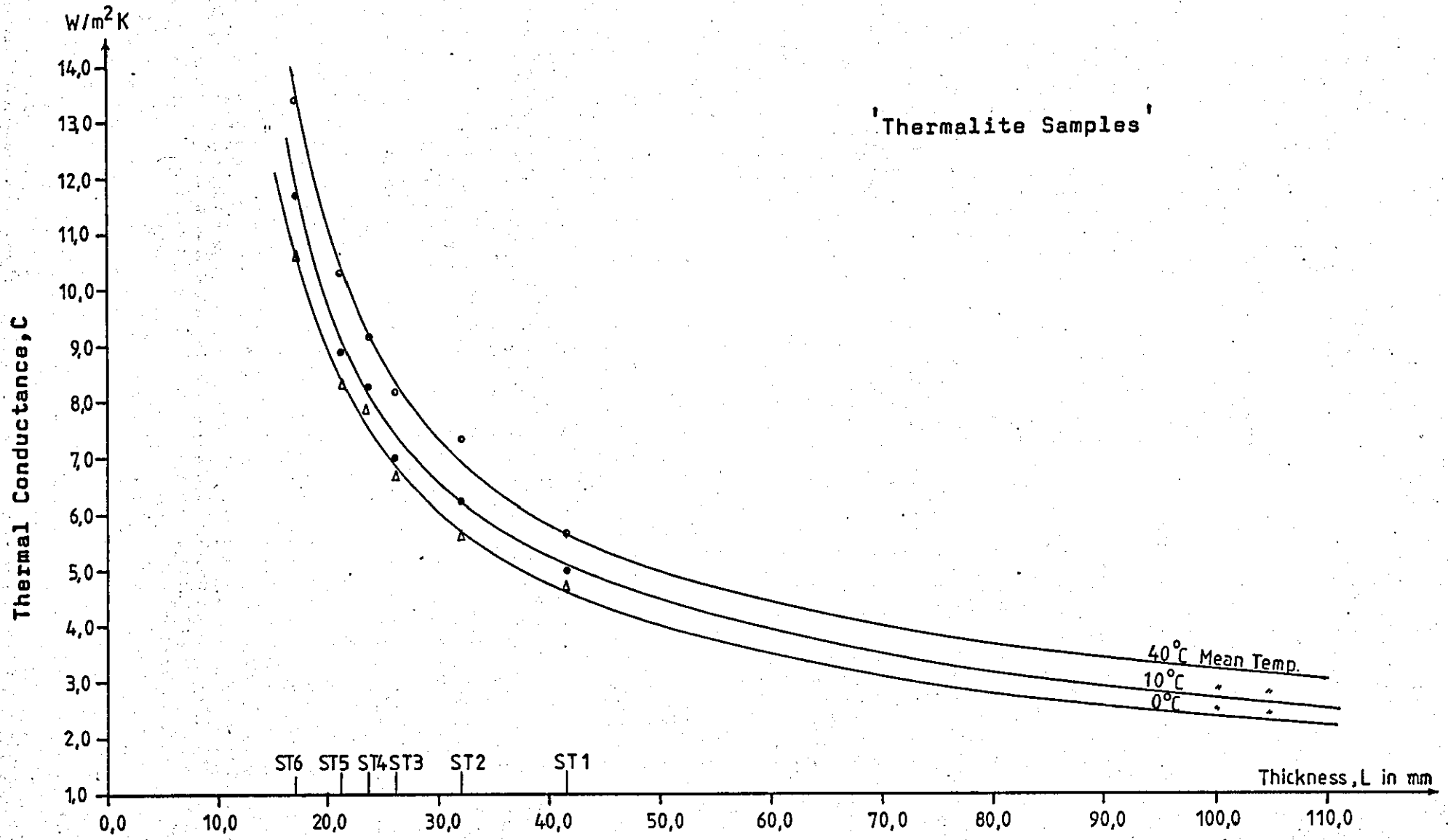


Figure 2.6.3.(7) Thermal Conductance Versus Sample Thickness : 'Thermalite' Samples.

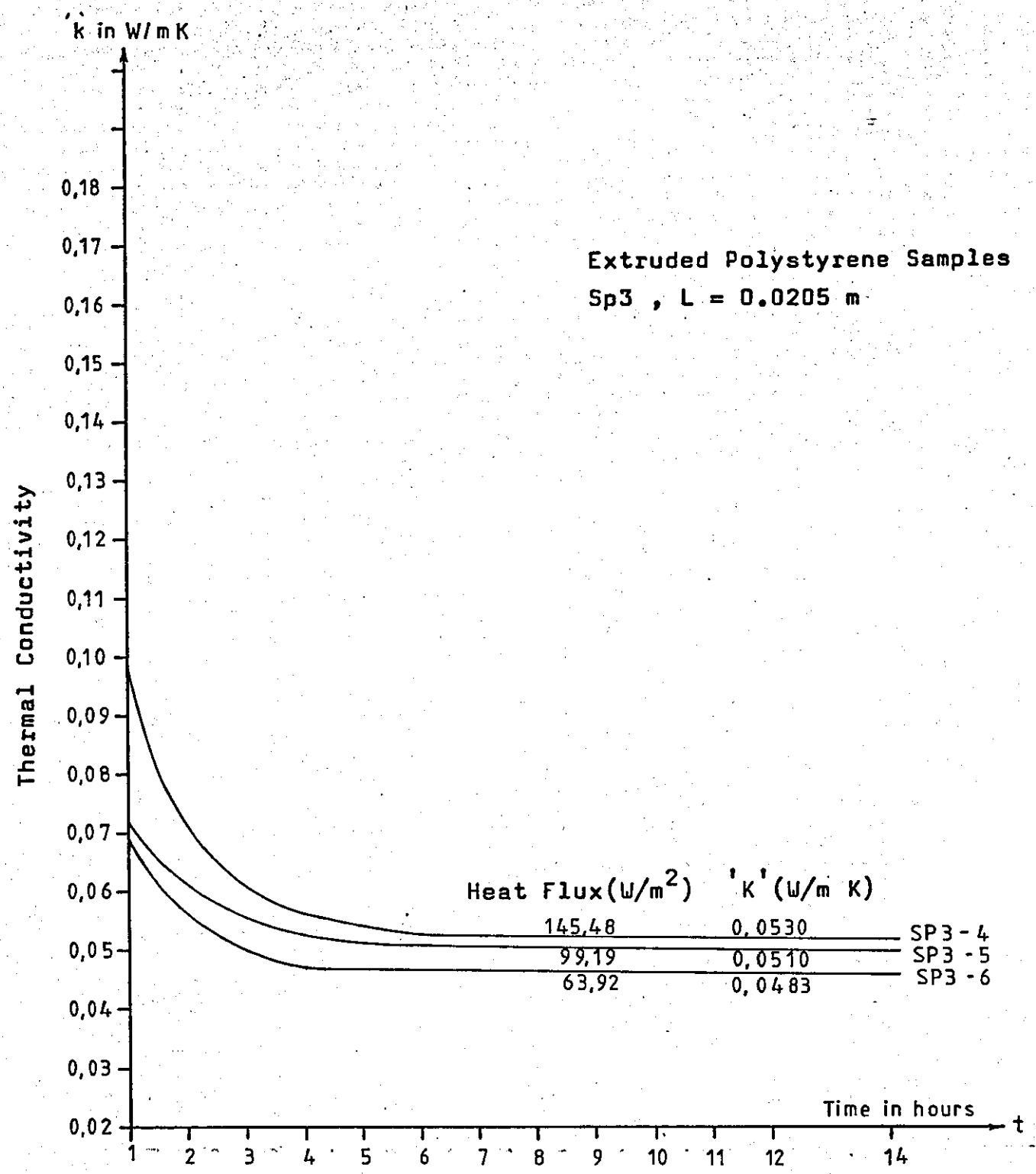


Figure 2.6.3.(8) Thermal Conductivity Vs. Time of Test for 'Styrofoam' Samples SP3 in the 'Steady State'.

Table 2.6.3. - 4 Calculation of the Relation $\xi = \frac{T_m - T_a}{T_1 - T_2}$ and its Relation with The Thermal Conductivity of "Styrofoam" (extruded polystyrene) samples

Sample No.	T_m, °C	T_a, °C	T_1, °C	T_2, °C	$\frac{T_m - T_a}{T_1 - T_2}$	k, W/m K	$x = \frac{k}{0.053} - 1$	'k' obtained for the given point
SP1-5	25.44	21.80	58.56	-7.68	0.0549	0.0755	+42.45	+0.1 0.0776 0.0 0.0729
SP1-6	15.86	21.50	39.90	-8.16	-0.1173	0.0674	+27.17	-0.1 0.0682 -0.5 0.0494 slope .0.047
SP2-5	23.69	23.10	54.82	-7.42	0.0095	0.0667	+25.85	+0.1 0.0693 0.0 0.0664
SP2-6	14.04	22.20	36.20	-8.11	-0.1842	0.0612	+15.47	-0.1 0.0636 -0.5 0.0522 slope 0.0284
SP3-4	20.34	21.20	48.50	-7.81	-0.0153	0.0530	0	+0.1 0.0541 0.0 0.0532
SP3-5	12.22	21.70	32.31	-7.86	-0.2360	0.0510	-3.77	-0.1 0.0522
SP3-6	6.80	21.00	20.76	-7.15	-0.5088	0.0483	-8.86 correlation slope	-0.5 0.0484 0.09997 0.00954

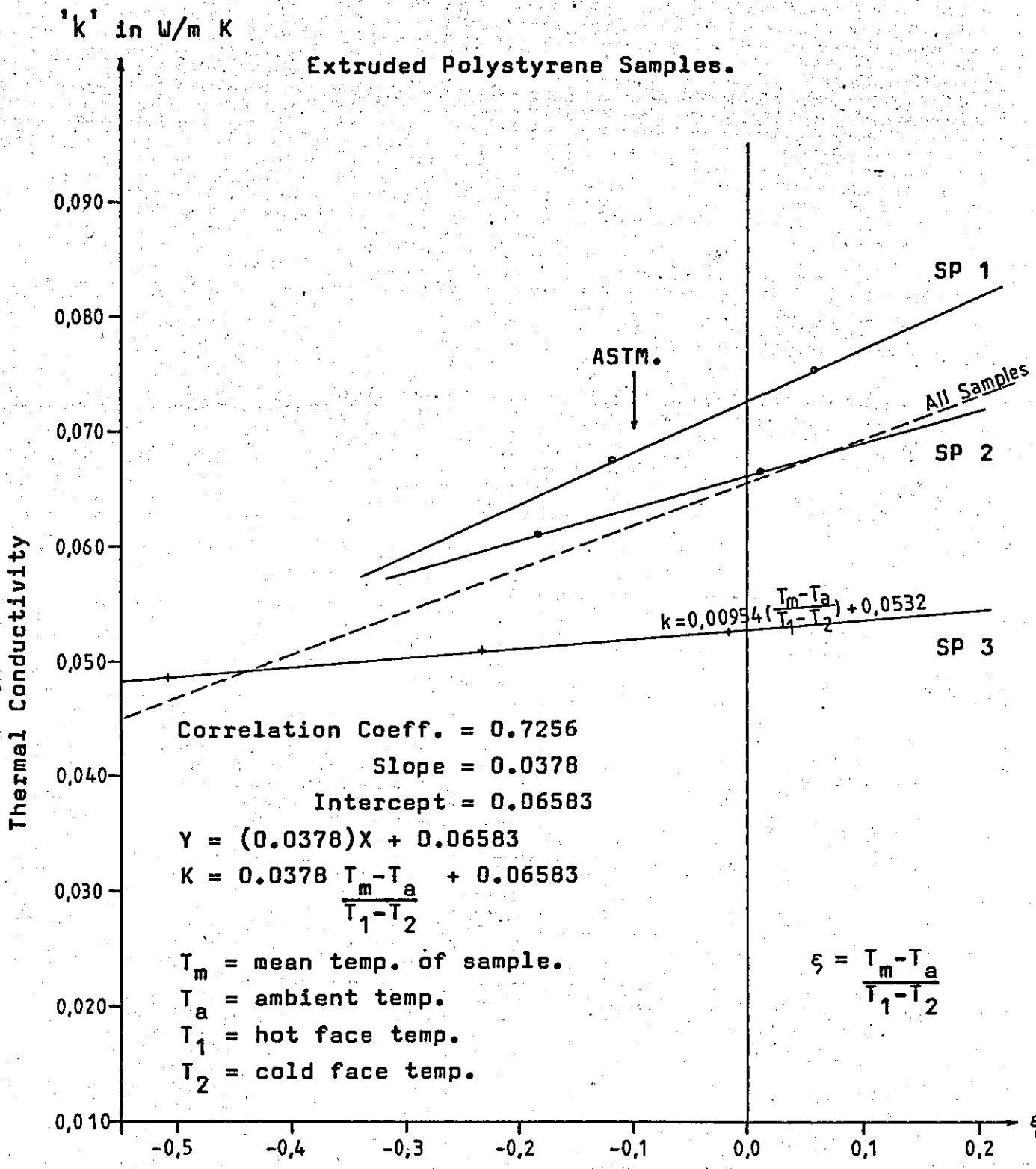


Figure 2.6.3.(9) Thermal Conductivity k, Vs. ξ ratio of 'Styrofoam' Samples in the 'Steady State' obtained from Table 2.6.3-4.

Table 2.6.3. - 5 Thermal Conductance of "Styrofoam" (extruded polystyrene) Samples, with the correlation coefficient and slope obtained for each sample.

Sample No.	T_m, °C	Mean k, W/m K	Thermal Conductance $C = \frac{k}{L}$, W/m^2 K	Correlation and (slope)	'C' Obtained for the given T,
SP1-5	25.44	0.0755	1.4950	1.00	40 = 1.7388
SP1-6	15.86	0.0674	1.3346	(0.01674)	20 = 1.4039
					0 = 1.0690
SP2-5	23.69	0.0667	1.611	1.00	40 = 1.8355
SP2-6	14.04	0.0612	1.4783	(0.01376)	20 = 1.5603
					0 = 1.2851
SP3-4	20.34	0.0530	2.5853	0.97995	40 = 2.9210
SP3-5	12.22	0.0510	2.4878	(0.01654)	20 = 2.5902
SP3-6	6.80	0.0483	2.3561		0 = 2.2594

	Correlation Coefficient	-0.3993	40 = 1.1526
All Samples	Slope	-0.0326	20 = 1.806
	Intercept	2.459	0 = 2.459

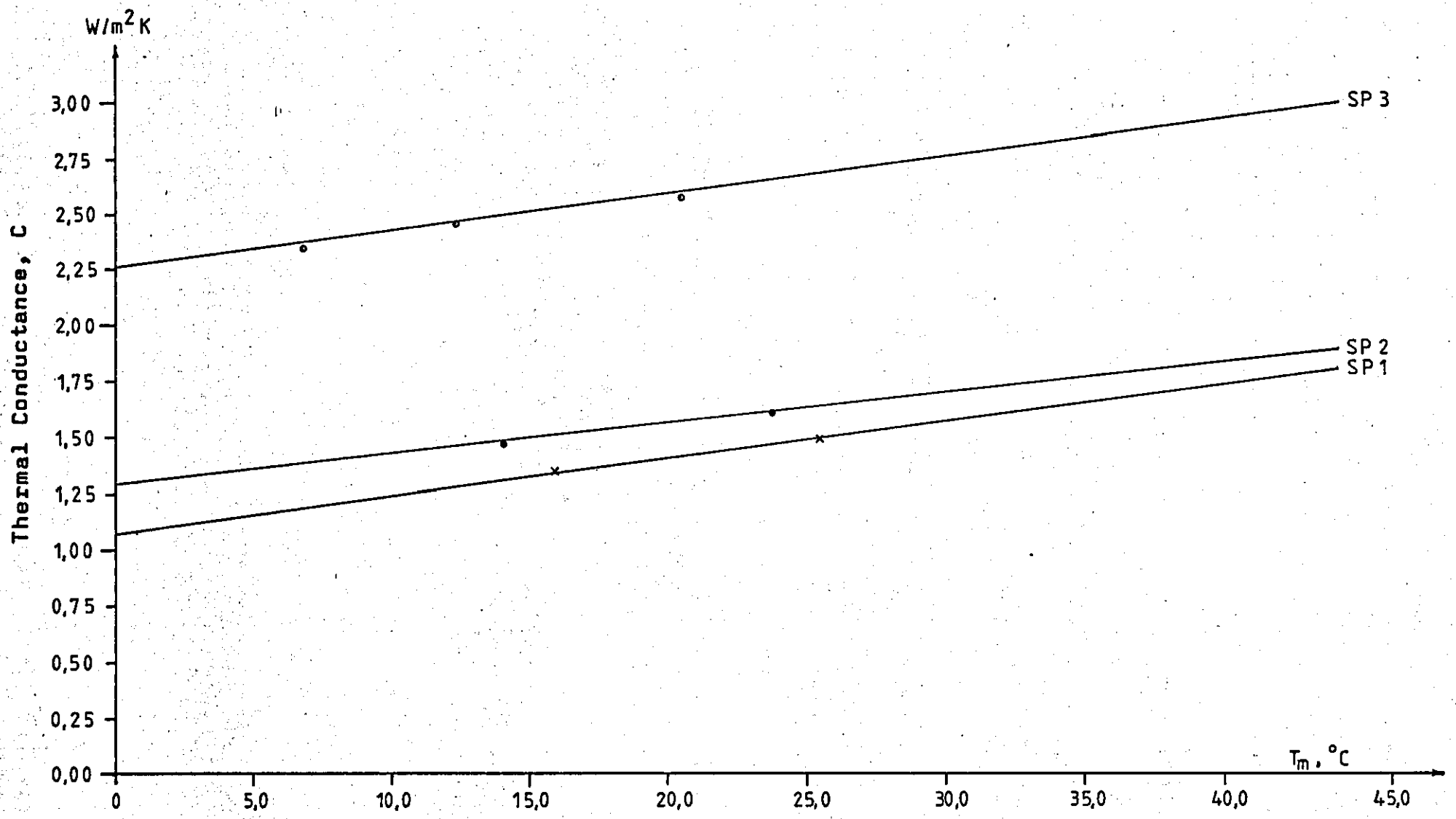


Figure 2.6.3.(10) Thermal Conductance Versus Mean Temperatures of 'Styrofoam' Samples obtained from Table 2.6.3-5

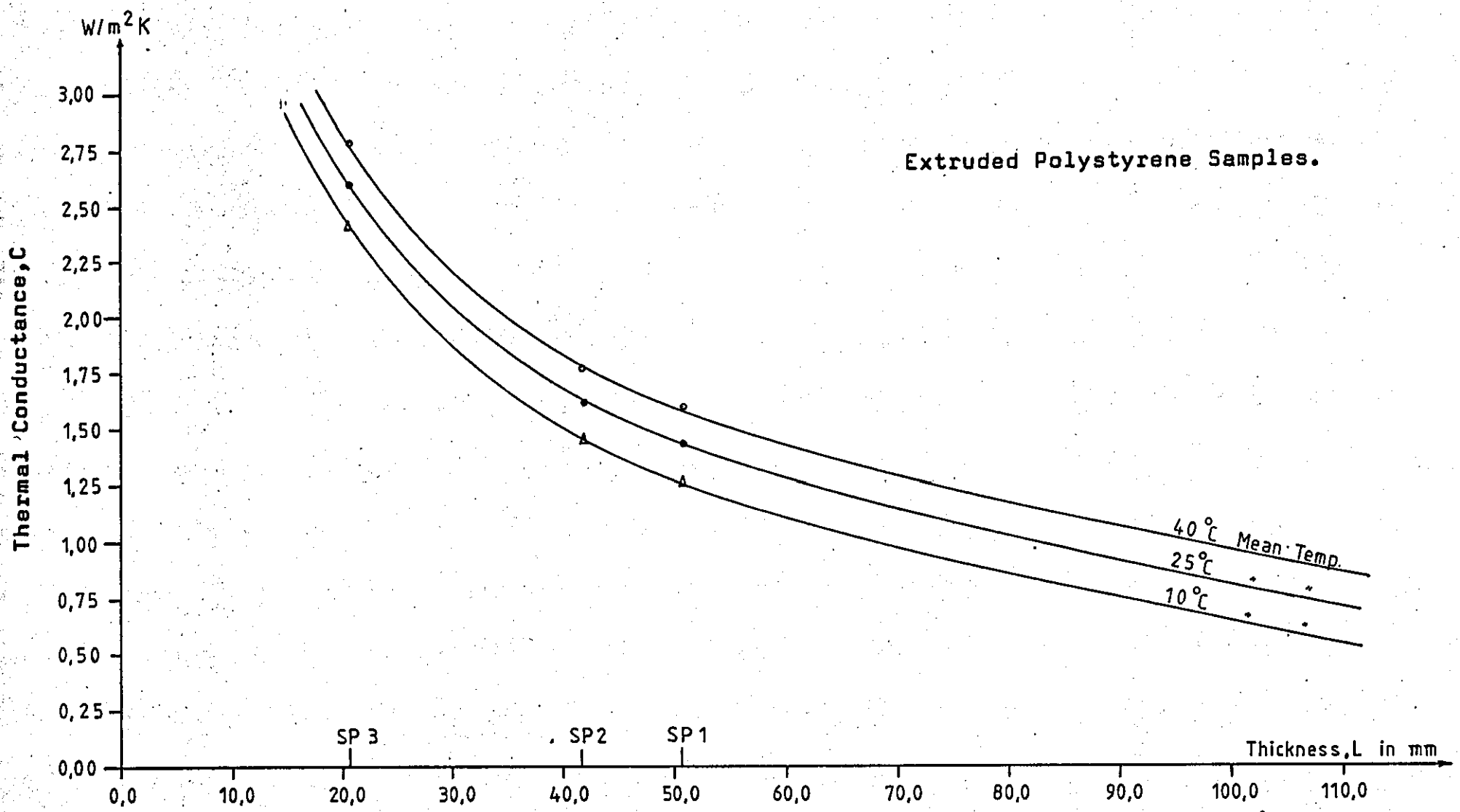


Figure 2.6.3.(11) Thermal Conductance Versus Sample Thickness : 'Styrofoam' Samples.

2.6.4. Composite Materials

The most common method which covers the measurement of thermal conductance and thermal transmittance of composite materials (panels) is the guarded hot box method. This method is covered in detail by the American Standard ASTM C 236 - 66 [100]. The construction of such an apparatus is very costly and complicated. The only test apparatus constructed in compliance with ASTM C236 in the U.K. is that of the Agrément Board [101]. It can measure the U-values of wall, roof and floor constructions of sizes up to 3 m by 3.5 m by 0.5 m thick . The experimental sample under investigation is composed of two layers, involving "Thermalite" block and extruded polystyrene board insulation. It is assumed that the two layers are in intimate contact with no air layers, as these would affect the experimental results. The apparatus used for testing these composite laminates was the guarded hot plate used for obtaining the thermal conductivity of the homogeneous component materials. The only difference was the use of heat flow "Sensables" which gave a direct readout in units of heat flow. The samples used were obtained from the same batch of materials used in the testing of homogeneous materials described in the previous sections.

Figures 2.5.4. (1) to 2.5.4. (11) show the values of thermal conductivities plotted against the time intervals for the four combinations of "Thermalite" and extruded polystyrene. The circles represent the average of three values of 'k_A' calculated by the steady state equation $k_A = \frac{q.L_c}{A(T_1 - T_2)}$, the result

is the overall value of thermal conductivity of the composite. The squares represent the average of three values calculated by using the model developed in section 2.2.3.3. In this model (originally developed for fibre reinforced composites) of unit volume, the total volume of reinforcement (foam) is concentrated into a single layer, and the matrix arranged into another layer adjacent to the first one. Both layers are arranged in series with respect to the direction of heat flow. The total resistance R of the composite will be the highest using this arrangement, and is calculated from the relation

$$R = \frac{1}{k_c} = \frac{V_F}{k_F} + \frac{1 - V_F}{k_M}$$

or

$$k_c = \frac{k_M \; k_F}{V_F \; k_M + (1 - V_F) \; k_F}$$

The fibre reinforcement is considered to be replaced in this instance by the "Styrofoam" (extruded polystyrene) layer, and the matrix is considered to be the "Thermalite layer. The thermal conductivity values were found to be in full agreement with those calculated using the "steady state" equation. The difference between these values is $\pm$ 3.5%. The reason for these differences is due to the difference between the temperatures of the cold plates and the temperatures obtained from the thermocouples embedded into the cold faces of the samples. The four combinations of samples have different thicknesses and different volumes of fibre (extruded polystyrene). These are shown in

Table 2.5.4. (1). The minimum thickness is attained for sample SC3, where L_c = 0.0374 m and the maximum thickness is attained for sample SC4, where L_c = 0.0648 m. It is expected that the edge heat losses for the above samples are excessive, as the most suitable thickness should not exceed one-sixth the diameter of the heating unit (d = 0.152m). However, the preparation of very thin layers of samples is not practical and can not be representative as the heat flow should pass many granules of the material. By analysing the results, it is seen that the values of both k_A and k_c decrease with decreasing heat flux and the mean temperatures of the samples. Also as the thickness (or volume) of extruded polystyrene in the composite sample increases, the overall thermal conductivity decreases. The thermal conductivity values of "Thermalite" k_M, and extruded polystyrene k_F used in calculating k_c are much higher than those obtained by testing them as homogeneous materials, except when the mean tmperature of the "Thermalite" is near the ambient temperature during the test. One reason is that the temperature gradient across the "Thermalite" sample is less than 15°C and the temperature gradient across the extruded polystyrene is very high.

Figures 2.5.4. ($\overline{1}$) to 2.5.4. ($\overline{11}$) show the values of the rate of heat flow per unit area, $\ddot{q}$ plotted against the time intervals during the test. These values are obtained from the heat flow sensables directly in the units of the heat flux. The measured $\ddot{q}$ values correspond with the heat input across the layered samples, and the heat losses from the edges will not effect

the results as the heat flow "Sensables" will record the net heat flow passing the samples. The thermal conductivity values of both the "Thermalite" k_M and the extruded polystyrene k_F samples in the composite combinations are calculated using the heat flux values obtained from the heat flow sensables, as shown in Table 2.6.4. - 1 The mean k_M is 0.21163 W/m K, this is 2.84% higher than the true 'k' value (0.2056 W/m K). The mean k_F is 0.05165 W/m K, this is 2.91% lower than the true 'k' value (0.0532 W/m K). These results are considered accurate enough considering the overall accuracy of the apparatus.

The thermal conductivities of the composite samples $\bar{k}_c$ are calculated using the values of heat flux $\ddot{q}$. The results are shown in Tables 2.5.4. - 6 to 2.5.4. - 16. It is clear that the values of k_A and k_c of the samples before reaching the "steady state" conditions, will be too high, as the relations for k_A and k_c are based on the steady conditions. Comparing the results of the samples in the "steady state", $\bar{k}_c$, k_A and k_c agree very well with each other for the lower range of heat flow. Table 2.5.4. -17 shows the % difference between the measured thermal conductivity values. The lower difference is obtained when the sample thickness is a minimum as indicated in the case of samples SC3-4, SC3-5 and SC3-6 (L_c = 0.0374 m). These are 12.41%, 6.68%, and-0.24% , lower than k_A values.

The difference between k_A and $\bar{k}_c$ is maximum for samples SC4-5 and SC4-6. These differences are 29.73% and 24.52% respectivley. The reason for this is due to the large thickness of these samples (L_c = 0.0648 m). The % difference between the maximum heat flux $\ddot{q}$ and the imposed heat flux q/A is also shown in Table 2.5.4. -17. These values increase when the thicknesses of samples increases or their mean temperatures increase. The values of $\bar{k}_c$ shown in the above table represent the true values for the composites without any effect due to the edge heat losses. The mean $\bar{k}_c$ values for samples SC1, SC2, SC3 and SC4 are 0.0967 (S.D.= 0.0014), 0.0885 (S.D.= 0.0014), 0.0800 (S.D.= 0.00149) and 0.0730 W/m K (S.D. = 0.002) respectively. These values are plotted against the extruded polystyrene (fibre) content in the composite , as shown in Figure 2.6.4. (1). Mean k_A and k_c values are plotted on the same figure, but as their values are scattered, it is difficult to fit any curve through them. The value of thermal conductivity for any composite sample can be estimated without any significant error from the plot of $\bar{k}_c$. If this curve is extrapolated at both ends, for V_F = 1 , the composite contains only extruded polystyrene and k_F = 0.049 W/m K. When V_F = o, the composite contains only "Thermalite", and $k_M \simeq 0.20$ W/m K.

Three theoretical approaches, $k_c = V_F k_F + (1-V_F) k_F$ (weighted arithmetic mean), $k_c = k_M^{(1-V_F)} . k_F^{V_F}$ (weighted geometric mean) and $k_c = \frac{k_M . k_F}{V_F k_F + (1-V_F) k_M}$ (weighted harmonic mean) are also plotted on the same graph. The values of the thermal conductivities, k_c are shown in Table 2.6.4-2. It is evident from the graph that the weighted harmonic mean approach correlates well with the bulk thermal conductivity values calculated from $k_c = \frac{\ddot{q} . L_c}{T_1 - T_2}$, using data from the heat flow sensables. The other two approaches do not give any correlation. The reason for this is that the harmonic mean approach is the best analogy for the experimental arrangement of the samples, in which the two component materials were connected in series with the hot and cold plates to form a laminate.

Table 2.6.4. -1 Thermal conductivities of "Thermalite" k_M and "Styrofoam" (extruded polystyrene) k_F for the shown composites.

Sample No.	k_M W/m K	k_F W/m K
SC1-4	0.2309	0.05026
SC1-5	0.2500	0.04842
SC1-6	0.1659	0.05139
SC2-3	0.2016	0.05485
SC2-4	0.1992	0.05500
SC2-5	0.1932	0.05690
SC3-4	0.2309	0.04979
SC3-5	0.2397	0.05203
SC3-6	0.1374	0.05182
SC4-5	0.2530	0.0500
SC4-6	0.2263	0.04772
Mean	0.21163	0.05165
Standard Deviation	0.0362	0.00288
Variance	0.001192	7.6×10^{-6}

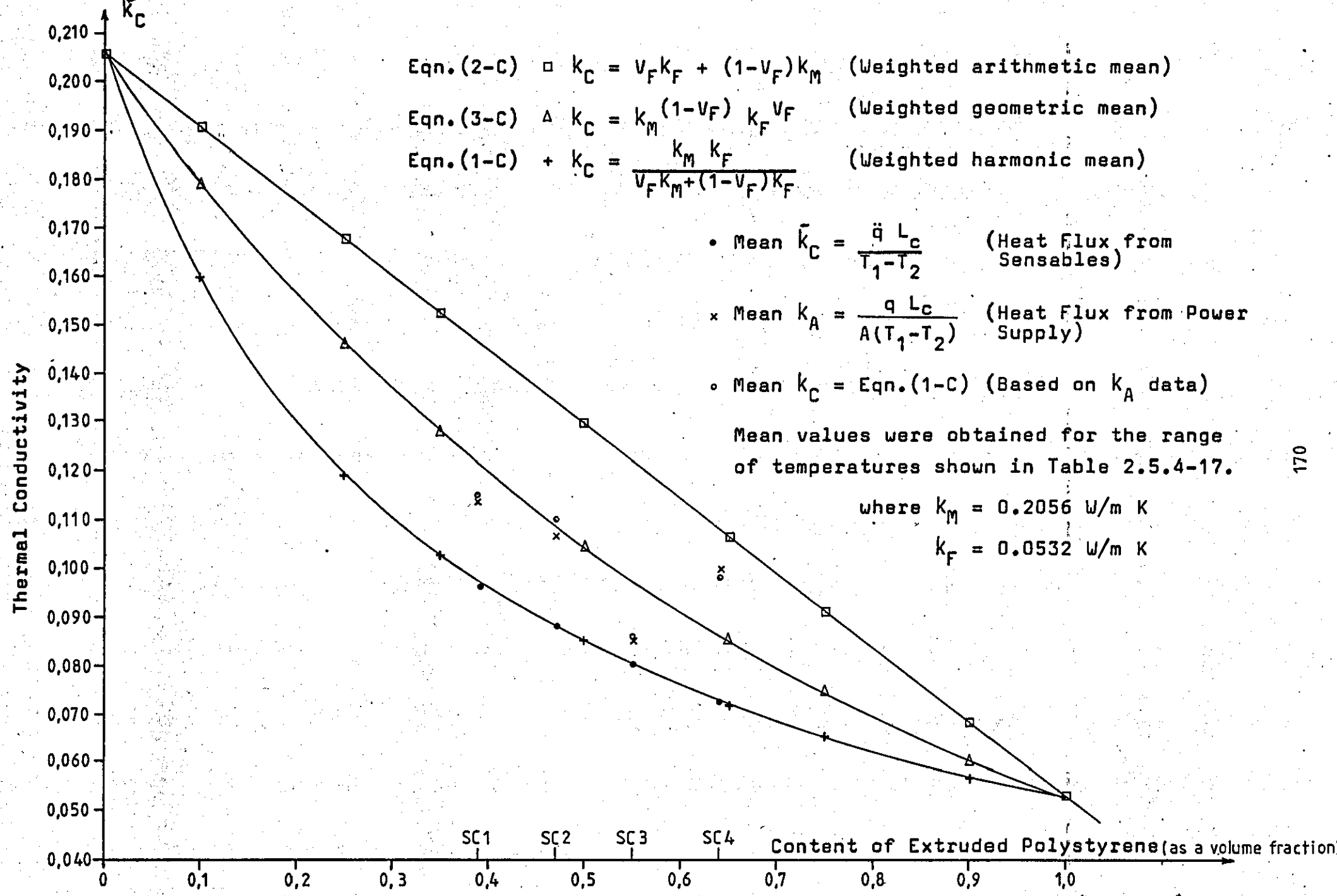


Figure 2.6.4 (1) Thermal Conductivity k Versus Extruded polystyrene content in the Composite "Thermalite/Styrofoam"

Table 2.6.4. - 2 Thermal conductivities of Composite Samples 'k_c', in W/m K calculated from the three equations, (1-C), (2-C) and (3-C) for the given Foam Volume Fraction shown in column (4).

Sample No.	Sample Thickness L_c, m	Foam Volume Fraction V_F	V_F	Thermal Conductivities, k_c, W/m K		
				Eqn. (1-C)	Eqn. (2-C)	Eqn. (3-C)
			0.00	0.2056	0.2056	0.2056
SC1	0.0526	0.392	0.10	0.1598	0.19036	0.1796
			0.25	0.1198	0.1675	0.1466
SC2	0.0440	0.468	0.35	0.1027	0.1522	0.1281
			0.50	0.0845	0.1294	0.1046
SC3	0.0374	0.551	0.65	0.0718	0.1065	0.0854
			0.75	0.0653	0.0913	0.0746
SC4	0.0648	0.639	0.90	0.0575	0.0684	0.0609
			1.00	0.0532	0.0532	0.0532

Equation (1-C) $$k_c = \frac{k_M \quad k_F}{V_F\, k_M + (1-V_F)\, k_F}$$

Equation (2-C) $$k_c = V_F\, k_F + (1-V_F)\, k_M$$

Equation (3-C) $$k_c = k_M^{(1-V_F)} \quad k_F^{\,V_F}$$

Where: Thermal conductivity of Thermalite = 0.2056 W/m K.
Thermal conductivity of Styrofoam = 0.0532 W/m K.
For sample mean temperatures = room temperature.

2.7. Conclusions

1. The thermal conductivities of "Styrofoam" IB (extruded polystyrene foam) and "Theramlite" (aerated cement building block) and composite combinations of the two may only be successfully measured using a guarded hot plate type of apparatus providing a whole series of precautions are taken including:

   a. extreme care with sample preparation, geometry and conditioning and,

   b. ensuring sample thickness is less than one sixth of sample diameter (to reduce edge heat loss)

   c. heat flux is measured directly by heat flow sensables (in the case of composite samples).etc.

2. If the composite laminate is considered theoretically as an "in-series" network of resistances the apparant bulk composite thermal conductivity may be described by the equation

$$k_c = \frac{k_M \cdot k_F}{V_F\, k_M + (1 - V_F)\, k_F}$$

where k_c = thermal conductivity of composite

k_M = thermal conductivity of "Thermalite"

k_F = thermal conductivity of "Styrofoam"

V_F = volume fraction of "Styrofoam" in total composite.

The equation effectively describes the weighted harmonic mean of the component thermal conductivities. The k_c value generated by the equation at different volume fractions correlates well with directly measured values of the bulk (overall) composite thermal

conductivities providing in all cases the heat flux data from heat flow sensables are used. If the data from the sensables are not used, then k_c value still correlates very well with the bulk thermal conductivity but both values are not accurate and do not fit the weighted harmonic mean graph.

3. Two alternative theoretical approaches for establishing 'k_c' involving the weighted arithmetic mean and the weighted geometric mean of component 'k' values have been found less effective than using the weighted harmonic mean described above. This is because the composite sample was arranged as a laminate of its component materials and as such, only satisfied the in-series net of resistances assumed in the theoretical model, whenever the other two approaches did not satisfy the experimental arrangements.

4. The theoretical time to reach the "steady - state" condition can be calculated from the complete solution of the homogeneous single layer given by Carslaw and Jaeger. This was found to be very much lower than the experimental time because it was assumed theoretically by Jaeger that the cold face temperature was zero. This was difficult to attain practically without waiting a long time before starting the test.

5. Both the bulk composite thermal conductivities and the thermal conductivities of its components may be predicted whilst the apparatus is in a non "steady state" mode providing heat flux data is provided by heat flow sensables. Also, provided this condition is met the accuracy of the results appear less dependent on overall sample thickness and subsequent energy loss through edge effects.

2.8. Suggestions for Further Work

1. The new approach of measuring thermal conductivities in non "steady state" conditions should be used to investigate new composite materials in the field of civil engineering.

2. The thermal behaviour of the existing walls and roofs of some houses may be investigated under extreme climatic conditions.

3. Field studies are required to investigate some polymeric composites and cellular plastics and their effectiveness in reducing heat flow.

4. An environmental chamber is required to study the effect of extreme climates, such as intense heat, high or low humidities and rain penetration on selected number of composites.

5. Studies on the effect of transient heat conduction in composite structures should be made and compared with steady state values using the above chamber.

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FIGURES AND TABLES

Figure 1: Traditional houses in Jeddah, with windows and balconies facing west to capture sea breezes.

Figure 2: Traditional houses in the background, with white washed walls and many windows.

Figure 3: Sun-dried, mud-brick house in Riyadh, with only a few windows facing to the outside.

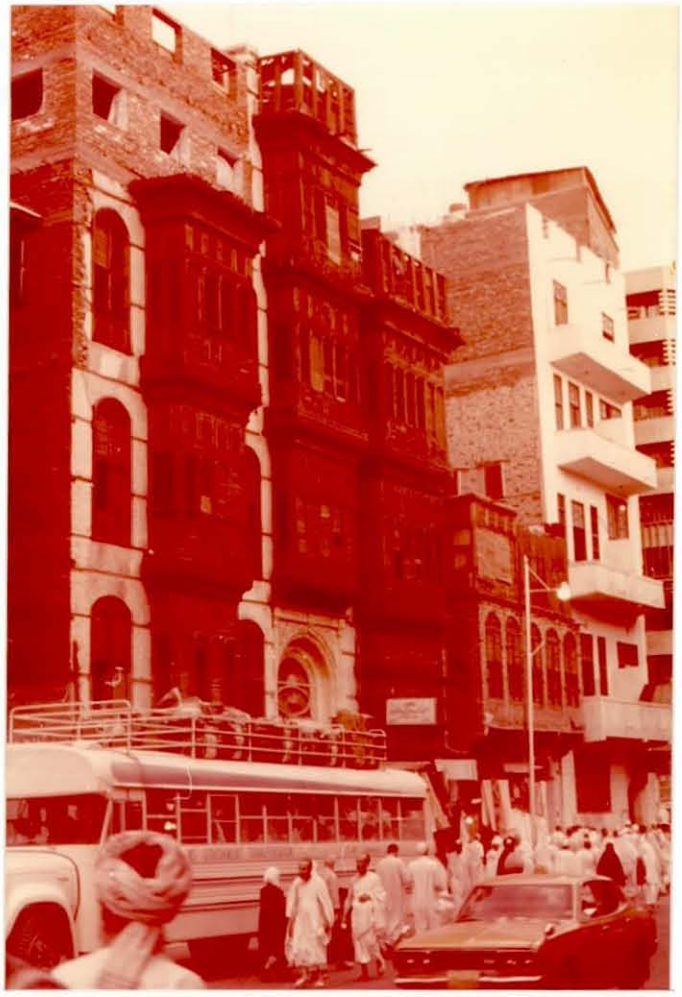

Figure 4:
Traditional houses in Mecca, with thick walls and large windows.

Figure 5: Traditional houses in Mecca, with thick granite walls.

Figure 6: Part of a traditional house in Jeddah, built with coral stones.

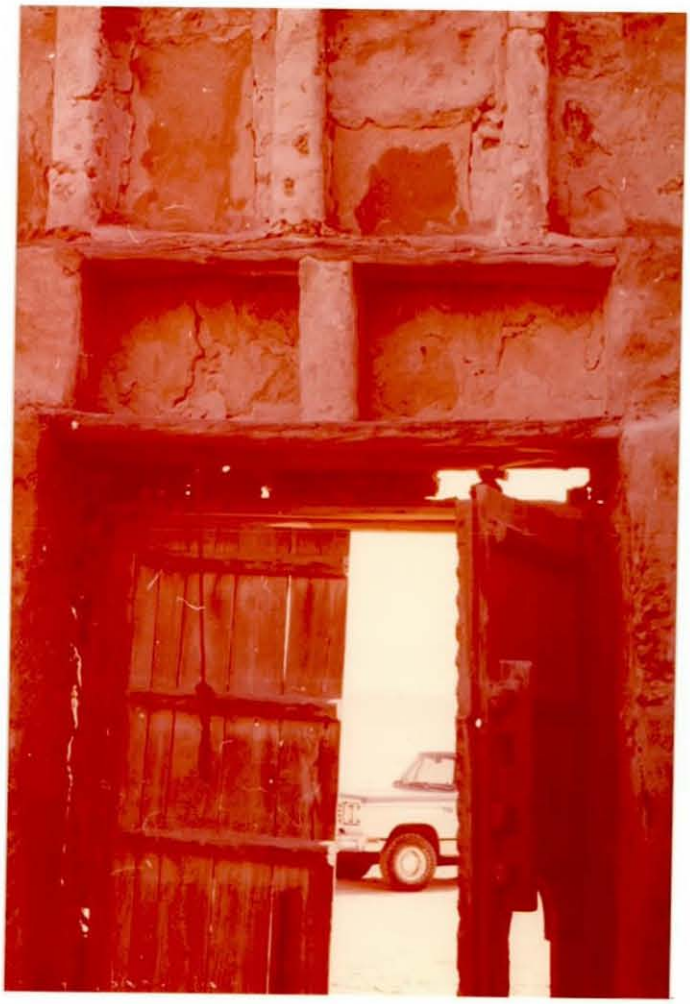

Figure 7: Inside of an external wall, where coral slabs are used and fixed with loam plaster, Dreen - East Coast of Saudi Arabia.

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Figure 9:
Close up showing the irregular stone wall structure of the above house.

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Figure 20: Natural trees used to shade windows, Jeddah.

Figure 21: Natural trees used to protect a house -to the left- from the sun, and another house painted white to reflect radiation.

Figure 22: Windows facing North and West to catch sea breezes, Jeddah.

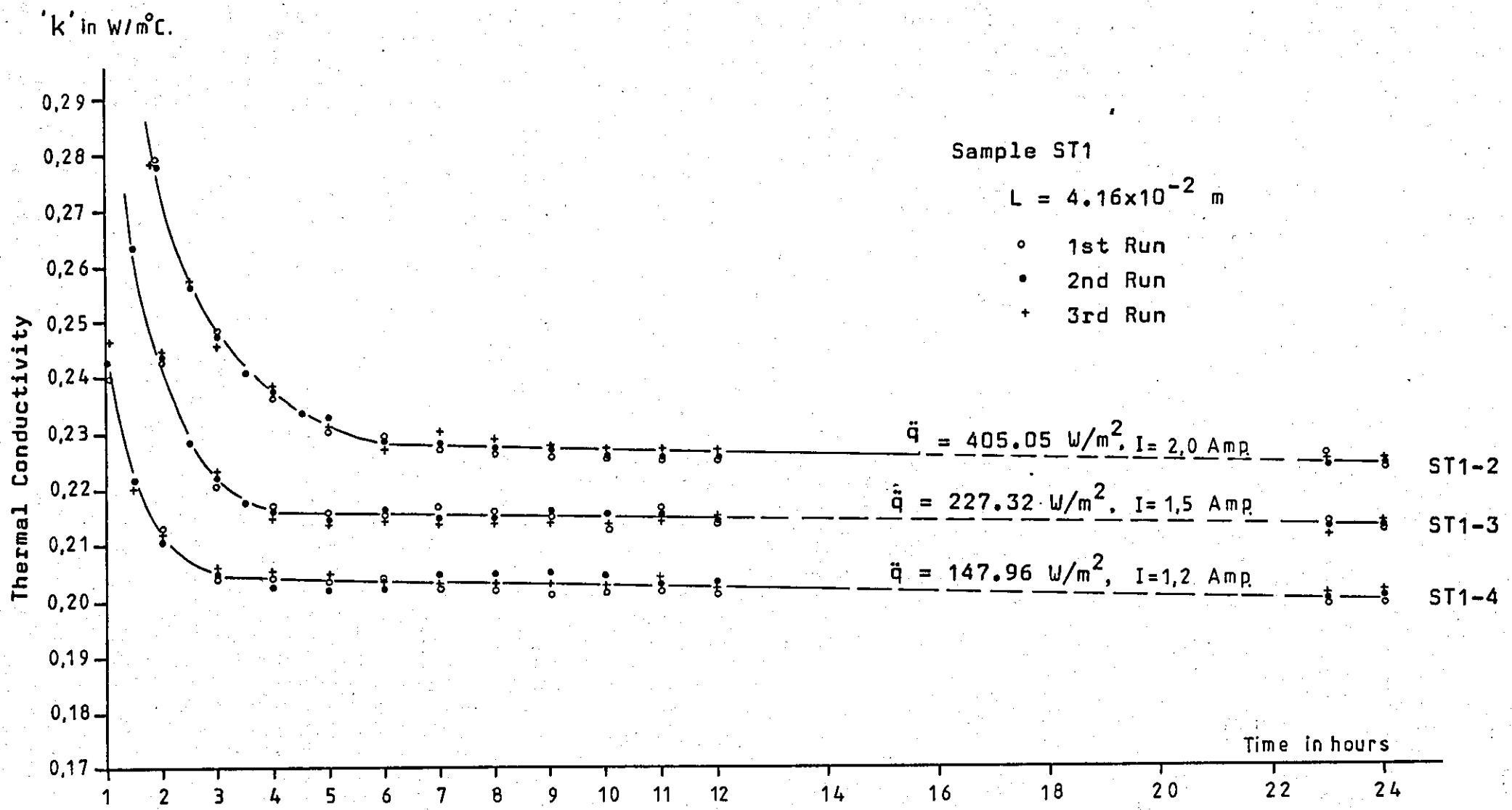


Figure 2.5.3.(1) Thermal Conductivity Versus Time : Thermalite Samples ST1

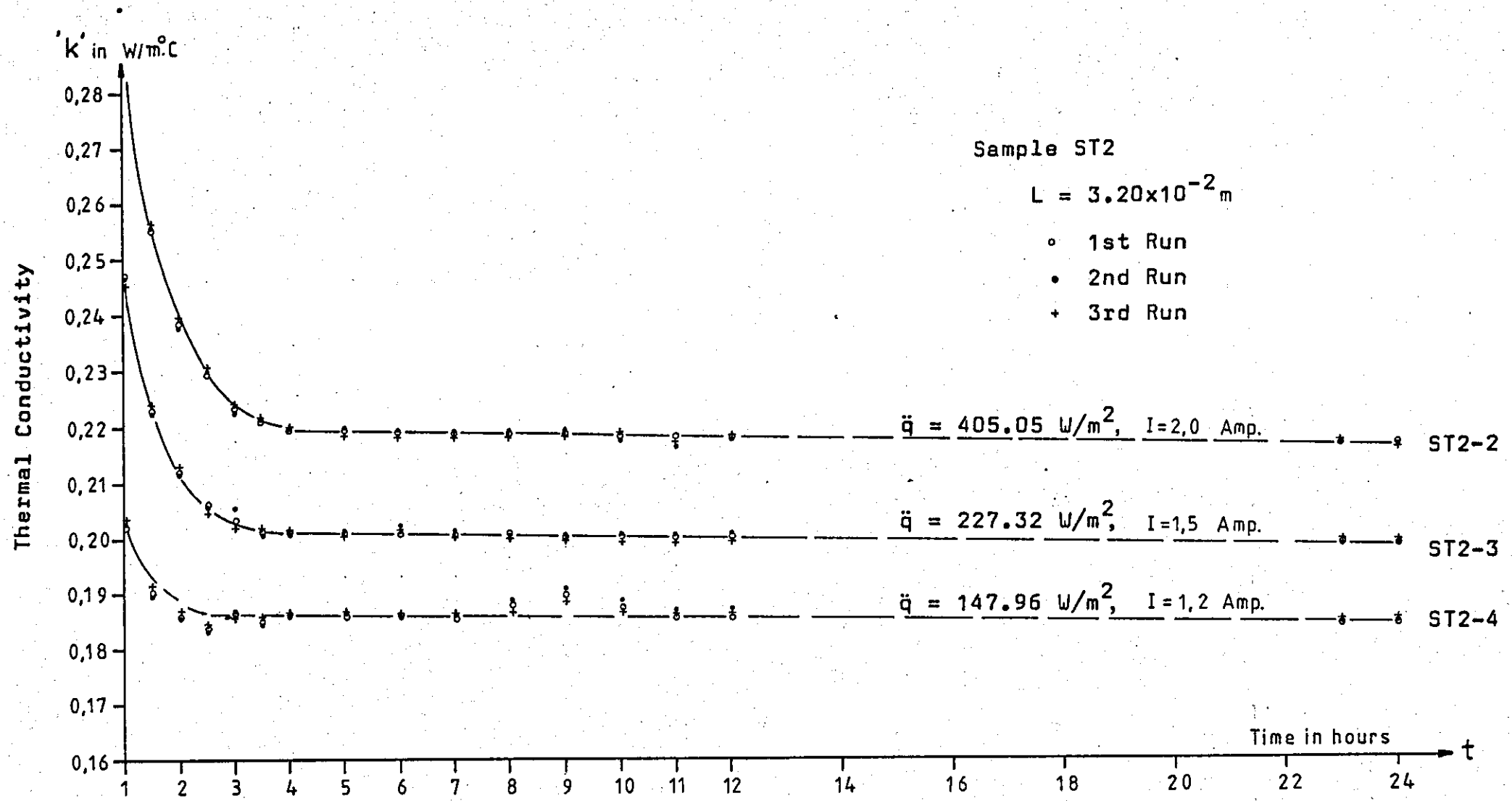


Figure 2.5.3.(2) Thermal Conductivity Versus Time of Test : Thermalite Samples ST2

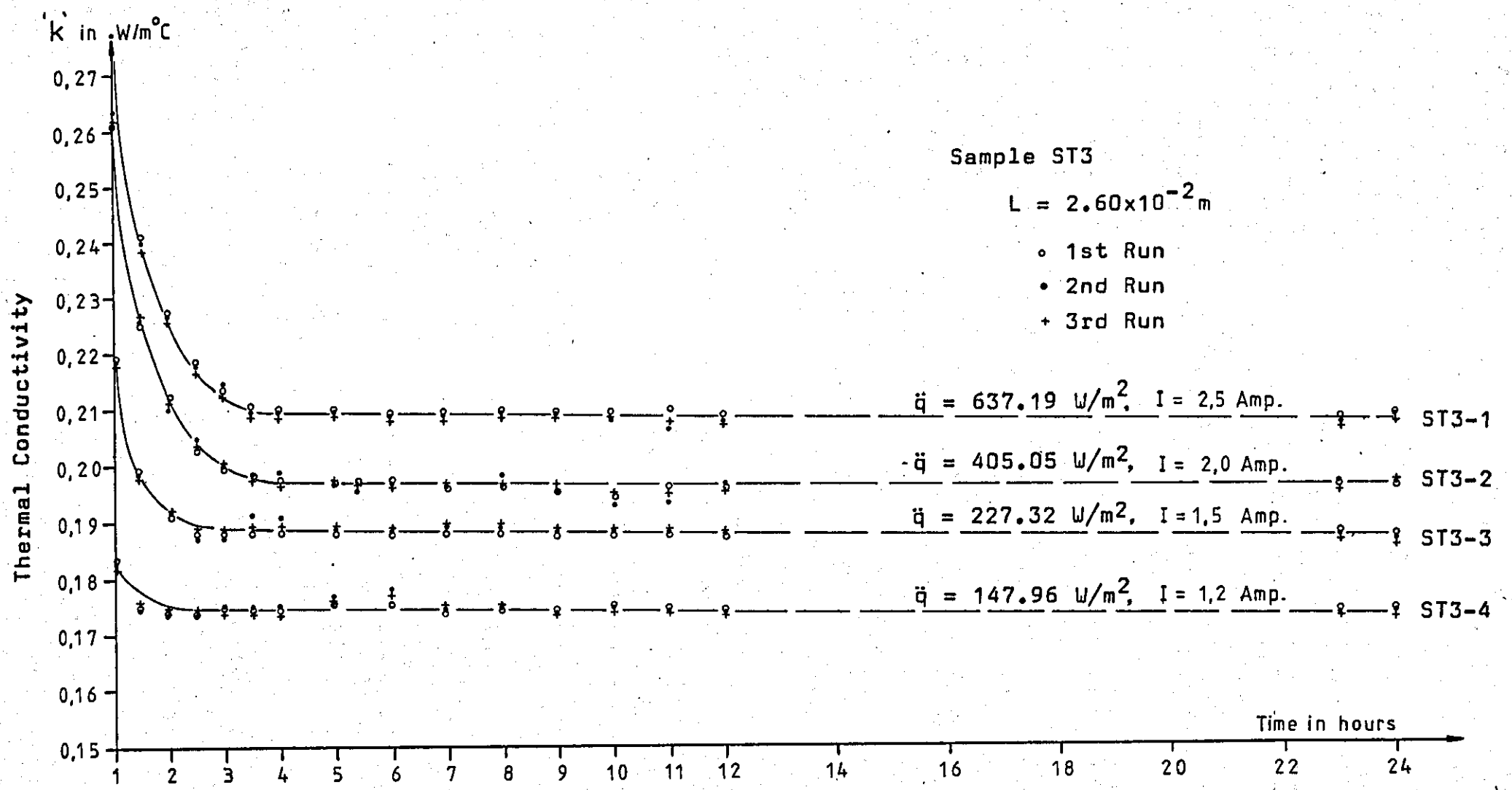


Figure 2.5.3.(3) Thermal Conductivity Versus Time of Test : Thermalite Samples ST3

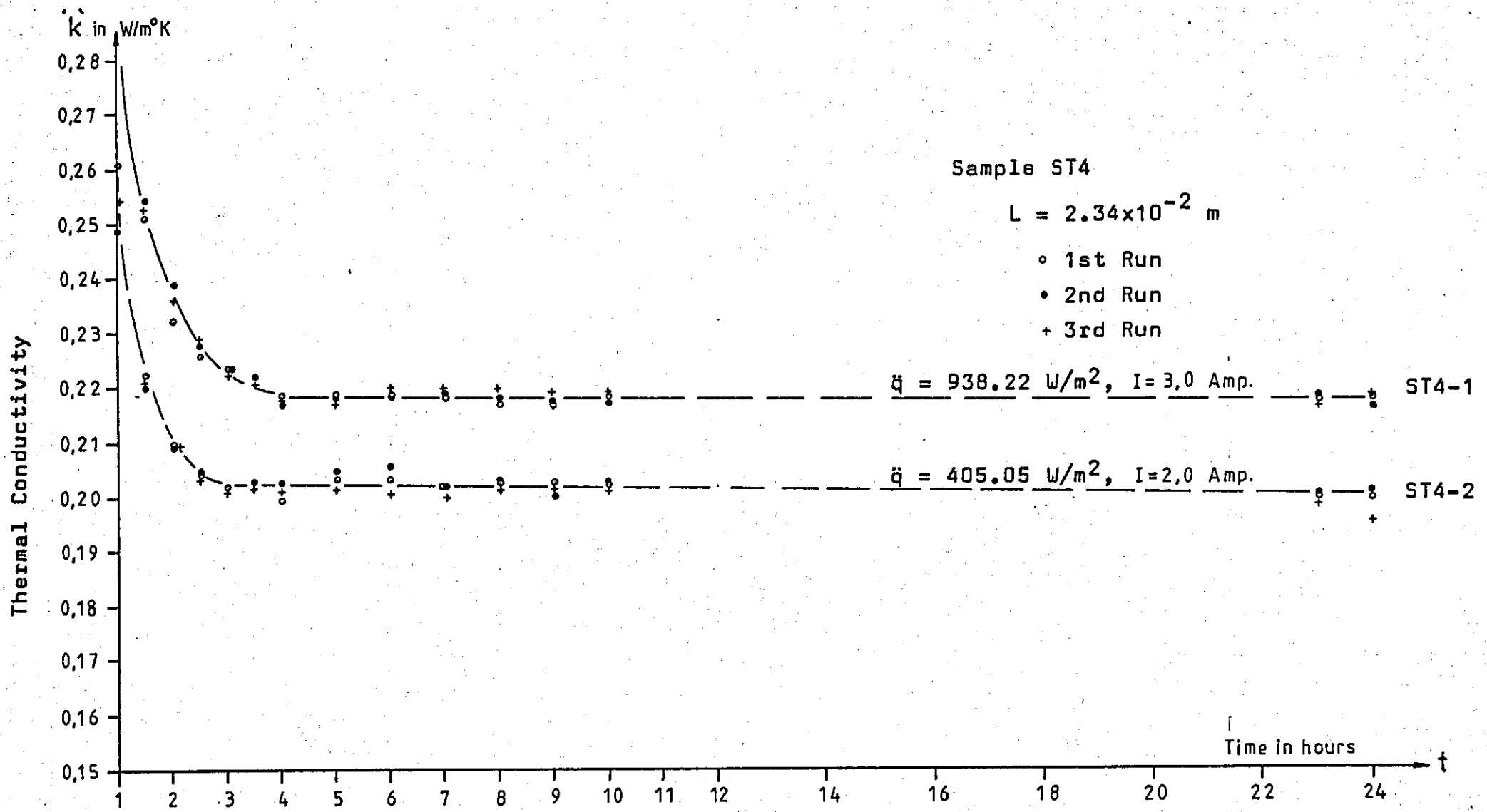


Figure 2.5.3.(4) Thermal Conductivity Versus Time of Test : Thermalite Samples ST4

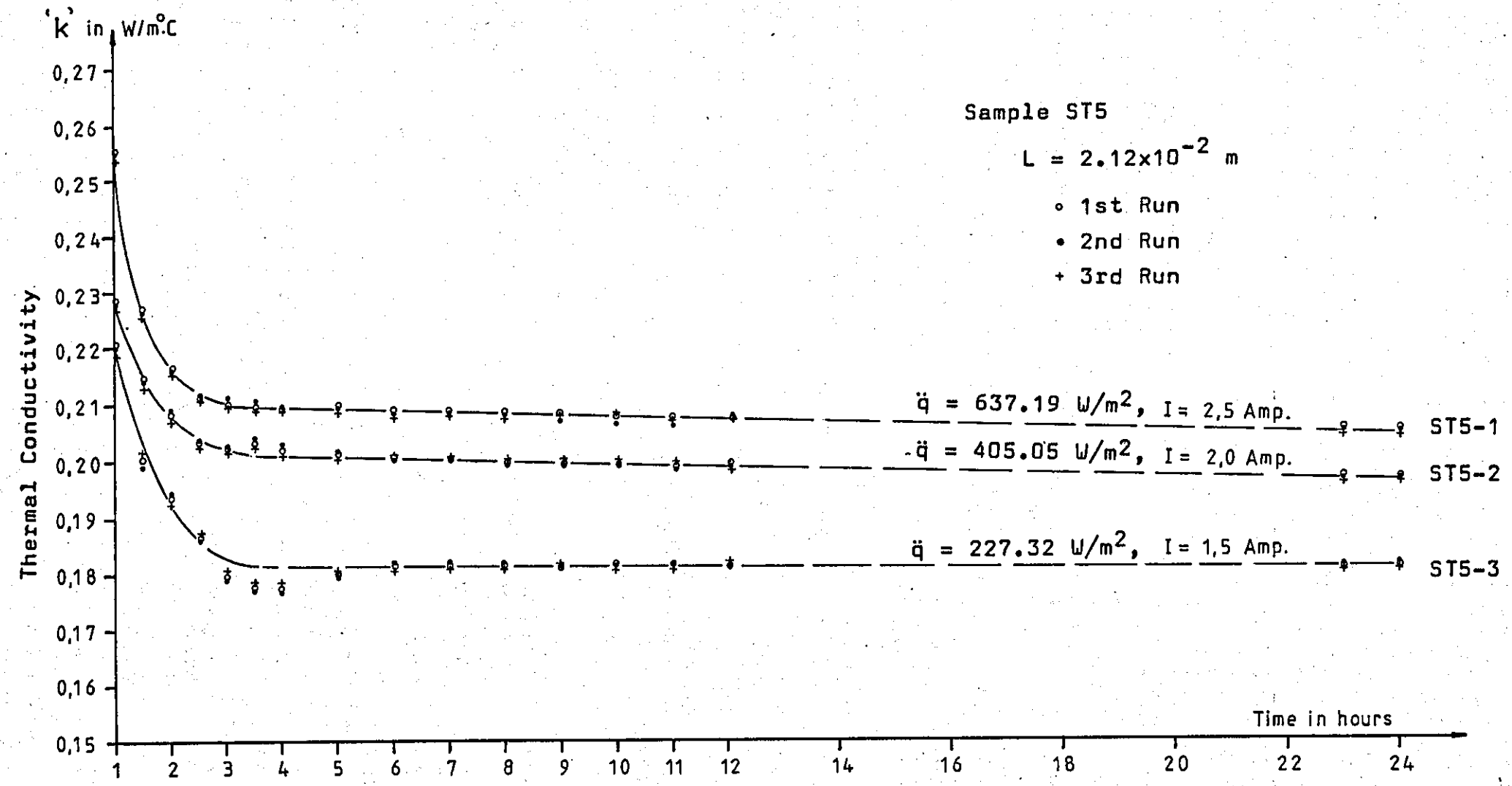
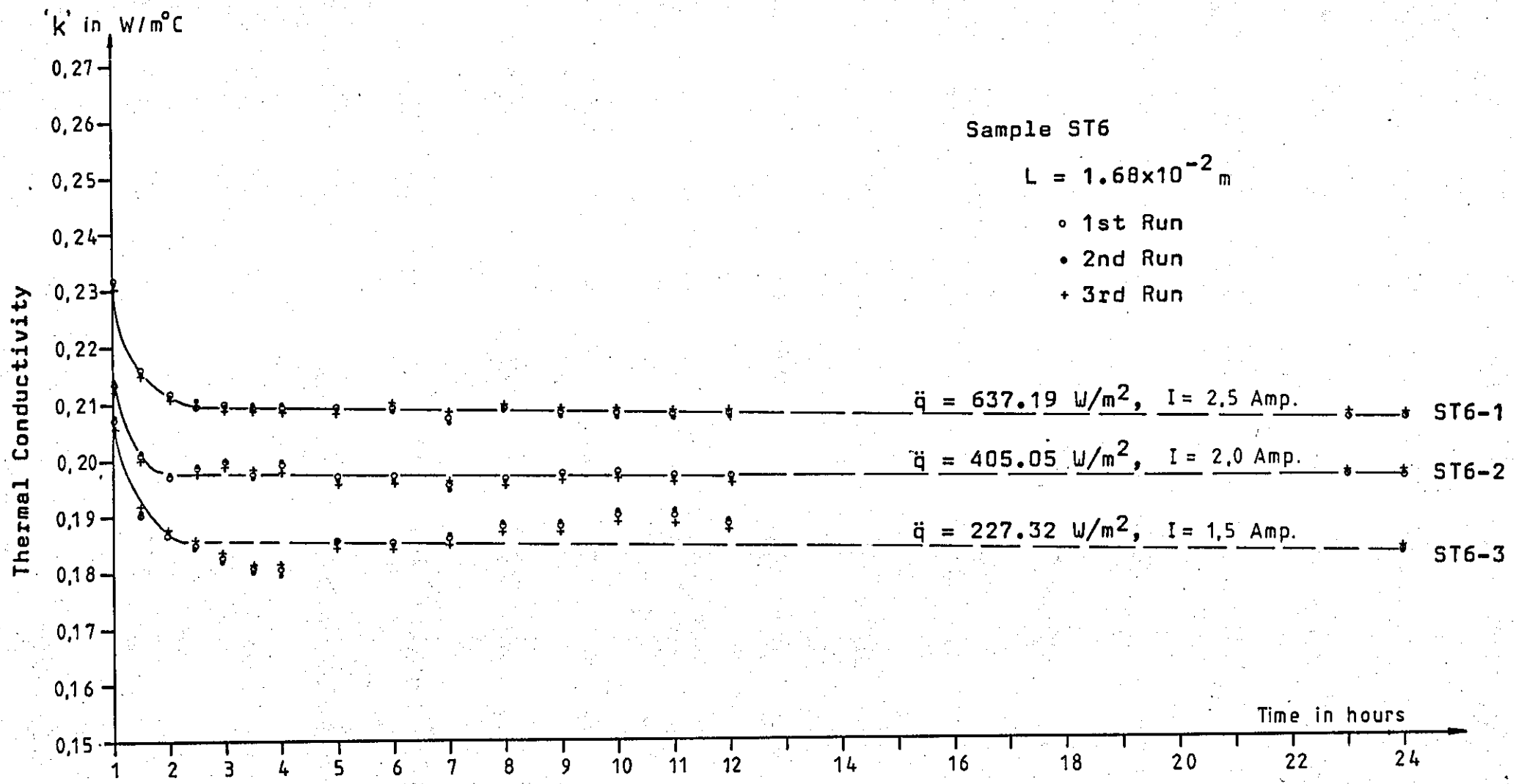


Figure 2.5.3.(5) Thermal Conductivity Versus Time of Test : Thermalite Samples ST5



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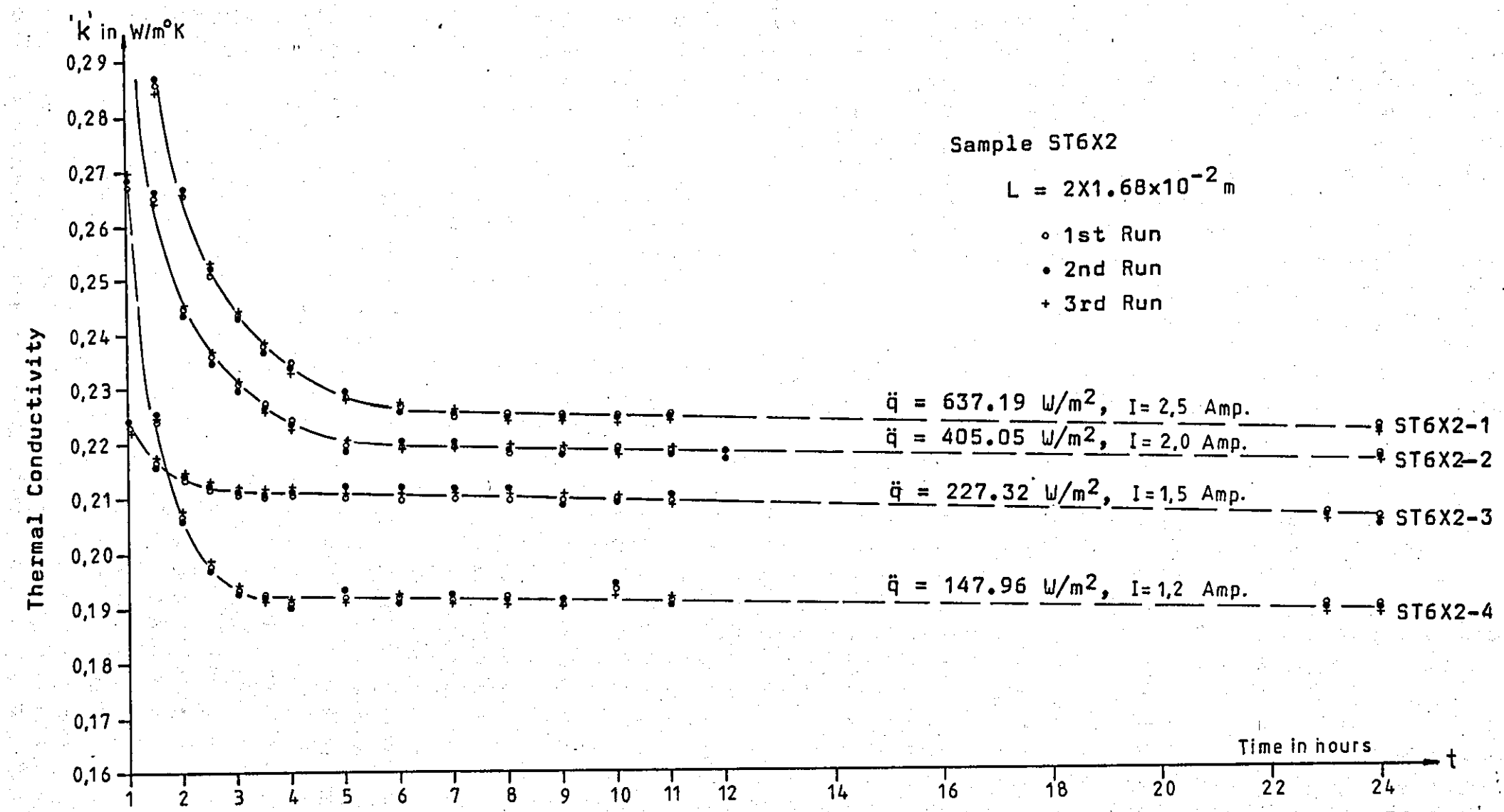


Figure 2.5.3.(7) Thermal Conductivity Versus Time of Test : Thermalite Samples ST6X2

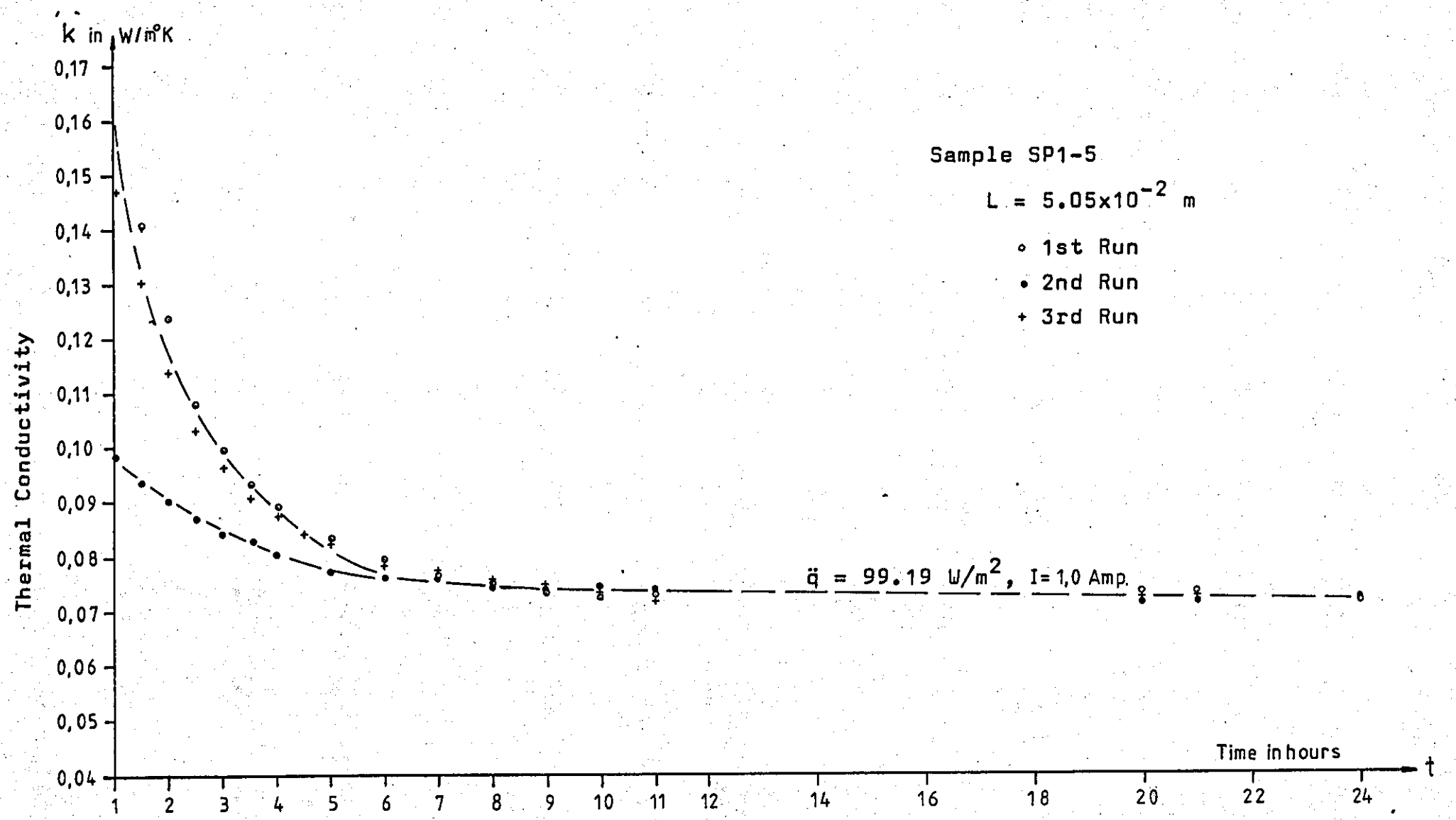


Figure 2.5.3.(8) Thermal Conductivity Versus Time of Test : Styrofoam Sample SP1-5

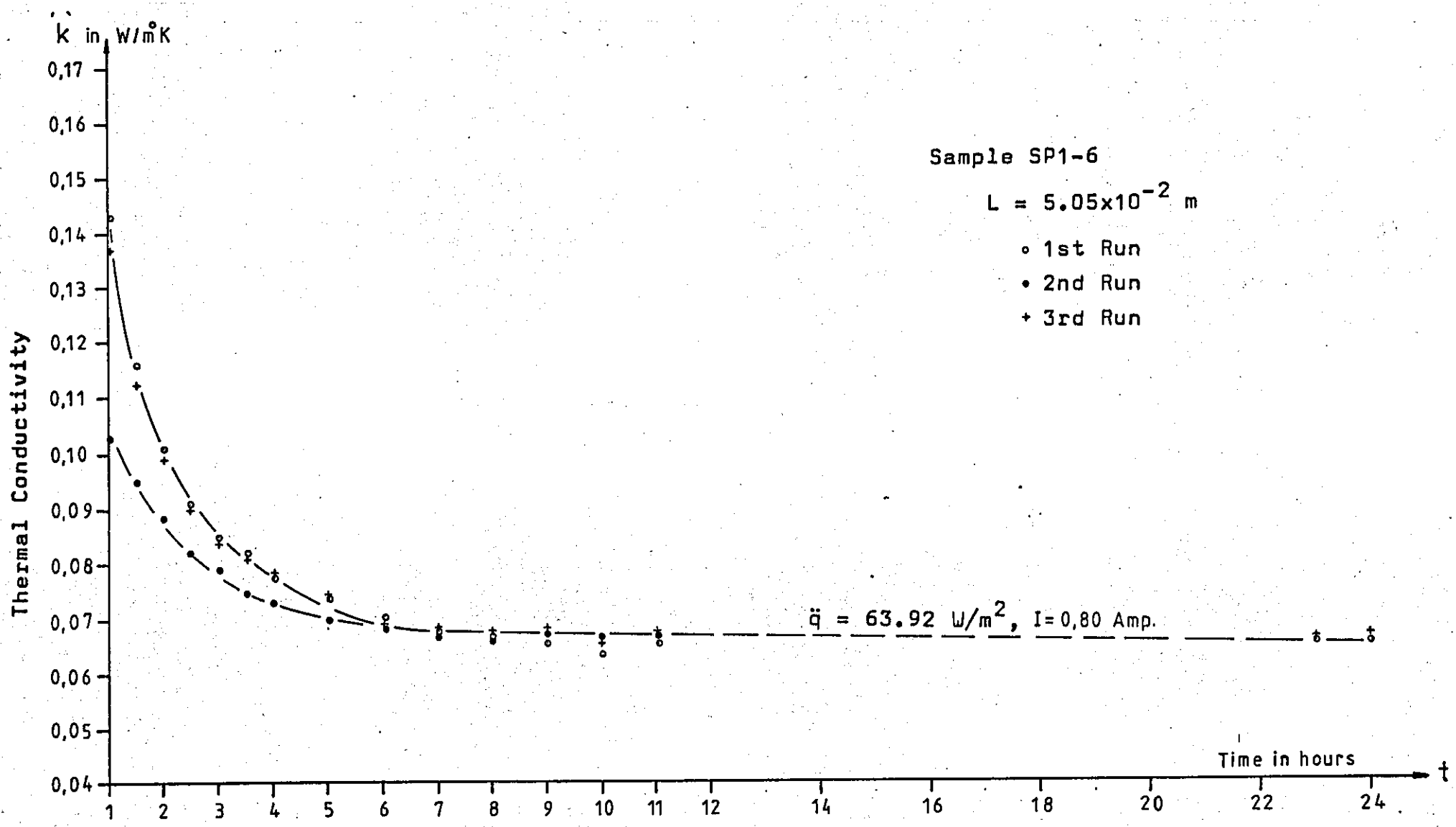


Figure 2.5.3.(9) Thermal Conductivity Versus Time of Test : Styrofoam Sample SP1-6

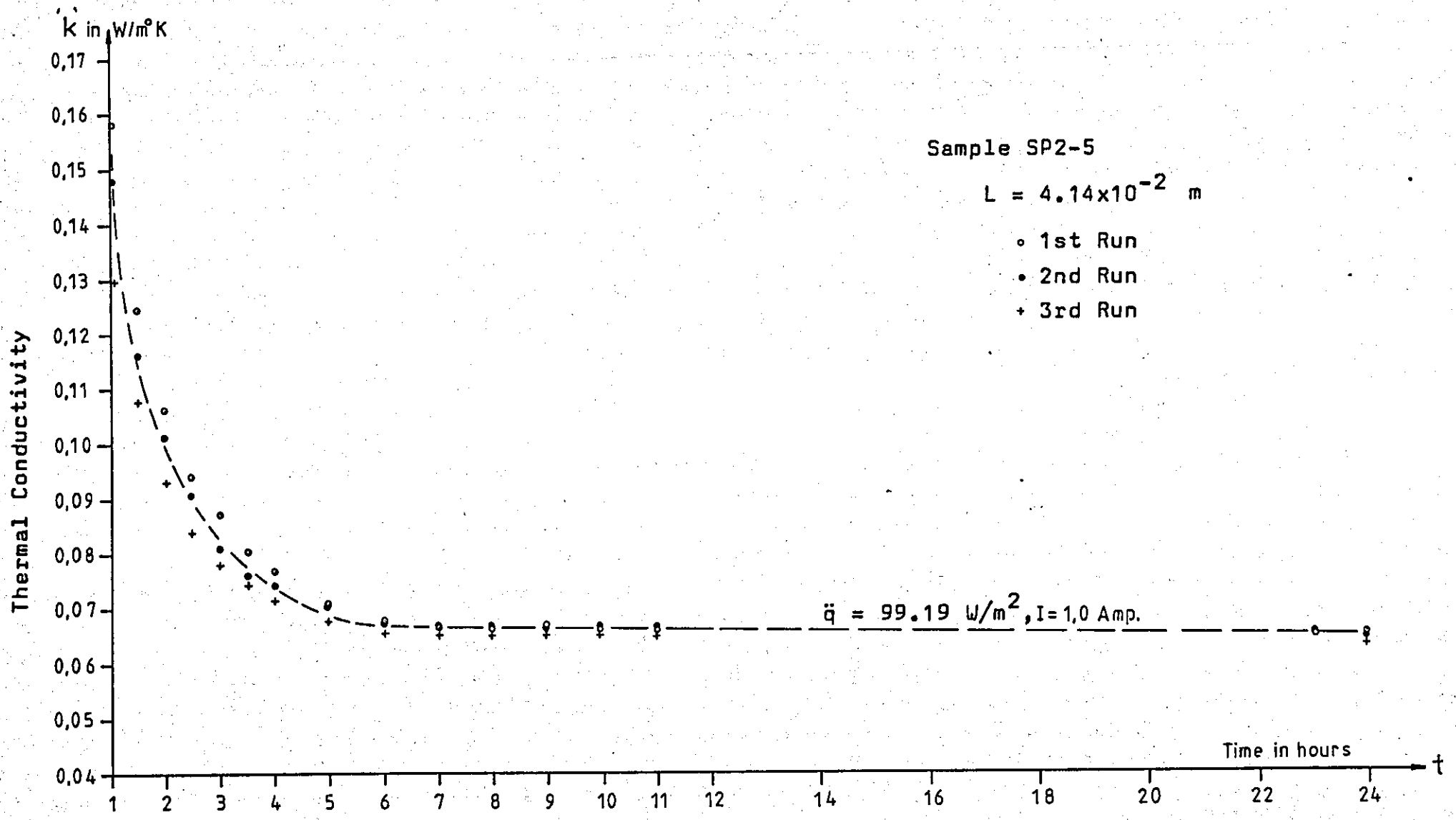
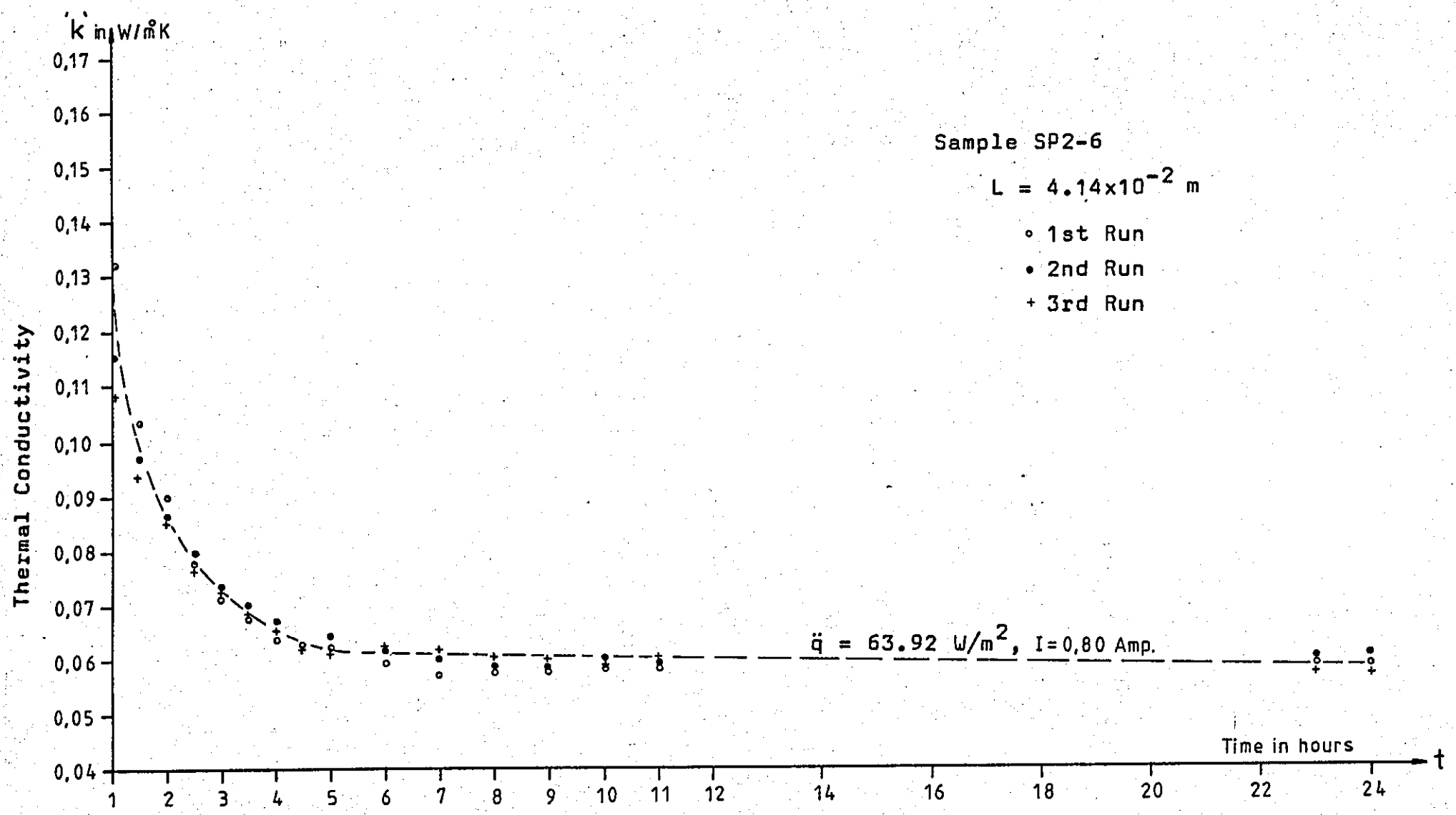


Figure 2.5.3.(10) Thermal Conductivity Versus Time of Test : Styrofoam Sample SP2-5



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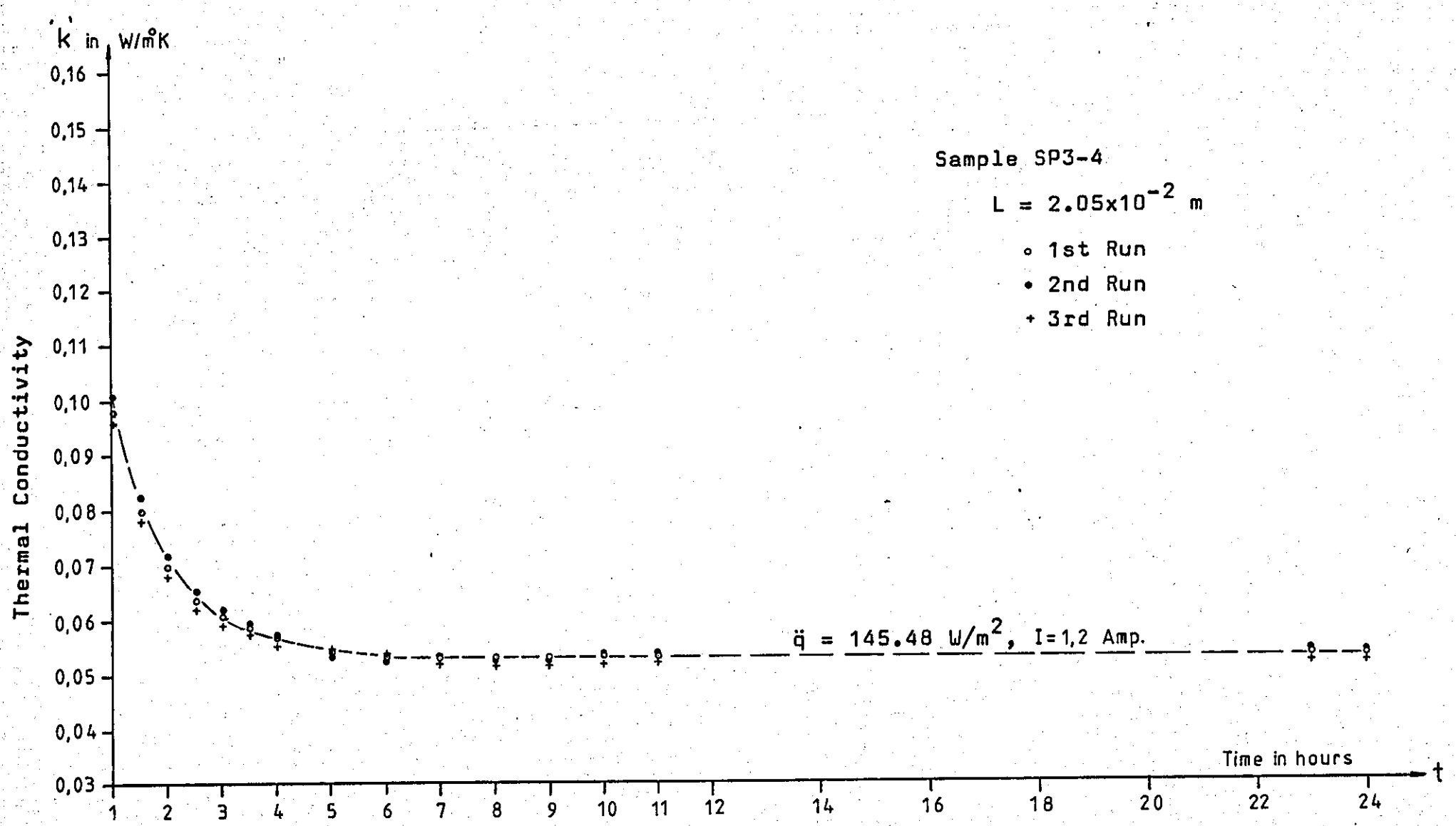


Figure 2.5.3.(12) Thermal Conductivity Versus Time of Test : Styrofoam Sample SP3-4

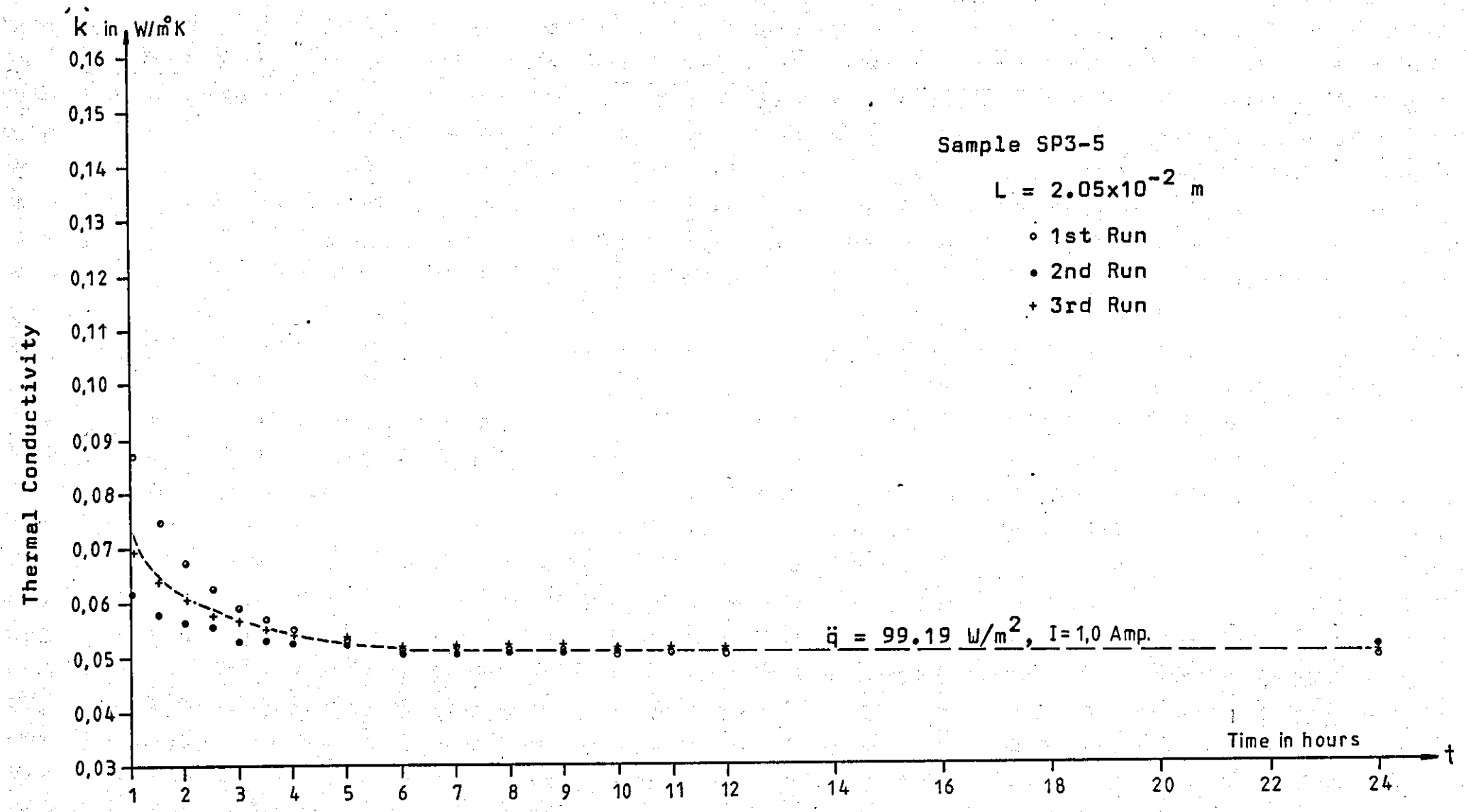


Figure 2.5.3.(13) Thermal Conductivity Versus Time of Test : Styrofoam Sample SP3-5

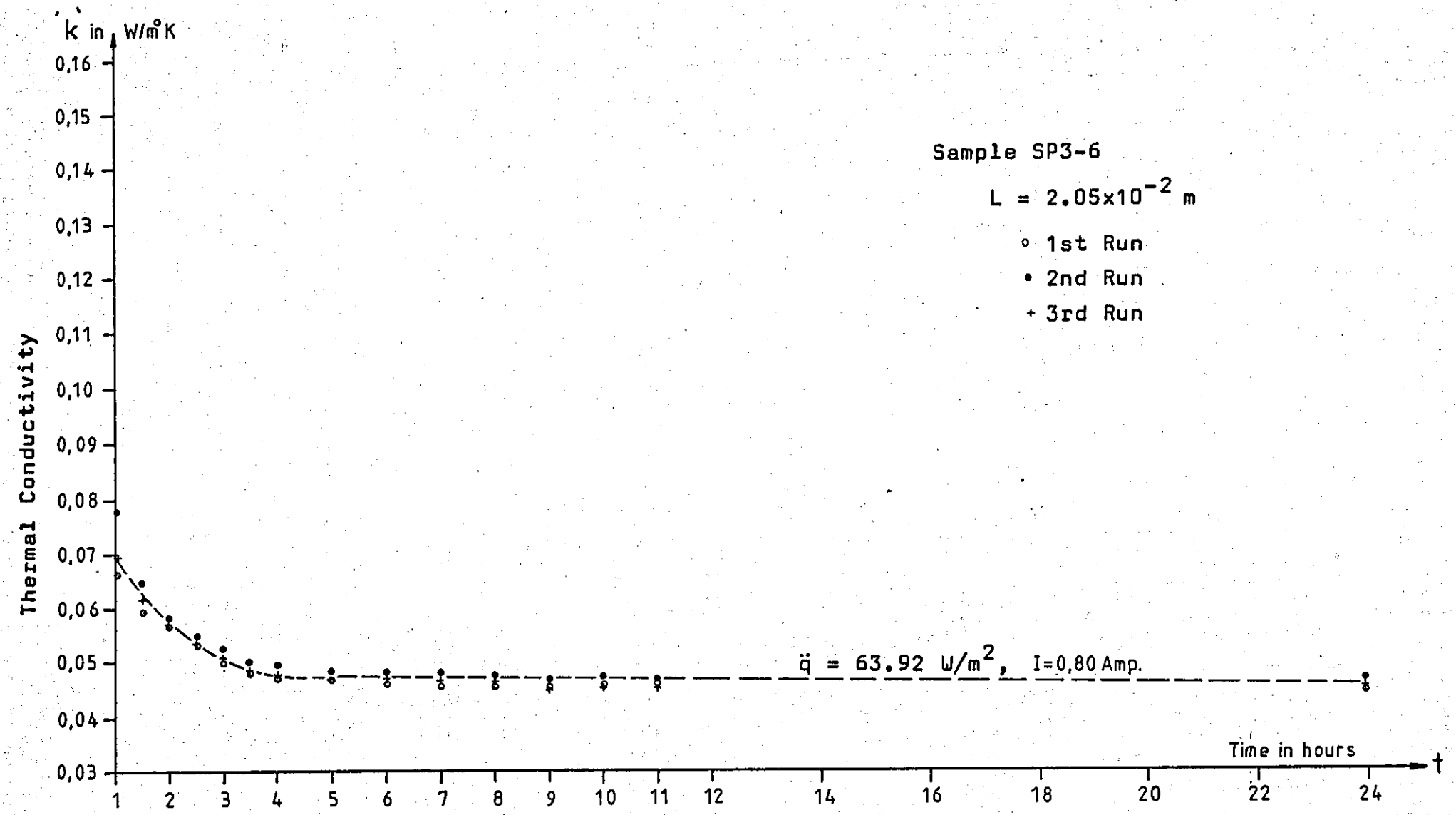


Figure 2.5.3.(14) Thermal Conductivity Versus Time of Test : Styrofoam Sample SP3-6

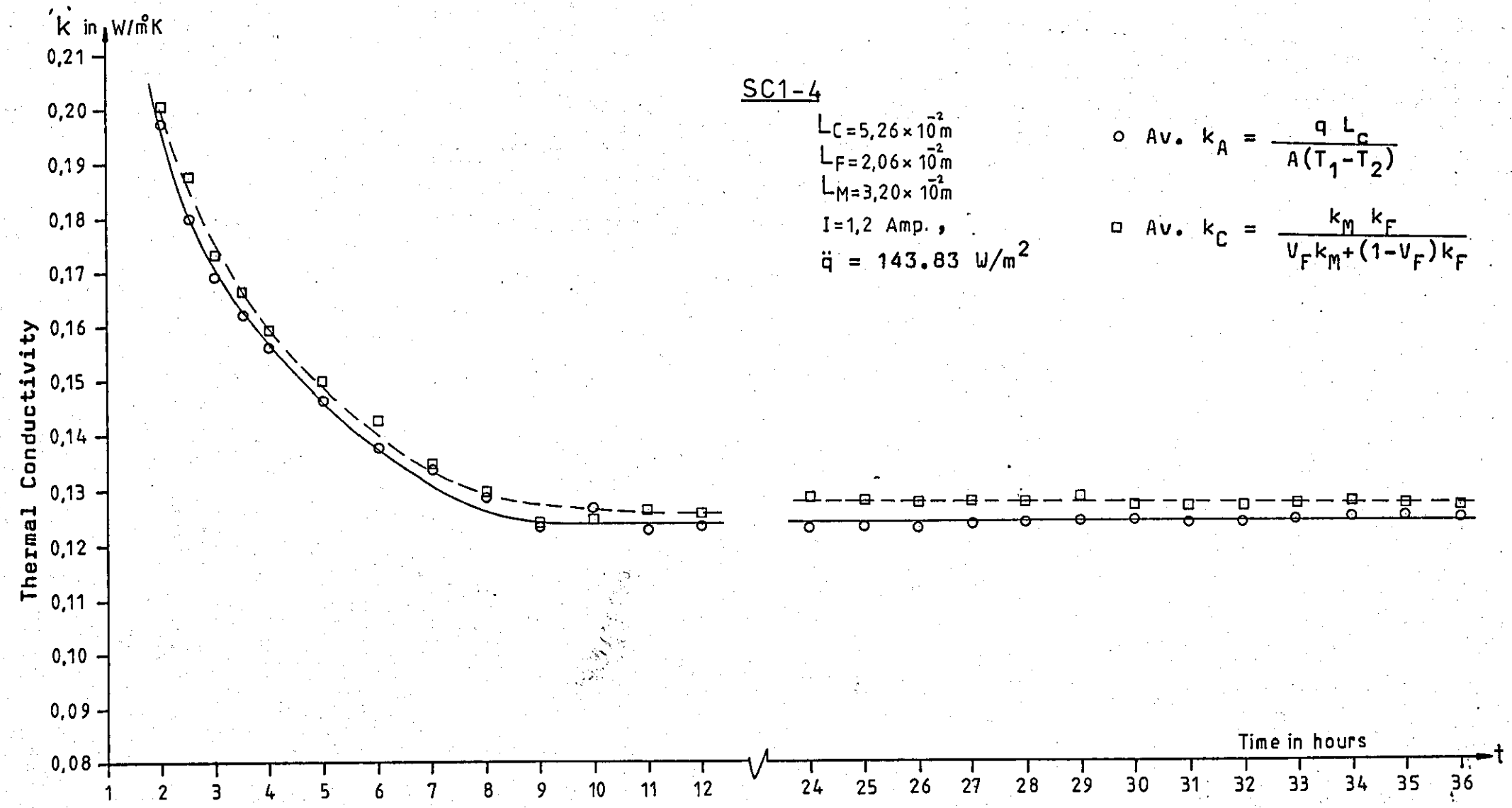
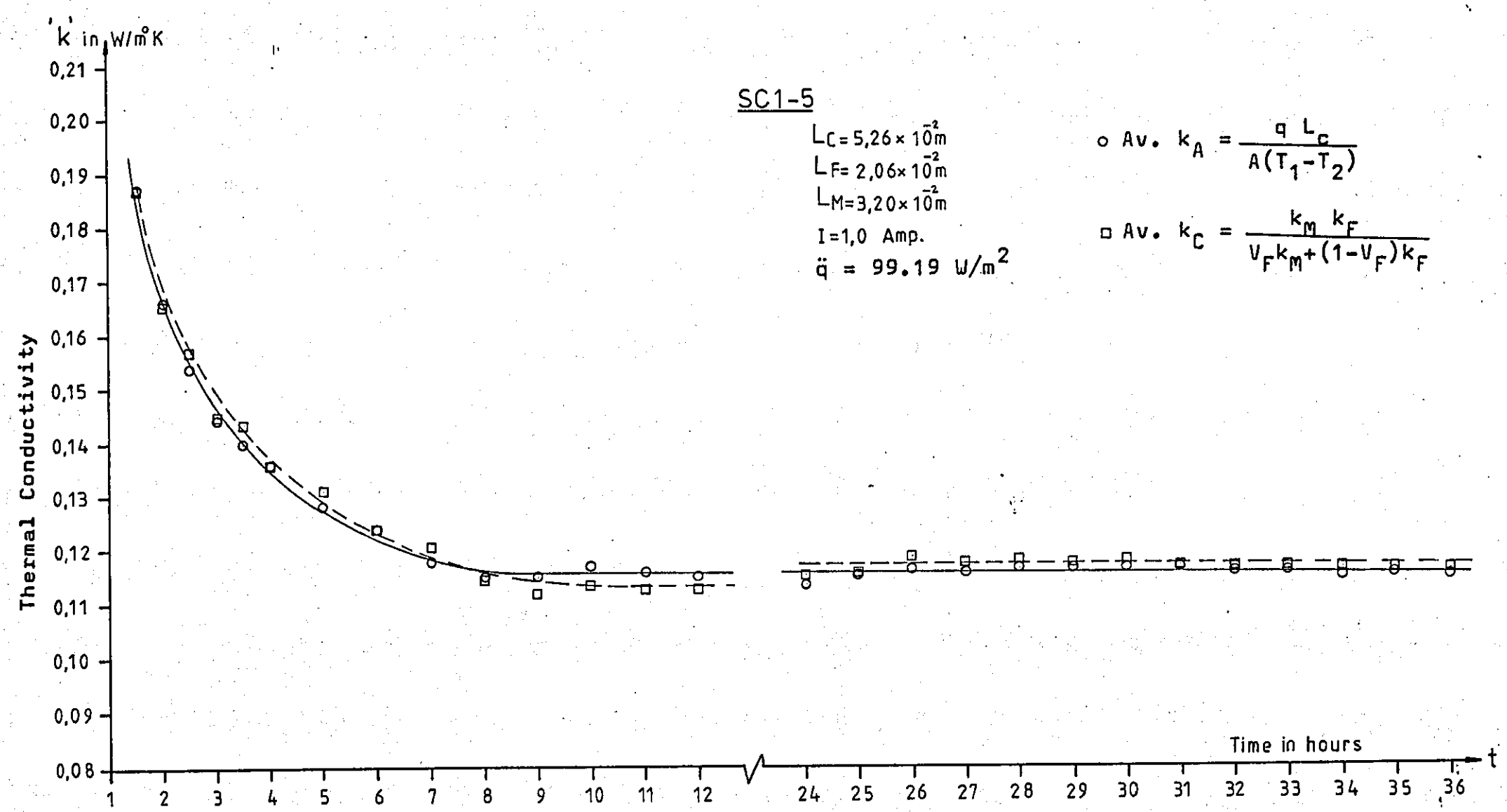


Figure 2.5.4.(1) Thermal Conductivity Versus Time of Test : Composite Sample SC1-4



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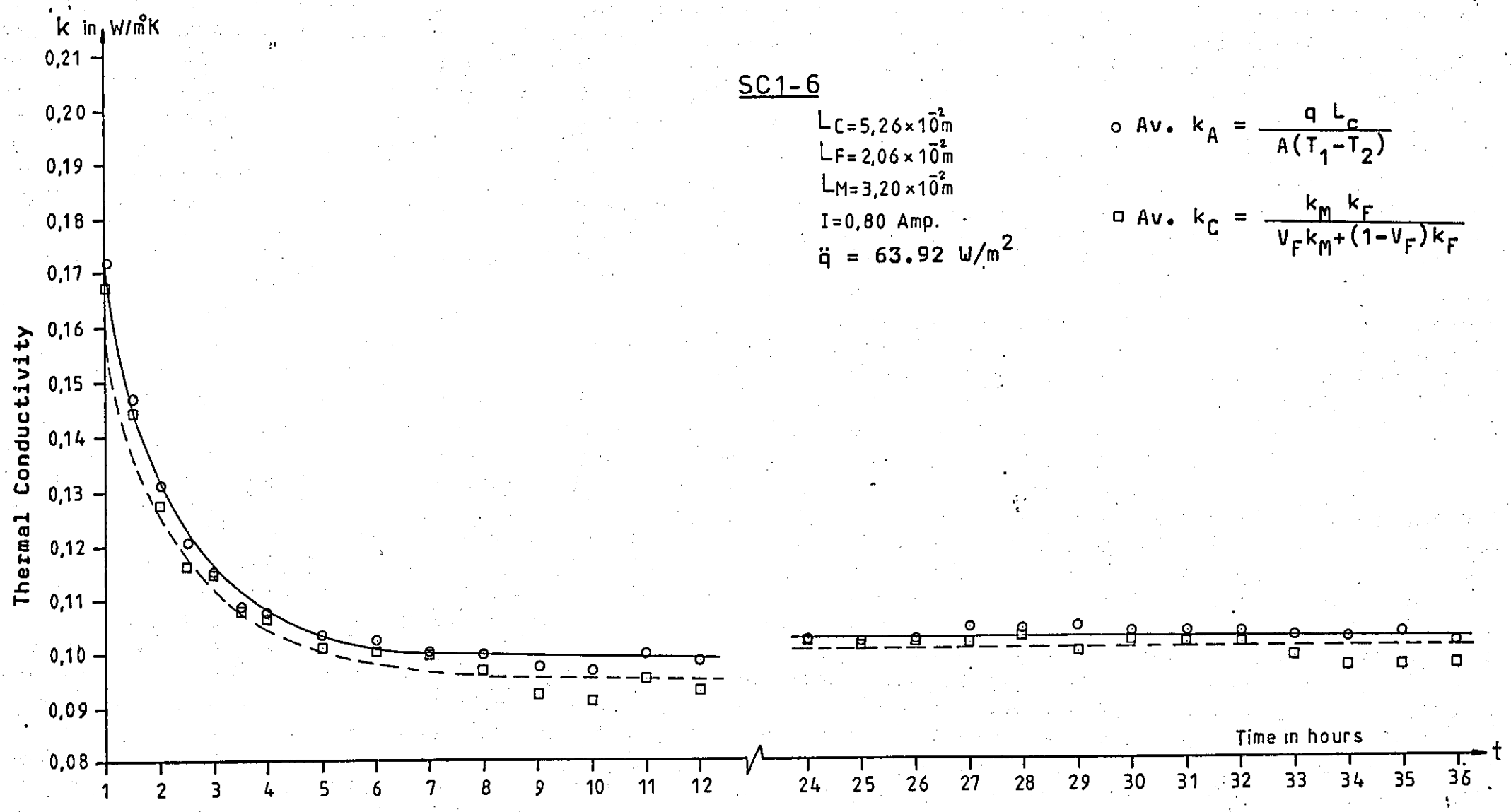


Figure 2.5.4.(3) Thermal Conductivity Versus Time of Test : Composite Sample SC1-6

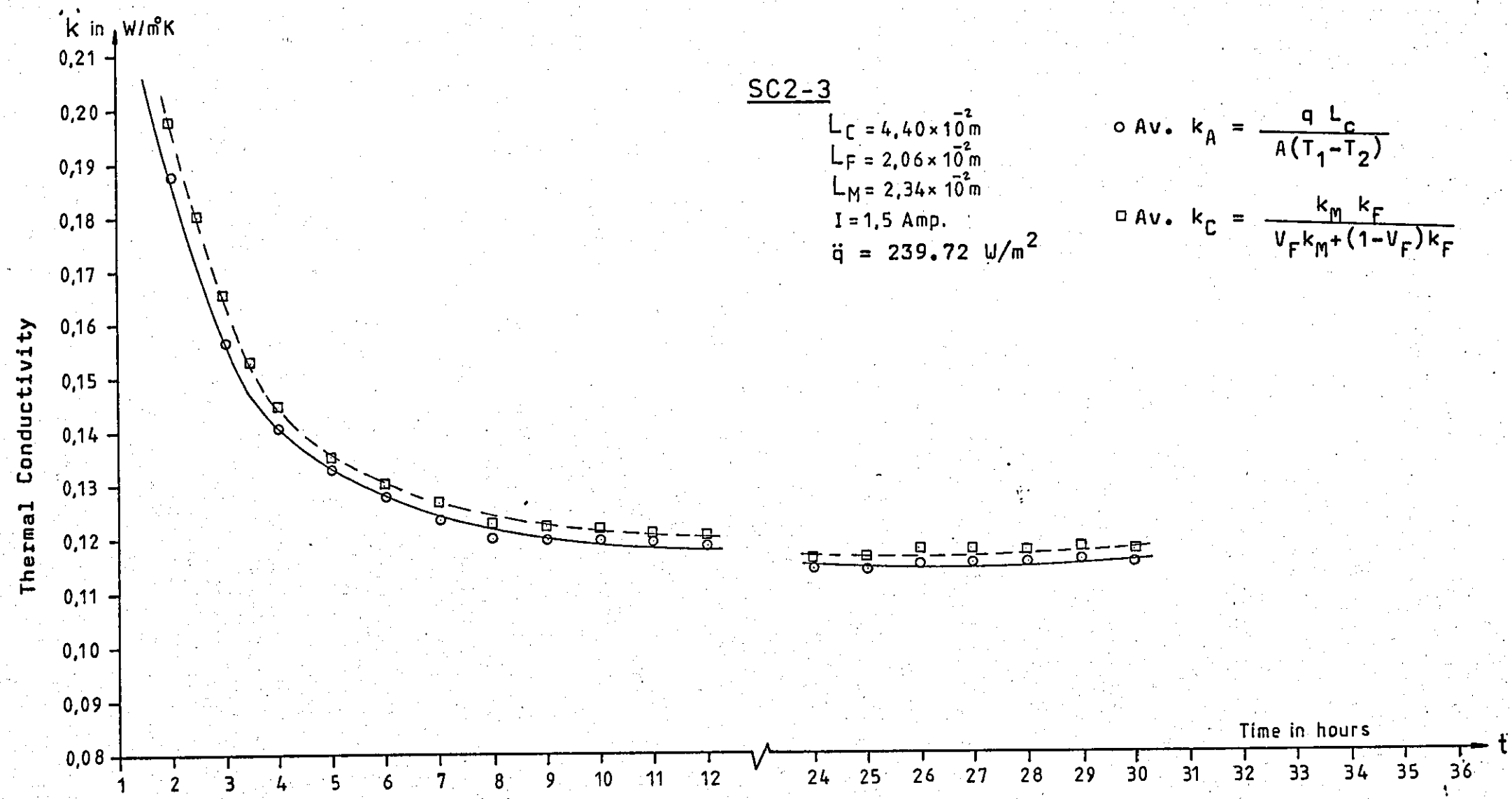
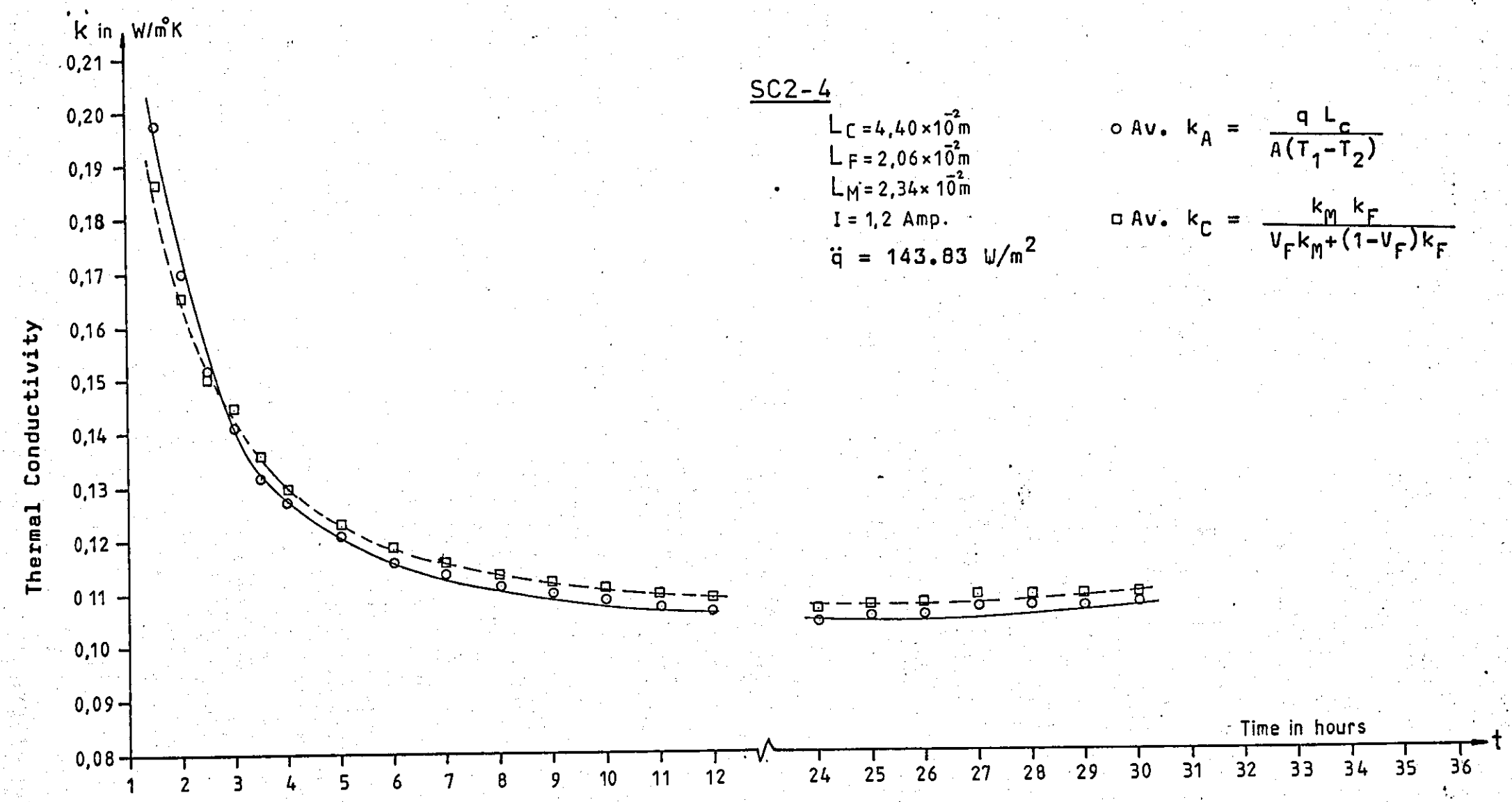


Figure 2.5.4.(4) Thermal Conductivity Versus Time of Test : Composite Sample SC2-3



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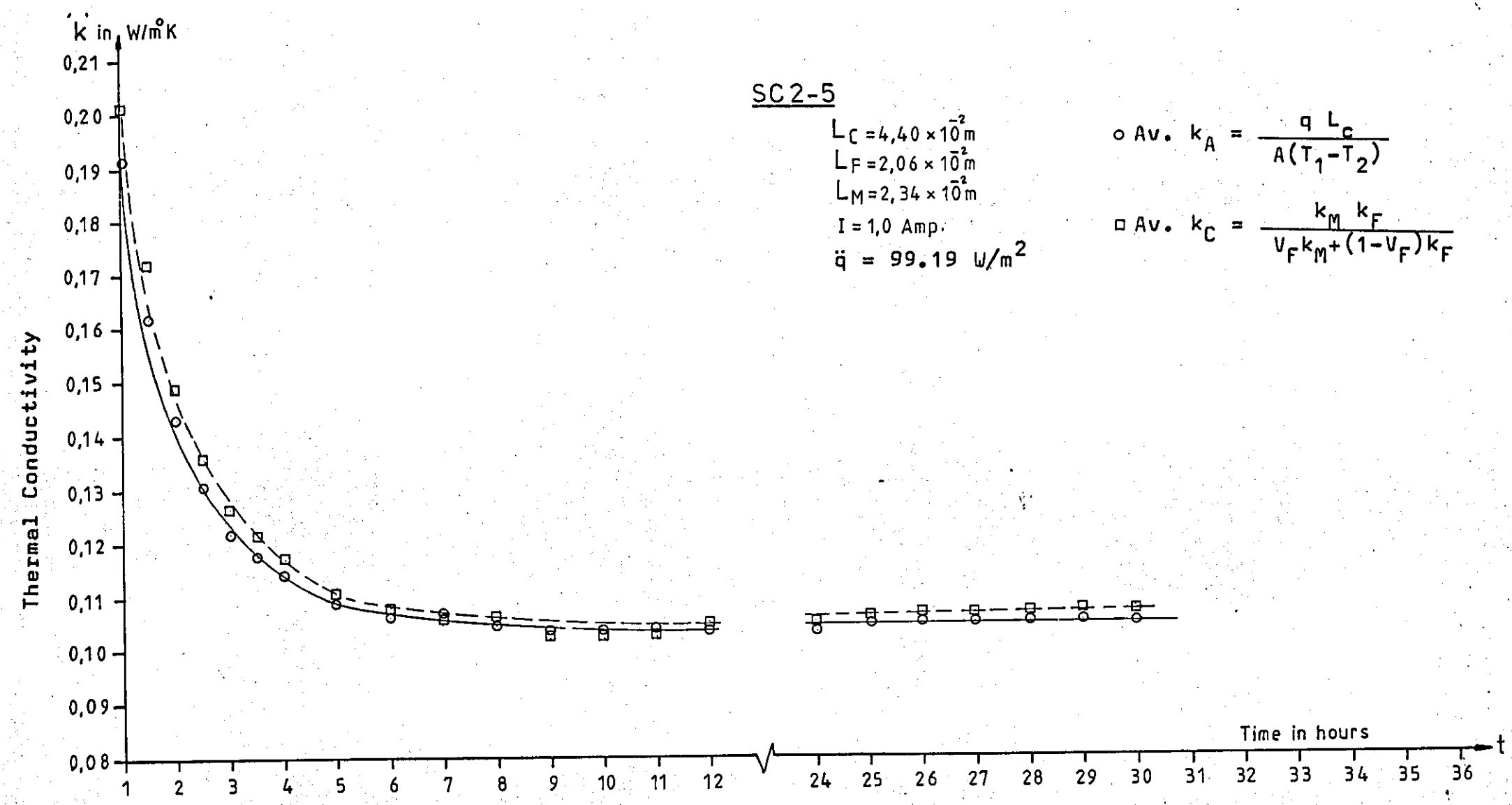

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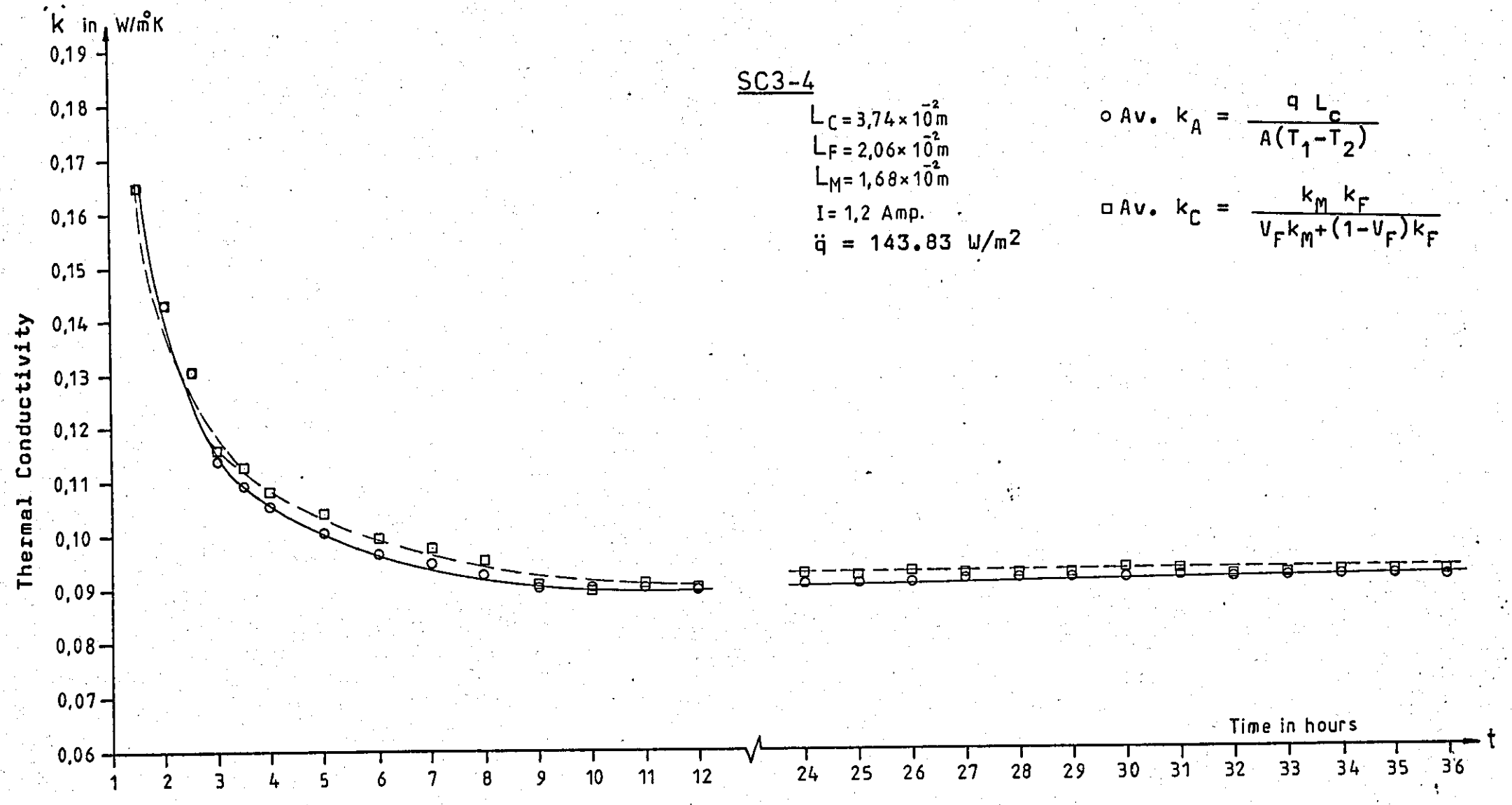


Figure 2.5.4.(7) Thermal Conductivity Versus Time of Test : Composite Sample SC3-4

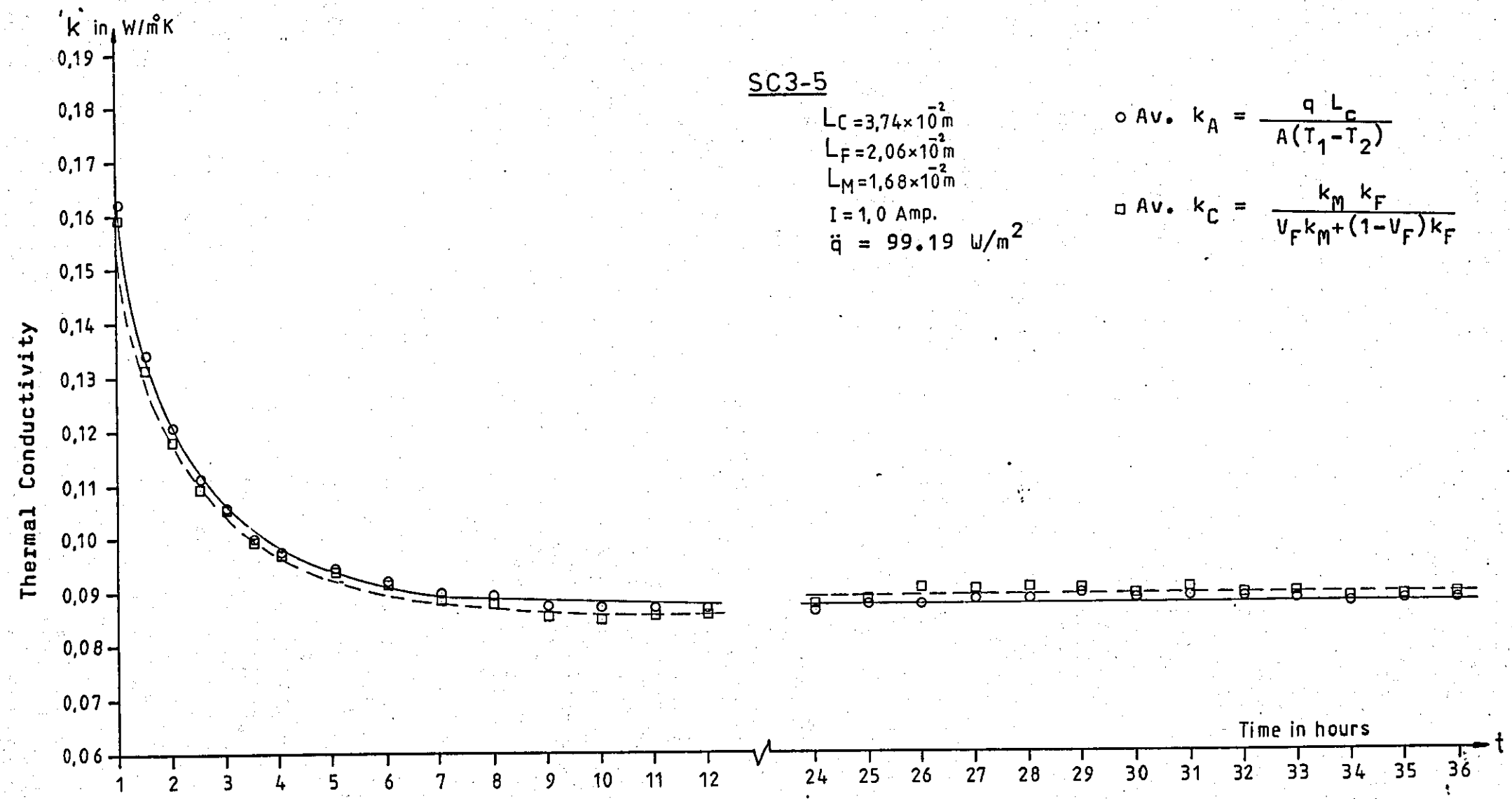


Figure 2.5.4.(8) Thermal Conductivity Versus Time of Test : Composite Sample SC3-4

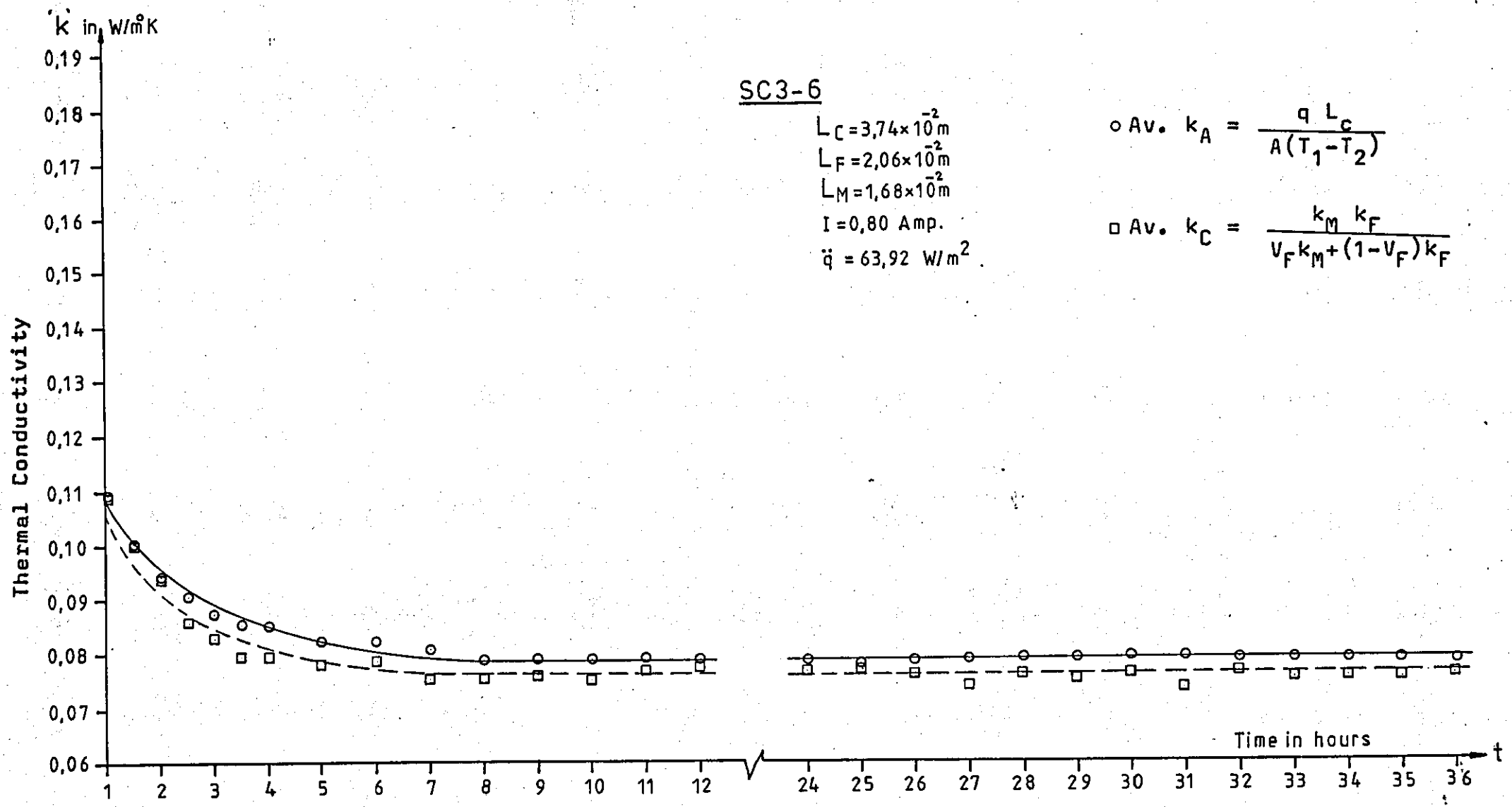


Figure 2.5.4.(9) Thermal Conductivity Versus Time of Test : Composite Sample SC3-6

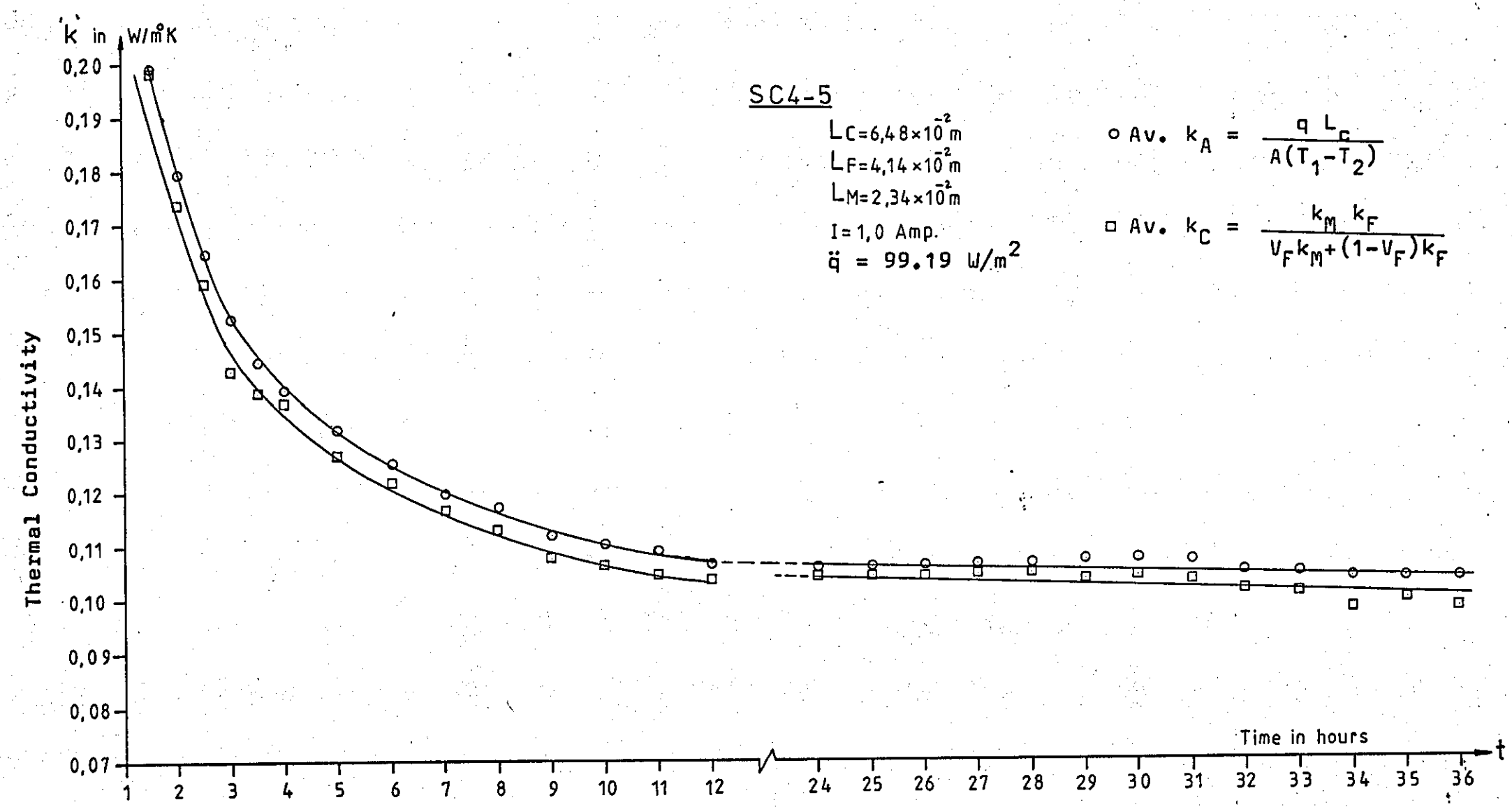


Figure 2.5.4.(10) Thermal Conductivity Versus Time of Test : Composite Sample SC4-5

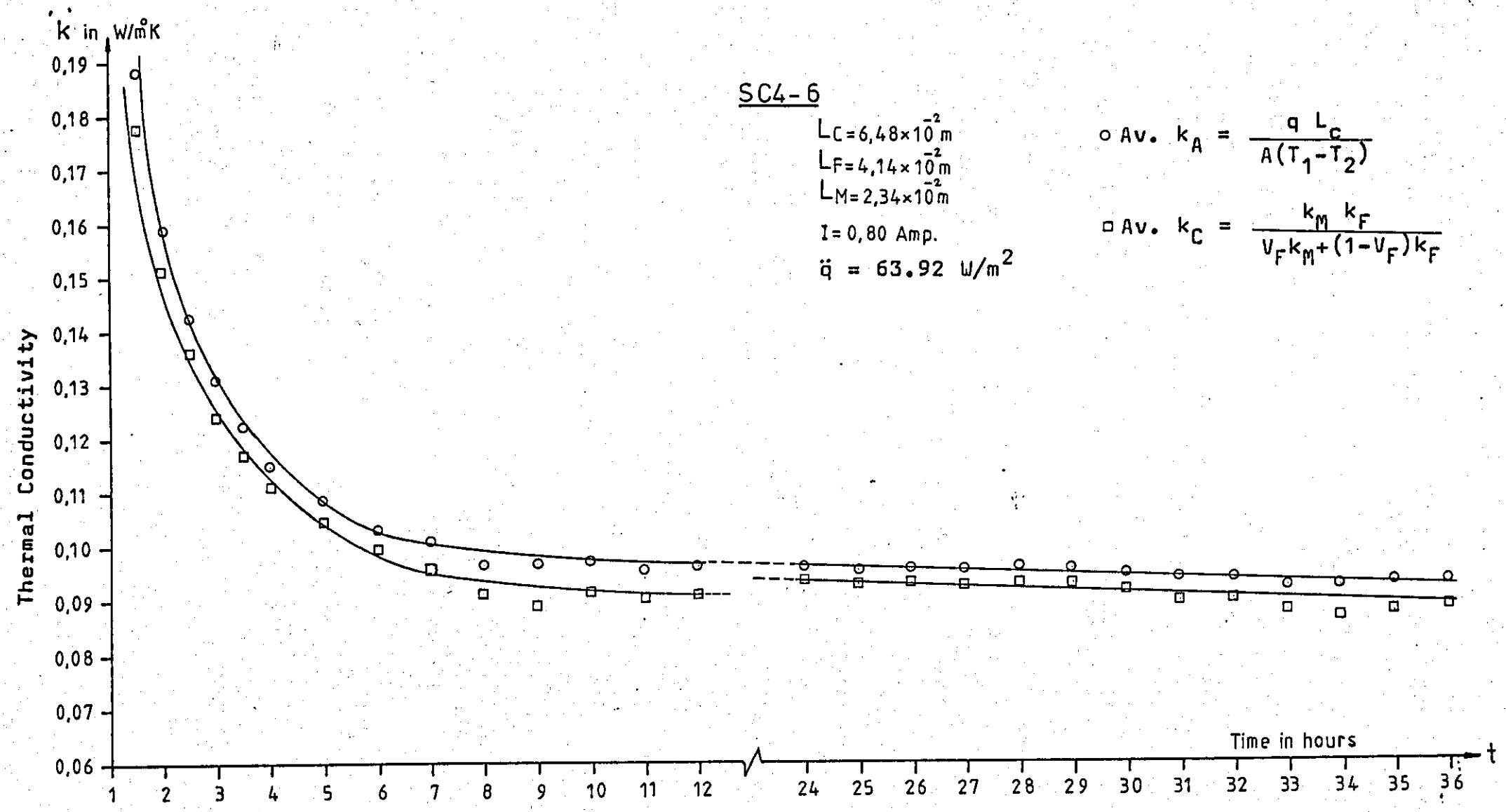


Figure 2.5.4.(11) Thermal Conductivity Versus Time Of Test : Composite Sample SC4-6

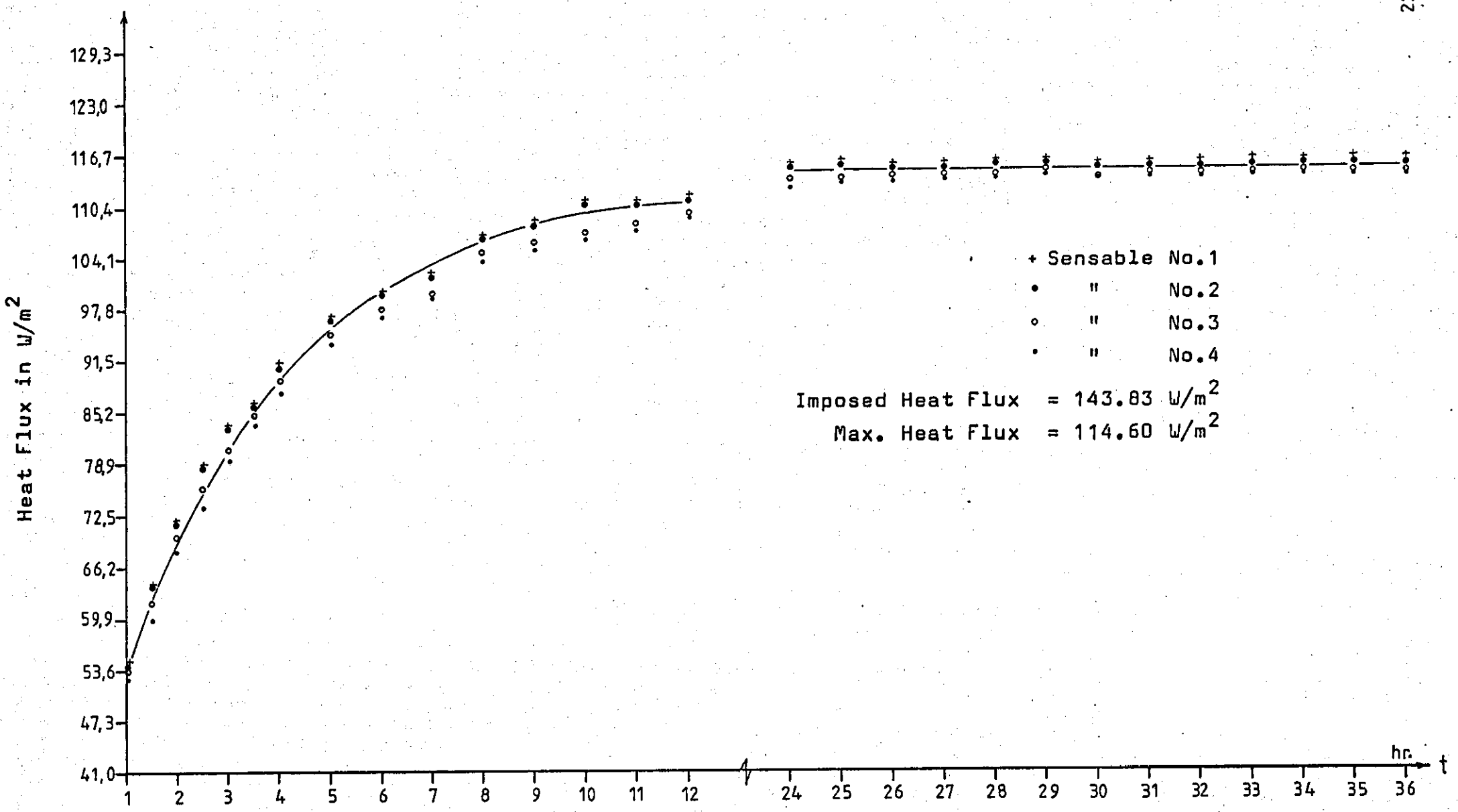


Figure 2.5.4.(1) Heat Flux Versus Time of Test : Composite Sample SC1-4

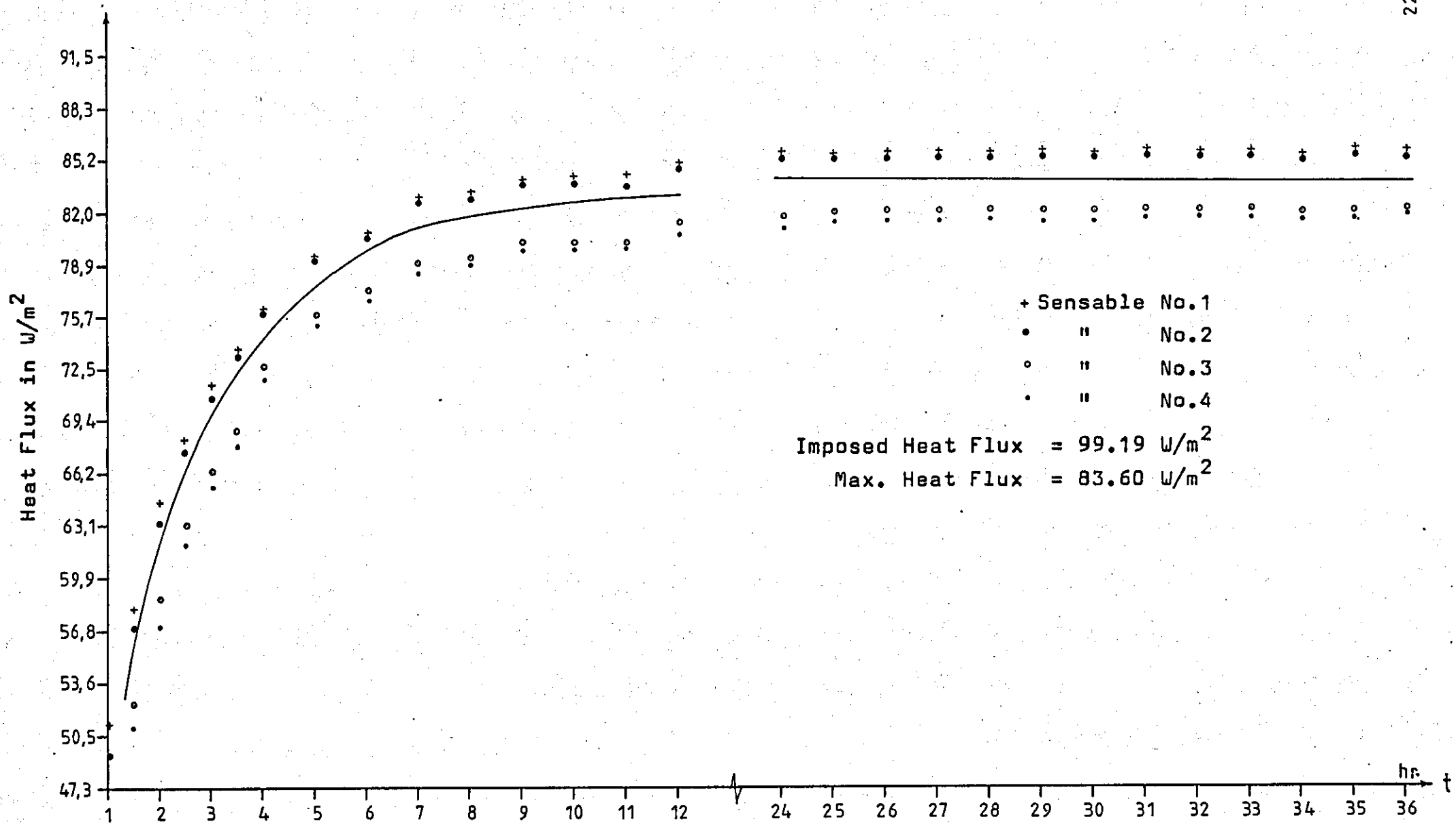


Figure 2.5.4.($\bar{2}$) Heat Flux Versus Time of Test : Composite Sample SC1-5

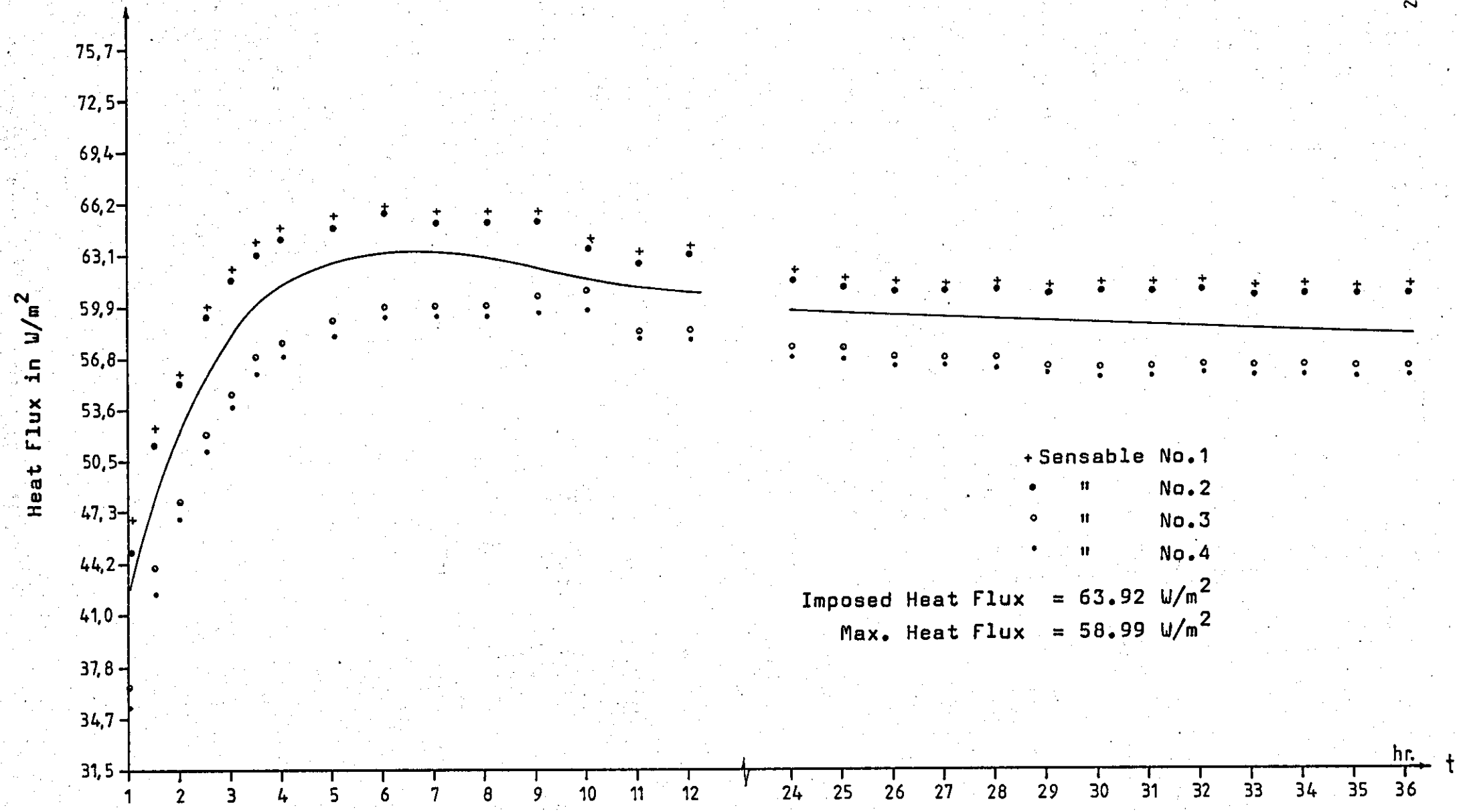


Figure 2.5.4.($\bar{3}$) Heat Flux Versus Time of Test : Composite Sample SC1-6

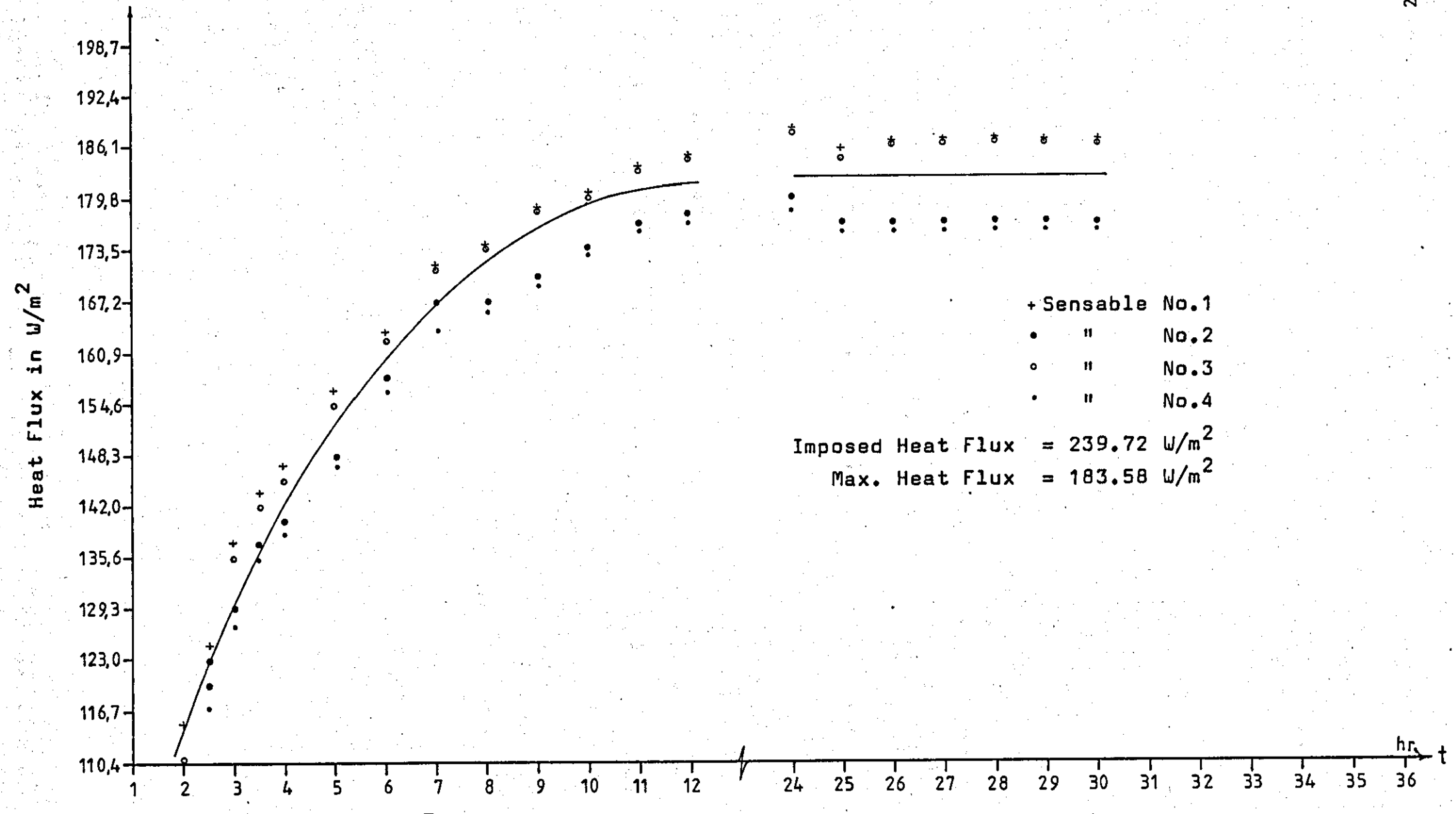


Figure 2.5.4.($\bar{4}$) Heat Flux Versus Time of Test : Composite Sample SC2-3

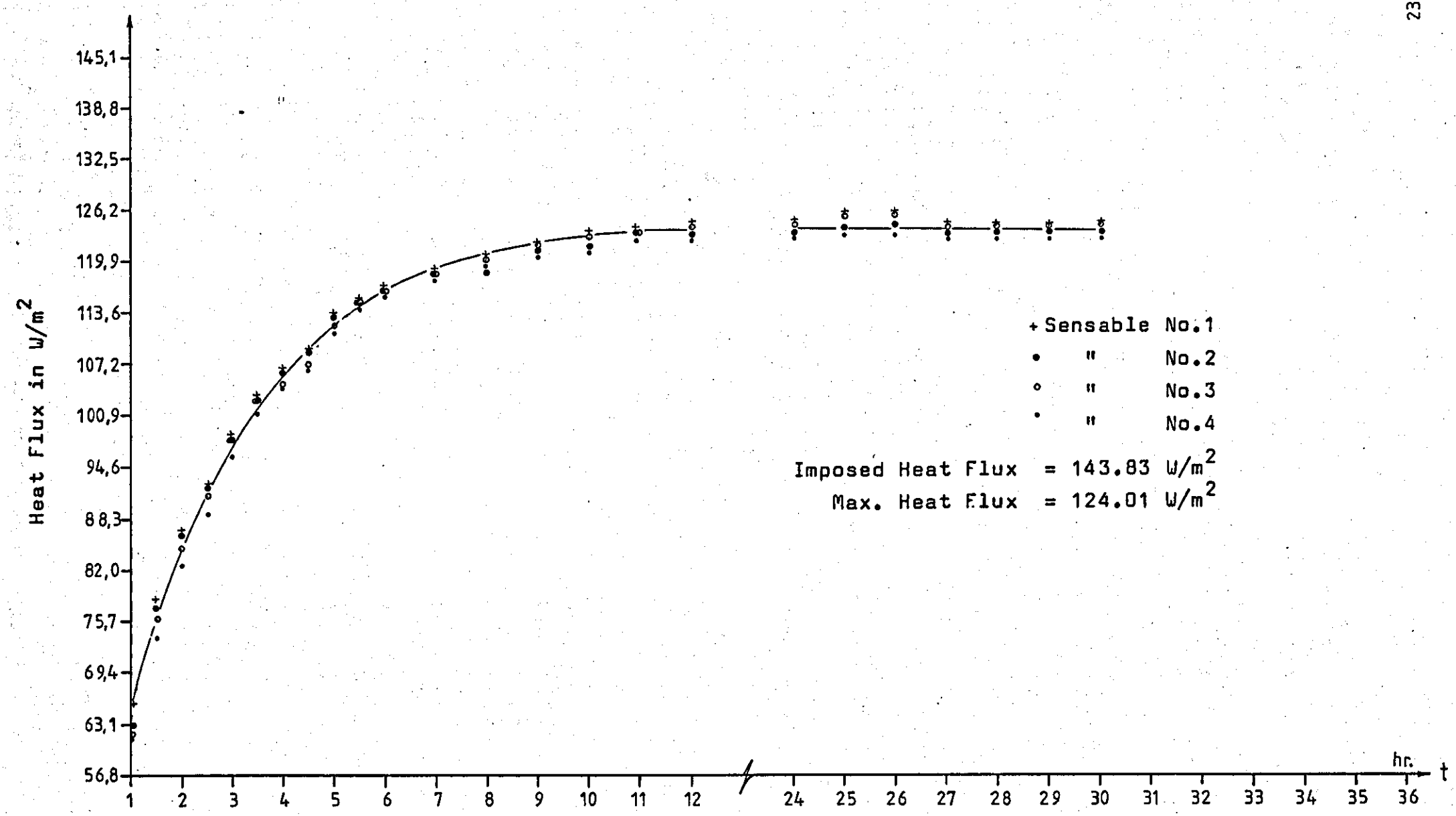


Figure 2.5.4.($\bar{5}$) Heat Flux Versus Time of Test : Composite Sample SC2-4

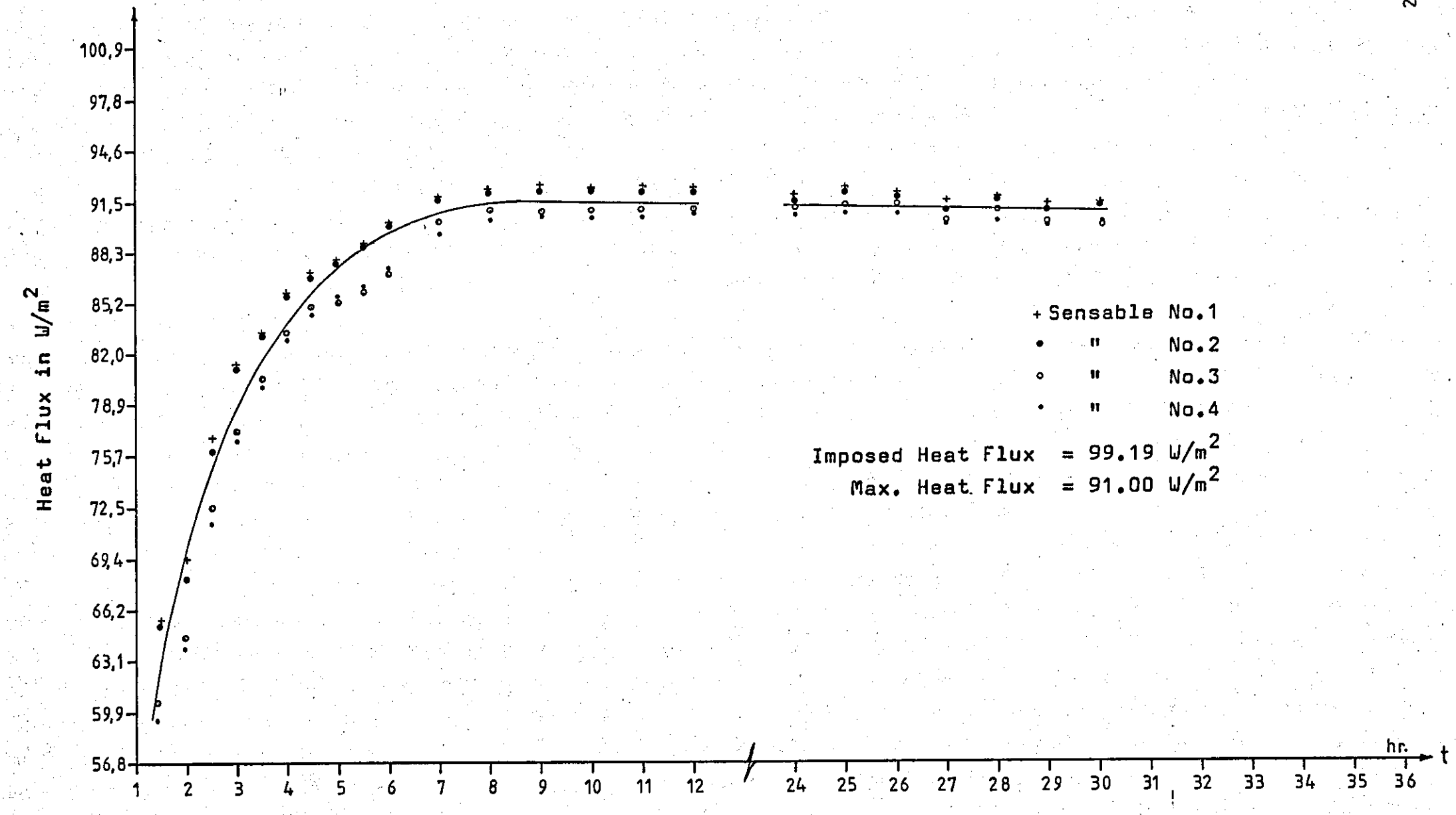


Figure 2.5.4.(6̄) Heat Flux Versus Time of Test : Composite Sample SC2-5

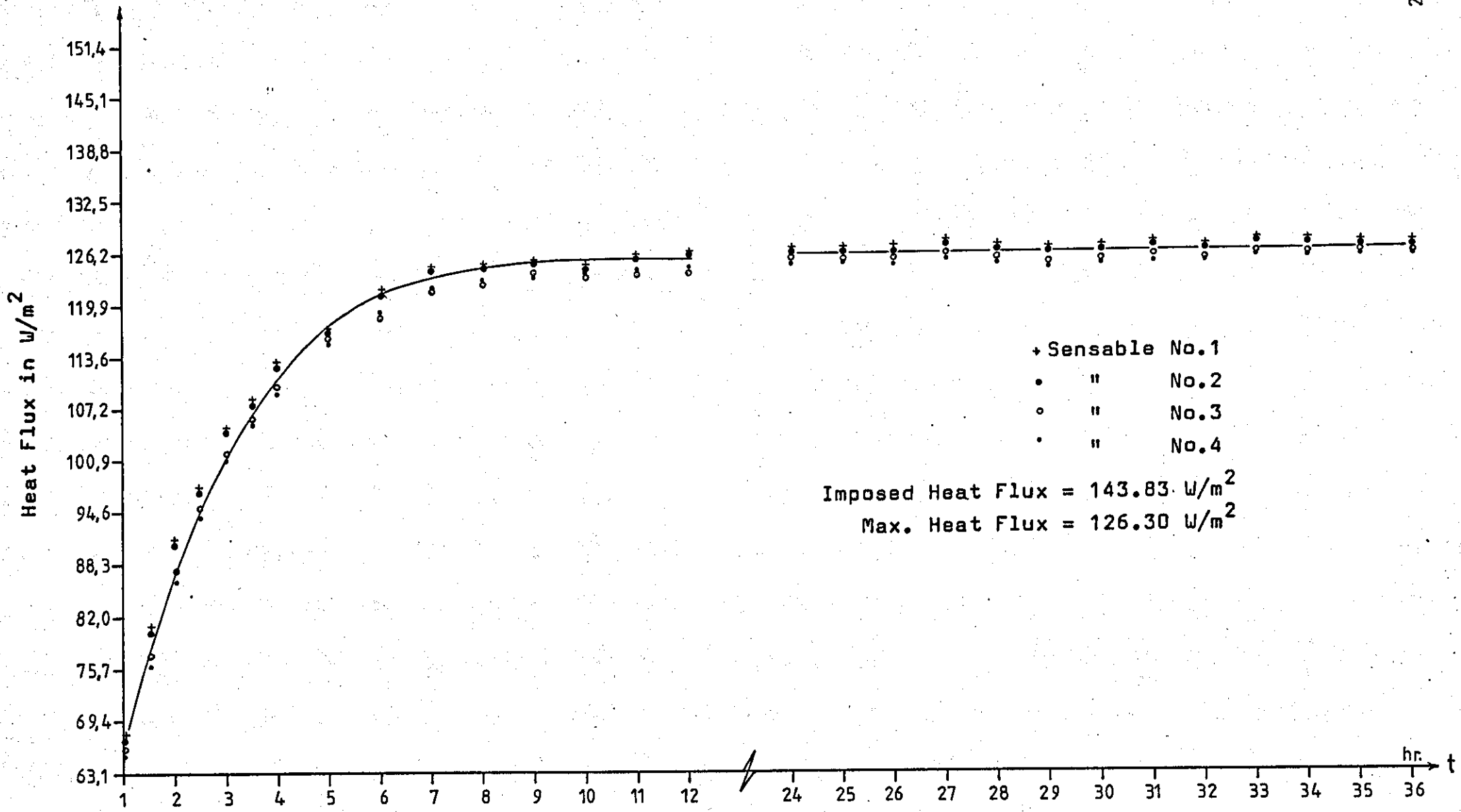
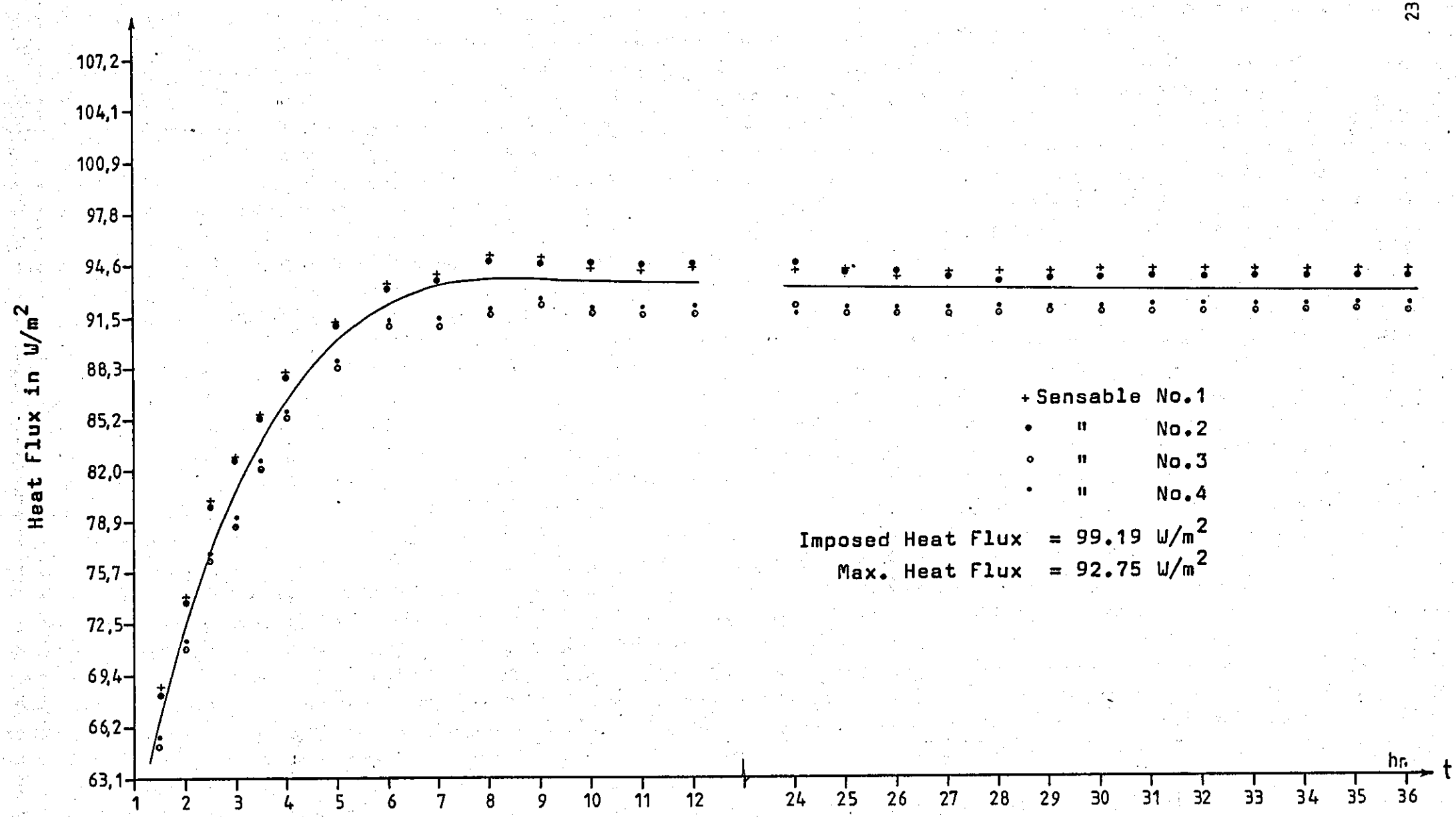


Figure 2.5.4.(7) Heat Flux Versus Time of Test : Composite Sample SC3-4



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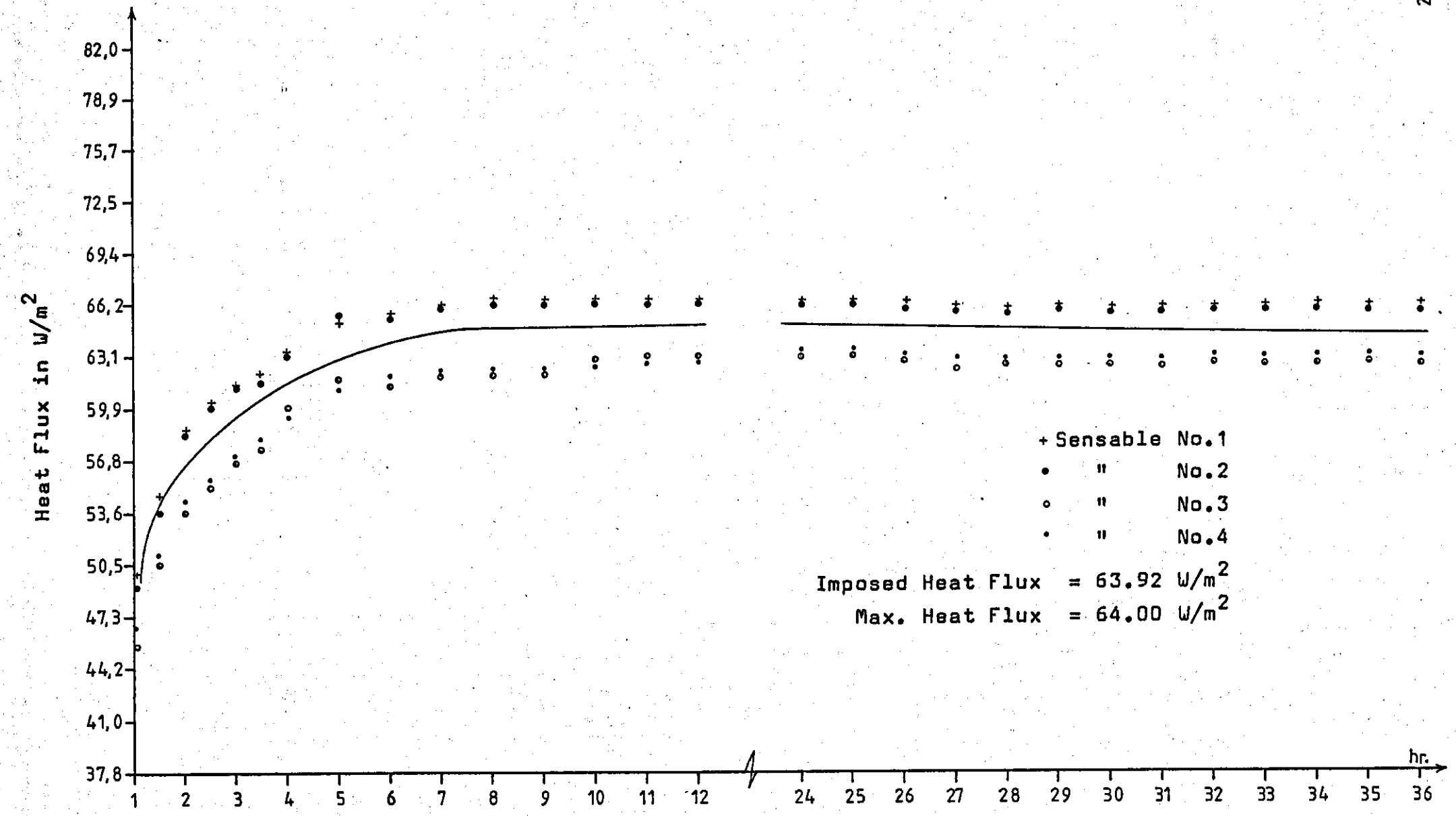


Figure 2.5.4.(9) Heat Flux Versus Time of Test : Composite Sample SC3-6

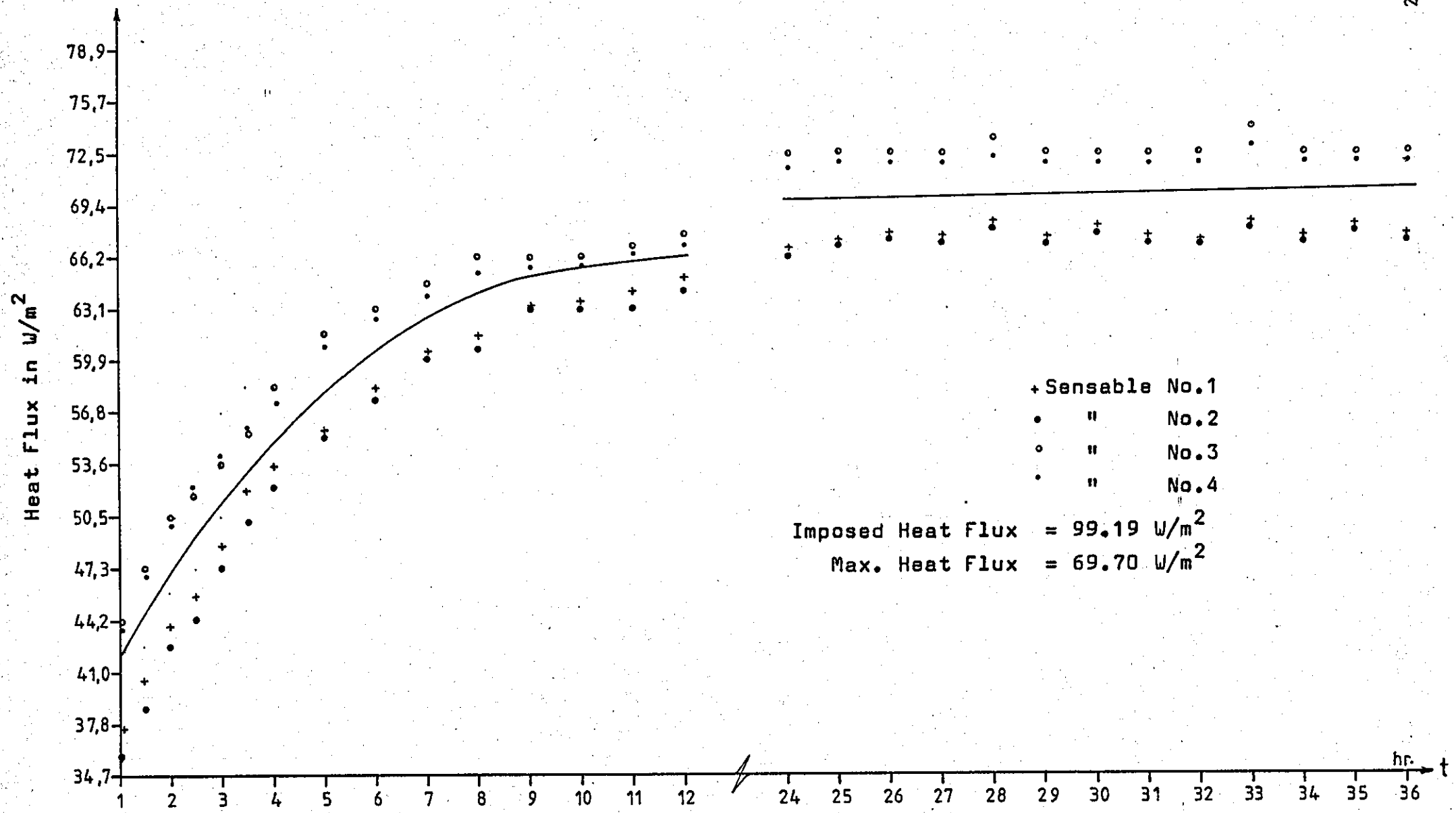


Figure 2.5.4.($\overline{10}$) Heat Flux Versus Time of Test : Composite Sample SC4-5

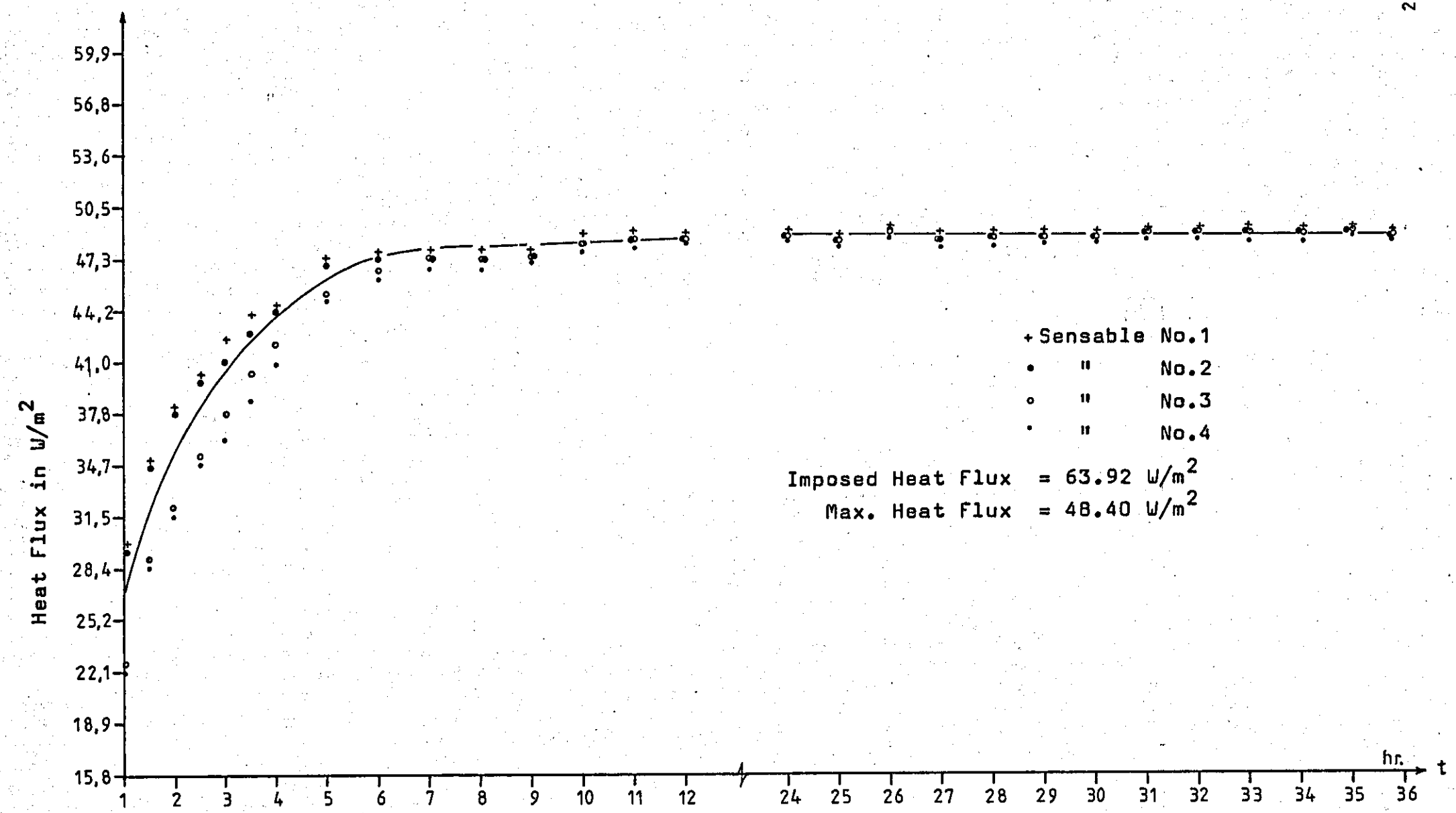


Figure 2.5.4.($\overline{11}$) Heat Flux Versus Time of Test : Composite Sample SC4-6

Table 2.5.3.-1 Thermalite samples, range of thickness, L in metre and volume, v in m^3, with heat flux, $\ddot{q}$ in W/m^2 during test.

Sample No.	Av. Sample Thickness as tested, m	Av. Sample Volume as tested m^3	Samples tested for I (Amp.)					
			3.0 A	2.5 A	2.0 A	1.5 A	1.2 A	I
				- 1	- 2	- 3	- 4	No.
			938.22	637.19	405.05	227.32	147.96	$\ddot{q}$
ST 1	4.16×10^{-2}	7.549×10^{-4}	-	-	ST1 - 2	ST1 - 3	ST1 - 4	
ST 2	3.20×10^{-2}	5.807×10^{-4}	-	-	ST2 - 2	ST2 - 3	ST2 - 4	
ST 3	2.60×10^{-2}	4.718×10^{-4}	-	ST3 - 1	ST3 - 2	ST3 - 3	ST3 - 4	
ST 4	2.34×10^{-2}	4.246×10^{-4}	ST4	-	ST4 - 2	-	-	
ST 5	2.12×10^{-2}	3.847×10^{-4}	-	ST5 - 1	ST5 - 2	ST5 - 3		
ST 6	1.68×10^{-2}	3.048×10^{-4}	-	ST6 - 1	ST6 - 2	ST6 - 3		
ST 6 x 2	$1.68 \times 2 \times 10^{-2}$	6.097×10^{-4}	-	ST6x2-1	ST6x2-2	ST6x2-3	ST6x2-4	

Note. Heat flux, is the time rate, of heat flow per unit area, W/m^2 $\ddot{q} = \frac{q}{A}$, and for each sample $\ddot{q} = \frac{q}{2A}$. Also, the time rate of heat flow $q = I\ V$, (Watts)

Table 2.5.3. - 2 Mass Loss of Thermalite Samples During Conditioning

Sample No.	Mass of Material in Samples						Mass Loss, Mr $Mr = \frac{M_1 - M_2}{M_2} \times 100$ during conditioning %
	Before conditioning, M_1 in Kg			After conditioning, M_2 in Kg			
	Top Sample	Bottom Sample	Average	Top Sample	Bottom Sample	Average	
Al1 ST1	0.54971	0.54999	0.54985	0.54950	0.54970	0.54960	0.045
Al1 ST2	0.42210	0.42240	0.42225	0.42200	0.42225	0.42212	0.031
Al1 ST3	0.34255	0.34241	0.34248	0.34247	0.34223	0.34235	0.038
Al1 ST4	0.30950	0.30935	0.30942	0.30934	0.30910	0.30922	0.064
Al1 ST5	0.28000	0.27953	0.27976	0.27976	0.27909	0.27942	0.122
Al1 ST6	0.22232	0.22318	0.22275	0.22217	0.22308	0.22262	0.058
Al1 ST6x2	0.44480	0.44572	0.44526	0.44454	0.44547	0.44500	0.058

Table 2.5.3. - 3 Mass Regain of Thermalite Samples During Test

Sample No.	Mass of Material in Samples						Mass regain $Mw = \frac{M_4 - M_3}{M_3} \times 100$ during test %
	After the test, M_4 in Kg			After second conditioning, M_3 in Kg			
	Top Sample	Bottom Sample	Average	Top Sample	Bottom Sample	Average	
All ST1	0.55167	0.55090	0.55128	0.54870	0.54875	0.54873	0.46
All ST2	0.42350	0.42342	0.42346	0.42095	0.42115	0.42105	0.54
All ST3	0.34360	0.34349	0.34355	0.34120	0.34130	0.34125	0.67
All ST4	0.31010	0.31003	0.31006	0.30871	0.30860	0.30865	0.45
All ST5	0.28105	0.28098	0.28102	0.27855	0.27861	0.27858	0.87
All ST6	0.22354	0.22431	0.22392	0.22175	0.22260	0.22217	0.78
All ST6x2	0.44615	0.44720	0.44667	0.44395	0.44505	0.44450	0.49

Table 2.5.3. - 4 Measurement of Bulk Densities of the conditioned samples as tested (Thermalite Samples)

Sample No.	Average Sample Thickness as tested, L, m	Average Sample volume, as tested, v m^3	Desnity of the conditioned sample as tested $\rho = \frac{M_2}{V}(Kg/m^3)$
ST 1	4.16×10^{-2}	7.549×10^{-4}	728.04
ST 2	3.20×10^{-2}	5.807×10^{-4}	726.91
ST 3	2.60×10^{-2}	4.718×10^{-4}	725.62
ST 4	2.34×10^{-2}	4.246×10^{-4}	728.26
ST 5	2.12×10^{-2}	3.847×10^{-4}	726.33
ST 6	1.68×10^{-2}	3.048×10^{-4}	730.38
ST6x2	$1.68 \times 2 \times 10^{-2}$	6.097×10^{-4}	729.86

Standard deviation of calculated density = $\pm$ 1.769

mean = 727.91 Kg/m^3

Standard error of the mean $= \frac{S.D}{\sqrt{n}} = + \frac{1.769}{\sqrt{7}} = +$ 0.668

Table 2.5.3. -5 Summary of Thermal Properties of Thermalite

Samples ST 1 ($L = 4.16 \times 10^{-2}$ m), Taken from figure 2.5.3. (1)

Sample No.	Time from start hr.	Room Temperature, °C	Average Sample Temperature °C				Thermal Conductivity k, W/mK	Thermal Resistivity $r = \frac{1}{k}$, Km/W	Thermal Resistance $R = \frac{L}{k}$, Km^2/W	Thermal Conductance $C = \frac{k}{L}$, W/m^2K
			Hot surface	Cold surface	Gradient K/m	mean				
	4	23.2	70.04	-2.33	8305.77	33.85	0.2381	4.200	0.1747	5.723
	6	23.3	70.94	-4.41	8377.40	33.26	0.2287	4.372	0.1818	5.497
ST1-2	12	23.3	71.38	-4.93	8400.48	33.22	0.2259	4.426	0.1841	5.430
I = 2.00 V = 7.35	24	23.2	70.87	-5.03	8390.62	32.92	0.2220	4.504	0.1873	5.336
	4	23.4	+41.64	-2.07	7616.82	19.78	0.2169	4.610	0.1918	5.214
	6	23.5	+39.26	-4.41	7615.86	17.42	0.2171	4.606	0.1916	5.218
ST1-3	12	23.5	+38.05	-5.71	7618.03	16.17	0.2166	4.617	0.1920	5.206
I = 1.5A V = 5.50	24	23.5	36.86	-7.55	7633.65	14.65	0.2135	4.683	0.1948	5.132
	4	22.7	26.68	-3.90	7301.20	11.39	0.2030	4.926	0.2049	4.880
	6	23.2	25.70	-4.93	7302.40	10.38	0.2026	4.936	0.2053	4.870
ST1-4	12	23.5	24.00	-6.50	7299.28	8.75	0.2034	4.916	0.2045	4.889
I = 1.20 V = 4.475	24	23.0	24.15	-6.30	7298.07	8.92	0.2021	4.947	0.2058	4.859

Table 2.5.3. - 6 Summary of Thermal Properties of Thermalite

Samples ST 2 ($L = 3.20 \times 10^{-2}$ m), Taken from Figure 2.5.3. (2)

Sample No.	Time from start hr.	Room Temperature °C	Average Sample Temperature °C				Thermal Conductivity k, W/mK	Thermal Resistivity $r = \frac{1}{k}$, Km/W	Thermal Resistance $R = \frac{L}{k}$, Km^2/W	Thermal Conductance $C = \frac{k}{L}$, W/m^2K
			Hot surface	Cold surface	Gradient K/m	mean				
	4	23.0	56.37	-3.10	10394.37	26.63	0.2199	4.547	0.1455	6.872
	6	23.0	55.23	-4.41	10399.69	25.41	0.2193	4.560	0.1459	6.853
ST2-2	12	23.2	54.76	-5.44	10417.19	24.66	0.2173	4.602	0.1472	6.790
I = 2.00 V = 7.35	24	23.0	54.50	-5.50	10410.93	24.50	0.2160	4.629	0.1481	6.751
	4	23.8	32.27	-4.15	9674.06	14.06	0.2002	4.995	0.1598	6.256
	6	23.5	30.34	-5.71	9662.50	12.31	0.2023	4.943	0.1582	6.322
ST2-3	12	24.0	29.36	-7.00	9672.18	11.18	0.2005	4.987	0.1596	6.265
I = 1.50 V = 5.50	24	23.8	29.21	-7.30	9676.87	10.95	0.1993	5.019	0.1606	6.226
	4	23.8	21.75	-3.64	9328.28	9.05	0.1859	5.379	0.1720	5.809
	6	23.5	19.52	-4.93	9300.0	7.29	0.1930	5.181	0.1660	6.031
ST2-4	12	24.0	18.00	-6.23	9293.12	5.88	0.1948	5.133	0.1642	6.087
I = 1.2 V = 4.475	24	23.8	18.12	-6.15	9294.37	5.98	0.1951	5.126	0.1640	6.096

Table 2.5.3. - 7 Summary of Thermal Properties of Thermalite

Samples ST 3 ($L = 2.60 \times 10^{-2}$ m), Taken from Figure 2.5.3. (3)

Sample No.	Time from start hr.	Room Temperature, °C	Average Sample Temperature °C				Thermal Conductivity k, W/m°K	Thermal Resistivity $r = \frac{1}{k}$, Km/W	Thermal Resistance $R = \frac{L}{k}$, Km^2/W	Thermal Conductance $C = \frac{k}{L}$, W/m^2K
			Hot surface	Cold surface	Gradient K/m	mean				
ST3-1	4	22.20	76.31	-3.10	13560.0	36.60	0.2091	4.782	0.1243	8.042
	6	22.30	75.64	-4.15	13574.61	35.74	0.2082	4.803	0.1248	8.007
	12	22.50	75.64	-4.66	13594.23	35.49	0.2068	4.835	0.1257	7.954
	24	22.00	75.00	-4.92	13579.61	35.04	0.2078	4.812	0.1251	7.992
ST3-2	4	22.50	50.81	-2.59	12559.61	24.11	0.1991	5.022	0.1306	7.657
	6	22.50	49.18	-4.93	12586.92	22.12	0.1964	5.092	0.1324	7.554
	12	22.50	48.47	-6.76	12630.0	20.85	0.1924	5.197	0.1351	7.400
	24	22.30	48.30	-6.87	12627.7	20.71	0.1910	5.238	0.1362	7.342

Table 2.5.3. - 7 Summary of Thermal Properties of Thermalite

Samples ST 3 ($L = 2.60 \times 10^{-2}$ m), Taken from Figure 2.5.3. (3)

Sample No.	Time from start hr.	Room Temperature, °C	Average Sample Temperature °C				Thermal Conductivity k, W/m°K	Thermal Resistivity $r = \frac{1}{k}$, Km/W	Thermal Resistance $R = \frac{L}{k}$, Km^2/W	Thermal Conductance $C = \frac{k}{L}$, W/m^2K
			Hot surface	Cold surface	Gradient °K/m	mean				
ST3-3	4	22.40	27.00	-4.15	11703.85	11.42	0.1902	5.257	0.1367	7.316
	6	22.30	25.00	-6.50	11717.31	9.25	0.1881	5.316	0.1382	7.234
	12	22.40	24.00	-7.55	11719.23	8.22	0.1878	5.325	0.1384	7.223
	24	22.30	24.00	-7.67	11723.84	8.16	0.1866	5.358	0.1393	7.178
ST3-4	4	22.70	17.52	-4.66	11358.85	6.43	0.1748	5.721	0.1487	6.723
	6	22.70	16.28	-5.44	11341.15	5.42	0.1785	5.602	0.1456	6.865
	12	22.70	17.20	-5.10	11363.46	6.05	0.1725	5.796	0.1507	6.635
	24	22.50	16.50	-5.25	11342.31	5.62	0.1768	5.654	0.1469	6.802

Table 2.5.3. - 8 Summary of Thermal Properties of Thermalite

Samples ST 4 ($L = 2.34 \times 10^{-2}$ m), Taken from Figure 2.5.3. (4)

Sample No.	Time from start hr.	Room Temperature, ^oC	Average Sample Temperature ^oC				Thermal Conductivity k, W/m^oK	Thermal Resistivity $r = \frac{1}{k}$, Km/W	Thermal Resistance $R = \frac{L}{k}$, Km^2/W	Thermal Conductance $C = \frac{k}{L}$, W/m^2K
			Hot surface	Cold surface	Gradient K/m	mean				
	4	23.00	99.00	0.00	15903.84	49.50	0.2192	4.562	0.1067	9.367
ST4	6	23.00	97.50	-1.50	15903.84	48.00	0.2192	4.562	0.1067	9.367
I = 3,0	10	23.00	97.00	-2.05	15905.98	47.47	0.2216	4.511	0.1056	9.472
V = amp	24	23.00	96.70	-2.50	15912.39	47.10	0.2213	4.518	0.1057	9.457
	4	23.50	48.00	0.00	13724.36	24.00	0.2014	4.965	0.1162	8.607
ST4-2	6	23.50	45.65	-2.60	13735.04	21.52	0.2004	4.990	0.1167	8.564
I = 2.0	12	23.50	43.50	-4.66	13731.19	19.42	0.2006	4.985	0.1166	8.572
	24	23.00	42.35	-7.29	13794.44	17.53	0.1948	5.133	0.1201	8.325

Table 2.5.3. - 9 Summary of Thermal Properties of Thermalite Samples ST 5 ($L = 2.12 \times 10^{-2}$ m), Taken from Figure 2.5.3. (5)

Sample No.	Time from start hr.	Room Temperature °C	Average Sample Temperature, °C				Thermal Conductivity k, W/m°K	Thermal Resistivity $r = \frac{1}{k}$, Km/W	Thermal Resistance $R = \frac{L}{k}$, Km^2/W	Thermal Conductance $C = \frac{k}{L}$, W/m^2 K
			Hot surface	Cold surface	Gradient K/m	mean				
ST5-1	4	22.50	60.29	-4.41	15936.32	27.94	0.2093	4.778	0.1013	9.872
	6	22.50	60.75	-4.15	15945.75	28.30	0.2086	4.794	0.1016	9.839
	12	22.50	61.43	-4.15	15977.83	28.64	0.2065	4.842	0.1026	9.740
	24	22.00	61.66	-4.67	16013.21	28.49	0.2041	4.899	0.1038	9.627
ST5-2	4	22.80	39.26	-2.59	14858.49	18.33	0.2057	4.861	0.1031	9.703
	6	22.70	38.00	-3.90	14860.85	17.05	0.2054	4.868	0.1032	9.688
	12	22.80	37.33	-4.92	14877.36	16.20	0.2037	4.909	0.1041	9.608
	24	22.80	37.00	-4.97	14864.15	16.01	0.2046	4.887	0.1036	9.651
ST5-3	4	22.50	23.47	-3.90	14175.47	9.78	0.1765	5.665	0.1201	8.325
	6	22.30	20.00	-6.50	14134.43	6.75	0.1823	5.485	0.1163	8.599
	12	22.70	18.52	-8.08	14139.15	5.22	0.1816	5.507	0.1167	8.566
	24	21.70	18.00	-8.60	14139.15	4.70	0.1816	5.507	0.1167	8.566

Table 2.5.3. - 10 Summary of Thermal Properties of Thermalite

Samples ST 6 ($L = 1.68 \times 10^{-2}$ m), Taken from Figure 2.5.3. (6)

Sample No.	Time from start hr.	Room Temperature °C	Average Sample Temperature °C				Thermal Conductivity k, W/m°K	Thermal Resistivity $r = \frac{1}{k}$, Km/W	Thermal Resistance $R = \frac{L}{k}$, Km^2/W	Thermal Conductance $C = \frac{k}{L}$, W/m^2K
			Hot surface	Cold surface	Gradient K/m	mean				
ST6-1	4	22.50	47.51	-3.63	19302.97	21.94	0.2098	4.766	0.0800	12.488
	6	22.50	47.51	-3.90	19319.05	21.80	0.2087	4.791	0.0805	12.423
	12	22.50	48.05	-3.60	19333.33	22.22	0.2072	4.825	0.0810	12.336
	24	22.50	47.20	-4.30	19324.40	21.45	0.2078	4.811	0.0808	12.372
ST6-2	4	22.70	31.31	-2.84	18291.66	14.23	0.1997	5.007	0.0841	11.887
	6	22.50	29.85	-4.92	18328.57	12.46	0.1962	5.097	0.0856	11.678
	12	22.40	29.36	-5.45	18330.95	11.95	0.1959	5.104	0.0857	11.661
	24	21.20	27.41	-7.29	18324.40	10.06	0.1966	5.086	0.0854	11.702
ST6-3	4	21.70	19.27	-2.07	17529.16	8.60	0.1794	5.574	0.0936	10.678
	6	21.50	15.52	-5.18	17491.07	5.17	0.1849	5.408	0.0908	11.006
	12	22.00	13.26	-7.00	17464.88	3.13	0.1889	5.294	0.0889	11.244
	24	21.50	13.50	-7.55	17511.90	2.98	0.1818	5.500	0.0924	10.821

Table 2.5.3. - 11 Summary of Thermal Properties of Thermalite Samples ST 6 x 2 ($L = 1.68 \times 2 \times 10^{-2}$m), Taken from Fogure 2.5.3. (7)

Sample No.	Time from start hr.	Room Temperature °C	Average Sample Temperature °C				Thermal Conductivity k W/mK	Thermal Resistivity $r = \frac{1}{k}$ Km/W	Thermal Resistance $R = \frac{L}{k}$ Km^2/W	Thermal Conductance $C = \frac{k}{L}$ W/m^2K
			Hot surface	Cold surface	Gradient K/m	mean				
ST6x2-1 I = 2.5A	4	19.50	87.75	-4.67	10880.06	41.54	0.2335	4.282	0.1439	6.949
	6	19.50	89.50	-6.23	10978.57	41.63	0.2254	4.436	0.1491	6.708
	12	19.70	89.93	-6.23	10991.37	41.85	0.2244	4.456	0.1497	6.678
	24	19.50	89.70	-6.50	10992.56	41.60	0.2225	4.493	0.1509	6.623
ST6x2-2	4	19.50	56.37	-5.18	9961.31	25.59	0.2232	4.480	0.1505	6.642
	6	20.00	56.60	-5.71	9983.93	25.44	0.2204	4.537	0.1524	6.559
	12	20.00	55.91	-7.55	10018.15	24.18	0.2164	4.621	0.1553	6.440
	24	19.00	55.22	-8.34	10021.13	23.44	0.2161	4.627	0.1555	6.431

Table 2.5.3. - 11 Summary of Thermal Properties of Thermalite

Samples ST 6 x 2 ($L = 1.68 \times 2 \times 10^{-2}$ m), Taken from Figure 2.5.3. (7)

Sample No.	Time from Start hr.	Room Temperature, ^oC	Average Sample Temperature ^oC				Thermal Conductivity k, W/mK	Thermal Resistivity $r = \frac{1}{k}$, Km/W	Thermal Resistance $R = \frac{L}{k}$, Km^2/W	Thermal Conductance $C = \frac{k}{L}$, W/m^2K
			Hot surface	Cold surface	Gradient K/m	mean				
ST6x2-3	4	21.50	29.61	-6.76	9211.90	11.42	0.2105	4.750	0.1596	6.265
	6	21.50	28.87	-7.29	9205.65	10.79	0.2117	4.724	0.1587	6.300
	12	21.80	28.87	-7.55	9213.39	10.66	0.2102	4.757	0.1598	6.256
	24	19.80	28.14	-9.39	9246.43	9.37	0.2040	4.902	0.1647	6.071
ST6x2-4	4	20.00	22.24	-3.89	8907.14	9.17	0.1896	5.2743	0.1772	5.643
	6	19.80	19.00	-7.03	8904.16	5.98	0.1904	5.2520	0.1764	5.667
	12	19.80	15.78	-9.66	8886.61	3.06	0.1948	5.1335	0.1725	5.797
	24	19.80	15.70	-9.92	8891.96	2.89	0.1940	5.1534	0.1731	5.775

Table 2.5.3. - 12 Extruded Polystyrene, (styrofoam 1B) samples, range of thickness, L in metre, volume, v in m^3, and heat flux, $\ddot{q}$ in W/m^2 during tests.

Sample No.	Av. Sample Thickness as tested m	Av. Sample volume as tested m^3	Samples tested for, I (Amp)			
			1.20	1.00	0.80	I
			4.40	3.60	2.90	V
			145.48	99.19	63.92	$\ddot{q}$
			-4	-5	-6	No.
SP 1	5.05×10^{-2}	9.163×10^{-4}		SP1-5	SP1-6	SP1
SP 2	$2.07 \times 2 \times 10^{-2}$ (4.14×10^{-2})	7.512×10^{-4}		SP2-5	SP2-6	SP2
SP 3	2.05×10^{-2}	3.720×10^{-4}	SP3-4	SP3-5	SP3-6	SP3

Table 2.5.3. - 13 Mass Loss of Extruded Polystyrene Samples During Conditioning

Sample No.	Mass of Material in Samples						Mass loss, Mr $Mr = \frac{M_1 - M_2}{M_2} \times 100$ during conditioning %
	Before conditioning, M_1 in Kg,			After conditioning, M_2 in Kg,			
	Top Sample	Bottom Sample	Average	Top Sample	Bottom Sample	Average	
All SP 1	26.72×10^{-3}	27.10×10^{-3}	26.91×10^{-3}	26.70×10^{-3}	27.08×10^{-3}	26.89×10^{-3}	0.074
All SP 2	21.41×10^{-3}	21.67×10^{-3}	21.54×10^{-3}	21.40×10^{-3}	21.67×10^{-3}	21.53×10^{-3}	0.046
All SP 3	10.74×10^{-3}	10.86×10^{-3}	10.80×10^{-3}	10.73×10^{-3}	10.86×10^{-3}	10.79×10^{-3}	0.092

Table 2.5.3. - 14 Mass Regain of Extruded Polystyrene Samples During Test

Sample No.	Mass of Material in Samples						Mass regain $Mw=\frac{M_4-M_3}{M_3} \times 100$ during test %
	After the test, M_4 Kg			After second conditioning M_3, Kg			
	Top Sample	Bottom Sample	Average	Top Sample	Bottom Sample	Average	
All SP 1	26.76×10^{-3}	27.13×10^{-3}	26.94×10^{-3}	26.68×10^{-3}	27.05×10^{-3}	26.86×10^{-3}	0.30%
All SP 2	21.45×10^{-3}	21.73×10^{-3}	21.59×10^{-3}	21.37×10^{-3}	21.64×10^{-3}	21.51×10^{-3}	0.37%
All SP 3	10.76×10^{-3}	10.88×10^{-3}	10.82×10^{-3}	10.72×10^{-3}	10.84×10^{-3}	10.78×10^{-3}	0.37%

Table 2.5.3. - 15 Measurement of Bulk Densities of The Conditioned Samples As Tested (Extruded Polystyrene).

Sample No.	Average Sample volume, v in (m^3)	Density of the conditioned sample as tested $\rho = \frac{M_2}{V}$ (Kg/m^3)
SP 1	9.163×10^{-4}	29.35
SP 2	7.512×10^{-4}	28.66
SP 3	3.720×10^{-4}	29.00

Standard deviation of the calculated density = + 0.345

mean = 29.00 Kg/m^3

Standard error of the mean = $\frac{S.D}{\sqrt{n}}$ + $\frac{0.345}{\sqrt{3}}$ = ± 0.199

Table 2.5.3. -16 Summary of Thermal Properties of Extruded Polystyrene samples SP 1 ($L = 5.05 \times 10^{-2}$m), Taken from Figures 2.5.3. (8) and 2.5.3. (9)

Sample No.	Time from Start, hr.	Room Temperature, °C	Average Sample Temperature, °C				Thermal Conductivity k, W/mK	Thermal Resistivity $r = \frac{1}{k}$, Km/W	Thermal Resistance $R = \frac{L}{k}$, Km^2/W	Thermal Conductance $C = \frac{k}{L}$, W/m^2K
			Hot surface	Cold surface	Gradient K/m	mean				
SP1-5	4	22.00	52.52	-6.05	6568.71	23.23	0.0854	11.709	0.5913	1.6911
	6	21.80	56.83	-7.29	6678.61	24.77	0.0778	12.853	0.6491	1.5406
	12	21.80	60.29	-8.08	6762.77	26.10	0.0731	13.679	0.6908	1.4475
	24	21.50	60.29	+8.60	6773.07	25.85	0.0726	13.774	0.6956	1.4376
SP1-6	4	21.75	36.94	-5.36	6246.53	15.79	0.0765	13.072	0.6601	1.5148
	6	21.63	39.10	-7.46	6330.89	15.82	0.0695	14.388	0.7266	1.3762
	12	21.30	40.69	-8.87	6390.29	15.91	0.0653	15.314	0.7733	1.2930
	24	21.35	39.50	-9.30	6375.25	15.10	0.0663	15.083	0.7617	1.3128

Table 2.5.3. - 17 Summary of Thermal Properties of Extruded Polystyrene samples SP 2 ($L = 2.07 \times 2 \times 10^{-2}$ m), Taken from Figures 2.5.3. (10) and 2.5.3. (11)

Sample No.	Time from Start hr.	Room Temperature, °C	Average Sample Temperature, °C				Thermal Conductivity k, W/mK	Thermal Resistivity $r = \frac{1}{k}$, Km/W	Thermal Resistance $R = \frac{L}{k}$, Km^2/W	Thermal Conductance $C = \frac{k}{L}$, W/m^2K
			Hot surface	Cold surface	Gradient K/m	mean				
SP2-5	4	22.90	50.72	-4.93	7942.03	22.89	0.0740	13.513	0.5594	1.787
	6	23.16	54.44	-6.77	8076.33	23.83	0.0672	14.881	0.6161	1.623
	12	23.00	55.20	-8.08	8126.32	23.56	0.0663	15.078	0.6242	1.602
	24	22.73	55.06	-8.51	8133.33	23.27	0.0647	15.456	0.6398	1.563
SP2-6	4	22.35	35.16	-5.19	7572.46	14.98	0.0658	15.197	0.6291	1.589
	6	22.20	36.40	-7.35	7654.59	14.52	0.0606	16.502	0.6832	1.464
	12	22.20	36.00	-8.87	7681.64	13.56	0.0619	16.157	0.6689	1.495
	24	21.35	34.72	-9.92	7676.09	12.40	0.0594	16.835	0.6969	1.435

Table 2.5.3. - 18 Summary of Thermal Properties of Extruded Polystyrene samples SP 3 ($L = 2.05 \times 10^{-2}$ m), Taken from Figures 2.5.3. (12) to 2.5.3. (14)

Sample No.	Time from Start, hr.	Room Temperature °C	Average Sample Temperature °C				Thermal Conductivity k, W/m K	Thermal Resistivity $r = \frac{1}{k}$, Km/W	Thermal Resistance $R = \frac{L}{k}$, Km^2/W	Thermal Conductance $C = \frac{k}{L}$, W/m^2K
			Hot surface	Cold surface	Gradient K/m	mean				
SP3-4	4	21.70	47.53	-4.92	15882.92	21.30	0.0570	17.544	0.3596	2.7805
	6	21.80	49.00	-6.76	16044.39	21.21	0.0536	18.656	0.3824	2.614
	12	20.50	48.00	-8.87	16098.53	19.56	0.0525	19.047	0.3905	2.561
	24	21.30	47.30	-8.87	16064.39	19.21	0.0532	18.797	0.3853	2.595
SP3-5	4	21.90	31.78	-5.97	15165.85	12.90	0.0542	18.450	0.3782	2.644
	6	21.90	32.59	-7.37	15273.66	12.61	0.0512	19.531	0.4004	2.497
	12	21.55	32.03	-8.35	15294.14	11.84	0.0507	19.724	0.4043	2.473
	24	21.35	31.18	-8.86	15277.56	11.16	0.0511	19.569	0.4012	2.492
SP3-6	4	21.55	21.75	-5.71	14663.90	8.02	0.0485	20.618	0.4227	2.366
	6	21.50	21.25	-6.50	14678.05	7.37	0.0486	20.576	0.4218	2.371
	12	20.50	20.27	-7.81	14694.14	6.23	0.0480	20.833	0.4271	2.341
	24	21.10	19.00	-8.73	14677.07	5.13	0.0468	21.367	0.4380	2.283

Table 2.5.4. - 1 Composite samples, range of thickness, L, in metre, volume of fibre (V_F), volume of matrix (V_M), and the total volume in m^3. Also the imposed heat flux, $\ddot{q}$, in W/m^2 during tests

Sample No.	Av. Sample Thickness, as tested, L_c, m	Av. Sample Volume, as as tested, m^3	Fibre (foam) Thickness L_F, m	Matrix (Thermalite) Thickness L_M, m	$V_F = \frac{L_F}{L_C}$	$V_M = \frac{L_M}{L_C}$	Samples tested for, I (Amp.)				
							1.50A	1.20A.	1.00A.	0.80A.	I
							5.80V	4.35V.	3.60V.	2.90V.	V
							239.72	143.83	99.19	63.92	$\ddot{q}$
							- 3	- 4	- 5	- 6	No.
SC 1	5.26×10^{-2}	9.545×10^{-4}	2.06×10^{-2}	3.20×10^{-2}	0.392	0.608		SC1-4	SC1-5	SC1-6	
SC 2	4.40×10^{-2}	7.984×10^{-4}	2.06×10^{-2}	2.34×10^{-2}	0.468	0.532	SC2-3	SC2-4	SC2-5		
SC 3	3.74×10^{-2}	6.787×10^{-4}	2.06×10^{-2}	1.68×10^{-2}	0.551	0.449		SC3-4	SC3-5	SC3-6	
SC 4	6.48×10^{-2}	11.758×10^{-4}	4.14×10^{-2}	2.34×10^{-2}	0.639	0.361			SC4-5	SC4-6	

Table 2.5.4. - 2. Summary of Thermal Conductivity of Composite Samples SC1 (L_c = 5.26 x 10^{-2}m)

L_F = 2.06 x 10^{-2}m, V_F = 0.392, L_M = 3.20 x 10^{-2}m, V_M = 0.608

Sample No.	Time from start hr.	Room Temperature °C	Average Sample Temperatures °C: Matrix Hot face (T_1)	Matrix Inter-face T_i	Matrix Mean	Foam Inter-face T_i	Foam Cold face (T_2)	Foam Mean	k_M	k_F	$k = \frac{q L}{A(T_1-T_2)}$	$k_c = \frac{k_M k_F}{V_F k_M + (1-V_F) k_F}$
	6	21.50	46.12	33.00	39.56	33.00	-7.15	12.92	0.3571	0.0739	0.1386	0.1426
	12	22.00	50.81	39.02	44.91	39.02	-10.18	14.42	0.3913	0.0603	0.1224	0.1245
SC1-4	24	21.70	52.44	39.38	45.91	39.38	-6.89	16.24	0.3533	0.0642	0.1226	0.1281
I = 1.20	30	22.00	52.90	39.26	46.08	39.26	-7.29	15.98	0.3383	0.0638	0.1233	0.1263
Amp	36	21.70	52.67	39.02	45.84	39.02	-7.55	15.73	0.3380	0.0637	0.1232	0.1261
	6	21.50	34.45	25.45	29.95	25.45	-7.81	8.82	0.3536	0.0616	0.1237	0.1241
	12	21.20	35.90	27.05	31.47	27.05	-10.71	8.17	0.3595	0.0542	0.1148	0.1124
SC1-5	24	21.00	36.14	27.65	31.89	27.65	-9.52	9.06	0.3748	0.0551	0.1135	0.1148
I = 1.0	30	21.50	35.66	26.68	31.17	26.68	-8.87	8.90	0.3543	0.0576	0.1161	0.1177
Amp	36	21.50	35.66	26.68	31.17	26.68	-9.39	8.64	0.3543	0.0568	0.1161	0.1164
	6	20.50	25.45	17.03	21.24	17.03	-8.34	4.34	0.2435	0.0520	0.1021	0.0999
	12	20.50	24.00	13.50	18.75	13.50	-12.57	0.46	0.1953	0.0506	0.0986	0.0923
SC1-6	24	20.20	22.25	13.25	17.75	13.25	-10.71	1.27	0.2278	0.0551	0.1022	0.1025
	30	20.50	22.25	13.72	17.98	13.72	-10.71	1.50	0.2152	0.0540	0.1047	0.1015
	36	20.70	22.50	12.00	17.25	12.00	-12.57	-0.28	0.1953	0.0537	0.1015	0.0962

Table 2.5.4. -.3. Summary of Thermal Conductivity of Composite Samples SC 2 (L_C = 4.40×10^{-2}m)

L_F = 2.06×10^{-2}m, V_F = 0.468 L_M = 2.34×10^{-2}m, V_M = 0.532

Sample No.	Time from start hr.	Room Temperature °C	Average Sample Temperatures °C						k_M	k_F	$k = \frac{q\ L}{A(T_1-T_2)}$	$k_c = \frac{k_M\ k_F}{V_F k_M + (1-V_F)k_F}$
			Matrix			Foam						
			Hot face (T_1)	Inter-face T_i	Mean	Inter-face T_i	Cold-face (T_2)	Mean				
	6	22.00	75.00	57.50	66.25	57.50	-4.15	26.67	0.2979	0.0794	0.1295	0.1302
	12	21.70	80.50	62.50	71.50	62.50	-6.23	28.13	0.3062	0.0714	0.1184	0.1206
SC2-3	24	20.75	82.00	64.10	73.05	64.10	-7.81	28.14	0.3096	0.0680	0.1134	0.1162
I = 1.5	30	22.00	82.50	63.40	72.95	63.40	-6.23	28.58	0.2885	0.0705	0.1154	0.1178
V = 5.80	36											
	6	22.50	51.30	39.50	45.4	39.50	-4.41	17.54	0.2950	0.0706	0.1153	0.1186
	12	22.00	54.00	41.64	47.82	41.64	-6.50	17.57	0.2651	0.0650	0.1061	0.1086
SC2-4	24	20.80	55.00	42.81	48.90	42.81	-6.23	18.29	0.2855	0.0614	0.1020	0.1055
I = 1.20	30	22.00	54.00	40.69	47.34	40.69	-4.41	18.14	0.2615	0.0672	0.1061	0.1091
V = 4.35	36											
	6	21.80	37.10	28.39	32.74	28.39	-5.18	11.60	0.2811	0.0642	0.1061	0.1088
	12	22.00	37.80	29.12	33.46	29.12	-6.50	11.31	0.2785	0.0606	0.1014	0.1038
SC2-5	24	21.50	36.85	28.63	32.74	28.63	-7.55	10.54	0.2984	0.0595	0.1000	0.1036
I = 1.00	30	22.20	37.10	27.90	32.50	27.90	-6.23	10.83	0.2627	0.0633	0.1035	0.1062
V = 3.60	36											

Table 2.5.4. -4 Summary of Thermal Conductivity of Composite Samples SC 3 ($L_C = 3.74 \times 10^{-2}$m)
$L_F = 2.06 \times 10^{-2}$m, $V_F = 0.551$, $L_M = 1.68 \times 10^{-2}$m, $V_M = 0.449$

Sample No.	Time from start hr.	Room Temperature °C	Average Sample Temperatures, °C, Matrix: Hot face (T_1)	Matrix: Inter-face T_i	Matrix: Mean	Foam: Inter-face T_i	Foam: Cold face (T_2)	Foam: Mean	k_M	k_F	$k = \frac{qL}{A(T_1-T_2)}$	$k_C = \frac{k_M k_F}{V_F k_M + (1-V_F)k_F}$
	6	21.00	48.00	40.45	44.22	40.45	-6.12	17.16	0.3208	0.0637	0.0966	0.0996
	12	21.00	50.35	45.18	47.76	45.18	-9.65	17.16	0.4685	0.0541	0.0898	0.0898
SC3-4	24	20.30	49.42	43.40	46.41	43.40	-9.00	17.20	0.4024	0.0566	0.0905	0.0923
I = 1.2	30	20.50	49.42	43.16	46.29	43.16	-8.60	17.28	0.3869	0.0574	0.0908	0.0930
Amp.	36	21.00	49.88	43.88	46.88	43.88	-8.73	17.57	0.4037	0.0564	0.0909	0.0920
	6	21.00	33.73	28.99	31.36	28.99	-6.63	11.18	0.3524	0.0575	0.0912	0.0922
	12	21.30	34.45	30.82	32.63	30.82	-9.39	10.71	0.4602	0.0509	0.0869	0.0848
SC3-5	24	21.30	33.97	29.00	31.48	29.00	-8.47	10.26	0.3361	0.0546	0.0857	0.0876
I = 1.00	30	22.00	33.97	29.24	31.60	29.24	-7.29	10.97	0.3532	0.0561	0.0890	0.0902
Amp.	36	21.70	33.97	29.48	31.72	29.48	-7.42	11.03	0.3721	0.0555	0.0879	0.0899
	6	21.60	21.75	15.27	18.51	15.27	-9.00	3.13	0.1661	0.0544	0.0818	0.0780
	12	21.80	22.00	16.14	19.07	16.14	-9.92	3.11	0.1837	0.0507	0.0804	0.0751
SC3-6	24	21.50	21.25	15.40	18.32	15.40	-9.91	2.74	0.1840	0.0521	0.0782	0.0769
I = 0.80	30	21.70	21.25	15.52	18.38	15.52	-10.31	2.60	0.1879	0.0511	0.0795	0.0760
Amp.	36	21.70	21.25	14.27	17.76	14.27	-11.25	1.51	0.1542	0.0517	0.0795	0.0737

Table 2.5.4. - 5 Summary of Thermal Conductivity of Composite Samples SC 4 ($L_c = 6.48 \times 10^{-2}$m)

$L_F = 4.14 \times 10^{-2}$m, $V_F = 0.639$ $L_M = 2.34 \times 10^{-2}$m, $V_M = 0.361$

Sample No.	Time from start hr.	Room Temperature °C	Average Sample Temperatures °C						k_M	k_F	$k = \frac{qL}{A(T_1-T_2)}$	$k_c = \frac{k_M k_F}{V_F k_M + (1-V_F)k_F}$
			Matrix			Foam						
			Hot face (T_1)	Inter-face T_i	Mean	Inter-face T_i	Cold face (T_2)	Mean				
	6	20.50	42.81	37.45	40.13	37,45	-10.18	13.63	0.4341	0.0864	0.1253	0.1215
	12	20.50	49.65	45.09	47.37	45.09	-12.97	16.06	0.5103	0.0709	0.1063	0.1029
SC4-5	24	20.50	50.81	46.59	48.70	46.59	-11.11	17.74	0.5514	0.0713	0.1056	0.1039
I = 1.00	30	20.70	51.00	46.83	48.91	46.83	-11.25	17.79	0.5580	0.0709	0.1067	0.1035
Amp.	36	21.00	52.90	49.17	51.03	49.17	-13.37	17.90	0.6238	0.0658	0.1030	0.0972
	6	21.00	33.24	30.70	31.97	30.70	-8.73	10.98	0.5904	0.0673	0.1031	0.0989
	12	21.00	34.00	31.78	32.89	31.78	-11.78	10.00	0.6755	0.0609	0.0962	0.0906
SC4-6	24	20.00	33.73	31.07	32.40	31.07	-11.92	9.57	0.5637	0.0617	0.0934	0.0909
I = 0.80	30	20.20	33.73	30.22	31.97	30.22	-11.78	9.22	0.4272	0.0631	0.0940	0.0911
Amp.	36	20.50	34.21	30.82	32.51	30.82	-13.37	8.72	0.4423	0.0600	0.0918	0.0872

Table 2.5.4. - 6. Results obtained for Composite Sample SC1-4 with $L_c = 0.0526$ m, $V_F = 0.392$

Time, hr.	Heat Flow $\ddot{q}$, W/m^2	T_1, ^oC	T_2, ^oC	T_1-T_2, ^oC	$\bar{k}_c = \frac{\ddot{q} L_c}{T_1-T_2}$	$k_A = \frac{q L_c}{A(T_1-T_2)}$	$k_c = \frac{k_M \cdot k_F}{V_F k_M + (1-V_F) k_F}$
1	53.30	26.68	-3.10	29.78	0.0941	0.2547	0.2595
1½	62.78	30.10	-4.15	34.25	0.0964	0.2214	0.2270
2	70.65	33.49	-4.92	38.41	0.0967	0.1974	0.2005
2½	76.97	36.14	-6.00	42.14	0.0961	0.1799	0.1874
3	82.02	38.29	-6.50	44.79	0.0963	0.1693	0.1733
3½	85.17	40.00	-6.76	46.76	0.0958	0.1622	0.1667
4	89.90	41.40	-7.29	48.69	0.0971	0.1557	0.1595
5	95.59	44.00	-7.81	51.81	0.0970	0.1463	0.1501
6	98.58	46.12	-8.60	54.72	0.0947	0.1386	0.1426
7	100.63	47.76	-8.87	56.63	0.0935	0.1339	0.1343
8	105.67	49.42	-9.39	58.81	0.0945	0.1289	0.1293
9	106.94	51.05	-10.44	61.49	0.0914	0.1233	0.1235
10	108.83	50.81	-9.13	59.94	0.0955	0.1265	0.1245
11	109.30	52.00	-9.92	61.92	0.0928	0.1224	0.1245
12							
24	114.50	52.44	-9.39	61.83	0.0974	0.1226	0.1281
25	114.66	52.67	-9.13	61.80	0.0976	0.1227	0.1274
26	114.50	52.44	-9.39	61.83	0.0974	0.1226	0.1272
27	114.50	52.67	-8.87	61.54	0.0978	0.1232	0.1269
28	114.50	52.67	-8.87	61.54	0.0978	0.1232	0.1270
29	115.05	52.44	-8.87	61.31	0.0987	0.1237	0.1281
30	114.50	52.90	-8.60	61.50	0.0979	0.1233	0.1263
24 to 30	Mean k				0.0978	0.12304	0.1273
	standard Deviation (S.D.)				0.00044	0.00042	0.00065
	Variance				2×10^{-7}	2×10^{-7}	4×10^{-7}
	% Difference from k_A				+20.51	0	-3.45

Table 2.5.4. -7 Results obtained for Composite Sample SCI-5 with L_c = 0.0526 m, V_F = 0.392

Time, hr.	Heat Flow $\ddot{q}$, W/m^2	T_1, °C	T_2, °C	T_1-T_2, °C	$\bar{k}_c = \frac{\ddot{q}\,L_c}{T_1-T_2}$	$k_A = \frac{q\,L_c}{A(T_1-T_2)}$	$k_c = \frac{k_M\,k_F}{V_F k_M+(1-V_F)k_F}$
1	46.69	24.71	+0.50	24.21	0.1014	0.2160	0.2121
1½	54.42	26.44	-1.55	27.99	0.1022	0.1868	0.1872
2	60.88	28.63	-2.84	31.47	0.1017	0.1662	0.1651
2½	65.30	29.61	-4.41	34.02	0.1010	0.1537	0.1571
3	68.45	30.83	-5.18	36.01	0.1000	0.1452	0.1456
3½	70.98	31.31	-6.00	37.31	0.1001	0.1402	0.1436
4	74.13	32.02	-6.50	38.52	0.1012	0.1358	0.1360
5	77.29	33.24	-7.55	40.79	0.0997	0.1282	0.1310
6	78.86	34.45	-7.81	42.26	0.0982	0.1237	0.1241
7	80.75	35.66	-8.87	44.53	0.0954	0.1174	0.1206
8	80.91	36.14	-9.13	45.27	0.0940	0.1155	0.1152
9	81.86	35.90	-9.65	45.55	0.0945	0.1148	0.1117
10	81.86	35.66	-9.13	44.79	0.0961	0.1167	0.1130
11	81.86	36.14	-9.13	45.27	0.0951	0.1155	0.1118
12	82.96	35.90	-9.65	45.55	0.0958	0.1148	0.1124
24	83.44	36.14	-9.92	46.06	0.0953	0.1135	0.1148
25	83.60	35.66	-9.39	45.05	0.0976	0.1161	0.1163
26	83.60	35.66	-9.39	45.05	0.0976	0.1161	0.1184
27	83.60	35.66	-9.65	45.31	0.0970	0.1154	0.1170
28	83.60	35.66	-9.39	45.05	0.0976	0.1161	0.1177
29	83.60	35.66	-9.39	45.05	0.0976	0.1161	0.1177
30	83.60	35.66	-9.39	45.05	0.0976	0.1161	0.1177
Period		Mean k			0.0972	0.1156	0.1171
24		S.D.			0.00086	0.00097	0.001205
to		Variance			6×10^{-7}	8×10^{-7}	1.2×10^{-6}
30		% Difference from k_A			+15.95	0	-1.254

Table 2.5.4. - 8. Results obtained for Composite Sample SCI-6 with $L_c = 0.0526$ m, $V_F = 0.392$

Time, hr.	Heat Flow $\ddot{q}$, W/m^2	T_1, °C	T_2, °C	T_1-T_2, °C	$\bar{k}_c = \frac{\ddot{q} L_c}{T_1-T_2}$	$k_A = \frac{q L_c}{A(T_1-T_2)}$	$k_c = \frac{k_M k_F}{V_F k_M+(1-V_F)k_F}$
1	40.69	23.72	+4.10	19.62	0.1091	0.1718	0.1677
1½	47.63	24.71	+1.79	22.92	0.1093	0.1471	0.1441
2	51.57	25.70	0.00	25.70	0.1055	0.1311	0.1276
2½	55.67	25.95	-2.07	28.02	0.1045	0.1203	0.1162
3	58.04	25.70	-3.63	29.33	0.1041	0.1149	0.1140
3½	59.93	26.19	4.92	31.11	0.1013	0.1083	0.1076
4	60.88	25.70	-5.71	31.41	0.1019	0.1073	0.1058
5	61.82	25.95	-6.76	32.71	0.0994	0.1030	0.1008
6	62.77	25.45	-7.55	33.00	0.1000	0.1021	0.0999
7	62.46	24.95	-8.60	33.55	0.0979	0.1005	0.0999
8	62.46	24.71	-9.13	33.84	0.0971	0.0996	0.0967
9	62.77	24.95	-9.65	34.60	0.0954	0.0974	0.918
10	62.14	24.71	-10.18	34.89	0.0937	0.0966	0.0905
11	60.41	24.00	-9.92	33.92	0.0937	0.0994	0.0950
12	60.72	24.00	-10.18	34.18	0.0934	0.0986	0.0923
24	59.46	22.25	-10.71	32.96	0.0949	0.1022	0.1025
25	59.46	22.25	-10.71	32.96	0.0949	0.1022	0.1015
26	58.82	22.50	-10.44	32.94	0.0939	0.1023	0.1016
27	58.82	22.25	-10.18	32.43	0.0954	0.1039	0.1015
28	58.82	22.25	-10.18	32.43	0.0954	0.1039	0.1025
29	58.36	22.25	-9.92	32.17	0.0954	0.1047	0.0994
30	58.36	22.25	-9.92	32.17	0.0954	0.1047	0.1015
period 24 to 30	Mean k				0.0950	0.1034	0.1012
	S.D.				0.00056	0.00115	0.00131
	Variance				3×10^{-7}	1.1×10^{-6}	1.5×10^{-6}
	% Difference from k_A				+8.094	0	+2.137

Table 2.5.4. - 9. Results obtained for Composite Sample SC2-3 with L_c = 0.0440 m, V_F = 0.468

Time hr.	Heat Flow $\ddot{q}$, W/m^2	T_1, °C	T_2, °C	T_1-T_2, °C	$\bar{k}_c = \frac{\ddot{q}\,L_c}{T_1-T_2}$	$k_A = \frac{q\,L_c}{A(T_1-T_2)}$	$k_c = \frac{k_M \cdot k_F}{V_F k_M + (1-V_F)\,k_F}$
1	72.55	42.58	+5.13	37.45	0.0852	0.2767	0.3209
1½	91.48	53.60	+1.75	51.85	0.0776	0.1998	0.2486
2	108.04	55.68	+0.25	55.43	0.0857	0.1869	0.1982
2½	121.45	61.20	-1.29	62.49	0.0855	0.1658	0.1802
3	132.49	64.16	-2.60	66.76	0.0873	0.1552	0.1656
3½	139.59	68.69	-3.37	72.06	0.0852	0.1440	0.1529
4	142.74	69.82	-3.90	73.72	0.0852	0.1405	0.1449
5	151.42	71.38	-5.45	76.83	0.0867	0.1348	0.1353
6	160.09	74.00	-6.00	80.00	0.0880	0.1295	0.13017
7	169.08	77.90	-6.23	84.13	0.0884	0.1232	0.1270
8	170.35	79.90	-6.50	86.40	0.0867	0.1198	0.1232
9	174.13	79.90	-6.76	86.66	0.0884	0.1195	0.1228
10	176.65	80.29	-7.00	87.29	0.0890	0.1187	0.1218
11	179.81	80.51	-7.00	87.51	0.0904	0.1184	0.1206
12	179.81	80.51	-7.00	87.51	0.0904	0.1184	0.1210
24	183.59	81.90	-9.40	91.30	0.0885	0.1134	0.1162
25	180.44	82.28	-7.82	90.10	0.0881	0.1150	0.1162
26	181.39	82.28	-7.82	90.10	0.0886	0.1150	0.1179
27	181.39	82.28	-7.82	90.10	0.0886	0.1150	0.1179
28	181.39	82.50	-7.29	89.79	0.0889	0.1154	0.1179
29	181.39	82.50	-7.29	89.79	0.0889	0.1154	0.1178
30	181.39	82.50	-7.29	89.79	0.0889	0.1154	0.1178
Period 24 to 30	Mean k				0.0886	0.1149	0.1174
	S.D.				0.00029	0.00071	0.00081
	Variance				7.4×10^{-8}	4.3×10^{-7}	5.6×10^{-7}
	% Difference from k_A				+22.88	0	-2.12

Table 2.5.4. - 10. Results obtained for Composite Sample SC2-4 with L_c = 0.0440 m, V_F = 0.468

Time hr.	Heat Flow $\ddot{q}$, W/m^2	T_1, ^oC	T_2, ^oC	T_1-T_2, ^oC	$\bar{k}_c = \frac{\ddot{q}\,L_c}{T_1-T_2}$	$k_A = \frac{q\,L_c}{A(T_1-T_2)}$	$k_c = \frac{k_M\,k_F}{V_F k_M+(1-V_F)k_F}$
1	62.30	34.00	3.30	30.70	0.0893	0.2133	0.2253
1½	76.65	37.60	0.75	36.85	0.0915	0.1975	0.1862
2	85.32	40.20	-1.30	41.50	0.0905	0.1700	0.1649
2½	91.48	42.50	-2.60	45.10	0.0892	0.1520	0.1513
3	97.80	44.50	-3.35	47.85	0.0899	0.1415	0.1447
3½	102.83	45.90	-4.10	50.00	0.0905	0.1320	0.1357
4	105.36	47.50	-4.40	51.90	0.0893	0.1270	0.1300
5	112.45	49.90	-4.66	54.56	0.0907	0.1194	0.1217
6	116.09	51.30	-5.40	56.70	0.0901	0.1153	0.1186
7	118.29	52.40	-5.40	57.80	0.0900	0.1132	0.1146
8	119.24	52.90	-6.00	58.90	0 0891	0.1112	0.1132
9	121.13	52.90	-7.00	59.90	0.0890	0.1092	0.1132
10	122.08	54.00	-6.00	60.00	0.0895	0.1092	0.1106
11	123.34	54.30	-6.20	60.50	0.0897	0.1082	0.1095
12	123.24	54.00	-7.30	61.30	0.0885	0.1061	0.1086
24	123.24	55.00	-8.90	63.90	0.0849	0.1020	0.1055
25	124.61	54.60	-8.60	63.20	0.0867	0.1030	0.1062
26	124.61	54.30	-8.60	62.90	0.0872	0.1050	0.1072
27	123.24	54.00	-8.00	62.00	0.0874	0.1051	0.1087
28	123.24	54.00	-8.00	62.00	0.0874	0.1051	0.1087
29	123.24	54.00	-8.00	62.00	0.0874	0.1055	0.1089
30	123.24	54.00	-7.50	61.50	0.0882	0.1061	0.1091
Period 24 to 30	Mean k				0.087	0.1044	0.1077
	S.D.				0.00104	0.00146	0.00145
	Variance				9.2×10^{-7}	1.8×10^{-6}	1.8×10^{-6}
	% Difference from k_A				+16.63	0	-3.21

Table 2.5.4. - 11. Results obtained for Composite Sample SC2-5 with L_c = 0.0440 m, V_F = 0.468

Time, hr.	Heat Flow, $\ddot{q}$, W/m^2	T_1, °C	T_2, °C	T_1-T_2, °C	$\bar{k}_c = \frac{\ddot{q}\,L_c}{T_1-T_2}$	$k_A = \frac{q\,L_c}{A(T_1-T_2)}$	$k_c = \frac{k_M\,k_F}{V_F k_M+(1-V_F)k_F}$
1	55.20	28.15	+3.60	24.55	0.0989	0.1915	0.2016
1½	62.93	29.90	+1.30	28.60	0.0968	0.1620	0.1722
2	66.40	32.00	-0.25	32.25	0.0906	0.1435	0.1491
2½	74.29	33.25	-1.80	35.05	0.0932	0.1305	0.1367
3	79.18	35.00	-2.33	37.33	0.0933	0.1214	0.1271
3½	81.86	35.50	-3.10	38.60	0.0933	0.1173	0.1218
4	84.38	36.15	-3.90	40.05	0.0927	0.1132	0.1173
5	86.44	36.85	-5.00	41.85	0.0909	0.1081	0.1123
6	88.48	37.10	-5.70	42.80	0.0909	0.1061	0.1088
7	90.85	37.30	-6.00	43.30	0.0923	0.1065	0.1070
8	89.27	37.30	-6.80	44.10	0.0891	0.1050	0.1050
9	91.48	37.80	-7.00	44.80	0.0898	0.1040	0.1032
10	91.48	37.80	-7.00	44.80	0.0898	0.1035	0.1038
11	91.48	37.80	-7.00	44.80	0.0898	0.1035	0.1032
12	91.48	37.80	-7.00	44.80	0.0898	0.1040	0.1038
24	91.17	36.85	-8.60	45.45	0.0883	0.1030	0.1036
25	91.64	36.85	-7.90	44.75	0.0901	0.1035	0.1048
26	88.96	36.85	-7.30	44.15	0.0886	0.1029	0.1049
27	90.53	37.10	-7.00	44.10	0.0903	0.1030	0.1054
28	91.17	37.30	-7.00	44.10	0.0903	0.1030	0.1063
29	90.38	37.10	-6.80	43.90	0.0906	0.1035	0.1062
30	90.53	37.10	-6.80	43.90	0.0907	0.1035	0.1062
Period 24 to 30	Mean k				0.0898	0.1024	0.1053
	S.D.				0.00098	0.00128	0.00099
	Variance				8.16×10^{-7}	1.41×10^{-6}	8.45×10^{-7}
	%Difference from k_A				+12.26	0	-2.83

Table 2.5.4. - 12. Results obtained for Composite Sample SC3-4

with L_c = 0.0374 m, V_F = 0.551

Time hr.	Heat Flow $\ddot{q}$, W/m^2	T_1, ^oC	T_2, ^oC	T_1-T_2, ^oC	$k_c = \frac{\ddot{q} L_c}{T_1-T_2}$	$k_A = \frac{q L_c}{A(T_1-T_2)}$	$k_c = \frac{k_M k_F}{V_F k_M + (1-V_F) k_F}$
1	65.93	30.10	+3.59	26.51	0.0930	0.2034	0.1996
1½	78.86	34.00	+1.28	32.72	0.0901	0.1648	0.1650
2	89.27	37.33	-0.25	37.58	0.0888	0.1435	0.1436
2½	96.22	39.74	-1.55	41.29	0.0871	0.1306	0.1306
3	103.15	43.05	-4.15	47.20	0.0817	0.1142	0.1162
3½	106.94	44.00	-5.18	49.18	0.0813	0.1096	0.1129
4	111.04	45.42	-5.71	51.13	0.0812	0.1054	0.1079
5	116.41	46.59	-7.03	53.62	0.0812	0.1005	0.1040
6	119.87	48.00	-7.81	55.81	0.0803	0.0966	0.0996
7	123.03	48.71	-8.34	57.05	0.0806	0.0945	0.0977
8	123.35	49.65	-8.60	58.25	0.0792	0.0926	0.0948
9	124.29	50.35	-9.65	60.00	0.0775	0.0898	0.0906
10	123.66	50.58	-9.39	59.97	0.0771	0.0899	0.0895
11	124.60	50.35	-9.39	59.74	0.0780	0.0902	0.0903
12	124.92	50.35	-9.65	60.00	0.0778	0.0898	0.0898
24	126.18	49.42	-10.18	59.60	0.0792	0.0905	0.0923
25	126.18	49.42	-10.18	59.60	0.0792	0.0905	0.0920
26	126.18	49.42	-10.18	59.60	0.0792	0.0905	0.0927
27	126.81	49.65	-9.65	59.30	0.0799	0.0909	0.0920
28	126.18	49.65	-9.65	59.30	0.0796	0.0909	0.0920
29	126.18	49.42	-9.92	59.34	0.0795	0.0908	0.0930
30	126.18	49.42	-9.92	59.34	0.0795	0.0908	0.0930
Period 24 to 30	Mean k				0.0794	0.0907	0.0924
	S.D.				0.00026	0.00019	0.00046
	Variance				5.9×10^{-8}	3.14×10^{-8}	2×10^{-7}
	% Difference from k_A				+12.41	0	-1.87

Table 2.5.4. - 13 Results obtained for Composite Sample SC3-5 with L_c = 0.0374 m, V_F = 0.551

Time, hr.	Heat Flow $\bar{q}$, W/m^2	T_1, °C	T_2, °C	T_1-T_2, °C	$\bar{k}_c = \frac{\bar{q}\ L_c}{T_1-T_2}$	$k_A = \frac{q\ L_c}{A(T_1-T_2)}$	$k_c = \frac{k_M\ k_F}{V_F\ k_M+(1-V_F)k_F}$
1	54.59	23.72	+0.77	22.95	0.0889	0.1620	0.1593
1½	66.57	27.17	-0.50	27.67	0.0899	0.1344	0.1315
2	72.39	28.63	-2.07	30.70	0.0882	0.1211	0.1183
2½	78.07	30.10	-3.10	33.20	0.0879	0.1120	0.1095
3	80.60	30.58	-4.41	34.99	0.0862	0.1063	0.1059
3½	83.60	31.78	-5.18	36.96	0.0846	0.1006	0.0999
4	86.43	32.27	-5.45	37.72	0.0857	0.0986	0.0979
5	89.59	33.00	-6.23	39.23	0.0854	0.0948	0.0942
6	91.95	33.73	-7.03	40.76	0.0844	0.0912	0.0922
7	92.27	33.97	-7.29	41.26	0.0836	0.0901	0.0885
8	93.06	33.97	-7.55	41.52	0.0838	0.0895	0.0879
9	93.37	34.21	-8.34	42.55	0.0821	0.0874	0.0855
10	93.06	34.45	-8.34	42.79	0.0813	0.0869	0.0848
11	93.06	34.45	-8.34	42.79	0.0813	0.0869	0.0848
12	93.06	34.45	-8.34	42.79	0.0813	0.0869	0.0848
24	93.37	33.97	-9.39	43.36	0.0805	0.0857	0.0876
25	92.75	33.97	-8.34	42.31	0.0820	0.0879	0.0901
26	92.75	33.97	-8.87	42.84	0.0810	0.0868	0.0902
27	92.75	33.97	-8.34	42.31	0.0820	0.0879	0.0901
28	92.59	34.21	-8.08	42.29	0.0819	0.0879	0.0905
29	92.59	23.97	-7.81	41.78	0.0829	0.0890	0.0902
30	92.59	33.97	-8.34	42.31	0.818	0.0879	0.0899
Period	Mean k				0.0817	0.0876	0.0898
24	S.D.				0.00077	0.00104	0.00099
to	Variance				5×10^{-7}	9×10^{-7}	8×10^{-7}
30	%Diference from k_A				+6.68	0	-2.53

Table 2.5.4.- 14 Results obtained for Composite Sample SC3-6 with L_c = 0.0374 m, V_F = 0.551

Time, hr.	Heat Flow $\ddot{q}$, W/m^2	T_1, °C	T_2, °C	T_1-T_2, °C	$\bar{k}_c = \frac{\ddot{q}\,L_c}{T_1-T_2}$	$k_A = \frac{q\,L_c}{A(T_1-T_2)}$	$k_c = \frac{k_M\,k_F}{V_F k_M + (1-V_F)k_F}$
1	47.32	18.03	-3.89	21.92	0.0807	0.1093	0.1093
1½	52.05	19.03	-4.92	23.95	0.0813	0.1000	0.0990
2	56.00	20.03	-5.45	25.48	0.0822	0.0940	0.0936
2½	57.57	20.75	-5.71	26.46	0.0814	0.0906	0.0847
3	58.99	21.25	-6.23	27.48	0.0803	0.0872	0.0824
3½	59.46	21.50	-6.50	28.00	0.0794	0.0856	0.0790
4	61.51	21.50	-6.76	28.26	0.0814	0.0848	0.0792
5	63.72	21.75	-7.55	29.30	0.0813	0.0818	0.0776
6	63.41	21.75	-7.55	29.30	0.0809	0.0818	0.0780
7	63.88	22.00	-7.81	29.81	0.0802	0.0804	0.0751
8	64.04	22.24	-8.34	30.58	0.0783	0.0784	0.0765
9	64.04	22.24	-8.34	30.58	0.0783	0.0784	0.0765
10	64.04	22.24	-8.34	30.58	0.0783	0.0784	0.0765
11	64.04	22.24	-8.34	30.58	0.0783	0.0784	0.0765
12	64.04	22.24	-8.34	30.58	0.0783	0.0784	0.0765
24	64.35	21.25	-9.39	30.64	0.0785	0.0782	0.0769
25	64.35	21.25	-9.39	30.64	0.0785	0.0782	0.0769
26	64.35	21.00	-9.39	30.39	0.0792	0.0788	0.0756
27	64.19	21.00	-9.39	30.39	0.0790	0.0788	0.0734
28	64.19	21.00	-9.39	30.39	0.0790	0.0788	0.0756
29	64.04	21.25	-9.13	30.38	0.0788	0.0789	0.0753
30	64.04	21.25	-8.87	30.12	0.0795	0.0795	0.0760
period	Mean k				0.0789	0.0787	0.0757
24	S.D.				0.00036	0.00045	0.00118
to	Variance				1×10^{-7}	2×10^{-7}	0.12×10^{-7}
30	% Difference from k_A				-0.24	0	+3.90

Table 2.5.4. - 15 Results obtained for Composite Sample SC4 -5 with L_c = 0.0648 m, V_F = 0.639

Time, hr.	Heat Flow $\dot{q}$, W/m^2	T_1, ^oC	T_2, ^oC	T_1-T_2, ^oC	$\bar{k}_c = \frac{\dot{q} L_c}{T_1-T_2}$	$k_A = \frac{q L_c}{A(T_1-T_2)}$	$k_c = \frac{k_M k_F}{V_F k_M+(1-V_F)k_F}$
1	40.06	26.92	+0.50	26.42	0.0982	0.2439	0.2315
1½	43.05	29.36	-2.99	32.35	0.0862	0.1992	0.1987
2	46.53	32.00	-3.89	35.89	0.0840	0.1795	0.1734
2½	47.95	34.21	-4.92	39.13	0.0794	0.1646	0.1591
3	50.47	36.14	-6.23	42.37	0.0772	0.1521	0.1426
3½	52.84	37.57	-7.00	44.57	0.0768	0.1445	0.1387
4	55.21	38.78	-7.55	46.33	0.0772	0.1391	0.1363
5	58.36	40.93	-8.08	49.01	0.0772	0.1315	0.1267
6	60.25	42.81	-8.60	51.41	0.0759	0.1253	0.1215
7	62.30	44.71	-9.13	53.84	0.0750	0.1197	0.1165
8	63.41	45.42	-9.65	55.07	0.0746	0.1170	0.1123
9	64.67	47.53	-10.18	57.71	0.0726	0.1116	0.1075
10	64.67	48.24	-10.44	58.68	0.0714	0.1098	0.1057
11	64.98	48.47	-10.71	59.18	0.0711	0.1088	0.1038
12	65.93	49.65	-11.00	60.65	0.0705	0.1062	0.1029
24	69.40	50.81	-10.18	60.99	0.0737	0.1056	0.1039
25	69.71	50.81	-10.18	60.99	0.0741	0.1056	0.1040
26	69.86	50.81	-10.18	60.99	0.0742	0.1056	0.1033
27	69.71	50.81	-9.92	60.73	0.0744	0.1061	0.1038
28	70.66	50.81	-9.92	60.73	0.0754	0.1061	0.1037
29	69.71	50.81	-9.65	60.46	0.0747	0.1065	0.1031
30	70.03	51.00	-9.39	60.39	0.0751	0.1067	0.1035
period	Mean k				0.0745	0.1060	0.1036
24	S.D.				0.00059	0.00045	0.00033
to	Variance				3×10^{-7}	2×10^{-7}	0.93×10^{-7}
30	% Difference from k_A				+29.73	0	+2.28

Table 2.5.4. - 16 Results obtained for Composite Sample SC4-6 with L_c = 0.0648 m, V_F = 0.639

Time, hr.	Heat Flow $\ddot{q}$, W/m^2	T_1, °C	T_2, °C	T_1-T_2, °C	$\bar{k}_c = \frac{\ddot{q}\,L_c}{T_1-T_2}$	$k_A = \frac{q\,L_c}{A(T_1-T_2)}$	$k_c = \frac{k_M\,k_F}{V_F k_M+(1-V_F)k_F}$
1	26.03	25.45	+8.46	16.99	0.0993	0.2444	0.2320
1½	31.86	27.17	+5.13	22.04	0.0936	0.1884	0.1769
2	35.01	28.39	+2.31	26.08	0.0870	0.1592	0.1516
2½	37.54	29.36	+0.25	29.11	0.0836	0.1426	0.1357
3	39.43	29.85	-1.81	31.66	0.0807	0.1312	0.1240
3½	41.64	31.07	-2.84	33.91	0.0796	0.1224	0.1169
4	43.21	31.54	-3.89	35.43	0.0790	0.1172	0.1109
5	46.05	32.51	-5.71	38.22	0.0781	0.1086	0.1046
6	47.00	33.24	-7.03	40.27	0.0756	0.1031	0.0989
7	47.32	33.73	-7.55	41.28	0.0743	0.1006	0.0953
8	47.32	34.69	-8.34	43.03	0.0713	0.0965	0.0908
9	47.32	34.45	-8.60	43.05	0.07122	0.0964	0.0887
10	48.27	34.21	-8.87	43.08	0.0726	0.0964	0.0907
11	48.58	34.93	-9.39	44.32	0.0710	0.0937	0.0859
12	48.27	34.00	-9.13	43.13	0.0725	0.0962	0.0906
24	45.58	33.73	-10.71	44.44	0.0708	0.0934	0.0909
25	48.27	33.48	-10.18	43.66	0.0716	0.0951	0.0922
26	48.43	33.48	-10.18	43.66	0.0718	0.0951	0.0925
27	48.27	33.24	-10.44	43.68	0.0716	0.0950	0.0921
28	48.58	33.48	-9.92	43.40	0.0725	0.0956	0.0923
29	48.27	33.00	-10.71	43.71	0.0715	0.0950	0.0921
30	48.27	33.73	-10.44	44.17	0.0708	0 0940	0.0911
Period 24 to 30	Mean k				0.0715	0.0947	0.0919
	S.D.				0.00059	0.00076	0.00062
	Variance				3×10^{-7}	5×10^{-7}	3×10^{-7}
	% Difference from k_A				+24.52	0	+3.02

Table 2.5.4. - 17 Values of Thermal conductivities of composite samples and the % difference between them.

Sample No.	Composite Mean Temp °C	Mean of the period 24 - 30 hours: Over all $k_A = \frac{q L_c}{A(T_1-T_2)}$	$\bar{k}_c$ measured from Heat flow $\ddot{q}$ $\bar{k}_c = \frac{\ddot{q} L_c}{T_1-T_2}$	% Difference from k_A = $\frac{k_A-\bar{k}_c}{k_A} \times 100$	k_c based on k_A data $k_c = \frac{k_M k_F}{V_F k_M + (1-V_F) k_F}$	Diff % from k_A	% Difference of Max $\ddot{q}$ from the imposed Heat Flux $\frac{(q/A-\ddot{q})}{q/A} \times 100$
SC1-4	22.50	0.12304	0.0978	+20.50	0.1273	-3.45	+20.32
SC1-5	13.50	0.1156	0.0972	+15.95	0.1171	-1.25	+15.72
SC1-6	5.80	0.1034	0.0951	+8.09	0.1012	+2.14	+7.70
SC2-3	37.25	0.1149	0.0886	+22.88	0.1174	-2.12	+23.42
SC2-4	23.00	0.1044	0.0870	+16.63	0.1077	-3.21	+13.78
SC2-5	14.75	0.1024	0.0898	+12.26	0.1053	-2.83	+8.25
SC3-4	20.25	0.0907	0.0794	+12.41	0.0924	-1.87	+12.19
SC3-5	13.45	0.0876	0.0817	+6.68	0.0898	-2.53	+6.49
SC3-6	6.45	0.0787	0.0789	-0.24	0.0757	+3.90	-0.19
SC4-5	21.00	0.1060	0.0745	+29.73	0.1036	+2.28	+29.73
SC4-6	12.00	0.09474	0.0715	+24.52	0.0947	+3.02	+24.12

APPENDICES

Appendix A : Tables 1

Appendix B : The Climate of Middle East (Saudi Arabia) 15

Appendix C : Thermal Comfort 44

Appendix D : Traditional Building Materials and Their Location 80

Appendix A-1

SI (Système International d'Unités) Units [102]

I: Base units

Quantity	Name	Symbol	Notes
length	metre	m	
mass	kilogram	kg	
time	second	s	
electric current	ampere	A	
thermodynamic temperature	kelvin	K	
amount of substance	mole	mol	
luminous intensity	candela	cd	

II: Supplementary units

Quantity	Name	Symbol	Notes
plane angle	radian	rad	
solid angle	steradian	sr	

III: Derived units

Derived units are expressed algebraically in terms of base units and/or supplementary units, and some of them have special names & sym. as listed here,

Quantity	Name	Symbol	Expressed in terms of SI units I, II, or III
frequency	hertz	Hz	$1\ Hz = 1\ s^{-1}$
force	newton	N	$1\ N = 1\ kg \cdot m/s^2$
pressure, stress	pascal	Pa	$1\ Pa = 1\ N/m^2$
energy, quantity of heat	joule	J	$1\ J = 1\ N \cdot m$
power	watt	W	$1\ W = 1\ J/s$
quantity of electricity	coulomb	C	$1\ C = 1\ A \cdot s$
electric potential, tension	volt	V	$1\ V = 1\ J/C$
electric resistance	ohm	Ω	$1\ \Omega = 1\ V/A$
electric conductance	siemens	S	$1\ S = 1\ \Omega^{-1}$

Appendix A-2

Conversion Factors

Table (1) Thermal Conductivity

	$\frac{W}{m.K}$	$\frac{W}{cm.K}$	$\frac{cal}{s.cm.K}$	$\frac{kg.cal}{h.m.K}$	$\frac{Btu}{h.ft.^{o}F}$	$\frac{Btu.in.}{h.ft^{2}.^{o}F}$
1 W/m.K =	1,000	1.000×10^{-2}	2.388×10^{-3}	0.8598	0.5778	6.933
1 W/cm.K =	100.0	1.000	0.2388	85.98	57.78	693.3
1 cal/s.cm.K =	418.7	4.187	1.000	360.0	241.9	2903.0
1 kg.cal/h.m.K =	1.163	1.163×10^{-2}	2.778×10^{-3}	1.000	0.6720	8.064
1 Btu/h.ft.°F =	1.731	1.731×10^{-2}	4.134×10^{-3}	1.488	1.000	12.00
1 Btu.in/h.ft.^{2}°F =	0.1442	1.442×10^{-3}	3.445×10^{-4}	0.1240	8.333×10^{-2}	1.000

Table (2) Thermal Conductance

	$\frac{W}{m^2\cdot K}$	$\frac{W}{cm^2\cdot K}$	$\frac{cal}{s\cdot cm^2\cdot K}$	$\frac{kg\cdot cal}{h\cdot m^2\cdot K}$	$\frac{Btu}{h\cdot ft^2\cdot {}^{o}F}$
1 $W/m^2\cdot K$ =	1.000	1.000×10^{-4}	2.388×10^{-5}	0.8598	0.1761
1 $W/cm^2\cdot K$ =	1.000×10^{4}	1.000	0.2388	8598.	1761.
1 $cal/s\cdot cm^2\cdot K$ =	4.187×10^{4}	4.187	1.000	3.600×10^{4}	7373.
1 $kg\cdot cal/h\cdot m^2\cdot K$ =	1.163	1.163×10^{-4}	2.778×10^{-5}	1.000	0.2048
1 $Btu/h\cdot ft^2\cdot {}^{o}F$ =	5.678	5.678×10^{-4}	1.356×10^{-4}	4.882	1.000

Appendix A-3

Converting thermocouple voltages into their equivalent measured temperatures.

Copper / copper - nickel thermocouples. Type T

Temperature : E.M.F. Reference junction at 0 degrees Celsius.

Temperatures in degrees Celsius (IPTS-68) e.m.f. in microvolts.

Temp.	e.m.f.	Temp.	e.m.f.	Temp.	e.m.f.	Temp.	e.m.f.	Temp.	e.m.f.	Temp.	e.m.f.
0	0	0	0								
-1	-39	1	39	26	1032	50	2035	73	3042	95	4044
-2	-77	2	78	27	1073	51	2078	74	3087	96	4091
-3	-116	3	117	28	1114	52	2121	75	3131	97	4137
-4	-154	4	156	29	1155	53	2164	76	3176	98	4184
-5	-193	5	195	30	1196	54	2207	77	3221	99	4231
-6	-231	6	234	31	1237	55	2250	78	3266	100	4277
-7	-269	7	273	32	1279	56	2294	79	3312	101	4324
-8	-307	8	312	33	1320	57	2337	80	3357	102	4371
-9	-345	9	351	34	1361	58	2380	81	3402	103	4418
-10	-383	10	391	35	1403	59	2424	82	3447	104	4465
-11	-421	11	430	36	1444	60	2467	83	3493	105	4512
-12	-458	12	470	37	1486	61	2511	84	3538	106	4559
-13	-496	13	510	38	1528	62	2555	85	3584	107	4607
-14	-534	14	549	39	1569	63	2599	86	3630	108	4654
-15	-571	15	589	40	1611	64	2643	87	3676	109	4701
-16	-608	16	629	41	1653	65	2687	88	3721	110	4749
-17	-646	17	669	42	1695	66	2731	89	3767	111	4796
-18	-683	18	709	43	1738	67	2775	90	3813	112	4844
-19	-720	19	749	44	1780	68	2819	91	3859	113	4891
-20	-757	20	789	45	1822	69	2864	92	3906	114	4939
-21	-794	21	830	46	1865	70	2908	93	3952	115	4987
-22	-830	22	870	47	1907	71	2953	94	3998		
-23	-867	23	911	48	1950	72	2997				
-24	-903	24	951	49	1992						
-25	-940	25	992								
-26	-976										

For complete tables refer to B.S. 4937-5[91]

Reference (cold) junction correction figures

For use with Temperature / E.M.F. table.

Thermocouples are type T

Temperature °C	e.m.f. microvolts	Temperature °C	e.m.f. microvolts
10	390	21	830
11	430	22	870
12	470	23	910
13	510	24	950
14	550	25	990
15	590	26	1030
16	630	27	1070
17	670	28	1110
18	710	29	1160
19	750	30	1200
20	790		

For complete figures refer to B.S. 4937-5 (1974)[91]

Appendix A-4 Thermal conductivity k, Specific heat c, Bulk density , and Thermal diffusivity of some Metals, Alloys, and Nonmetals.

Material	t, °C	k, W/m°K	c, J/Kg°K	ρ, Kg/m³	α, ×10⁵ m²/s
-Metals:					
[2]Aluminum	0;100	202.4;205.9	870.85	2707	8.595
[2]Copper,pure	0;100	387.5;377.1	381.00	8940	11.408
[2]Iron,pure	0;100	61.9; 63.3	435.42	7865	1.806
[3]Iron,cast	0;100	50.2; 48.4			
[3]Steel,mild	0;100	62.3; 57.1			
[2]Tin	0;100	62.3; 58.8	226.08	7305	3.768
[2]Zinc	0;100	112.5;110.7	381.00	7145	4.129
-Alloys:					
[2]Brass,70%Cu, 30%Zn.	0;100	96.9;103.8	385.18	8520	2.942
[2]Bronze,75%Cu, 25%Sn.	0	26.0	343.32	8650	0.8775
[2]Constantan, 60%Cu,40%Ni.	0;100	21.5; 22.1	418.68	8922	0.5678
[2]Steel,mild,1%C	0;100	45.8; 45.0	460.55	7850	1.2650
-Structural and heat-resistant:					
Stones:					
[4]Basalt	0-100	1.28-2.77	858.18_m	2707	
[4]Basalt	100	1.76	1088.57_m	3204	
[4]Granite	.....	3.11-4.15	849.92_m	2500--3000	
[4]Granite	48.9	1.28-2.60	1046.70	2530-2640	
[2]Limestone,dry	21.1	0.69	921.10	1682	0.0438
[4]Limestone	100-300	1.26-1.33	908.53_m	2560	
[4]Limestone	0	2.21	.....	....	.....
[4]Marble	.....	1.28-3.37	879.23_m	2707	.....
[4]Sandstone,humid	20	1.68	.....	2258	.....
[4]Sandstone,dry	20	1.30	728.50_m	2242	
[5]Shale	.....	0.86	.....		
[5]Travertine	.....	1.04	.....		

Appendix A-4 (Continued)

Material	t, °C	k, W/m°K	c, J/Kg°K	ρ, Kg/m³	a, ×10⁵ m²/s
Concrete, Plasters:					
[2]Concrete, stone	21.1	0.93	837.36	2306	0.0490
[2]Concrete, 10% H_2O	21.1	1.21	.....	2242	0.0645
[4]Concrete	20	1.28	883.41_t	2274	.....
[4]Concrete, full set	20	0.76	1130.43_m	2178	.....
[5]Concrete, cinder aggregate	23.9	0.71	.....	1554	.....
[5]Cement, mortar	....	1.73	.....	1842	.....
[5]Gypsum, plaster	21.1	0.48	.....	1120	.....
[5]Lime-cement, plaster	....	1.16	.....	1762	.....
[1]Plaster, metal lath	21.1	0.47	.....	....	.....
[1]Plaster, wood lath	21.1	0.28	.....	....	.....
Bricks:					
[4]Hand formed, dry	25	0.40	741.06_m	1566	.....
[4]Machine made, dry	50	0.48	921.10_m	1620	.....
[1]Building, common	20	0.69	.....	....	.....
[1]Building, face	...	1.31	.....	....	.....
[4]Brickwork, old, dry	20	0.41	.....	1842	.....
[4]Brickwork, old, dry	47.2	0.45	.....	1842	.....
[4] " " " , new, humid	10	1.40	.....	1960	.....
[4] " " ", 4½ months old	10	0.97	.....	1762	.....
[2]Brick, fire-clay	200	1.00	837.36	2307	0.0516
[2]Brick, masonry	21.1	0.66	837.36	1700	0.0465
[2]Brick, zirconia	200	1.45	.....	4870	.....
[2]Chrome brick	200	1.42	.....	3940	.....
[4]Silica 95% SiO_2	50	1.16	1356.52_m & 1122.06_m	1874	.....
[4]Silica brick " "	200	0.66	782.93_m & 795.49_m	1650	.....
[1]Magnesite brick	204.4	3.81	.....	.....	.....
[1] " " " " " "	648.9	2.77	.....	....	.....
[1] " " " " " "	1204.4	1.90	.....	....	.....

Appendix A-4 (Continued)

Material	t, °C	k, W/m°K	c, J/Kg°K	ρ, Kg/m³	a, ×10⁵ m²/s
Soil:					
[2]Soil, dry	21.1	0.35	1842.19	....	0.0258
[2]Soil, wet	21.1	2.60	.....	....	0.0774
[2]Sand, dry	20	0.35	.....	1520	.....
[2]Sand, 10% H_2O	20	1.04	.....	1600	.....
[4]Soil, dry	20	0.52	837.36	1340-1906	.....
[4]Soil, loamy, fresh	0	2.32	.....	2018	.....
[4]Sandy ground	20	1.07	.....	....	.....
Glass:					
[2]Glass, window	21.1	0.78	837.36	2723	0.0335
[5]Ordinary, soda-lime-silica	48.9	0.97	.....	2515	.....
[5]Opaque, coloured	48.9	1.21	.....	....	.....
[5]Pyrex	48.9	1.09	.....	2226	.....
Woods:					
Hardwoods:					
[5]Elm	....	0.14	.....	528.6	.....
[5]Mahogany	....	0.13	.....	544.6	.....
[2]Oak ⊥ to grain	21.1	0.21	2386.47	816.9	0.0106
[2]Oak II to grain	21.1	0.35	2386.47	816.9	0.0178
Softwoods:					
[4]Balsa	0	0.055	.....	200.2	.....
[4]Balsa	50	0.076	.....	200.2	.....
[5]Douglas fir	....	0.140	.....	496.6	.....
[5]Fir	....	0.118	.....	400.4	.....
[2]Pine ⊥ to grain	21.1	0.104	2805.15	496.6	0.0075
[2]Pine II to grain	21.1	0.24	2805.15	496.6	0.0173
[5]Spruce	....	0.104-0.121	.....	.....	.....

Appendix A-4 (Continued)

Material	t, °C	k, W/m°K	c, J/Kg°K	ρ, Kg/m³	α, ×10⁵ m²/s
-Insulating material:					
[2]Asbestos	0	0.15	1046.70	576.6	0.0258
[2]Asbestos	200	0.208	.....	576.6	0.0258
[5]Asbestos cement semi-comp.BS 690	....	0.37	.....	1522	.....
[5]Asbestos cement fully comp.BS4036	....	0.65	.....	1698min.	.....
[5]Asbestos board, corrugated	43.9	0.069	.....	320.4	.....
[5]Asbestos paper, corrugated	65.6	0.064	.....	272.3	.....
[5]Board,glass-fiber	26.7	0.038	.....	176.2	.....
[5] " "vegetable- "	26.7	0.048	.....	235.5	.....
[5]Board,wood-fiber	26.7	0.050	.....	251.5	.....
[2]Cork	30	0.043	167.47	160.2	0.0155
[5]Corkboard	26.7	0.038	.....	110.5	.....
[2]Cotton,fabric	93.3	0.079	.....	.....	.....
[2]Diatomaceous earth, powdered	37.8	0.052	879.23	224.2	0.0258
[2] " " " " " " " "	148.9	0.062	.....	224.2	.....
[2]Glass wool,fine	37.8	0.054	.....	24.0	.....
[2]Glass wool,packed	37.8	0.038	.....	96.1	.....
[5]Gypsum board	21.1	0.208	.....	929.0	.....
[2]Hair felt	37.8	0.047	.....	131.3	.....
[2]Kaolin insulating	200	0.086	.....	304.3	.....
[2] " " " " firebrick	760	0.19	.....	304.3	.....
[4]Kapok	20	0.035-0.040	1356.52t	150.6	.....
[2]85% magnesia	0	0.055	.....	272.3	.....
[2]85% magnesia	93.3	0.064	.....	272.3	.....
[2]Rockwool	-6.7	0.029	.....	128.1	.....
[2]Rockwool	93.3	0.052	.....	128.1	.....

Appendix A-4 (Continued)

Material	t, °C	k, W/m°K	c, J/Kg°K	ρ, Kg/m³	a, ×10⁵ m²/s
[5]Vermiculite	65.6	0.078	.....	144.2	.....
[3]Wood shavings	23.9	0.059	.....	.....	.....
[4]Wool	0	0.038	1360.71$_m$	136.1	.....
[4]Wool	30	0.042	1720.77$_m$	40.1	
[6]Expanded polystyrene	....	0.035; 0.033	.....	16.0; 24.0	.....
[6]Foamed polyurethane	....	0.024; 0.039	.....	24.0; 40.0	.....
[6]Aerated concrete	....	0.084-0.180	.....	320 - 700	.....
[6]Aerated concrete, high density	....	0.650	.....	1602	.....
[6]Compressed straw	....	0.101	.....	365	.....
[6]Foamed slag concrete	....	0.22-0.51	.....	961 - 1682	.....
Miscellaneous matr.					
[4]Asphalt	20	0.76	921.10$_t$	2114	.....
[4]Chalk	....	0.94; 0.92	879.23$_m$	1794; 2595	.....
[5]Felt,wool	....	0.052	.....	.....	.....
[2]Ice	0	2.21	1925.93	913.0	0.1239
[4]Leather,sole	30	0.16	1494.69$_t$	1000	.....
[4]Paraffin	22.8	0.26	.....	920	.....
[2]Rubber	0	0.15	2009.66	1200	0.0062
[4]Rubber,hard	25-50	0.16	1419.32	1190	.....
[4]Rubber,soft	30	0.17	.....	1100	.....
[5]Sawdust,dry	20	0.069	.....	214.6	.....
[5]Vaseline	20	0.18	.....	.....	.....

Notes: i- Superscripts figures 1 to 6 denote references (73 and 63 to 67).

ii- For Metals and Alloys taken from reference (63),

the values of c, ρ, and α were determined at $0^{o}C$.

iii- The subscript t refers to the true specific heat at the temperature : t , and the subscript m refers to the mean specific heat.

iv- The bulk density is the weight of 1 m^3 of the material in a state that is found in practice, and thus including the volume of its pores.

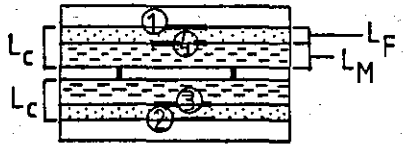
v- All the values have been converted to SI units.

Date:	Sample:	No. of Run:	I: Amp.	V: Volts	L: $\times 10^{-2}$ m	$k = \frac{q\,L}{A(T_1 - T_2)}$

Time,																			
Temperature, °C.,																			
Ref. J. Correction																			
Hot Plate							e.m.f. in 'Millivolts'												
	5																		
	6																		
	7																		
	8																		
	9																		
	10																		
	Av. e.m.f.																		
Hot Face e.m.f.																			
Hot Face Temp. °C., T_1																			
Lower Cold Plate	1																		
	2																		
	3																		
	4																		
Upper Cold Plate	11																		
	12																		
	13																		
	14																		
Av. Cold Face e.m.f.																			
Cold Face e.m.f.																			
Cold Face Temp. °C., T_2																			
$(T_1 - T_2)$, °C.,																			
k, W/m.°C.,																			

Table : 1CS/	Sample :	L_c =	'k' = $\frac{q\,L_c}{A(T_1-T_2)}$
Date :	No. of Run : I = Amp. V = Volts.		

Time :																	
Temperature, °C.,																	
Ref. J. Correction, Millivolts,																	
Hot Plate	Point No. 5																
	" 6																
	" 7																
	" 8																
	" 9																
	" 10																
	Av. e.m.f., Millivolts,																
Hot Face e.m.f., Millivolts,																	
Hot Face Temp., °C., T_1,																	
Lower Cold Plate	Point No. 1																
	" 2																
	" 3																
	" 4																
Upper Cold Plate	" 11																
	" 12																
	" 13																
	" 14																
Av. Cold Face e.m.f.,																	
Cold Face e.m.f., Millivolts,																	
Cold Face Temp., °C., T_2,																	
$(T_1 - T_2)$, °C.,																	
'k' Composite, W/m°C.,																	

Table : 2CS/	Sample :		$V_F = \frac{L_F}{L_C} =$ ___
Date :	No. of Run :	$L_C =$	$V_M = \frac{L_M}{L_C} =$ ___
	I = Amp.	$L_F =$	
	V = Volts.	$L_M =$	

Time,																	
Data from Table : 1CS/	Temperature, °C.,																
	Ref. J. Correction, mV,																
	Hot Face Temp. °C., T_1,																
	Cold Face Temp. °C., T_2,																
	'k' Composite, W/m°C.,																
Top Sample	Interface e.m.f. @ ④																
	Corrected e.m.f., mV,																
	Interface Temp., °C.,																
Bottom Sample	Interface e.m.f. @ ③																
	Corrected e.m.f., mV,																
	Interface Temp., °C.,																
Av. Interface Temp., °C., $T_{③④}$																	
$T_1 - T_{③④}$, °C.,																	
k_M, W/m°C.,																	
Top Sample	Cold Face e.m.f. @ ①																
	Corrected e.m.f., mV,																
	Cold Face Temp., °C.,																
Bottom Sample	Cold Face e.m.f. @ ②																
	Corrected e.m.f., mV,																
	Cold Face Temp., °C.,																
Av. Cold Face Temp., °C., $T_{①②}$																	
$T_{③④} - T_{①②}$, °C.,																	
k_F, W/m°C.,																	
$k_C = \frac{k_M \cdot k_F}{V_F \cdot k_M + (1 - V_F) k_F}$																	

Appendix B

B - The Climate of Middle East (Saudi Arabia)

B-1. Introduction

During the last Ice Age, which ended some 15,000 years ago, Arabia is known to have enjoyed a more temperate climate, with greater rainfall than at present. Much of the desert was then grassland, and the great wadi systems still seen in Arabia testify to the eroding power of the runoff from the highlands[36]. Experts now generally agree that the climate changes at the end of the Ice Age resulted in a weather pattern that has altered little to this day.

The region is characterised by extremely arid summers, and a winter-spring maximum of precipitation. Continental effects are so marked in the centre of the main land mass of Arabia, and the precipitation is so low that population is confined to oases or thinly scattered as nomadic groups, except in the main cities, where the human activities depend on the religious, political, commercial and the new industrial centres[103].

B-2. Topography

The topography of Saudi Arabia[3,21], can be described in a simple way. To the east of the Red Sea, the highest land in this zone is found at the south western corner of the Arabian Peninsula. Here in Yemen altitudes of more than 3,700 m are attained. Highland also occurs along the whole of the western part of Arabia, with the general level of the land declining to the north and east. In central Saudi Arabia, characteristic of the relief are a series of westward facing escarpments, in arc-like form around the main highland of the west coast. The low land belt of the region stretches from northern Iraq to the coast of the Indian

Ocean in Oman. It continues as an attenuated zone along the western shore of the Arabian Gulf to broaden into an extensive plain in south eastern Arabia. In this latter zone the largest sand area in the World, the Rub Al-Khali, is situated, here some of the dunes are more than 200 m in height[37]. At the eastern-most tip of Arabia, a belt of uplands, called Gebel Al-Akhdar ('Green Mountain') reach a maximum height of more than 3,000 m.

B-3. Deserts in Middle East

B-3.1. General Circulation

No desert area is completely rainless, though in extreme cases, several years may be elapse between individual storms. The subtropical anticyclones undergo only minor seasonal variations so the desert cores are liable to remain rainless[38], but rainfall is apt to increase and become more seasonal towards the poleward and equatorial limits.

Rainfall within desert regions normally results from disturbances arising outside the true desert areas. For instance, upper cold pools and troughs from the middle latitudes bring rainfall to the poleward margins of the deserts; similarly, disturbances forming near the equator can bring rainfall to the equatorward margins. As middle latitude troughs are most intense and nearest to the equator in winter, the poleward margins of the deserts usually experience a winter rainfall maximum. The equatorial trough tends to move north-south with the sun; in contrast to the poleward margins, the equatorial limits of the desert areas normally experience summer rainfall maximums. It is therefore possible to

recognize two distinct rainfall regimes in desert areas.

B-3.2. The Topographical Effect

It is clear from the atmospheric moisture balance model[36] which is shown in Figure (B/1), that where topographical factors are added to those caused by the general circulation, the aridity is greatly increased and in these areas the most severe desert conditions in the world can be found.

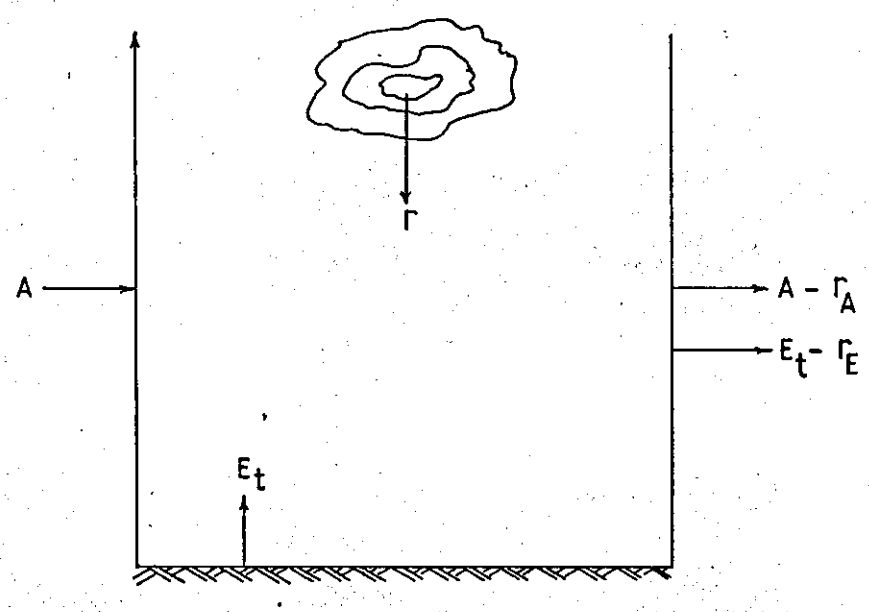


Figure (B/1): The hydrological cycle in the atmosphere over a small land area (After Drozdov and Grigoréva)[36]

rainfall: $r = r_A + r_E$

r_A: moisture advected into the area

r_E: moisture evaporated

E_t: local evapotranspiration

$E_t = r_E + C$ (advected out of the area)

The rainfall must either flow out of the unit area as rivers or ocean currents, or be used in the local evapotranspiration.

It has been noted that in the tropics the moisture available for rain formation is trapped in a shallow layer below an inversion. The depth of this moist layer varies, but it is usually between 1 km and 2 km. If a mountain barrier projects through the moist layer, it will interrupt the surface flow and the surface moist layer will not penetrate behind the mountain range. Even if the mountains do not completely block the moist layer, the reduction in moisture advection to the lee of the range can still be substantial.

Dryness can be increased by subsidence of air from near the inversion down the lee slopes of the range, and for this reason mountain-enclosed inland basins are often extremely arid. Rub Al-Khali[18, 21] (Empty Quarter), which is the immense sand body in southern part of Saudi Arabia, is a good example.

B-3.3. Definition of Aridity

Angström (1936) expressed aridity in terms of a relationship between precipitation (P) and evapotranspiration (E_t).

$$I_{arid} = f_1 (E_t, P)$$

However, since temperature is an approximate measure of the energy available for evapotranspiration through net radiation and sensible heat advection, indexes using it have proved useful for the description of climates on a world scale.

B-4. Climate Classification

Climate may be described as the average condition of the atmosphere over a long period of time. The most popular and widely used systems of classification are based on the work of Köppen, although there have been numerous minor changes and revisions since the original system was devised. The climate types described below represent one of these revisions (Köppen-Trewartha)[40]. Where the climate of Saudi Arabia occur in two main types of this classification, as follows:

B-4.1. (B) Dry

(B W) Arid (Desert)

- Potential evaporation averages greater than precipitation throughout the year.
- Exact boundaries of climate determined by temperature - precipitation formula.
- Approximately 0 - 380 mm of annual rainfall in low latitudes and 0 - 250 mm in mid - latitudes.
- h (hot and k (cold) subtypes distinguished by Köppen as separated by average annual temperature of 18°C.

(B S) - Semi arid (Steppe)

- Potential evaporation averages greater than precipitation as in BW.
- Potential evaporation and climate boundary determination as in BW.
- Approximately 380 - 760 mm of annual rainfall in low latitudes and 250 - 500 mm in mid - latitudes.
- h (hot and k (cold) subtypes distinguished as in BW.

B-4.2.(F)Undifferentiated Highlands

- A variety of climates found in a limited number of areas due to variation in slope, altitude, and exposure.
- If tropical, these climates identified fairly readily.

Due to the latitudinal extent of Saudi Arabia[21] from approximately 16°N to 32°N, it has varied physical conditions, with two different latitudinal zones, namely the North Tropical Zone and the Sub-Tropical Zone. The North Tropical zone extends between 10°N to 25°N astride the Tropic of Cancer, where the sun takes a path close to the zenith at one solstice and is appreciably lower at the opposite solstice. Thus a marked seasonal cycle exists, but is combined with a potentially large total insoluation. The Sub-Tropical Zone which extends from latitude belt 25°N to 35°N, is characterised by medium seasonal contracts in insoluation.

Throughout Arabia BW (arid) climate predominate. BS (semi-arid) climates occur in the extreme northern part of Saudi Arabia. The main characteristics of these climates[32] are the high day temperatures, low night temperatures, low humidity, low precipitation and little air movement except for local thermal, winds and dust storms. In locations, where sea and desert meet, diurnal variations are less and humidity very high, with land and sea breezes caused by the differential heating and cooling of land and sea.

Part of the Saudi region, however, does possess mountainous regions which do not fit easily into a climatic classification owing to the very large changes which can occur over relatively short distances.

B-5. Weather Systems

B-5.1. Air Masses

Saudi Arabia comes under the influence of five air masses[18,36] at different timesof the year. During the summer months, there is relatively little air movement throughout the area, and a (continental tropical air mass) which is very hot and dry prevails. A very different situation occurs in winter when air masses from four major source areas can enter the region as the result of cyclonic activity.

The (maritime polar air-mass), originating over the North Atlantic, contains large amounts of moisture and provdies most of the precipitation experienced throughout the Middle East. With the passage of a depression (continental polar air-mass) is drawn into northern and eastern parts of saudi Arabia from eastern Europe and Siberia. This is very cold and dry and with its progression across the area, temperatures can drop rapidly. Associated with the warm sectors of cyclones is (continental tropical air) from North Africa, or (maritime tropical air-mass) from the Red Sea, the Arabian Gulf and the Indian Ocean . The former is hot, even in winter, and very dry, while the latter is warm and moist. The relative penetration of these two air-masses into the area depends to a large degree on the form and stage of development of the cyclone, together with the path of its movement.

During the winter months it is sometimes possible to dis -tinguish a fifth air-mass to which the term (mediterranean air - mass) it is sometimes given. This is normally (maritime polar) air originating over the North Atlantic, which has been stationary over

the Mediterranean Sea for a considerable period.

In general it is considerably milder than the maritime polar air, but it is equally as moist since water vapour is added to it during its sojourn over the Mediterranean. With the passage of a cyclone, this air is drawn into the general circulation system and can penetrate eastwards to the Arabian Gulf region.

B-5.2. Cyclonic Disturbance

The weather patterns of the Middle East and Saudi Arabia can best be explained by reference to the succession of cyclones which pass over the area. Cyclones are wave disturbances generated along the polar front, separating polar and tropical air-masses. They develop over the North Atlantic and especially the Mediterranean Sea, and travel over the Middle East.

Three types of cyclonic disturbance have been recognized in the region:

1. Shallow waves moving rapidly in the upper troposhere, which cross the area along a west-east corridor between southern Turkey and northern Saudi Arabia. Rain associated with these disturbances reaches a maximum during the winter months, and falls mainly in the northern parts of Saudi Arabia, Lebanon, Syria and Jordan.

2. Stationary cyclones: created by cold troughs in the upper atmosphere in certain regions, and moves very slowly through the Mediterranean eastward, where they draw in moist air from the Arabian Gulf region and cause precipitation along the line of Zagros Mountains and north - western parts of Iranian Plateau.

Maximum precipitation associated with these systems occurs during spring.

3. Khamsin Type Cyclones: originates over the northern Sahara and moves eastwards over the southern part of the Middle East and Saudi Arabia. Occasionally they come into contact with a cold upper air trough and under such conditions can give rise to appreciable rainfall amounts.

B-6. Rainfall

The seasonal distribution of precipitation in the Middle East reflects the passage of winter cyclones. Winter precipitation maxima predominate almost everywhere with the exception of parts of the southern coastlands of Arabia where summer monsoon conditions often penetrate. The monsoons of the Indian Ocean account for relatively abundant rains of about 200 - 350 mm a year in the Asir Mountains[21] as in Khamis - Mushait south west of Saudi Arabia.

In the northern half of the peninsula periodic rains are brought by the systems of low atmospheric pressure that move in from the Mediterranean basin. Those rains are scattered, however and may be almost completely lacking in some years. The unpredictable and local nature of the rainfall is a characteristic of most desert regions[38]. The rains in the Eastern Province of Saudi Arabia usually start in November or December and end in May, as indicated for Dhahran in Table B-6-2.[104-106]. Parts of the great sand mass of the "Rub Al-Khali" have been known to be without rain for ten years at a time. When rain does fall in the country it is likely to come in torrential downpours, causing flash floods which do considerable damage to homes and cultivated fields. As an example the amount of rain-

fall in Jeddah[18] was 173.0 mm extended over 11 days in May 1968 (Table B-6-1.) of which 88.0 mm fell in 24 hours as indicated in Table B-6-2.

Almost all rainfall that actually occurs is associated with thunder showers produced by low-pressure areas from the eastern Mediteranean that move accross the northern parts of the country during the winter period, and by the incursion of tropical maritime air caused by the northward extension of the Sudan low-pressure trough during the spring and early summer period. Summer rains or showers are common over the Inter-tropical Convergence Zone.

B-7. Radiation and Temperature

The intense heat of the summer months is probably the best known feature of the Saudi Arabian Climate. Temperaturesin the Shade frequently exceed 46°C (115°F) over much of the Arabian peninsula, (see Tables B-7-1. to B-7-5.[18,104-106]. Furthermore, the summer is longer than in more temperate regions.[107]. The dryness of the interior makes the heat more durable, but along the coasts the humidity is high, particularly at night as in Jeddah, Jizan and Dhahran, where the average maximum relative humidity exceeds 80%, as is shown in Table B-7-6.[104-106], and hence the heat in these areas is less endurable.

Riyadh (24° 42' N, 46 44' E)[108], has a typical continental desert location, the soil is dry and the average annual rainfall is minimum. Most of the available net radiation is used in heating the air, leading to extremely high temperatures[39]. At Riyadh, summer afternoon temperatures regularly exceed 38°C (May to September) and temperatures above 46°C have been recorded on a number of occasions. Medina (24° 33' N, 39° 43 E) has an average annual rainfall below 50 mm, with extremely high temperatures during the summer.

The highest values of the diurnal temperature range are experienced in desert locations, where the soil is generally dry and the atmosphere contains little water vapour. The very high temperatures occur because nearly all the net radiation is available for heating the air and soil[109]. The low vapour content of the air allows relatively large long wave radiaion losses from the surface, leading to low temperatures at night. Net radiation values in the poleward regions of the subtropical deserts undergo large seasonal variations, and lead to large seasonal variations in temperature.

The high summer temperatures at Riyadh, Tabouk, Hail and Qaseem in Saudi Arabia are familiar, but in January and February, the night temperatures can fall as low as $0^{o}C$. Indeed, large areas of Central and North Saudi Arabia have recorded absolute minimum temperatures of $-5^{o}C$ or below, indicating that frost is not unknown.

In coastal regions diurnal temperature ranges tend to be smaller than in the interior stations, as shown in Table B-7-R. and on the tables in references, (22,110 and 111).

8

belts ?

Table B-7-R.

Ref.Table	July temperatures at stations in The Middle East, with mean daily temperature greater than 30°C					
	Coastal Stations	Average Max. °C	Daily Min. °C	Mean daily range °C	Absolute Max. °C	Absolute Min. °C
T-1	Jeddah (Saudi Arabia)	37.2	26.1	11.1	42.2	21.1
B-7-3.	Jizan (" ")	36.2	29.8	6.4	38.5	23.7
B-7-5.	Yanbo (" ")	36.1	26.3	9.8	38.5	21.2
T-3	Bahrain(Bahrain)	37.2	29.5	7.7	44.5	23.9
T-7	Kuwait City(Kuwait)	39.5	30.0	9.5	47.8	25.6
	Interior Stations					
T-2	Riyadh (Saudi Arabia)	41.7	25.5	16.2	45.0	19.5
B-7-4.	Hail (" ")	37.7	23.4	14.3	40.9	18.9
B-7-4.	Tabouk (" ")	38.5	24.1	14.4	42.6	21.3
T-5	Baghdad(Iraq)	43.3	24.5	18.8	49.7	16.7
T-11	Aswan (Egypt)	41.1	26.1	15.0	51.1	21.1

The highest annual values of global solar radiation occur over the Tropics of Cancer and Capricorn, in the high pressure builts of the northern and southern hemispheres. The highest annual totals however appear to be recorded in North East Africa and Saudi Arabia [39]. The clear skies of the subtropics not only allow large amounts of radiation

SI units

to penetrate through the atmosphere to the earth's surface, but also lead to low values of diffuse radiation which can fall to 10 - 15% of the global radiation in the subtropical summer. Maximum values of net radiation are recorded at about 20° N and 20° S over the sea, and unlike the global radiation, values over the sea, are always higher than those over land.

This is because of differences in albedo and terrestrial radiation. Sea surface albedos are normally less than those of land surfaces. Despite the large global radiation values in the deserts the outgoing terrestrial radiation is high, so the net radiation over land remains low. During January the radiation balance is low over the northern hemisphere, and increases southwards where it reaches a maximum near the Tropic of Capricorn. In July, the features in the northern and southern hemispheres are reversed, and the maximum values are recorded over the sea in the region of the Tropic of Cancer.

Global radiation over Saudi Arabia ranges from 200 K cal cm^{-2} $year^{-1}$ in the north to 100 K cal cm^{-2} $year^{-1}$ in the south. The net radiation in January ranges from 2-4 K cal cm^{-2} $month^{-1}$ from north to south, and in July[36,39] it ranges from 12-10 K cal cm^{-2} $month^{-1}$. In December, January and February, temperatures drop below freezing in central and northernArabia, snow and ice are common in the highest places like Khamis-Mushait and Al-Sodah, both in the Asir high mountains.

knot is not
not length

B-8. Winds

The winds of Saudi Arabia vary greatly[18], being affected by the surrounding seas. In the Eastern Province the prevailing wind comes from the north-northwest. This wind known as the Shamal[37], frequently whips up sandstorms in its path, but it cools the land somewhat, with average speed ranges from 5-15 knots per hour (1 knot = 2.132 km) reaching a maximum of around 50 knots per hour. In the Arabian Gulf, the south wind, the Kaws, is potentially dangerous to shipping because of the fierce storms it stirs up without warning. On the equatorward side of the sub-tropical highs there are generally easterly winds, and where these originate over land-masses, they are extremely dry. This dryness is carried over the oceans to leeward of the land-masses.

In Riyadh the prevailing wind comes from the north, north-east during summer, and varies greatly in the rest of the year. whenever in Jeddah the prevailing wind comes from the north to north-west most of the year. Both of Medina and Taif are exposed to easterly winds most of the year. The prevailing wind in Khamis-Mushait, south east of Saudi Arabia is mainly south-westerly[18].

B-9. Sand and Dust Storms

A special weather phenomenon that affects chiefly the Eastern Province is the blowing dust or dust-storms with strong north westerly winds called "The Shamals". These are predominant during the late spring and early summer, reaching a peak in June when it is common to have 23 days out of 30 with blowing dust and strong winds[37], particularly in the afternoon. These sand or dust storms are caused by east

ward moving low pressure zones meeting colder air over the north and eastern part of the country. They are rare in other regions of the Kingdom, chiefly due to lack of sandy terrain.

Table: B-6-1 Amount of Rainfall and Number of Rainy Days in Year, According to Meteorological Stations, Saudi Arabia. Period: 1966 - 1973.

City / Year	RIYADH		JEDDAH		DHAHRAN		HAIL		MEDINA		JIZAN		KHAMIS-MUSHAIT		TAIF	
	mm	d	mm	d	mm	d	mm	d	mm	d	mm	d	mm	d	mm	d
1966	14	6	66	12	40	21	73	7	26	9	257	10	--	--	155	23
1967	216	32	34	8	33	17	61	12	4	2	24	--	247	34	126	25
1968	107	27	173	11	92	32	107	18	72	14	22	2	268	37	453	29
1969	173	27	129	6	174	18	192	16	83	5	4	2	343	32	29	22
1970	15	9	68	5	4	4	27	10	14	4	15	12	216	40	109	18
1971	132	16	106	7	47	11	56	18	104	9	14	8	174	25	260	15
1972	230	36	104	5	77	18	134	30	40	11	9	5	97	33	213	32
1973	69	14	27	7	14	7	58	12	1	2	59	7	164	27	105	23
Aver.	120		88		60		89		43		51		216		181	

Notes: Rainfalls are measured in millimeters by ordinary raingauges installed near the thermometer screens.

Table: B-6-2 Maximum Rainfall during 24 Hours (mm) 1968 A.D. Saudi Arabia, and Number of Occurrences of Rain in Different Months for 4 Years : 1968-1970--1971 and 1973

City / Month	RIYADH		JEDDAH		DHAHRAN		HAIL		MEDINA		JIZAN		KHAMIS-MUSHAIT		TAIF	
	mm	No.	mm	No	mm	No	mm	No	mm	No	mm	No	mm	No	mm	No
Jan.	--	2	--	3	T	4	--	2	--	3	--	2	4.0	4	--	2
Feb.	4.7	1	--	2	25.2	4	2.0	4	--	-	11.0	3	65.6	2	2.0	2
Mar.	1.6	3	--	-	2.8	4	--	-	--	1	--	2	2.5	3	--	2
Apr.	16.0	4	2.0	3	2.3	3	6.0	3	13.0	4	--	1	24.0	3	31.0	4
May	10.8	2	88.0	2	T	3	11.4	2	8.0	3	--	1	21.0	4	20.0	4
June	--	-	--	-	--	-	--	-	2.0	1	--	-	8.0	2	5.0	2
July	--	1	--	-	--	-	--	-	--	-	--	2	8.4	4	--	2
Aug.	--	-	--	-	--	-	--	-	--	-	--	2	4.0	4	8.0	3
Sep.	--	-	--	1	--	-	--	-	--	-	--	1	--	2	--	2
Oct.	--	-	--	-	--	-	40.0	1	--	-	--	2	--	1	--	1
Nov.	4.5	1	16.0	3	15.1	2	11.0	4	16.0	2	--	3	11.2	3	9.4	3
Dec.	3.5	4	40.0	4	2.6	3	--	3	2.0	4	--	3	--	3	--	2

Notes: No. = Number of occurrences of rain in different months.
T = Trace.

Table: B-7-1 Maximum and Minimum Temperatures in The Main Meteorological Stations, Saudi Arabia.

City / Month	RIYADH (0624m) Period (1968-1973) 24 42N 46 44E				JEDDAH (0017m) Period (1968-1973) 21 30N 39 12E			
	1	2	3	4	1	2	3	4
January	20.3	7.5	27.1	1.9	27.9	19.3	32.3	14.8
February	23.7	10.0	31.5	3.9	29.1	18.4	32.7	15.2
March	28.5	14.1	35.9	7.6	30.9	21.0	35.6	17.2
April	32.6	18.4	38.2	12.9	34.0	23.5	38.9	18.8
May	38.2	23.7	42.8	18.1	34.7	23.5	40.8	18.1
June	40.8	24.3	43.7	21.6	35.7	25.0	41.8	21.9
July	42.3	26.3	44.4	23.6	37.3	26.9	40.5	23.8
August	42.4	26.1	45.2	23.9	36.6	26.9	39.7	23.8
September	38.6	22.9	42.6	19.6	35.4	25.9	40.9	22.6
October	33.7	17.5	37.4	13.6	34.4	23.0	39.5	20.0
November	28.0	13.1	33.4	8.6	32.1	22.4	35.2	18.7
December	21.8	8.7	28.9	2.6	29.2	19.7	32.2	15.0
Year			46.0	-1.0			48.2	11.4
No.of Years	4				4			

Notes: Thermometers are installed in ventilated screens at a height of 1.25m above the ground, except at Jeddah, Medina, and Riyadh where heights are from 4.0 to 5.0m. All readings are taken in the shade and in degrees Celsius.

Column 1 = Average maximum temperature in the month.
Column 2 = Average minimum temperature in the month.
Column 3 = Absolute maximum temperature in the month.
Column 4 = Absolute minimum temperature in the month.

Table: B-7-2 Maximum and Minimum Temperatures in The Main Meteorological Stations, Saudi Arabia.

City / Month	DHAHRAN (0022m) Period (1968-1973) 26 16N 50 10E				MEDINA (0646m) Period (1968-1973) 24 33N 39 43E			
	1	2	3	4	1	2	3	4
January	20.5	9.9	25.0	4.8	23.0	11.2	29.6	6.0
February	22.8	10.5	30.1	5.8	27.4	14.5	33.0	8.6
March	26.8	15.7	33.8	9.3	31.2	17.8	36.6	12.3
April	30.2	18.3	40.5	13.4	34.0	19.7	39.1	15.0
May	37.4	24.4	42.8	18.3	38.6	24.1	40.7	18.3
June	39.8	27.1	44.0	22.3	42.3	28.3	44.5	23.3
July	42.1	28.8	46.1	25.6	42.0	28.6	43.0	24.5
August	41.3	28.0	45.2	23.4	42.5	28.9	45.7	25.4
September	39.1	24.7	43.9	20.5	42.0	27.9	44.5	23.5
October	25.3	19.8	39.4	16.0	36.8	21.4	38.9	18.9
November	28.7	16.5	33.8	12.6	28.9	17.7	34.5	15.0
December	22.6	12.1	27.8	5.3	24.4	13.1	20.3	8.7
Year			48.3	1.4			46.0	1.0
No.of Years	4				4			

Notes: As for Table: B-7-1

Table: B-7-3 Maximum and Minimum Temperatures in The Main Meteorological Stations, Saudi Arabia.

City / Month	TAIF (1471m) Period (1968-1973) 21 29N 40 32E				JIZAN (0005m) Period (1968-1973) 16 52N 42 35E			
	1	2	3	4	1	2	3	4
January	21.5	7.5	26.1	2.3	29.1	22.1	30.6	18.8
February	23.9	9.2	27.9	5.2	29.6	22.4	31.2	20.6
March	26.6	12.0	30.4	8.2	32.3	24.0	33.3	21.9
April	28.4	14.7	31.3	11.1	34.3	25.9	36.9	23.5
May	31.7	17.3	34.7	12.4	36.2	28.1	38.6	25.5
June	34.6	20.5	37.1	17.0	36.4	28.9	38.1	25.5
July	33.6	21.1	36.4	17.2	36.2	29.8	38.5	23.7
August	34.8	22.3	35.8	20.2	36.4	30.2	38.4	26.9
September	33.0	19.8	36.1	16.1	36.3	28.5	38.2	26.1
October	29.4	14.1	31.6	11.2	35.5	26.0	37.8	22.8
November	25.6	11.3	28.6	9.2	32.5	23.9	35.5	21.9
December	21.9	8.3	25.9	2.9	29.7	20.4	31.8	18.6
Year			38.9	-1.0			39.4	14.8
No.of Years	4				4			

Notes: As for Table: B-7-1

Table: B-7-4 Maximum and Minimum Temperatures in The Main Meteorological Stations, Saudi Arabia.

City / Month	TABOUK (0771m) Period (1968-1973) 28 22N 36 35E				HAIL (0992m) Period (1968-1973) 27 31N 41 44E			
	1	2	3	4	1	2	3	4
January	17.5	4.6	26.6	-1.2	16.8	3.5	24.1	-2.7
February	21.4	5.4	28.9	2.1	20.0	6.0	28.3	2.1
March	25.2	7.0	34.1	2.2	24.0	9.4	32.5	2.2
April	28.7	11.7	37.1	5.9	27.5	13.7	35.0	7.0
May	34.9	17.6	39.5	12.1	33.3	19.0	38.1	12.6
June	36.9	21.4	40.0	18.1	36.3	20.9	39.8	16.2
July	38.5	24.1	42.6	21.3	37.7	23.4	40.9	18.9
August	37.7	22.8	40.5	20.3	38.0	21.4	41.4	18.4
September	36.7	18.6	39.7	16.0	36.4	19.4	41.1	13.9
October	32.0	13.7	36.2	9.7	30.5	13.5	35.5	7.3
November	23.3	7.6	28.2	2.0	23.5	9.4	29.2	5.5
December	18.6	3.9	26.8	-0.1	17.3	5.6	25.1	-1.8
Year			44.6	-5.2			46.2	-6.0
No.of Years		4				4		

Notes: As for Table: B-7-1

Table: B-7-5 Maximum and Minimum Temperatures in The Main Meteorological Stations, Saudi Arabia.

City / Month	YANBO (0006m) Period (1968-1973) 24 07N 38 03E				KHAMIS-MUSHAIT (2060m) Period (1968-1973) 18 18N 42 48E			
	1	2	3	4	1	2	3	4
January	27.5	13.1	33.4	6.5	19.7	7.2	24.0	1.8
February	27.5	14.3	32.1	6.6	21.7	9.3	25.6	5.9
March	29.1	16.9	35.0	11.1	23.8	11.5	26.9	8.2
April	31.1	19.9	38.4	15.3	24.5	13.0	27.1	9.1
May	33.5	23.9	37.7	19.5	26.2	15.1	30.4	12.3
June	35.0	24.4	42.0	22.4	30.2	16.6	31.8	14.0
July	36.1	26.3	38.5	21.2	28.8	17.0	32.3	14.8
August	35.8	24.9	39.1	19.4	31.7	17.2	32.1	14.9
September	35.9	24.5	41.5	19.8	31.2	15.4	30.8	11.9
October	34.3	23.1	38.3	17.8	24.5	11.4	27.1	8.6
November	30.8	18.9	34.1	14.3	22.7	8.3	24.7	5.9
December	28.0	15.2	33.0	9.9	20.4	7.3	24.7	3.8
Year			44.6	5.4			33.6	-3.6
No.of Years		4				4		

Notes: As for Table: B-7-1

Table: B-7-6 Average Maximum and Average Minimum Relative Humidity According to Meteorological Stations in Saudi Arabia.

City / Month	RIYADH R.H.%		JEDDAH R.H.%		DHAHRAN R.H.%		HAIL R.H.%		MEDINA R.H.%		JIZAN R.H.%		KHAMIS-MUSHAIT R.H.%		TAIF R.H.%	
Jan.	52	21	76	39	93	43	66	32	57	25	87	58	76	29	83	32
Feb.	45	16	82	46	86	41	60	28	46	22	84	57	90	57	76	20
Mar.	45	15	77	39	79	24	45	20	36	14	81	57	88	31	61	19
Apr.	63	22	78	38	79	19	39	17	34	14	75	48	86	39	57	18
May	39	11	69	39	64	21	32	11	27	10	72	45	87	32	55	17
June	20	8	86	47	53	15	26	10	19	7	80	50	71	17	33	8
July	15	7	83	40	59	23	25	10	23	8	75	53	77	22	33	14
Aug.	15	5	85	49	93	24	22	9	26	8	79	57	74	17	30	12
Sept.	20	8	91	56	90	26	25	10	25	9	86	60	58	15	49	12
Oct.	26	12	90	41	93	28	34	11	27	9	81	49	60	15	57	11
Nov.	51	20	82	43	80	31	60	29	45	20	75	51	83	32	81	26
Dec.	60	25	83	43	89	42	70	37	51	23	81	52	88	31	86	32
Year	38	14	82	43	80	28	42	19	35	14	80	53	78	28	58	18

Notes: The values of relative humidity (R.H.%) tabulated are the average values taken over a period of 4 years between 1968 - 1973.

Table T-1

JEDDAH 21°28' N 39°10' E 6.09 m

JEDDAH Period 1941-46	Temperature: Average daily Max. °C	Temperature: Average daily Min. °C	Temperature: Average of highest each month °C	Temperature: Average of lowest each month °C	Temperature: Absolute Max. °C	Temperature: Absolute Min °C	Relative Humidity: Average of observations at 0800 %	Relative Humidity: Average of observations at 1400 %	Precipitation: Average monthly fall mm	Precipitation: Maximum fall in 24 h mm	Precipitation: Average No. of days with 1mm or more
January	28.9	18.9	32.2	13.3	33.3	9.5	58	54	5.1	12.7	0.8
February	28.9	18.3	33.9	12.8	35.0	11.1	52	52	< 2.5	2.5	0.3
March	29.5	19.5	36.1	14.5	38.3	12.8	52	52	< 2.5	2.5	0.3
April	32.8	21.1	37.8	15.0	40.0	12.2	52	56	< 2.5	2.5	0.5
May	35.0	23.3	39.5	18.3	42.2	12.8	51	55	< 2.5	< 2.5	0
June	36.1	23.9	42.2	20.5	47.2	19.5	56	55	0.0	0.0	0
July	37.2	26.1	40.0	22.2	42.2	21.1	55	50	< 2.5	< 2.5	0
August	37.2	26.7	40.5	23.3	42.2	22.8	59	51	< 2.5	< 2.5	0
September	35.6	25.0	39.5	22.2	42.2	21.1	65	61	< 2.5	< 2.5	0
October	35.0	22.8	38.9	20.5	40.5	20.0	60	61	< 2.5	< 2.5	0
November	32.8	21.7	36.7	18.3	40.5	17.2	55	59	25.4	56.0	2
December	30.0	19.5	33.3	15.0	33.9	10.0	55	54	30.5	139.7	1
Year	33.3	22.8	43.3	11.1	47.2	9.5	56	55	63.5	139.7	5
No. of Years	5	5	5	5	5	5	5	5	5	5	5

Table T-2

RIYADH 24° 39' N 46° 42'E, 591 m

RIYADH Period 1941-45	Temperature: Average daily Max. °C	Temperature: Average daily Min. °C	Temperature: Average of highest each month °C	Temperature: Average of lowest each month °C	Temperature: Absolute Max. °C	Temperature: Absolute Min. °C	Relative Humidity: Average of observations at 0500 %	Relative Humidity: Average of observations at 1600 %	Precipitation: Average monthly fall mm	Precipitation: Maximum fall in 24 h mm	Precipitation: Average No. of days with 1mm or more
January	21.1	7.8	28.9	0.0	30.0	-7.2	70	44	2.5	5.1	1
February	22.8	8.9	32.2	2.8	32.8	-1.7	63	37	20.3	58.3	1
March	27.8	13.3	35.5	5.0	38.3	0.6	65	36	22.9	61.0	3
April	31.7	17.8	38.3	8.9	40.0	2.2	64	34	25.4	50.8	4
May	37.8	22.2	41.7	17.2	43.3	15.0	51	31	10.2	17.8	1
June	41.7	25.0	44.5	21.1	45.0	19.5	47	31	< 2.5	< 2.5	0
July	41.7	25.5	44.5	20.5	45.0	19.5	33	19	0.0	0.0	0
August	41.7	23.9	43.3	20.0	45.5	16.7	35	19	< 2.5	< 2.5	2.5
September	38.9	22.2	42.2	17.8	43.9	17.2	42	24	0.0	0.0	0
October	34.5	16.1	37.2	11.7	38.3	10.0	47	25	0.0	0.0	0
November	28.9	12.8	33.3	7.8	34.5	1.7	60	33	< 2.5	< 2.5	0
December	21.1	9.5	27.2	2.8	30.6	0.0	75	52	< 2.5	< 2.5	0
Year	32.2	17.2	44.5	-1.7	45.0	-7.2	54	32	81.3		
No. of Years	3	3	3	3	3	3	3	3	3	3	3

Table T-3

BAHRAIN 26° 12' N, 50° 30' E, 6 m	BAHRAIN Period 1928-43	Temperature: Average daily Max. °C	Temperature: Average daily Min. °C	Temperature: Average of highest each month °C	Temperature: Average of lowest each month °C	Temperature: Absolute Max. °C	Temperature: Absolute Min. °C	Relative Humidity: Average of observations at 0730 %	Relative Humidity: Average of observations at 1530 %	Precipitation: Average monthly fall mm	Precipitation: Maximum fall in 24 h mm	Precipitation: Average No. of days with 1mm or more
	January	20.0	13.9	26.1	8.9	29.5	5.0	85	71	7.6	30.5	1
	February	21.1	15.0	28.9	10.6	34.5	7.2	83	70	17.8	33.0	2
	March	23.9	17.2	31.7	12.2	35.0	10.6	80	70	12.7	25.4	1
	April	28.9	21.1	36.7	16.1	40.6	13.3	75	66	7.6	38.1	1
	May	33.3	25.6	39.5	21.1	42.2	18.9	71	63	<2.5	5.1	<2.5
	June	35.6	27.8	40.0	23.9	43.9	21.1	69	64	0.0	0.0	0
	July	37.2	29.5	42.2	26.1	44.5	23.9	69	67	0.0	0.0	0
	August	37.8	29.5	42.2	26.1	45.0	23.9	74	65	0.0	0.0	0
	September	35.6	27.2	40.0	23.3	44.5	21.7	75	64	0.0	0.0	0
	October	32.2	23.9	36.1	20.6	39.5	18.9	80	66	0.0	0.0	0
	November	27.8	20.6	32.8	16.7	36.1	14.5	80	70	17.8	70.6	1
	December	21.7	15.6	27.8	11.7	31.1	8.9	85	77	17.8	43.2	2
	Year	29.5	22.2	43.3	8.3	45.0	5.0	77	68	81.3	70.6	8
	No. of Years	16	16	16	16	16	16	16	9	16	16	16

Table T-5

BAGHDAD 33° 20' N, 44° 24' E, 34 m

BAGHDAD Period 1888-1918 1937-1952	Temperature: Average daily Max. °C	Temperature: Average daily Min. °C	Temperature: Average of highest each month °C	Temperature: Average of lowest each month °C	Temperature: Absolute Max. °C	Temperature: Absolute Min. °C	Relative Humidity: Average of observations at 0600 %	Relative Humidity: Average of observations at 1500 %	Precipitation: Average monthly fall mm	Precipitation: Maximum fall in 24 h mm	Precipitation: Average No. of days with 1mm or more
January	15.6	3.9	20.0	-1.7	25.0	-7.8	84	51	22.8	35.6	4
February	17.8	5.6	23.3	1.1	30.0	-5.0	78	42	25.4	33.0	3
March	21.7	8.9	28.9	4.5	32.2	-2.8	73	36	27.9	55.9	4
April	29.5	13.9	33.9	10.0	40.0	2.8	64	34	12.7	20.3	3
May	36.1	19.5	40.0	14.5	44.5	10.6	47	19	< 2.5	15.2	1
June	38.3	22.8	44.5	20.6	48.3	14.5	34	13	< 2.5	< 2.5	0
July	43.3	24.5	46.7	22.8	49.7	16.7	32	12	< 2.5	< 2.5	0
August	43.3	24.5	47.2	22.2	48.9	17.8	33	13	< 2.5	< 2.5	0
September	40.0	21.1	44.5	17.2	46.7	10.6	38	15	< 2.5	< 2.5	0
October	33.3	16.1	38.9	12.2	41.7	3.9	49	22	< 2.5	15.2	1
November	25.0	10.6	30.0	4.5	34.5	-1.7	70	39	20.3	35.6	3
December	17.8	5.6	21.7	0.6	26.1	-6.7	84	52	25.4	33.0	5
Year	30.6	15.0			49.7	-7.8	57	29	139.7	55.9	24
No. of Years	15	15	25	25	15	15	15	15	15	15	15

Table T-7

KUWAIT CITY 29°21' N, 48°00' E, 5.0 m

KUWAIT CITY Period 1908-53	Temperature: Average daily Max. °C	Temperature: Average daily Min. °C	Temperature: Average of highest each month °C	Temperature: Average of lowest each month °C	Temperature: Absolute Max. °C	Temperature: Absolute Min. °C	Relative Humidity: Average of observations at 0530 %	Relative Humidity: Average of observations at 1430 %	Precipitation: Average monthly fall mm	Precipitation: Maximum fall in 24 h mm	Precipitation: Average No. of days with 1mm or more
January	16.1	9.5	21.7	4.5	27.8	0.55	77	61	22.9	25.4	2
February	18.3	10.6	22.8	6.7	25.6	2.2	68	61	22.9	43.2	2
March	22.2	15.0	28.3	9.5	32.2	4.5	72	61	28.0	38.1	2
April	28.3	20.0	35.6	14.5	39.5	12.2	67	55	5.1	12.7	0.9
May	34.5	25.0	40.6	18.9	42.8	15.6	67	55	<2.5	7.6	0.3
June	36.7	27.8	42.8	25.0	48.3	22.2	62	49	0.0	0.0	0
July	39.5	30.0	45.0	26.7	47.8	25.6	45	41	0.0	0.0	0
August	40.0	30.0	45.0	28.9	46.1	20.0	50	46	0.0	0.0	0
September	37.8	27.2	43.3	25.6	47.2	19.5	52	51	0.0	0.0	0
October	32.8	22.8	38.3	18.3	40.6	13.9	64	60	2.5	25.4	< 0.1
November	25.0	16.7	31.7	11.7	37.8	6.1	66	59	15.3	55.9	1
December	18.3	11.7	23.9	8.9	26.1	2.2	76	65	28.0	30.5	3
Year	29.5	20.6	46.1	3.3	48.3	0.55	64	55	129.5	55.9	11
No. of Years	14	15	13	12	16	16	2	3	10	10	10

Table T-11

ASWÂN 24° 02' N, 32° 53' E, 110.0 m

ASWÂN Period 1901-45	Temperature: Average daily Max. °C	Temperature: Average daily Min. °C	Temperature: Average of highest each month °C	Temperature: Average of lowest each month °C	Temperature: Absolute Max. °C	Temperature: Absolute Min. °C	Relative Humidity: Average of observations at 0800 %	Relative Humidity: Average of observations at 1400 %	Precipitation: Average monthly fall mm	Precipitation: Maximum fall in 24 h mm	Precipitation: Average No. of days with 1mm or more
January	23.3	10.0	31.7	5.6	37.8	3.3	52	29	<2.5	<2.5	<0.1
February	25.6	11.1	34.5	6.1	38.9	1.7	46	22	<2.5	<2.5	<0.1
March	30.6	14.5	40.0	8.9	43.3	6.1	36	17	<2.5	<2.5	<0.1
April	35.6	18.9	43.9	13.3	46.1	9.5	29	15	<2.5	2.5	0.1
May	39.5	23.3	46.1	17.2	47.8	11.1	29	15	<2.5	5.1	0.5
June	41.7	25.6	47.2	21.7	50.6	20.0	26	16	<2.5	<2.5	0
July	41.1	26.1	46.1	23.3	51.1	21.1	31	16	0.0	0.0	0
August	41.1	26.1	45.6	23.3	48.9	19.5	34	18	0.0	0.0	0
September	39.5	23.9	44.5	20.6	47.2	17.2	37	19	0.0	0.0	0
October	36.7	21.7	42.8	17.2	44.5	13.9	40	21	<2.5	5.1	0.1
November	30.6	16.7	38.3	11.6	41.7	6.1	46	26	<2.5	<2.5	0.1
December	25.0	11.7	32.8	6.1	37.2	4.5	50	31	<2.5	<2.5	<0.1
Year	34.5	19.5	48.3	5.0	51.1	1.7	38	20	<2.5	5.1	20.3
No. of Years	46	46	20	20	20	20	21	20	11	11	11

Appendix C

C-1 Physiological Comfort

C-1.1. General

The average human body is most efficient at a core temperature of 37°C. Compared with the natural fluctuations of air-temperature, the human body is comfortable within only a narrow thermal range. Beyond an internal body temperature of 26-40°C irreversible deterioration often results, although recovery has been recorded from falls as low as 18°C and rises as high as 43.5°C. In practice, bodily comfort is experienced on the more sensitive areas of the skin surface, which is naturally 2-5 deg. C cooler than the core temperature, and usually lies between 31 and 35°C. Outside these limits, the body adjusts the rate of heat production or loss in various ways. Thus, at a skin temperature of around 30°C, shivering occurs in an attempt to generate more heat, whereas sweating is employed as the main cooling mechanism at high levels of heat and humidity. The relative importance of the various heat transfer processes differs markedly according to the prevailing climatic conditions[112]. For example in a temperate climate a resting individual clothed normally loses about 60 percent of bodily heat production by radiation. When the ambient temperature reaches 32°C, the radiative heat loss may drop to zero.

C-1.2. Bodily Adaptation

Physiological reactions to the atmospheric environment[112] are further complicated by differences in tolerance exhibited by individuals or certain ethnic groups and by adaptation achieved

through prolonged acclimatization. Bodily adaptation to tropical conditions occurs with a progressive increase in the sweat rate, although Portig (1968) has claimed that the purely climatic stress associated with the humid tropics is less than is often believed. In the desert areas and during the dry season, additional stresses are imposed by the large diurnal range of temperatures and the considerable differences in net radiation received by insolated and shadowed parts of the body, and the dyring power of the air is also marked. It is probable that the largest solar radiation intensities on earth occur in high, arid sub-tropical mountains during summer.

C-1.3. Bodily Discomfort Measurement (ET)

The degree of bodily discomfort arising from excessive heat is usually measured by one or more of the many biometeorological temperature indices which have been specially derived for the purpose. One of the most common indices is that of effective temperature (ET) which was introduced by Houghton and Yaglou (1923)[113] and may be defined as the temperature of still air saturated with water vapour in which subjects experience a subjectively equivalent sensation of comfort. In a series of controlled experiments, over 90 percent of the test subjects found an ET of 25.6°C too warm for comfort whereas only about 10 percent considered an ET of 22.2°C to be uncomfortable.

The concept of effective temperature can be used to illustrate some of the geographical variations of human comfort within the tropics, bearing in mind that the "comfort zone" for

acclimatized persons living in low latitudes is normally taken as 18.9 - 22.4°C ET. Stephenson (1963)[112] has demonstrated that although forced ventilation by fans or other means is incapable of providing 'comfortable' conditions during the April-June period 130 km north of the equator at Singapore, the ET only rarely exceeds 29.4°C and outdoor sports can be safely indulged in throughout the year. This contrasts markedly with conditions at Bahrain (Middle East). latitude 26°N, where the ET is some 3 deg C higher than at Singapore during the least comfortable part of the year. Forced ventilation is inadequate to deal with conditions during the greater part of the summer and excessive exercise could prove dangerous at times between July and September but especially in August, which had a mean monthly ET of 28°C over the 1962-66 period (Watt, 1967). In complete contrast, a temperature station, like London (Britain), experiences cold rather than warm discomfort and, despite the fact that ET values may occasionally rise to become similar to those in tropics, forced ventilation can easily restore comfortable conditions (Foord, 1968).

C-2. Physiological Model: controlled loss (not body heating)

C-2.1. General

Body chemistry oxidises foodstuffs to produce energy to maintain body temperature, for the muscular movements of the heart and lungs, for the performance of external work and for the various synthesising processes such as protein and hormone build-up in the tissues. This oxidation is metabolism. Two necessary though insufficient physiological conditions for long term thermal comfort are:

1. The body temperature needs to be correctly controlled. This temperature varies from person to person by over 1°C and there is a further daily variation of 1½°C from a maximum in the mid-evening to a minimum in the early hours of the morning.

2. The heat loss must match the metabolic rate so that there is no net heat loss or gain over the day.

This temperature regulation is achieved through two control systems, on e peripheral and one central. The peripheral mechanism involves the skin temperature sensors and through reflex action can control regional heat loss of, for example, hands. This mechanism usually compensates for rapid and small changes in the environmental temperature. The central mechanism involves a very sensitive (0.1°C) blood temperature sensor within the brain which controls sweating for high temperature and instigates shivering in cold conditions. Small adjustments in heat loss are achieved by altering the blood flow pattern under the skin. To dissipate heat, the blood flow is increased through dilated blood vessels just

under the skin. This is the 'flushed' state. To conserve heat, the outer blood vessels constrict and increase the effective insulation of the subcutaneous tissue to give the pale 'goose pimple' state. Other further small adjustments in more severe cold are made by shivering and hence generating heat within the muscles to counter the loss. In overheating, some two million sweat glands can provide evaporative cooling. Sweating of hands and feet can readily be induced by anxiety and emotional stress and is not normally considered an important part of the heat regulating mechanism[114]. Heat generation is closely associated with physical activity.

Table C-2(1) Relation between body activity and total heat production[115]

Degree of activity	Total heat production (adult male)
	J/s (W)
Seated at rest	115
Light work	140
Walking slowly	160
Light bench work	235
Medium work - dancing	265
Heavy work	440

Typical cumulative values over a day for an office worker would be 10.8 MJ, of which 7.92 MJ would be basal metabolism, 1.44 MJ would

be simple home activities such as sitting, dressing and washing, and a further 1.44 MJ would be used in normal office duties.

C-2.2. Body Heat Losses

The human body maintains a balance with its environment through minor physiological changes (i.e.) by increasing or decreasing the flow of blood to the skin.

Body heat losses are primarily by:

- convection (about 40%)
- radiation (about 40%)
- evaporation (about 20%)
- conduction (usually very little)

The relative importance of the three factors, convection, radiation and evaporation varies according to the room temperature.

+ RH

Evaporative cooling has itself three components:

- insensible perspiration
- lung exhalation
- sweating

The insensible perspiration is not related to the sweat glands but passes through the skin by diffusion and osmosis and is very little affected by the ambient water vapour pressure (i.e. room humidity). The moisture content lost due to breathing is influenced to a small extent by the room humidity, but the total non-sweating evaporative loss dissipates approximately 0.45 KWh over the day. Sweating can produce a substantially larger cooling effect but is sensitive to room relative humidity, particularly

? J

the high values of relative humidity which inhibit evaporation. Sweating is closely related to skin temperature and usually starts almost simultaneously over the whole skin at a skin temperature of 34.5°C. While the body core temperature remains at a consistent level, there are a range of normal preferred skin temperatures for the various parts of the body. The peripheral parts of the body prefer a cooler temperature. When the body loses heat faster than the metabolic rate the limbs cool first [114].

A study by P.O. Fanger [11] of (American male and female college-age persons at different activity levels) showed that the sensation of thermal comfort was closely connected with mean skin temperature and with sweat rate.

A regression analysis of the data, for persons in thermal comfort, gives the following functional dependency between skin temperature and activity level (internal heat production per unit surface area) and between sweat secretion and activity level.

$$\text{Skin temperature } \bar{t}_{sk} = 35.7 - 0.032 \frac{H}{A_{D_u}} \quad (^{\circ}C)$$

$$\text{Sweat secretion } E_{rsw} = 0.42\, A_{D_u} \left(\frac{H}{A_{D_u}} - 50\right) \quad (\text{k cal/hr})$$

(1 k cal= 4.1868 k J)

where

H = the internal heat production in the human body

A_{D_u} = DuBois area (the surface area of the nude body (m^2)

H/A_{D_u} = Internal heat production per unit body surface area.

nst- SI

It can be seen that for constant comfort, the mean skin temperature decreases with increasing activity (for H/A_{D_u} = 50 K cal/hr m^2, $\bar{t}_{sk}$ is 34°C, for H/A_{D_u} = 150 K cal/hr m^2, $\bar{t}_{sk}$ is 31°C). The sweat secretion at thermal comfort is zero for sedentary activity ($H/A_{D_u} \sim$ 50 K cal/hr m^2). At higher activities moderate sweat secretions are necessary for thermal comfort (environments so cold that sweat secretion is completely suppressed would be felt much too cool for persons in activity). It has often been claimed earlier that it was a condition for thermal comfort that the mean skin temperature was 33-34°C, and that sweating did not occur. The present results show that this is approximately true only for sedentary persons. At higher activities the skin temperature necessary for comfort falls, and moderate sweating takes place[11].

C-3. Physical Model of Thermal Comfort

The physical model has six [13] factors that influences body heat loss, these are:

- Air Temperature
- Radiation (mean radiant temperature)
- Air motion (relative air velocity)
- Relative Humidity (water vapour pressure in ambient air)
- Activity level (heat production in the body)
- Thermal resistance of the clothing (clo-value)

The above six variables are the most important variables which influence the condition of thermal comfort, here we have to take every variable, and discuss it in detail.

Personal factors affecting thermal comfort:

C-3.1. Activity Level:

It is important to know the energy expended during the course of routine physical activitives, since body heat production increases in proportion to exercise intensity.

The type of activities chosen are those which one performs steadily rather than intermittently. The highest energy level one can maintain for any continuous length of time is approximately 50% of his maximal capacity to utilize oxygen (maximum energy capacity). Although heart rate is not a factor in the heat balance equation, it is closely correlated with metabolic rate. For a normal mature man, heart rate rises rapidly from a value of 70 to 90 beats per minute (bpm) during rest to 120 to 140 bpm at 5 mets of exercise,

and finally more slowly to a maximal value of 180 to 200 bpm at 10 mets, (one met is defined as 58.2 w/m^2 ($J/S\ m^2$), 50 K cal/ (m^2) (hr), or 18.4 Btu/hr. The met unit represents the average heat produced by a sedentary man). Maximal heart rate decreases progressively with age and reaches a value about 150 bpm at age 60. The heart rates for women and preadolescent children tend to be about 10 percent higher than for men over this range. Heart rate may thus be used as a rough index of metabolic energy cost, if the direct measurement of oxygen consumption is impossible. A normal healthy man has a maximum energy capacity of approximately 12 mets at 20 years of age. This maximum drops to approximately 7 mets at 70 years of age. Women tend to have maximum levels about 30 percent lower than these values. Long distance runners and trained athletes have a maximum as high as 20 mets; an overall average for untrained person at 35 years of age can be considered as 10 mets.

Activities performed continuously above the 5 mets level by an untrained 35 year old man may prove exhausting and uncomfortable for him[10].

Table C-3.(1) Metabolic Rate at Different Typical Activities [10]

Activity		Metabolic Rate in mets units
RESTING	Sleeping	0.7
	Reclining	0.8
	Seated, quiet	1.0 = 50 K cal/m^2hr
	Standing , relaxed	1.2 (58.2 J/S m^2)
WALKING	On the level mph Km/hr	
	2 = 3.2	2.0 = 100 K cal/m^2hr
	3 = 4.8	2.6 (116.4 J/S m^2)
	4 = 6.4	3.8
	(1 K m/hr = $\frac{1}{3,6}$ m/s)	
MISCELLANEOUS OCCUPATIONS	Carpentry:	
	Machine sawing, table	1.8 - 2.2
	Sawing by hand	4.0 - 4.8
	Planning by hand	5.6 - 6.4
Foundry work:	Using a pneumatic hammer	3.0 - 3.4
	Tending furnaces	5.0 - 7.0
General Laboratory work		1.4 - 1.8
Machine work:	Light (e.g., electrical industry)	2.0 - 2.4
	Heavy (e.g., steel work	3.5 - 4.5
Vehicle driving:	Car	1.5
	Heavy vehicle	3.2
DOMESTIC WORK WOMEN	House cleaning	2.0 - 3.4
	Cooking	1.6 - 2.0
OFFICE WORK	Typing	1.2 - 1.4
	Misc. office work	1.1 - 1.3
	Drafting	1.1 - 1.3
LEISURE ACTIVITIES:		
	Stream fishing	1.2 - 2.0
	Calisthenics exercise	3.0 - 4.0
	Dancing, social	2.4 - 4.4
	Tennis, singles	3.6 - 4.6
	Squash, singles	5.0 - 7.2
	Basketball, half court, interamoral	5.0 - 7.6
	Wrestling - competitive or intensive	7.0 - 8.7
	Golf, swinging and walking	1.4 - 2.6

explain

expected

One met is defined as 58.2 w/m^2 ($J/S\ m^2$), 50 K cal/ (m^2) (hr), or 18.4 Btu/(ft^2) (hr). For an average size man, the met unit corresponds approximately to 90 K cal/ hr, 100 watts (J/S), or 400 Btu/hr.

For many of the exercises chosen in Table C-3.(1). the calculated mechanical efficiency (ε) as defined by engineers, is at or near zero. The exercise physiologists sometimes define efficiency as the ratio W/(M-44), where 44 is the basal metabolic rate in w/m^2 ($J/S\ m^2$), M is the metabolic rate, W is the external mechanical power. For walking 3.2 to 6.4 K m/hr on a 5% grade man's mechanical efficiency (ε) is approximately 10%; on a 15 to 25% grade, the efficiency rises to about 20%. Man's best mechanical efficiencies 20-22% occur with leg exercises that involves lifting body weight.

?

For the design of air-conditioning equipment useful for the upper limits for comfort and health, the more conservative estimate when the efficiency factor (ε) is considered zero,

The energy costs (metabolic rates) for resting positions, tend to lower with age (2% per decade). For heavier exercise the question is man's ability to do work, as judged by his maximal energy capacity and the relation of his work task intensity to his capacity.

The relationship between grade of physical effort, ventilation rate, and oxygen consumption for an average size man is shown in Table C-3.(2).

Table C-3.(2). Classification of Physical Effort

(fro steady state work)[10]

Classification	Ventilation volume liters per minute	Oxygen Consumption liters per minute	Metabolic Rate met	Heart Rate, (bpm) for normal subjects
Very light	10	0.5	1.6	80
Light	10-20	0.5-1.0	1.6-3.2	80-100
Moderate	20-35	1.0-1.5	3.3-5.0	100-120
Heavy	35-50	1.5-2.0	5.0-6.7	120-140
Very Heavy	50-65	2.0-2.5	6.7-8.3	140-160
Unduly Heavy	65-85	2.5-3.0	8.3-10.0	160-180
Exhausting	85+	3.0+	10.0+	180

The energy released by the oxidation processes in the human body per unit time (metabolic rate M) is sometimes partly converted to external mechanical power W, but is mainly converted to internal body heat, H,

so that $M = H + W$ (K cal/hr)

Introducing the following definition of external mechanical efficiency

$$\eta = \frac{W}{M} = \varepsilon$$ into the above equation

gives $H = M\ (1 - \eta)$ (K cal/hr)

or expressed per unit body surface area:

$$\frac{H}{A_{D_u}} = \frac{M}{A_{D_u}}\ (1 - \eta) \quad (\text{K cal/hr m}^2)$$ [11]

C-3.2. Thermal Resistance of the Clothing (Clo-value)

Clothing is an important factor contributing to human response. It is controlled in climate chambers, but it is not controlled in field studies, but has often been recorded. The record may be as little as a description of the normal manner of dress, or as detailed as an item by item account obtained from the respondent at the same time as his assessment of the thermal environment. As an example; in a study by Webb[15] about subjects in Roorkee (near New Delhi), Northern India and in Baghdad, Iraq, he described their clothes as they were consisted of a light cotton shirt, lightweight trousers and light cotton undergarments. At night, the Indian subjects wore a cotton vest and cotton pyjamas, They had a sheet and a pillow, and were protected by a mosquito net. Details of night clothing were not obtained from the Iraqi subjects. They did not use mosquito nets. Another study by E. R. Ballantyne and J. W. Spencer [46] of thermal comfort in a humid tropical area (Port Moresby, Papua and New Guinea) give description of subjects typical clothing worn throughout the year as it is shorts and shirt for men, often with long socks and shoes, and lightweight dresses for women, usually without stockings.

The usefulness of the record of clothing is twofold; it gives insight into the way people have adjusted to the prevailing temperatures and, if the thermal insulation of the ensemble is estimated, a theoretical prediction of the respondent's thermal state can be made from a comfort equation.

The unit of clothing insulation is the 'clo', originally chosen such that one 'clo' would represent the amount of

clothing needed for sedentary work at 21°C. It is now defined as a surface-to-surface resistance of 0.155 m^2 °c/w. This is the insulation value of the material alone.

Female clothes are usually fashion-sensitive and therefore change rapidly. Clothing design and fit, together with fabric flexibility, have a strong influence on the additional ventilation loss which body movement can create, e.g. a bellows action.

The moisture permeability and absorption characteristics of the clothes fabric become important in hot conditions. The type and colour of the outer clothes can have an important influence on the radiant energy interchange with room or heater.

The thermal resistance of a given textile system depends first and foremost on the thickness and porostiy of the individual textile layers. For all ordinary textile materials intended for clothing, the variation in porosity is, however, so moderate that the thickness is the most important property which determines the conductive resistance of the indivdual textile layer. The type of textile fibre (wool, cotton, silk, rayon, nylon, glass) does not seem to be of great significance.

Changes in humidity content of the textile caused by variations in the airhumidity have only a small influence on the conductive resistance. On the other hand, if the textile becomes really "wet", i.e. if the air between the fibre and the yarn is replaced by water, the conductive resistance will of course be reduced considerably.

Apart from the conductive resistance of the textile itself, the layers of air between the textile layers are also of importance, and it thus follows that the tailoring and fit have a certain influence on the clo-value. For very loosely hanging clothing a certain ventilation of the air layers can occur, arising from a "chimney effect". For high air velocities the dynamic pressure of the air current can create an air stream through the clothing, depending on the permeability of the clothing material. This ventilation heat loss could be treated together with I_{cl}, i.e., the I_{cl} values could be measured for different clothing ensembles as a function of the velocity. However, for the low velocities usually encountered in indoor environments, it may normally be assumed that this ventilation heat loss is negligible.

Gagge et al [116] introduced the term I_{cl} as a dimensionless expression for the total thermal resistance from the skin to the outer-surface of the clothed body. I_{cl} is defined by

$$\underline{I_{cl}} = \frac{R_{cl}}{0.18} \quad \underline{(Clo)}$$

where R_{cl} = the total heat transfer resistance from skin to outer surface of the clothed body (m^2 hr ^oC/K cal).

Another term is used, "tog", introduced by Peirce and Rees [117]

$$1 \text{ "tog"} = 0.100\ ^oC\ m^2/w = 0.116\ ^oC\ m^2\ hr/K\ cal$$

$$= \underline{0.645\ Clo}$$

The dry heat transfer from skin to the outer surface of the clothed body can hereafter be expressed by the following formula:

$$K = A_{D_u} \frac{\bar{t}_{sk} - t_{cl}}{0.18 \cdot I_{cl}} \quad (K\ cal/hr)$$

The magnitude of I_{cl} for a certain clothing ensemble is rather difficult to measure. For example it is not sufficient to measure the conductive resistance of each textile layer, analogous to the measuring of conductive resistances for building materials.

In order to obtain resonably accurate measurements it is necessary to use a heated manikin in life size which is garbed in the whole actual clothing ensemble(textile system). As heated manikins including the necessary electronic equipment are expensive to produce, only very few examples are to be found in operation, most of them being in connection with military and aeronautical applications. Unfortunately, therefore, there exist in the literature, clo-values for relatively few clothing ensembles. Some of these clo-values are listed in Table C-3.(3), which furthermore comprises values for the f_{cl} factor (ratio of the surface area of the clothed body to the nude body).

Table C-3.(3) Data for Different Clothing Ensembles [11]

Clothing Ensemble	I_{cl} Clo	f_{cl}
Nude	0	1.0
Shorts	0.1	1.0
Typical Tropical Clothing Ensembles: Shorts, open-neck shirt with short sleeves, light socks and sandals	0.3 - 0.4	1.05
Apollo Constant Wear Garment (astronauts): Light cotton undergarment with short sleeves and ankle length legs, cotton socks	0.35	1.05
Light summer Clothing: Long lightweight trousers, open neck shirt with short sleeves	0.5	1.1
Light Working Ensemble: Athletic shorts, woollen socks, cotton work shirt (open neck), and work trousers, shirt tail out	0.6	1.1
U.S. Army "Fatigues", Man's: Lightweight underwear, cotton shirt and trousers, cushion sole socks and combat boots	0.7	1.1
Combat Tropical Uniform: Same general components as U.S. Army fatigues but with shirt and trousers of cloth, wind resistant, poplin	0.8	1.1
Typical Business suit	1.0	1.15
Typical Business suit + cotton coat	1.5	1.15
Light Outdoor Sprotswear: cotton shirt, trousers, T-shirt, shorts, socks, shoes, and single ply poplin (cotton and dacron) jacket	0.9	1.15
Heavy Traditional European Business suit: cotton underwear with long legs and sleeves, shirt, woollen socks, shoes, suit including trousers, jacket and vest	1.5	1.15-1.2
U.S. Army Standard Cold-Wet Uniform: Cotton-wool undershirt and drawers, wool and nylon flannel shirt, wind resistant, water repellent trousers and field coat, cloth mohair and wool coat liner and wool socks	1.5 - 2.0	1.3 - 1.4
Heavy Wool Pile Ensemble: (Polar weather suit)	3 - 4	1.3 - 1.5

Ref. (11) Table 2, P.O. Fanger, Thermal Comfort

The clo-values given in Table C-3.(3), refer to the clothing ensemble itself. If a person sits in an upholstered chair or lies on a divan, the effective clo-value will be greater than the clo-value for a standing person in the same clothing ensemble, and therefore allowances must be made for certain additions to the values given in the table.

The vapour diffusion resistance of ordinary clothing is mostly relatively low, and all the sweat secreted by persons in thermal comfort will therefore normally evaporate.

Variables that Influence the Condition of Thermal Comfort

C-3.3 Air Temperature

Temperature is defined as the thermal state of matter with reference to its tendency to communicate heat to matter in contact with it. If no heat flows upon contact, there is no difference in temperature. The air temperature has long been used as a convenient measure of warmth, but there are cases where it is unsatisfactory, misleading and not easy to measure accurately unless a sling or aspirated and shielded thermometer is used. For example, air temperature is inadequate when there is a combination of extreme temperature and high air speed, when there is a strong interchange of either radiant or convective heat between people and their environment or when the environment is warm enough to cause perspiration.

The comfort range for an individual wearing normal clothing is approximately 9°C e.g. (18.5 - 27.5°C) without jackets. This covers the descriptions 'comfortably cool', 'comfortable' and 'comfortably warm'. However, since individuals vary, the acceptable range for a group of people will be narrower than this.

Fanger [11] introduced a statistical approach to comfort. In general sedentary people wearing standard clothing require 3°C rise in their ambient environment to alter their vote from say 'comfortable' to 'comfortably warm'. For a group of people the standard deviation in comfort votes is 0.8 vote for a constant temperature. Experiments with people wearing normal clothes but without jackets or pullovers confirmed these results.

Vertical Temperature Gradients

Comfort guides recommended higher air temperature at foot level than head level. The preferrred pattern of skin temperatures are as follows:

Head 34°C, Trunk 34.5°C, Forearms 31°C,

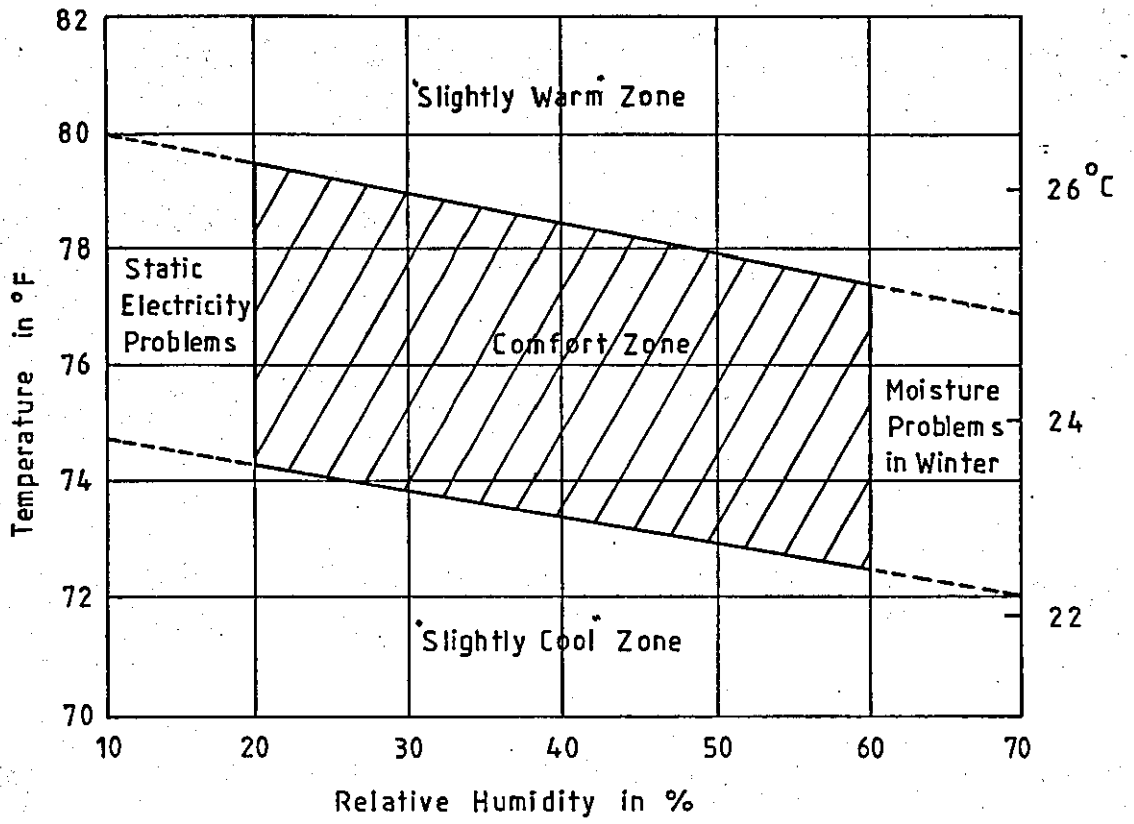
Hands 30°C, Thighs 33°C, Calves 31°C,

Feet 30°C

The opinion may accurately reflect the clothing distribution of women or may be a restatement of the fact that if people are cold it is noticed first in the feet. In the absence of data a 2°C vertical gradient in air temperature is acceptable in either direction, i.e. the head being 2°C cooler than the feet or vice versa.

Temperature and Humidity Criteria for Rooms

The relationship between air temperature in °F and (°C) relative humidity in % is shown by the graph below[118]. The graph is based on test data from lightly clothed subjects engaged in sitting activities. The shading region indicates an average zone for human thermal comfort.



Ref. Nevins, R. G., "Criteria for Thermal Comfort". Institute for Environmental Research, Report No. 12. Kansas State University[118].

Note: In the comfort zone, human tolerance to humidity is much greater than tolerance to temperature. Consequently, air room temperatures must be more carefully controlled. Humidity control is also important, however, since high room humidity can cause condensation on glass surfaces in winter, and low room humidity can cause static electricity problems. Typical humidity limitations are indicated in the comfort zone on the above graph.

only? why such on glass?

Suggested Air Temperatures for Rooms[119]

The suggested temperatures in Table C-3.(4) represent guidelines for design based on room heating for winter comfort

requirements. For summer conditions, slightly higher temperatures, about +3°F (1.6°C) are appropriate.

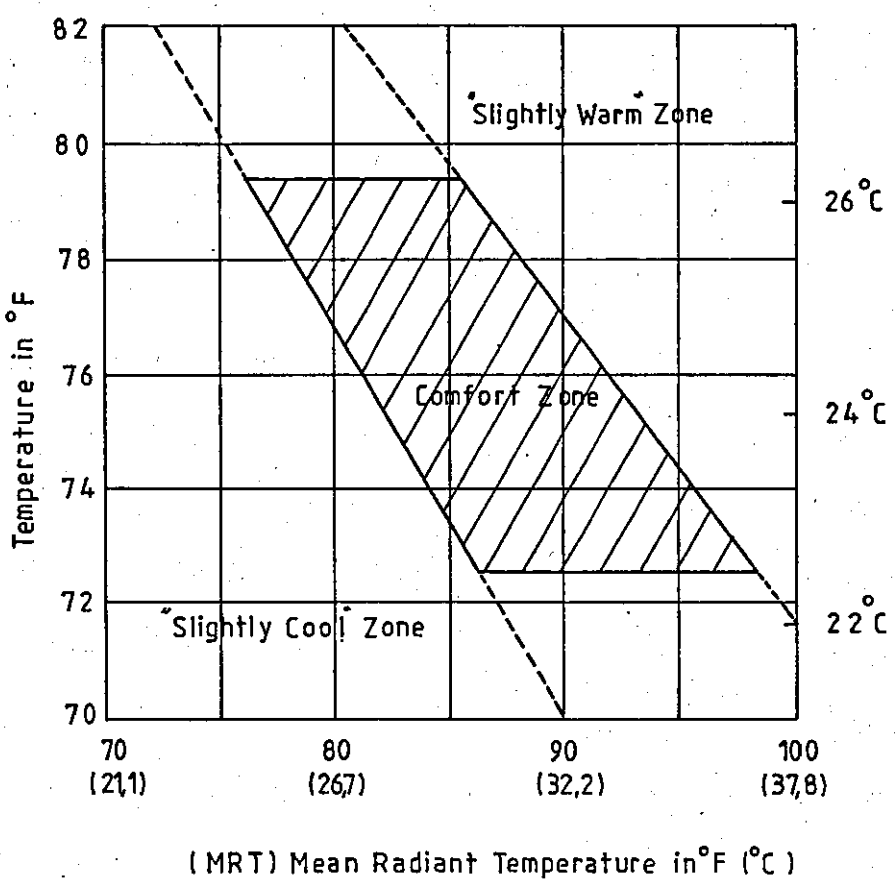
Human sensitivity to changes in temperature is normally about ± 1½°F (0.8°C) (temp. of 21.1°C may be excessively warm for persons exercising in a gymnasium, but the same conditions may be too cool for reading in a residence). Ideally, mechanical systems should have temperature control for each room as occupant comfort requirements can vary with age (older people generally prefer warmer temperature), sex (very little), clothing worn, and level of physical activity. Requirements can also vary from day to day for the same individual.

Table C-3.(4)

Type of Space	Temperature in (°C)
- Bathrooms, swimming pools, industrial paint shops, etc.	24°C and above
- Residences, hotels, apartments, homes for the aged, etc.	23.0° to 24°C
- Courtrooms, churches, classrooms, offices, conference rooms, etc.	22.0 to 23.0°C
- Theatres, large meeting rooms, corridors, lounges, cafeterias, and restaurants, etc.	20°C to 22.0°C
- Kitchens, laundries, retail shops and stores, hotel ballrooms.	18.0 to 21.0°C
- Garages, factories, industrial shops, gymnasiums, etc.	18.0°C and below

C-3.4. Mean Radiant Temperature Criteria for Rooms[120]

The relationship between air temperature in °F (°C) and mean radiant temperature (MRT) in °F (°C) is shown by the graph below. The shaded region indicates an average zone for human thermal comfort. The graph is based on test data[11] from lightly clothed subjects engaged in sitting activities. Relative humidity is 50% and air velocities range from about 15 to 60 fpm (0.076 to 0.305 m/s) for the data presented.



Ref. Fanger, P.O. Thermal Comfort, New York: McGraw-Hill, Inc., 1972.[11]

Note: The higher the MRT value, the lower the corresponding air temperature for comfort conditions as indicated by the slope of the

comfort zone. Radiant panel heating systems for example, can provide satisfactory comfort conditions at low air temperatures.

C-3.5. Relative Humidity (RH)

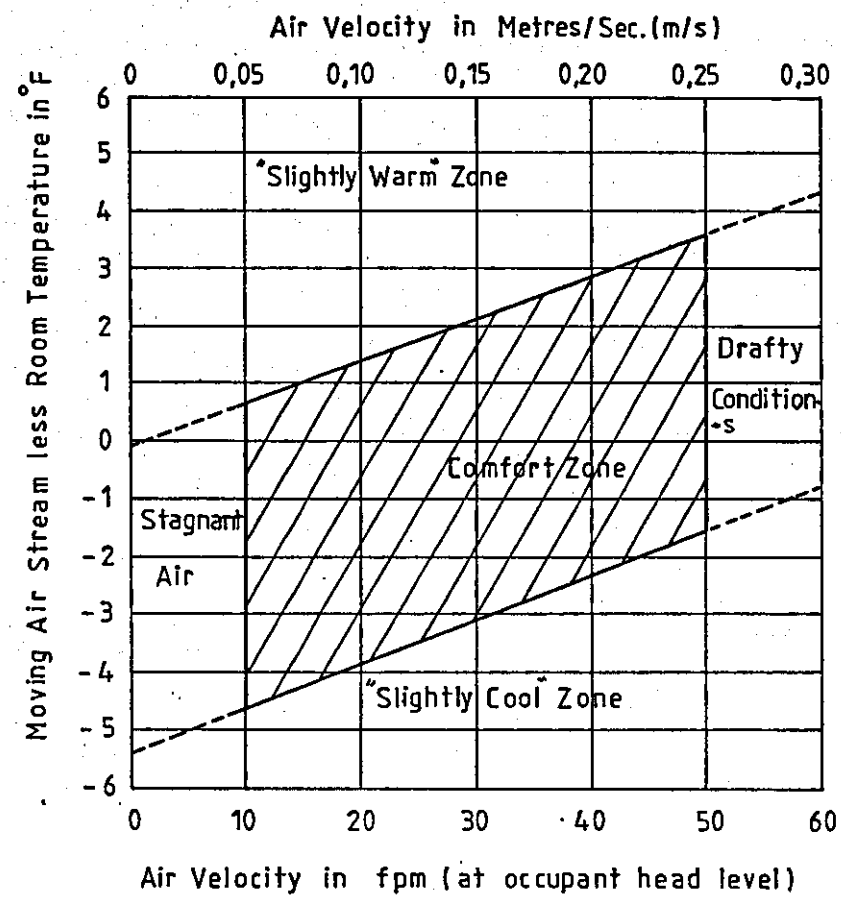
(RH) in % is the amount of moisture in air compared to the maximum amount that can exist at a given temperature without condensation. (RH) can be measured by a device called a 'sling psychrometer'; it consists of two mercury-filled glass thermometers mounted side by side on a frame fitted with a handle by which the device can be whirled through the air. One of the thermometers has a cloth sock that can be wetted. As moisture from the wet sock evaporates, the "wet bulb" temperature lowers. The drier the air surrounding the sling psychrometer, the more moisture that can evaporate from the sock. This evaporation lowers the wet bulb temperature. The greater the difference between the wet bulb and dry bulb temperatures (called "wet bulb depression") the lower the relative humidity.

We can use a psychrometric chart for finding the (RH) from wet and dry bulb temperatures for 75°F (24°C) dry bulb reading and 63°F (17°C) wet bulb reading RH = 50% .

Temperature and Air Velocity Criteria for Rooms.

The relationship between moving air stream temperature (i.e. amount above or below room air temperature) in °F and air velocity in fpm (m/s) is shown by the graph below [120].

The shaded region indicates an average zone for human thermal comfort.



Ref. Reinmann, et al , "Evaluation of Three Room Air Distribution Systems for Summer Cooling" ASHRAE Transactions, Vol. 65, 1959[120].

Note: Under some conditions air motion can be pleasant cooling breeze while under others it can be a draft. Consequently, the combination of air velocity and temperature must be carefully controlled. Typical temperature and velocity limitations are indicated in the comfort zone on the graph.

C-3.6. Air Velocity

Moving air contributes to thermal comfort by removing the moisture and heat surrounding the body.

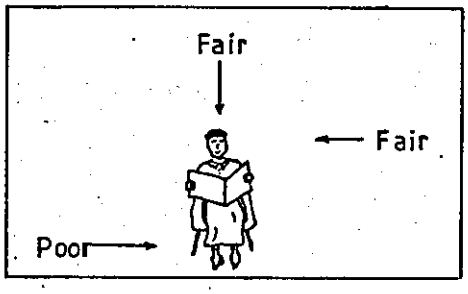
Air velocity at Head Level of Occupant in fpm (m/s)	Tropical subjective Occupant Evaluation
0-10 (0-0.05)	Complaints about stagnant air
10-50 (0.05-0.25)	Generally favourable (manufacturers of air outlet devices, e.g. base performance on 50 fpm (0.25 m/s) air velocity in occupied zone.
50-100 (0.25-0.5)	Awareness of air motion, but can be comfortable (e.g. some retail shops and stores) when temp. of moving air is above room air temp.
100-200 (0.5-1.0)	Constant awareness of air motion, but can be acceptable (e.g. some factories) if air supply is intermittent and above room air temp.
200 (about 2 mph) and above (1.0 m/s and above)	Increasingly drafty conditions with complaints about "wind" in disrupting a task, activity, etc.

Note: The combination of air motion and air temperature is an important consideration for achieving comfort (e.g. at air velocities of 30 fpm (0.15 m/s) and above, a 15 fpm (0.075 m/s) increase is equal to about a 1°F (0.55°C) drop in temperature.

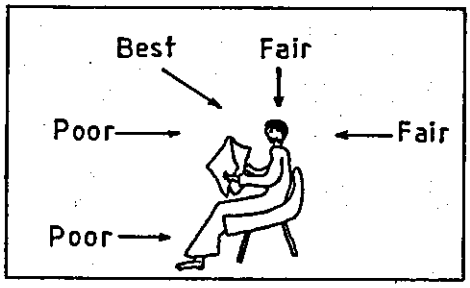
Air Motion

Air Stream Motion (Influence of Air Direction)[119]

A guide to desirable air stream directions for seated persons is given below. Note that typical subjective comfort evaluations are indicated for front, rear, side, and overhead air stream directions.

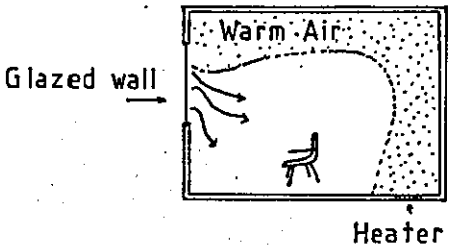


Air from Sides or Overhead

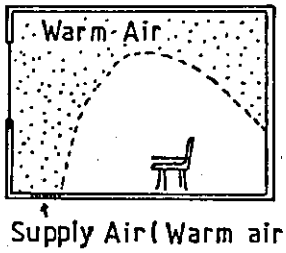


Air from Front, Rear or Overhead

Poor: Draft from cold glass surfaces are directed toward room occupants



Better. Continuous warm-air supply counteracts downdraft at glass surface



Natural Air Convection (Influence of Glass in Winter)

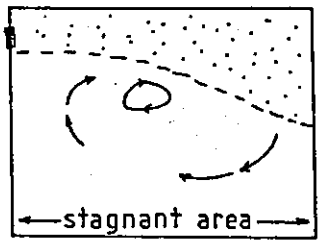
Air distribution is shown above for two heating air supply locations in a room having a glazed exterior wall. Air supply location can greatly influence occupant comfort and air motion by convection (i.e, tendency of warm air to rise) as shown.

Air Distribution in Rooms

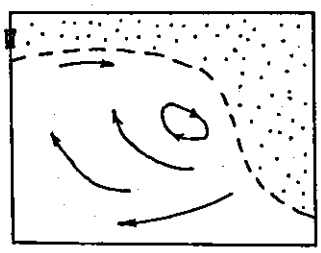
- The best supply air outlet locations for heating are located near the floor (preferably at outside walls under glass areas to prevent cold downdrafts).

- For cooling, the best supply air outlet locations are high on inside walls or in the ceiling.

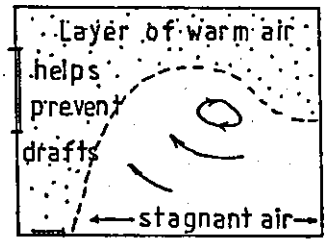
Consequently, the primary comfort requirements of the climate region-heating or cooling should influence supply air outlet location.



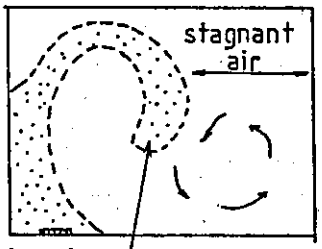
Drafts across floor from cold wall surfaces (H:1) Heating



(C:1) Cooling



(H:2)



(C:2)

Air at low temp. is dense and will drop down

Ref.[121] "Room Air Distribution Considerations" National Warm Air Heating and Air Conditioning Association, 1st Ed., Manual E (1965)

Suggested Air Changes for Rooms [119]

Type of Space	Air Change (per hr)
Machinery spaces, maintenance shops (such as for electrical equipment), school and industrial shops, etc.	8 to 12
Cafeterias, restaurants, offices, reception areas, hospitals residences, garages, etc.	6 to 12
Churches, libraries, reading rooms, bowling alleys, retail shops and stores, etc.	15 to 25
Auditoriums, theatres, classrooms, kitchens, conference rooms, etc.	10 to 30

The table above suggests ranges of room air change (i.e., complete displacement of room air) for acceptable air motion [119]. The appropriate air change value depends on the number and activity of room occupants. Note that the values given in the table are also well above the requirements to replace the oxygen consumed in breathing (2 cfm per person) (2 x 27 litres/minute per person) and to control the carbon dioxide concentrations in the air (3 cfm per person). Air change is related to airflow volume in cubic feet per minute (cfm) by the formula

$$N = 60 \frac{Q}{V}$$

where

N = number of air changes per hour(each)

Q = airflow volume in cfm

V = room volume in cubic feet

Room air change can contribute to comfort and condensation control by removing heat and moisture produced by room activities.

Sources of Moisture in Buildings[119]

Moisture control in buildings is important as high humidity can cause condensation on glass surfaces in winter. Also, moisture from buildings occupants, equipment, etc. influences the size of refrigeration elements required for summer cooling because moisture will change the condition of the air. Exhaust systems are provided to directly ventilate spaces such as kitchens, exercise rooms, toilet rooms, etc. for odour control as well as moisture control and heat removal.

Source	Moisture (in kg)
Cooking and dishwashing	2.7 kg per day
Physical exercise	2.2 kg per person per day
House cleaning (wet cleaning)	1.5 kg per each 10 m^2
Vegetation	0.9 kg each plant per day (Live plants are excellent "humidifiers" for residences)
Taking shower	0.2 kg each shower

High humidity retards human heat loss by evaporative cooling (i.e., sweating) and by respiration. Low humidity tends to dry throat and nasal passages. In buildings, low humidity can also cause loosened furniture joints, cracked book bindings, etc.

Humidification devices are available that can introduce moisture directly into the air stream of mechanical systems.

C-3.7. The Influence of Certain Special Factors on the Thermal Comfort

National-Geographic Location, Age and Sex

The results of the experiments at the Technical University of Denmark[11] which were designed to obtain the best possible comparison with the American Study of Nevins, show surprising agreement between the temperatures desired for thermal neutrality for the two national-geographic groups.

The Danish subjects preferred a slightly higher temperature (25.71°C) than the Americans (25.55°C), but the difference is less than 0.2°C and is not statistically significant.

The experiments were performed for only one combination of clothing (0.6 clo), activity and relative velocity (0.1 m/s), and for mean radiant temperature = air temperature.

Since the comfort equation (of P.O. Fanger)[11]

$$\frac{M}{A_{D_u}} (1 - \eta) - 0.35 \left[43 - 0.061 \frac{M}{A_{D_u}} (1 - \eta) - P_a\right] - 0.42 \left[\frac{M}{A_{D_u}} (1-\eta) - 50\right] - 0.0023 \frac{M}{A_{D_u}} (44 - P_a) -$$

$$0.0014 \frac{M}{A_{D_u}} (34 - t_a) = 3.4 \cdot 10^{-8} f_{cl} \left[(t_{cl} + 273)^4 - (t_{mrt} + 273)^4\right] + f_{cl} h_c (t_{cl} - t_a)$$

agrees very well with the results of Nevins, the results of this study suggests that the equation can readily be used for college-age persons in Denmark or more generally, at national-geographic locations within the temperate climate zones.

The actual differences in practice between preferred temperatures in the USA and in Europe which have been reported, especially in earlier field studies, probably reflect only differences in clothing habits, however, the differences in clothing habits have been considerably reduced during the past few decades, with a strong trend in Europe away from the traditional heavy clothing towards lighter textiles such as those used generally in the USA.

C - 4 . Thermal Comfort in UK

M. A. Humphreys [16] collected data from more than thirty field studies of thermal comfort. They come from a wide variety of climates and countries, ranging from winter in Sweden to summer in Iraq. In his survey he mentioned nine research workers whom they stated fifteen different field studies of thermal comfort covering wide variety of activities, seasons, sex, and age in England.

Here we can define the thermal comfort in United Kingdom, considering the field studies which were conducted in England. In these studies, the mean air or globe temperature can be regarded as a broad indication of the thermal environment prevailing during the study. It is fairly representative of the daytime conditions experienced by the respondents. The mean temperatures range from 17°C for the elderly in their homes during a fairly mild English winter (Fox) where almost 800 men and women were involved, to 24°C for young students (age 12) taking school lessons during the summer (Humphreys). The range of daytime mean temperatures covered by the studies during the winter is 17°C to 19.9°C, and during the summer was 19.3°C to 24°C.

Neutral Temperature:

For adults in England the neutral temperatures ranged from 17.5°C for the elderly in their homes (Fox) to 19.4°C for office workers (Black) during the winter, and ranged from 19.3°C for men mostly sedentary (light industry) (Hickish) to 22.3°C for office workers (Black) working mostly in air-conditioned single offices during the summer. Neutral temperatures for adults all year round were found

to be 20.5°C for office workers, and surgeons, nurses, anaesthetics in operating theatres (Wyon). For children in their schools, in several classes, the neutral temperature ranged from 16.8°C to 21.1°C during the summer and it was 18.1°C during the winter (Auliciems).

Three factors, apart from the thermal environment, can combine to produce different neutral temperatures. They are the level of activity, the thermal insulation of the clothing and the physiological state which is considered by the respondents to be 'neutral'. For elderly people such as Fox's respondents the metabolic heat generation would have been rather low, both because of their age and because of the relative inactivity which usually accompanies it.

M. A. Humphreys [16] in his paper stated the existance of a close relationship between the mean temperature and the neutral temperature. The correlation coefficient is 0.96, and over 90 percent of the variation of the neutral temperature is associated with the variation of the mean temperature, so the relationship is

$$T_n \quad 2.6 + 0.831\, T_m$$

where T_n is the neutral temperature and T_m is the mean temperature. The standard error of prediction is 1.1°.

Choice of clothing, regulation of physical activity and physiological acclimatisation could be regarded as a learning process directed towards achieving thermal comfort. If this were so, the learning would be most effective for the mean of the conditions experienced. One would therefore expect, apart from random effects, that the neutral temperture would coincide with the mean temperature

if the process were complete. That the neutral temperature is almost always below the mean thus requires explanation. It suggests that either people prefer to be slightly warmer than the condition they describe as neutral, or that the mean temperatures of the observations do not truly represent the respondents' total thermal experience. The possibility that people prefer a sensation which differs systematically from the neutral should not be dismissed. In Fox's study of the elderly, although the overall sensation was one of thermal neutrality, many of the respondents reported coldness of the extremities and most said that they would have preferred it somewhat warmer. In a recent survey at the BRS during winter (Humphreys and Gidman), the respondents were asked which of the categories of the Bedford Scale they considered to be a preferable state. The mean preference lay between 'comfortable' and 'comfortably warm'.

Appendix D

D-1. Traditional Building Materials and Their Location

Stones, sun - dried mud bricks, burnt clay bricks and wood are the basic traditional building materials, used in Saudi Arabia. The common factor in selecting any of these materials are: their cost, transportation, the function of the building, the availability of an expert builder, and the social, economic and cultural conditions of the owner. The most impontant factors of all are the influences of the climate and the local materials which come from the ground surface formations, in each of following regions.

D-1.1.Coastal Plains in the West

In the western province[23], sedimentary rocks outcrop in thin bands along the coast of the Red Sea, within a narrow plain whose width varies from one place to another. The plane is 20 kilometres wide near Jeddah and 17 km wide near Yanbo'. It is characterised by extensive eolian sand, alluvium and related surficial deposits, and sabakhas and is called "Tihama"[23]. The economical building material around this area is limestone in the form of marine deposits. Often they contain fossils of various marine organisms, such as molluscs and corals[24]. The shoreline at Jeddah and Yanbo' is in most instances 1 to 2 metres high, composed of coral rocks, which are made irregular and highly porous by the action of sea waves erosion. The top of these rocks is flat, covered with silt and sand, and is continuous with the planes to the east. The local people cut these moderatly soft to hard corals into stones, to build their traditional houses, as shown in Figure (6) . A form of coral reefs underlies

the coastal shallow waters. This was used for the same purpose, when it was exposed in some areas as small islands bordering the coast, or attached to the mainland.

D- 1 .2.Sarawat Mountains in the West

To the east of the coastal plains, basement rocks of Pre-Cambrian age occupy almost one third of Arabia, out cropping sporadically along the south fringe of the peninsula, and are called the west and south Arabian shields. They are eastern extensions of the much larger African shield which is a stable, rigid nucleus of igneous and metamorphic rocks[26]. These mountains are broken by great valleys, of which the most important are Wadi Jizan,Wadi Yanbo' and Wadi Fatima near Mecca The decline of this range of mountains is nearly vertical towards the west; consequently the flood waters wash most of the silt on the coast plains and deposit silt and clay layers on the valleys. A good example of a traditional building material is near Mecca, where clay deposits were used for making hand made bricks burnt in primitive kilns.

The rocks in Mecca Mountains are mostly igneous rocks, and most of the stones used in building traditional houses were granite and diorite rocks, cut in shape to the size required for building walls and door sells. Igneous rocks, which include granite and diorite, are hard, weather resistant materials and possess compressive strengths in the range 110 - 180 MN/m^2. Quartz (silica) which is a very hard mineral is a major constituent in granites[24,25].

The highest mountains are in Asir 'south western region' [23], where peaks rise to over 3000 metres. Then they decline to 2400 metres to the east of Mecca, to 1200 metres to the west of Mahd Adh-Dhahab and to 1000 metres at Medina. The range extends to the north with the same elevation. Most of the scattered settlers around these areas, built their homes by using a combination of granite, diorite stones, and sun-dried mud bricks, as in Khamis-Mushait, Taif and Medina. In Medina, the stones used were of lava flow, volcanic origin.

D - 1.3. Central and Northern Regions

Directly to the east of this range of mountains, lies the Interior Homocline in the Najd plateau 'central region' [23], which is bordering the shield to the west and south. The Interior Homocline is a belt of sedimentary rocks that dip towards the Rub-al-Khali and the arabian Gulf basins slightly and uniformly, reflecting the attitude of the basement. The width of the Homocline is about 400 km, and follows the eastern margin of the shield from the northwest border to the east Rub-al-Khali and is dominated by a series of west facing strike escarpments without significant interruption. The older rocks of the Homocline are of Paleozoic age and occur in the west. Successively younger rocks of Mesozoic and early Tertiary ages occur to the east. East of the Homocline is the Interior platform. This is a broad area of relatively low relief terrain in which older rocks are buried by Tertiary and younger deposits [26].

The Najd plateau has an average height of 1200 - 1800

metres. The elevation drops to 600 metres at the Ad-Dahna desert which faces the Arabian Gulf. Also it extends southward to Wadi Ad-Dawaser, then runs parallel to the Rub-al-Khali (the empty quarter). A great number of marshes are scattered throughout the Najd. These are considered remnants of inland seas which existed in ancient times. To the north, the plains of Najd extends for nearly 1400 kilometres past Hail, until they join the Iraqi and Jordanian borders. This area is called the Northern region[23]. There are number of mountainous areas in Najd such as the mountains of Aja and Selma, and the Tuwaiq Limestone range, which run from southwest to northwest into the Nafud. The Nafud are sandy hills having the form of ribs extending towards the north where they come together in what is called the Great Nafud.

Traditional building materials in these areas as in Riyadh and Hail were sun-dried mud bricks and sometimes a combination of limestones and mud bricks. Much of the earth around Riyadh is made up of sedimentary rocks, which are often well stratified and show well defind bedding planes. These sedimentary rocks were cleaved and cut easily into fairly regular shapes. Sedimentary rocks in this area are limestones and dolomites, formed by the precipitation of calcium carbonates, or calcium and magnesium carbonates, from solution. Limestones and dolomites are very hard, with compressive strengths of the order of 150 MN/m^2.

Mud and clays have been used extensively in building most of the traditional houses. It came from the top surface layer of the soil in the areas of building sites and from the nearby valleys where silt and clay been deposited by the action

of water flooding.

D - 1.4. Coastal Areas in the East

In the eastern province[23] along the Arabian Gulf, geological information was obtained in connection with petroleum and some civil engineering works. This describes the geology of the coastal areas[27-29] in which the early settlers built their homes. Most of this region lies within the Arabian platform, which is a largely flat area of early to late Tertiary rocks covered by eolian sand, gravel and other deposits, except for some rock outcrops and sabakhas (low laying inland and coastal salt flats) bordering on the sea. Sometimes unconsolidated deposits are underlain by weathered rock, at relatively shallow depth. The soil is mainly a disintegrated weathered rock and fine wind blown sand and silt overlying limestone, frequently interbedded with dolomites, marl and shale. The main features inland are low escarpment where coral stones, sometimes referred to as calcareous gritstone are exposed and were quarried in the past for local materials. A form of coral rocks underlies the coastal waters, exposed in some places and in others covered by several metres of sand or silt[4]. The very fine silts were used also as a building mud-brick material.