MASS AND HEAT DIFFUSION IN
THE BLANCHING OF VEGETABLES

by

Rafid Khalil Abdul-Rezzak, BSc, MSc.

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Supervisor: Dr J D Selman

Department of Chemical Engineering

Loughborough University of Technology

To my Mother and Father

who I love so much

CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgements and that neither the thesis nor the original work contained herein has been submitted to this or any other institution for a degree.

R k Abdul-Rezzak

PUBLICATIONS

Selman, J D, Rice, P and Abdul-Rezzak, R K. (1983).
*"A study of the apparent diffusion coefficients for solute
losses from carrot tissue during blanching in water".*
J. Fd. Technol. 18 (4), 427-440.

Selman, J D and Abdul-Rezzak, R K. (1983).
*"A comparative study of the leaching of reducing sugars from
potato slices during an industrial blanching process".*
Department of Chemical Engineering Report No. 280683,
Loughborough University, England.

ACKNOWLEDGEMENTS

ABSTRACT

In this work, laboratory scale experiments were carried out to determine and quantify the mechanisms by which water, sugar and other solutes are transferred from vegetable tissue to blanch water. Samples of commercial potato and carrot varieties were studied and Fick's law of diffusion was applied to describe the mass transfer of solutes during blanching of cylinders and cubes of the vegetable tissues.

Diffusivities (D_a) for solute and sugar were determined for various conditions of blanch water concentrations (0-15% sucrose), temperature (60-90°C), time (120-1800 sec) and tissue dimensions (0.005-0.007m for carrot cylinders and 0.01-0.018 m for potato cubes). Apparent diffusivities were found to be dependent on both temperature and concentration of the blanch medium and independent of tissue dimension. Values of (D_a) were found to be in the range 3.07×10^{-10} to 7.64×10^{-10} m^2s^{-1} for solute loss from carrot, 4.25×10^{-10} to 7.75×10^{-10} m^2s^{-1} for solute loss from potato, and 3.71×10^{-10} to 16.32×10^{-10} m^2s^{-1} for reducing sugar loss from potato.

Diffusivity and temperature were related by an Arrhenius type relationship, having an activation energy of 28.2 kJ mol^{-1} for solute diffusion from carrot, 41.6 kJ mol^{-1} for solute diffusion from potato and 27.6 kJ mol^{-1} for reducing sugar diffusion from potato.

Solute and sugar losses during the first 300 sec blanching were due not simply to diffusion but also to expulsion of cell sap solute as turgor was lost on cell death, while in the period 600-1800 sec the solute losses appeared to arise solely by diffusion. The gelatinisation of starch in potato tissue appears to have little influence on solute loss during blanching, but did affect water retention within the tissues.

The numerical solution for the unsteady state diffusion equation for diffusion out of a slab was also used successfully to predict the apparent diffusivity of sugars from potato slices during a commercial blanching operation.

The simultaneous heat transfer occurring during blanching was also investigated for various heating and cooling temperatures, times, sample sizes and agitation rates, to aid prediction of heating and cooling rates. Thermal diffusivity for potato was calculated from the experimental time-temperature curves and found to increase with temperature reaching a maximum of 1.34×10^{-7} $m^2 s^{-1}$ at $70^{\circ}C$. The temperature and moisture content was found to have strong correlation with specific heat and thermal conductivity and a linear relation was shown to exist between them (r = +0.93 for specific heat and +0.97 for thermal conductivity). The specific heat of potato at 76% moisture content ranged from 2.7351 $kJ/kg^{\circ}K$ at $40^{\circ}C$ to 4.0154 $kJ/kg^{\circ}K$ at $90^{\circ}C$, while thermal conductivity at 76% moisture content ranged from 0.4101 $W/m^{\circ}K$ to 0.5571 $W/m^{\circ}K$ at **40-90°C**.

Results of this study indicate that the heat transfer process involved in water blanching of potato is quite rapid relative to the mass transfer process involved, the latter was found requiring approximately 3600 sec to reach equilibrium while heat transfer required only less than 900 sec.

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1. INTRODUCTION

1.1 Tissue and Cell Structure

1.1.1 Cell Structure

A brief description of the basic cell structure may help the understanding of how heat affects the cells and how solutes and water are transported through them (see Figure 1.1). The first feature of the cell is the cell wall which surrounds the cell. The cell wall is elastic in young cells and is highly permeable being composed almost entirely of fibrils of cellulose. Cell walls are composed of three layers; a primary wall, a secondary wall and a middle lamella. The outer region of the cell wall is the middle lamella. It is the region shared between adjacent cells. The middle lamella of young cells is composed of pectic compounds which serve to cement the cells together and which under certain conditions of physical and chemical treatment during processing may soften and allow the cells to separate. As the cell grows older the nature of these cementing substances often changes, lignins and other compounds are deposited and the cellulose layer of the cell wall thickens. Also at this stage the permeability of the cell wall will be reduced. Another feature of the cell is the cytoplasm which is a colloidal solution of protein and other substances dispersed in water, containing enzyme systems responsible for cell metabolism. The cytoplasm is not uniform, but differentiated into various regions and cell parts.

The membrane surrounding the cytoplasm and separating it from the cell wall within the cell is called the cell membrane (plasmalemma). It is thin and flexible and is mainly composed of protein and lipid bilayer. This membrane acts as a differentially permeable membrane allowing the water and some other small molecules to pass in and out of the cell. The inner boundary of the cytoplasm separating the cytoplasm from the vacuole is called the tonoplast which is a relatively tough differentially permeable
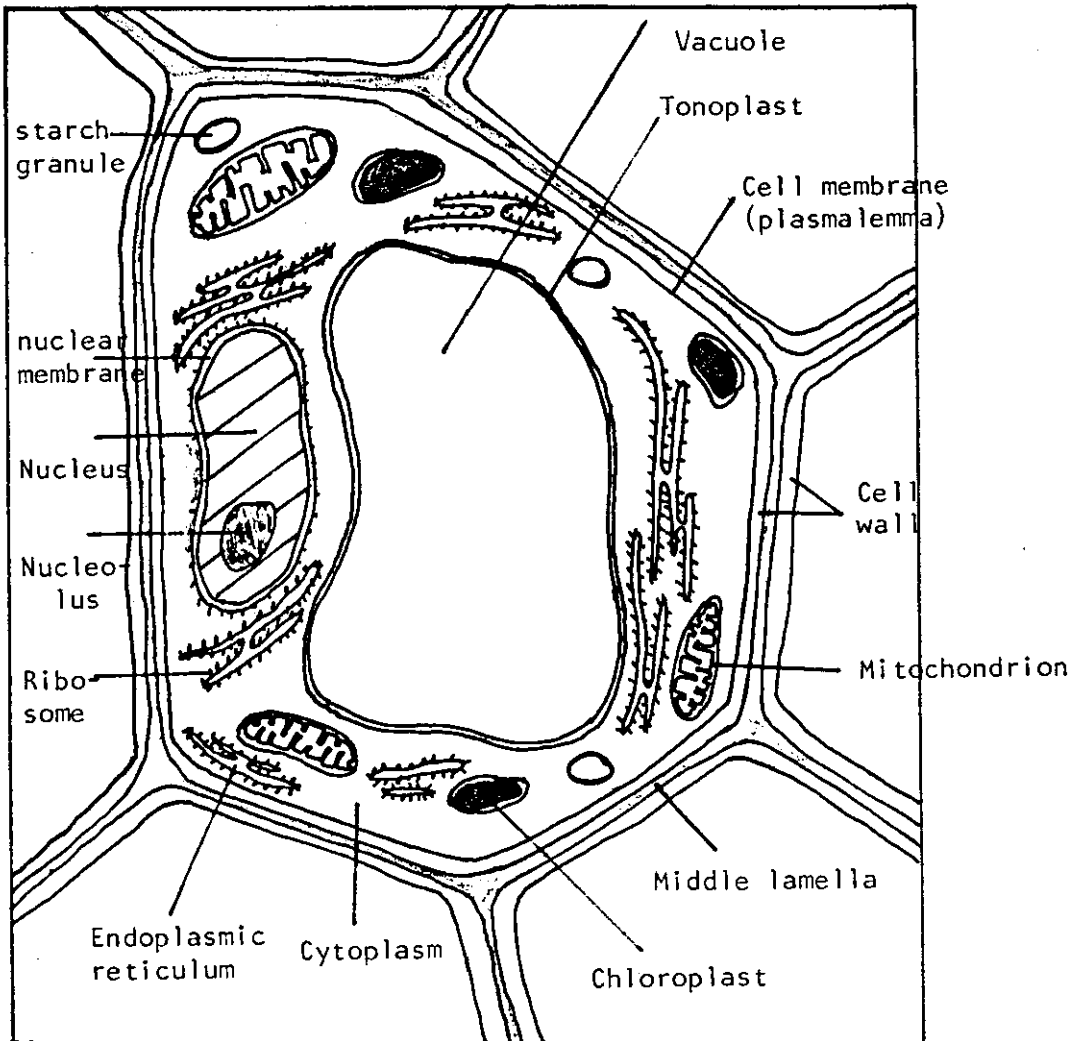
FIGURE 1.1: General plant cell

membrane. This membrane is responsible with the cell membrane for the cell acting as an osmotic system maintaining cell turgor pressure. There is usually a large vacuole in the cell filled with an aqueous solution of many compounds such as sugar, salt and other soluble materials called cell sap. The vacuole in some plant cells may also contain a colloidal substance. In young cells the vacuoles are small and numerous. As the cell grows, the size of the vacuoles increases much more than does the cytoplasm, by the imbibition of water and other small molecules. In old cells, the vacuoles become larger in size and smaller in number with often only one large vacuole occupying most of the cell, leaving the cytoplasm as a layer around the periphery. The other features of the cell are shown In Figure 1.1.

1.1.2   Tissue Structure

1.1.2.1   Carrot structure

Structurally, the carrot is a tapering root, which in transverse section, is circular having dark rings on the outside (cortex), lighter rings towards the centre and a greenish-yellow section at the core (Priestley, 1979). The cells of the outer cortex are distinguished in cross-section from those of the outer epidermis by their greater size and thicker wall. This surrounds the phloem which is mainly composed of parenchymatous cells with scattered sieve tubes. These two zones are of considerable width and the greater part of the food reserves occur here, although starch is absent or present in only small amounts in the cortex.

The centre is occupied by a xylem (core). The core is separated from the cortex by several layers of narrow elongated cells called the cambium.

The walls of the xylem are composed primarily of cellulose which with growth becomes thickened with lignin. The walls of the phloem contain little lignin. The xylem in young roots consists

labels: xylem parenchyma · secondary xylem · Cambium · oil duct · secondary phloem · phloem parenchyma · core · cortex · old carrot · young carrot
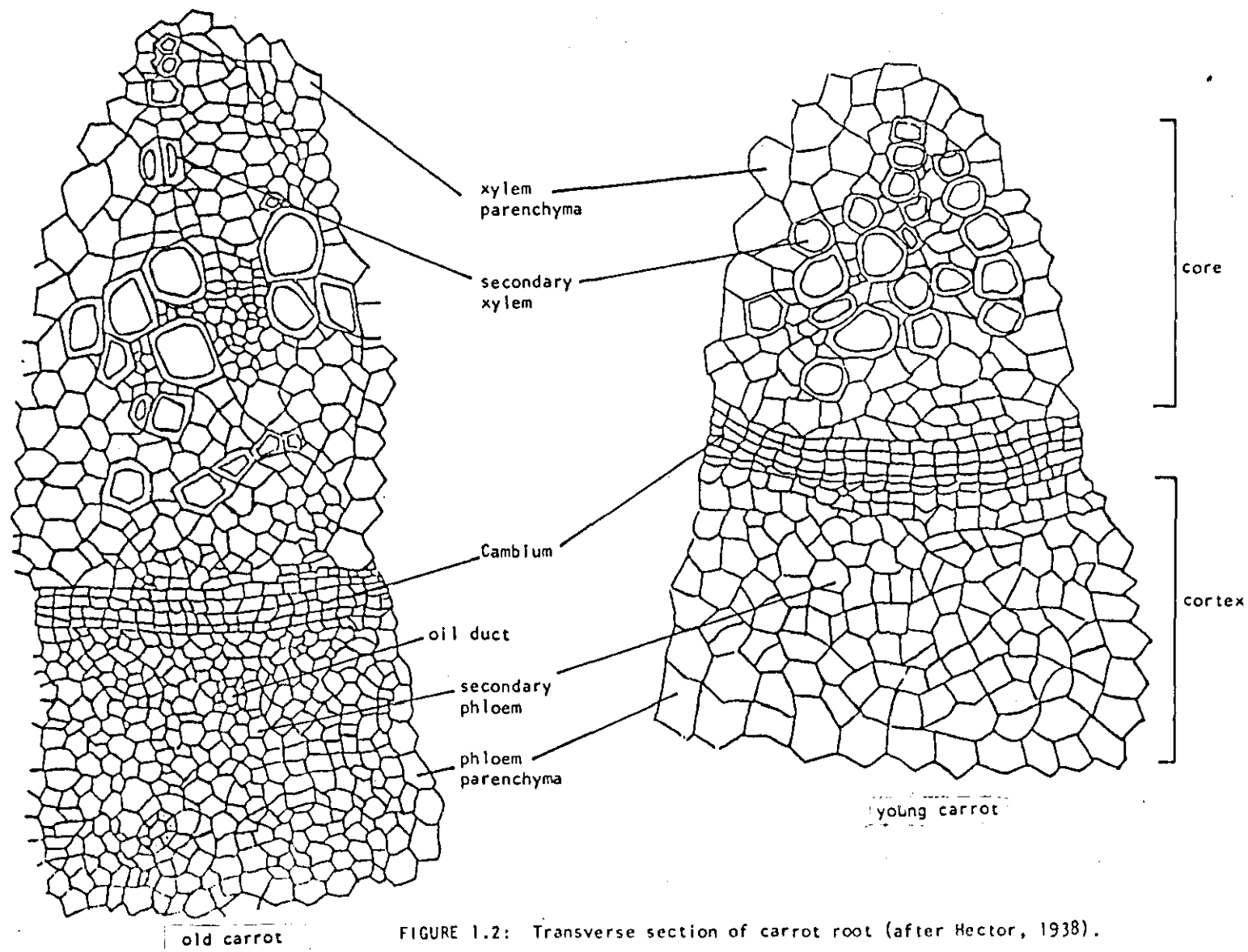
FIGURE 1.2: Transverse section of carrot root (after Hector, 1938).

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of large parenchymatous cells, traversed by narrow medullary rays. The walls of the parenchyma become thickened with age.

The cells in old carrot roots are more densely packed than those in young roots (see Figure 1.2) (Hector, 1938).

1.1.2.2 Potato structure

The potato has stem characteristics in its internal structure (Fedec et al., 1977) as shown in Figure 1.3.

The young, immature tuber has an epidermis which is replaced in the fully matured potato by a layer of corky periderm, some 10-11 cells in depth which appears to serve the purpose of retarding loss of moisture and resisting attack by fungi.

Next to the periderm is a zone of external phloem (cortex), which is a narrow layer of parenchyma tissue. Vascular storage parenchyma high in starch content is also present in the cortex. The inner cells in the cortex contain mostly large oval-shaped starch grains (average 32 x 54 μm). These inner cells appear to be the largest in the tuber with dimensions up to 146 x 189 μm.

The xylem and the internal phloem are found in minute strands or bundles, most of which form a narrow, discontinuous ring. The internal phloem zone is characterized by the presence of starch storage parenchyma cells containing starch grains similar in size to those of the cortex.

The xylem is separated from the internal phloem by several large cells with starch. Cambium cells occur only in the bundle rays between the external phloem and the xylem. In the centre of the tuber, the pith or 'water core' is readily distinguished and it consists of small cells containing lower starch content. The cell size ranges from 70 x 132 to 96 x 158 μm.

FIGURE 1.3: Potato tuber cross-section (after Fedec et al., 1977)

cork

phelloderm

storage parenchyma cells
(contain starch)

external phloem

cambium vascular

xylem

internal phloem

storage parenchyma cells
(contain starch)

pith

cork (skin)

cortex (external phloem
storage parenchyma)

pith

Samples
taken from
here

stem end

bud
end

xylem ring

internal phloem

pith ray
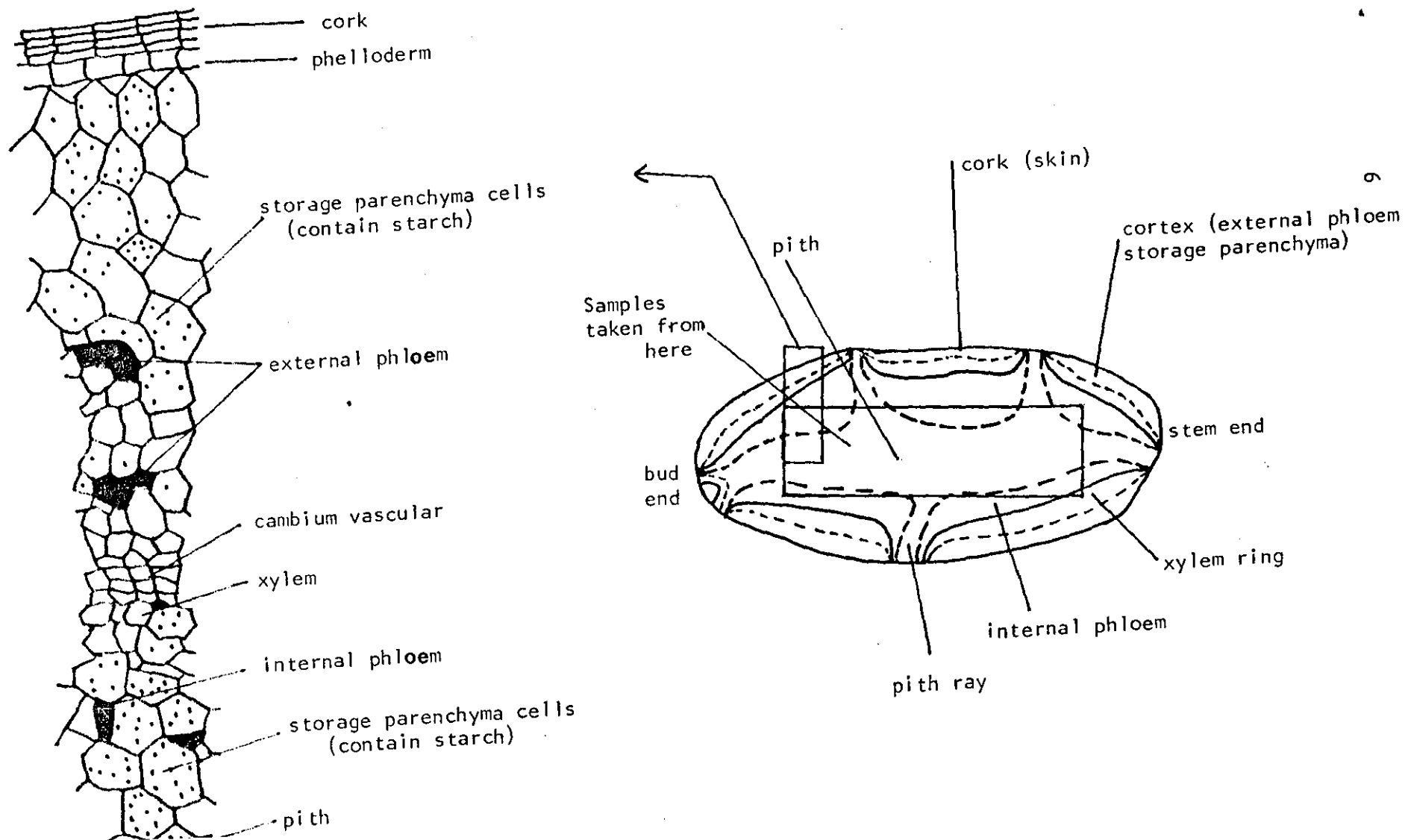
1.2 Nutrient Transport During Blanching

1.2.1 Diffusion and Osmosis

Diffusion is the term applied to the transport of solute from a region of high solute concentration to one of low solute concentration. The driving force for transfer is a concentration difference or a concentration gradient. The concentration gradient tends to move the solute, in such a direction as to equalise concentrations and remove the gradient.

The rate at which solute is then transferred from one region to the other depends upon the departure of the system from equilibrium. The transfer of the solute between the regions obviously requires time, and then the net transfer stops when equilibrium is attained.

While osmosis describes the transport of water molecules across a semi-permeable membrane from a region of dilute solution (higher potential) to one of more concentrated solution (lower potential).

The rate at which osmosis takes place depends on the difference between the concentration of the two solutions. The water transport results from random diffusion and the net movement eventually equalises the chemical potential on each side of the membrane. As a result of this transport a pressure build-up may occur on the concentrated solution side of the membrane. This pressure is termed 'osmotic pressure'.

During the initial seconds of water blanching osmosis can take place across the differentially permeable membranes of the cells, but this will cease on cell death when the cytoplasmic membranes become disorganised.

During immersion of living plant cells in a hypotonic solution, there will be a water uptake or a net diffusive movement of water
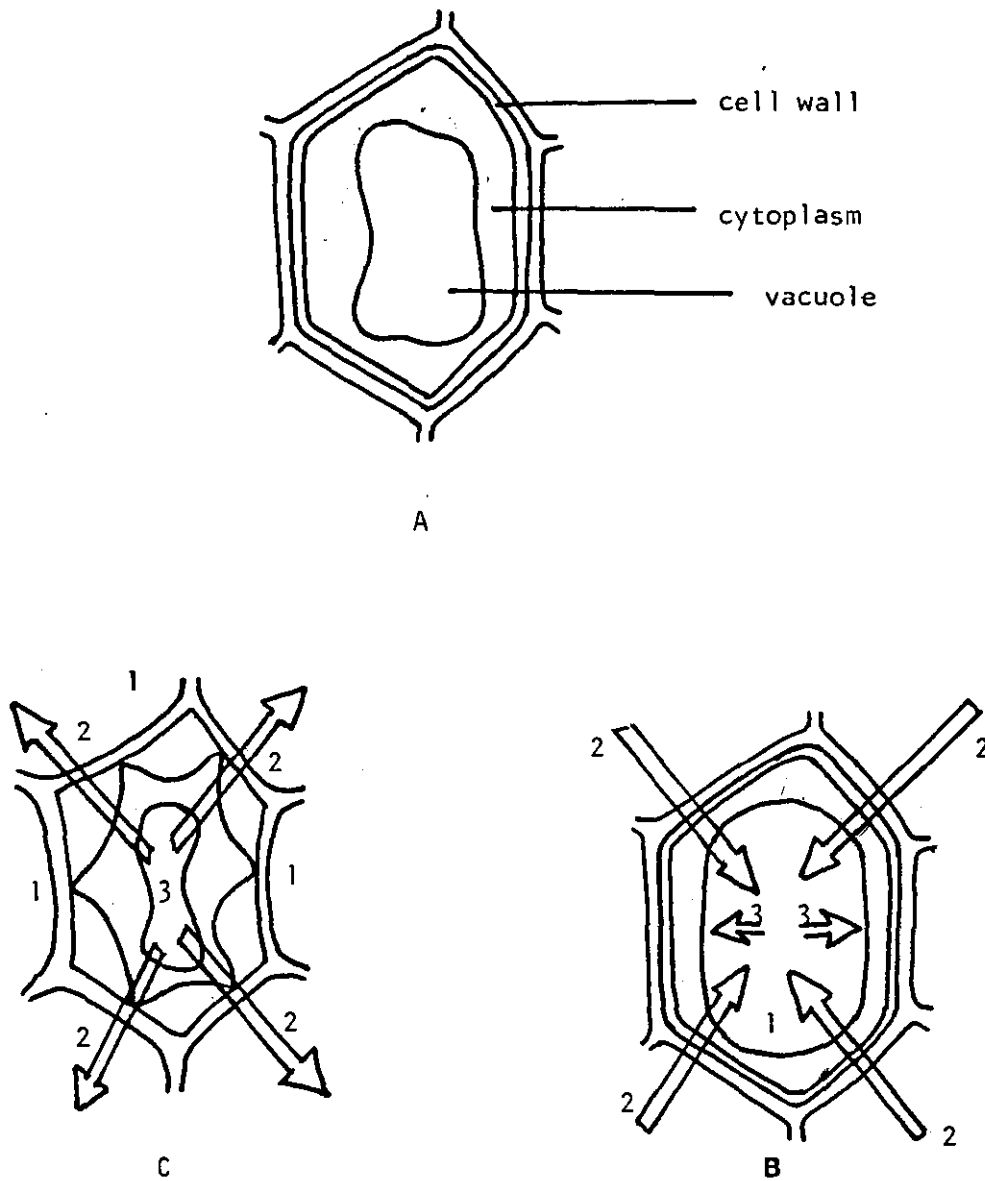
FIGURE 1.4: Turgor and plasmolysis in plant cells.

A: Cells in isotonic solution

B: Cells in hypotonic solution

    1. The concentration in the cell sap is higher than the solution outside the cell.

    2. Water enters by osmosis passing through the permeable cell wall and the semi-permeable cytoplasm.

    3. The cell sap volume inside the vacuole increases **and** pushes outwards on the cell wall making the cell turgid.

C: Cell in hypertonic solution

    1. The solution outside the cell is more concentrated than the cell sap.

    2. Water passes out of the vacuole by osmosis.

    3. The vacuole shrinks, pulling the cytoplasm away from the cell wall and leaving the cell flaccid.

into the cell, and the cells become turgid. The opposite may
happen (plasmolysis) if the immersion solution is hypertonic
to the cell solution, when a net loss of cell water would
occur.

However when the cell is immersed in isotonic solution,
there will be equal water diffusion in both directions. Figure
1.4 shows the diffusion of water in and out of the cell, under
these conditions.

1.2.2 Mechanism of Nutrient Transport During Water Blanching

There are several views about the mechanism of nutrient
transport during water blanching.

Selman and Rolfe (1979) suggested that when vegetable
tissue comes in contact with water during blanching, water is
absorbed by osmosis until heat destroys the permeability of the
cytoplasmic membranes of the cell. On loss of turgor cell
solution is lost as cell volume contracts. Thereafter loss of
solutes (and water) occurs by diffusion.

Lathrop and Leung (1980) suggested that the leaching of
vitamin C during water blanching was also controlled primarily by
diffusion.

Further support for this mechanism comes from the work of
Kozempel et al. (1981 and 1982), which suggested that diffusion
is the rate controlling step in the mass transfer of solute and
other nutrients during water blanching.

According to this view, the transport of solute and nutrients
from the interior of the tissue to the blanch water is caused
by a concentration gradient and follows the basic equation of
diffusion:

$$\frac{dc}{dt} = D_a \frac{d^2C}{dx^2}$$

where: D_a = diffusion coefficient, C = concentration, t = time and x = distance.

Based on these views and others such as Vukov (1977), Islam and Flink (1982), one can describe the mechanism of nutrients transport during water blanching in the following manner.

The influence of temperature and blanch time on permeability of tissue leads to a partition of the mass transport into three fundamental stages: osmosis, disorganisation and diffusion.

In the first stage water enters the cell by osmosis through the differentially permeable membrane. Some solutes may move out in this stage from the ruptured cells on the surface of the tissues. In the second stage as temperature increases, denaturation of the proteins in the cell membranes results in increased permeability of the membranes and loss of turgor, and cell solution is forced out of the cell by the cell wall pressure.

The duration of these two stages depends on the blanching temperature and the time needed for denaturisation. After the completion of these two initial stages, the third stage 'diffusion' can be considered as the rate controlling factor.

During this latter stage nutrients and water will be transported by diffusion and follow the general law of molecular diffusion. Therefore, the solute molecules diffuse gradually from the tissue (regions of high concentration) to the blanch water (regions of lower concentration). The tendency to diffuse increases as the concentration difference between tissue and blanch medium increases.

As the blanching process continues, the rate of diffusion
starts decreasing gradually from a high initial value until
equilibrium is approached.

Figure 1.5 shows how the rate of diffusion decreases with
time during blanching.
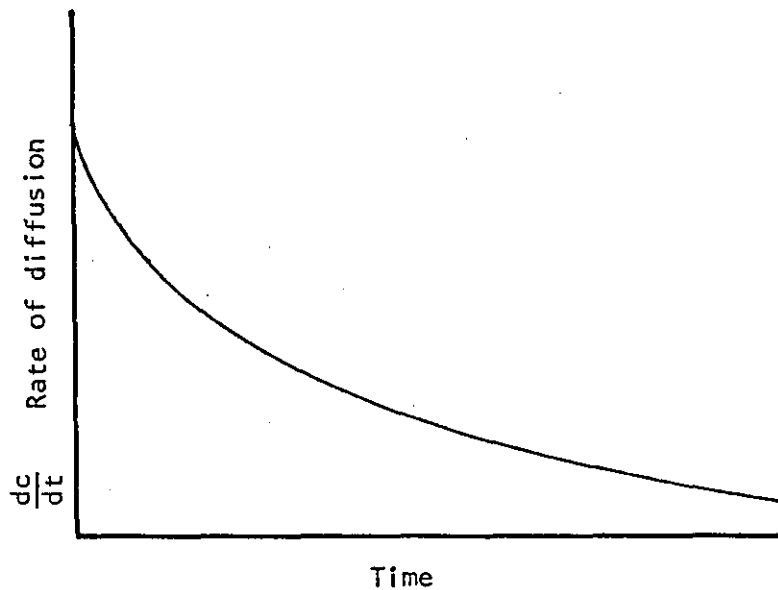
FIGURE 1.5: The decrease in diffusion rate with time during
blanching of vegetable tissue

Similarly as the blanching process continues, the concentration
in the blanch medium and tissue will change. Figure 1.6 illustrates
the changes in concentration in the tissue and blanch medium with
time.

Curve A shows the change of the solute concentration in
tissue with time and curve B shows the corresponding concentration
change in the blanch medium. After a blanch time of t_1, most of
the solutes in the cells of the tissue will have diffused out into
the blanch medium, and little further loss is obtained by increasing
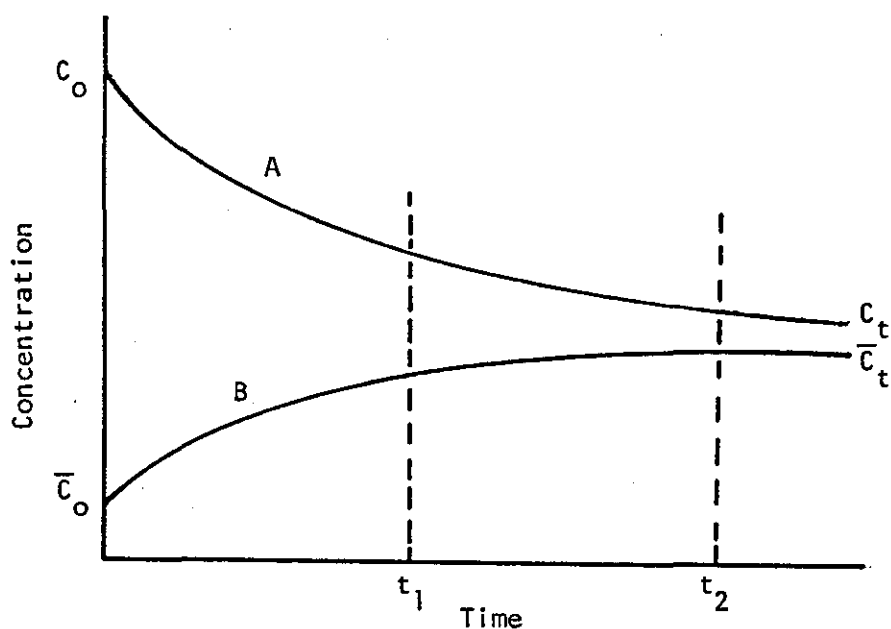
FIGURE 1.6: Change of solute concentration in tissues and blanch medium with time (where C_o and $\overline{C}_o$ are the initial concentration at time = 0, and C_t and $\overline{C}_t$ are the concentration at time = t for tissue and blanch medium respectively).

the time to t_2. The distance between curves A and B at any time represents the magnitude of the concentration gradient.

The diffusion of solutes from tissue to blanch medium may be considered to take place in two stages (Charm, 1978). The solutes in solution within the body of the tissue close to the tissue surface first diffuse to the surface of the tissue, and then the solutes diffuse from the surface to the blanch water. The interior solutes will then have to penetrate this outer layer before reaching the surface, and the process will become progressively more difficult and the diffusion rate will slow down.

An illustration of how the solute molecules diffuse from the tissue into the blanch water, may be made by considering a cylindrical cross-section of the tissue, see Figure 1.7.

Solute concentration

C₁ → C_1

C_t → C_t

C_{wt}

C_{w1}

1 2 3 4 5

r

Centre   Radius   Surface
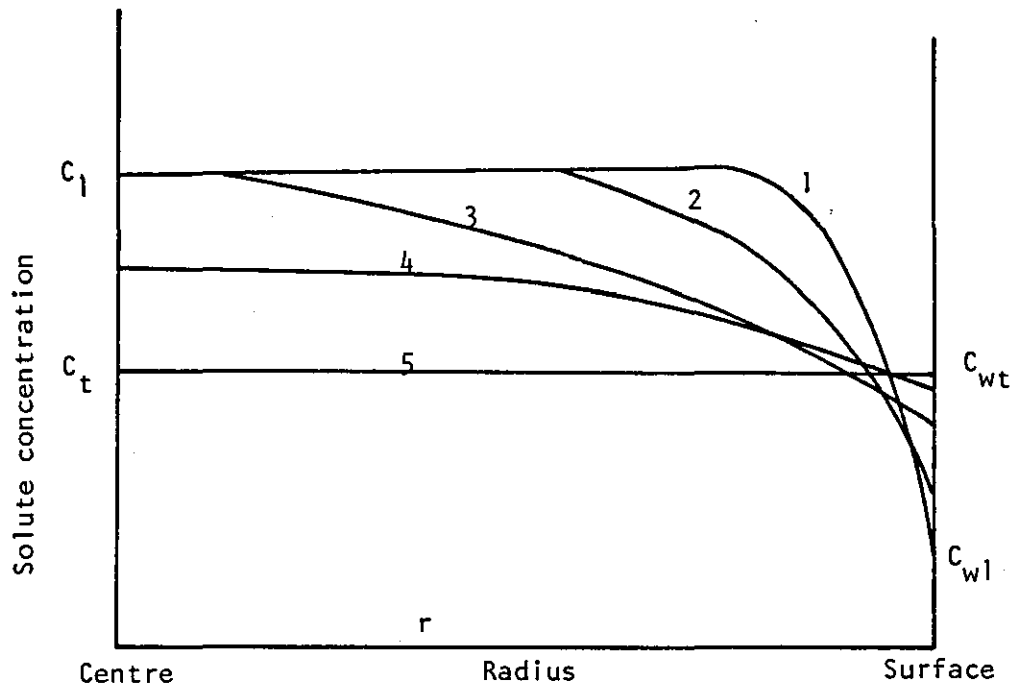
FIGURE 1.7: Solute concentration within cross-section of tissue at successive times during immersion in medium of C_w concentration (where C_1 is the initial concentration in the tissue, at t = 0, C_t, is the concentration in the tissue, at t = t, C_{w1} is the initial concentration at the surface at t = 0 and C_{wt} is the concentration at time t = t at the surface.

The radius of the cross-section is denoted by r, the concentration of solutes in the cross-section of the tissue (C) is uniform and the solute concentration in the blanch water is C_w.

When tissue is immersed in the blanch water and C is greater than C_w, then diffusion will start at the surface, and a concentration gradient will develop within the tissue along the radius r. As time is required for solute to diffuse from cell to cell in the tissue, the concentration gradient will have a gradually falling slope receeding from the surface. Therefore the concentration of solutes in the tissue will resemble successively curves 1, 2, 3 and 4 as time passes.

When equilibrium is reached, the concentration within the tissue will again be uniform, and a straight line graph will result (curve 5).

The speed with which a solute molecule will diffuse depends on:

1. Size of tissue sample:

    The reduction in the tissue sample size should result in a greater rate of diffusion due to the increase in the surface area to volume ratio and to the reduction in the distance the solute has to move within the tissue sample to get to the surface.

2. Concentration gradient:

    The concentration gradient between that at the surface of the tissue and that in the blanch medium is important, since the driving force is the difference in concentration. The direction of diffusing also depends on that concentration gradient.

3. Temperature:

    An increase in the temperature may increase both the solubility of solutes in water and the rate of diffusion of solutes through the tissue, and so will increase the diffusion coefficient.

4. Agitation rate:

    Agitation of the blanch medium increases eddy diffusion and so increases the diffusion rate (Charm, 1978).

1.2.3 Water Retention Mechanism

There are various views in the literature on the mechanism controlling the retention of water in the cell (Kuprianoff, 1958, Ling and Walton, 1976; Duckworth, 1976).

However the most generally accepted view is the one presented by Weier and Stocking (1949). In this view the chief internal factors that control water retention of the cell are:

1. The concentration of osmotically active materials within the cytoplasm and cell vacuole.

2. The permeability of the protoplasm.
3. The amount of colloidally active materials within the vacuole, cytoplasm, and cell wall.

4. The elasticity of the cell wall.
5. The presence of intercellular spaces in the tissue.

According to this view, any heat treatment which alters the permeability of the protoplasm, the ability of solutes to be retained within the cell, the elasticity of the cell wall or the colloidal nature of the cell contents, will alter the water retaining power of the cell. Therefore cells having large quantities of protoplasm, starch grains or other colloidally active material are likely to retain more of their water on death than cells of smaller or without colloidal content.

Weier and Stocking (1949) also pointed out that tissues having highly elastic cell walls at full turgor will have a larger water content. The death of this type of tissue will result in the contraction of the distended cell wall which forces out the large amount of watery solution. If the tissue cell walls are rigid and less elastic the death of such tissue will result in much less contraction of the cell wall on losing turgor, and therefore less loss of cell solution.

1.3 Effect of Heating on Vegetable Tissues

Heating vegetables tissues brings about a series of chemical, physical and histological changes depending on the severity of the process. Priestley (1979) summarised the general effects brought about by heat:

1. Physical changes in tissue such as:
    a) Denaturation of proteins.
    b) Gelatinisation of starch.
    c) Breakdown of pectic substances.
    d) Changes in cell structure.
    e) Changes in intercellular air.

2. Chemical changes, such as:
    a) Enzymic hydrolysis.
    b) Oxidation and development of flavour components and colour.

3. Histochemical changes, such as change in texture.

4. Materials loss in the form of solutes, water, and volatile substances.

1.3.1 Cell Membrane Disorganisation

During immersion of living cells in water only a very slow diffusion process takes place. The concentration equilibrium results from osmosis. This indicates that living cells do not allow direct diffusion of solutes because the cytoplasmic membrane in its natural state controls the mass transfer in and out of the cell.

For rapid diffusion of the solute molecules from the cell to the blanch water, and for cell solute transfer by means of diffusion, the semi-permeability of the cytoplasmic membrane has to be neutralised. This can be achieved by heat or chemical treatment, (Weier and Stocking, 1949).

The denaturation of the protein of the cytoplasm and the cell membranes by heat resulted in cell membrane disorganisation. In denaturation, the physical action is not reversible (it can be if not adequate).

Denaturation of the protein of the cytoplasm and cell membrane starts at temperatures above $50^{\circ}C$ and is accelerated at higher temperatures. The time required for complete denaturation depends on the temperature and physical condition of vegetable tissue. At temperatures above $70^{\circ}C$ the disorganisation of the cytoplasmic membrane is completed in a short time (less than 300 seconds depending on the tissue. As a result of cytoplasmic membrane disorganisation, the cell membranes lose their selective permeability and the remaining cell walls are fully. permeable to solutes.

In this state, solutes and water can freely pass out of and into the cell by diffusion.

According to Dousse et al. (1977), on using heat as a means of denaturation for apple tissue cell membranes, a correlation between temperature and time will result as shown in Figure 1.8.
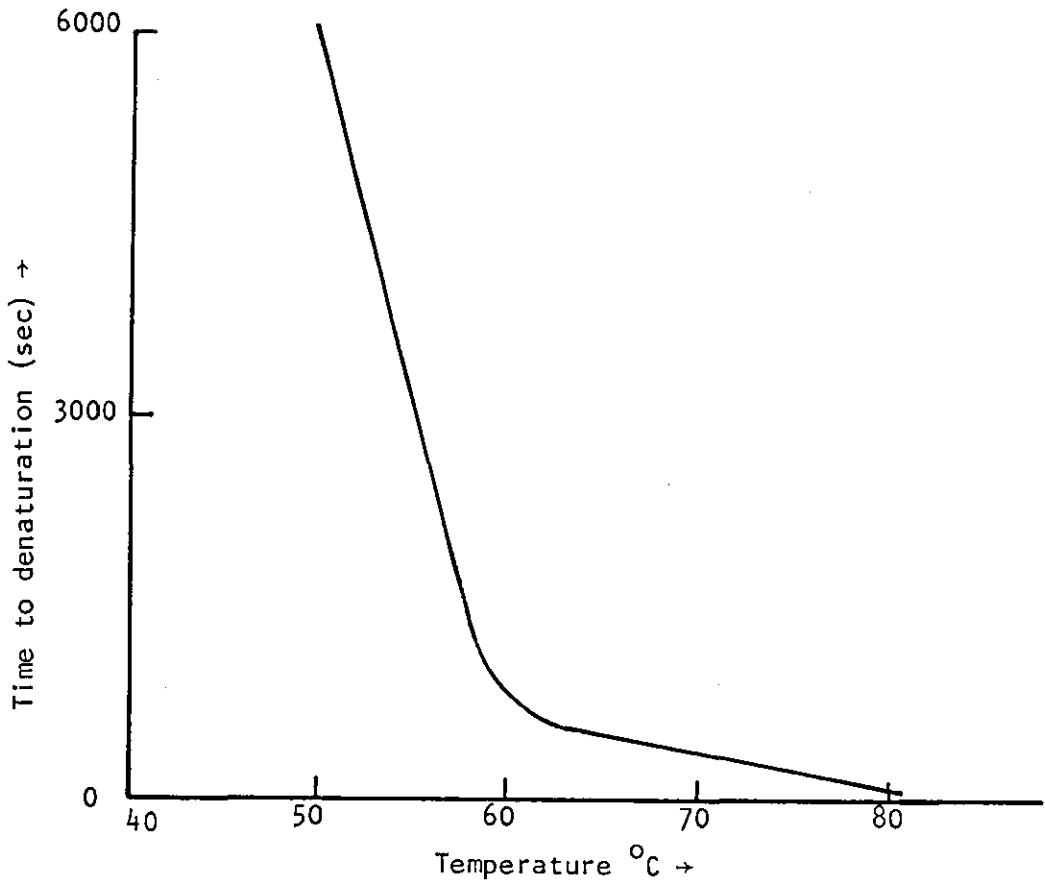
FIGURE 1.8: Time for denaturation of apple tissue cell mem-
            branes as function of temperature (after Dousse
            et al., 1977)

1.3.2 Changes in Starch

Most starches contain both amylose and amylopectin within
the granule. Usually the amylose represents between 20 and 30%
of the total starch (Paul and Palmer, 1972). According to
McCready and Hassid (1947) amylose and amylopectin are present
in a ratio of 1:3 in potato starch.

Amylose is best described as a linear polymer of α,1-4 linked D-glucose units (70-350 glucose units) together with molecules possessing a very limited amount of branching (Priestley, 1979). Amylopectin is a branched chain of glucose polymer (up to 1000 glucose units) in which the α,1-4 linkages are branched by an α,1-6.

The major change that occurs within the cells of the starchy vegetables during heating is the gelatinisation of starch in the typical temperature range of 50-75°C. When starchy vegetable tissue is heated to above 50°C, starch granules slowly and reversibly start to absorb water and swell. This swelling is reversible until at a certain temperature the so-called gelatinisation temperature, material is leached from the starch granule and structural order is irreversibly lost, (Priestley, 1979).

When the gelatinisation temperature is reached starch rapidly absorbs large quantities of water, several times its own weight. Once gelatinisation starts, it proceeds very rapidly.

Temperature ranges inducing gelatinisation are however variable, being influenced by the size of the starch grain, heating time, pH, degree of maturity and variety of vegetable tissue (Weier and Stocking, 1949; Radley, 1968). Potato starch begins to gelatinise in the range of 64 to 72°C, (Roberts and Proctor, 1955), while carrot starch has a gelatinisation temperature around 50°C, (Mann and Weier, 1944).

The swelling of starch, particularly amylose is believed to occur through the binding of water (Kerr, 1950; Mayer, 1978). In starch granules, amylose and amylopectin molecules are loosely bound together by hydrogen bonds of the hydroxyls. As the temperature of water-starch mixture rises, hydrogen bonding decreases for both the starch-starch bonds and water-water bonds and the size of the particles diminishes. Then the water molecules

begin to penetrate between the starch molecules. Therefore the gelatinisation process involves the breaking of H-bonds that hold the micellar structural units together and the permeation of the weakened starch structure by dissociated water molecules which hydrate the hydroxyl groups of the starch molecules. In potatoes of high starch content the cells tend to separate and round off largely because of the swelling of the gelatinised starch, while in potatoes of low starch content, the cells tend to retain their original orientation with respect to each other (Talburt and Smith, 1975).

Another change that occurs in starch granules during heating (processing) is the hydrolysis of starch to dextrins and maltose by the activity of the amylases.

In general there are two kinds of storage starch in vegetables which are characterized by differences in gelatinisation temperatures in relation to the inactivation temperature of the amylase (Mann and Weier, 1944). The storage starch in carrot, parsnip and turnip roots gelatinises at a lower temperature ($40-50^{\circ}C$) than that of enzyme inactivation ($75^{\circ}C$) whereas the storage starch in white potato and peas does not gelatinise until after the enzyme has been inactivated. According to Mann and Weier (1944), a slow rate of heating during blanching of carrot has caused conversion of gelatinised starch to dextrin before the enzymes are inactivated. However no such chemical change in the structure of the starch molecule has been observed during rapid blanching.

It seems that in general, gelatinisation of the starch grains in carrots results in the immediate hydrolysis of starch to dextrins, unless the amylase is inactivated. Bettelheim and Sterling (1955) noticed that total starch content invariably decreased during the cooking process of different varieties of potato, but the amylose content decreased in some varieties and increased in others. The percentage of amylose in potato starch

decreased during cooking in cases where the amylose percentage
of raw potato starch was above 10%, and increased where it was
below this value. It was suggested that the possible explanation
of this behaviour was based on simple diffusion and enzyme
activity. According to Bettelheim and Sterling (1955), the starch
content of cooked potato was dependent not only on the starch
content of the raw potatoes, but also on other factors such
as the solubility of the heated starch and the permeability of
the cell wall and cell membranes during processing.

Permeability is important because loss of soluble starch
occurs by diffusion into the cooking medium.

1.3.3 Changes in Pectic Substances

Pectic substances are widely distributed in plant tissue.
In most vegetables the pectic substances occur in the middle
lamella, which acts as a cementing material holding the cells
together. Also it occurs in the primary wall of many cells.

Any agent or heat process which breaks down these substances
can obviously bring about softening and separation in the tissue
of fruits and vegetables (Meyer, 1978). When the pectic substances
diminish in the middle lamella, the cells can be separated more
readily. When they diminish in the cell walls the walls become
thinner and more readily punctured. Simpson and Halliday (1941)
investigated the change in pectic substances in carrots and
parsnips before and after steaming. They steamed carrots and pars-
nips for 20 minutes and 45 minutes. They found that while there
was a steady increase in the amounts of pectins and pectates as
steaming progresses, there was a decrease in the protopectin as
well as in the total pectic substances. Histological observation
of the tissue wall showed that tissue steamed for 45 minutes had
a much thinner middle lamella than the fresh tissue. They concluded
that these changes may have been brought about by the hydrolysis of
protopectin to pectin.

Lee et al. (1979) found that the firmness of carrots increased as the blanch temperature was raised from 54 to 75°C, and decreased as the blanch temperature was raised from 75° to 100°C. This firming effect was attributed to the effects of pectin methyl esterase (PME) which is activated by the low temperature blanch and inactivated by the high temperature blanch.

Bartolome and Hoff (1972) showed the same observation during heating potato. They proposed that heating at temperatures above 50°C led to loss of integrity of the cellular membrane allowing intercellular electrolytes to contact the cell wall materials thereby activating pectin methyl esterase (PME). This enzyme increases the number of free carboxyl groups in the cell wall pectin which are available to form bridges with calcium and magnesium. This leads to an increased resistance of the tissue to further thermal degradation. Above 70°C the enzyme is rapidly destroyed and exerts no effect on the cell wall material.

Therefore it appears that the softness occurring during heating fruits and vegetables is partially the result of changes in the pectic substances, i.e. the large molecules of insoluble proto-pectins are in some fashion hydrolysed to smaller soluble pectic substances which are able to form colloidal dispersions in water.

1.3.4 Change in Intercellular Air

Most parenchyma tissue in fresh vegetables and fruits contains large intercellular spaces filled with air or gas of similar composition. In some fruits and vegetables the amount of air is appreciable, in others quite small (Meyer, 1978). Weier and Stocking (1949) reported that 15% of the volume of fresh peaches is intercellular space, compared to 20-25% for apple (Reeve, 1953) and approximately 1% in potato tuber (Burton and Spragg , 1950). Intercellular air in fruit and vegetable tissues determines to a large extent their appearance and also may to some extent act as an insulator restricting the inward penetration of

heat and the outward movement of water. The changes in inter-
cellular air during blanching have been investigated by Crafts
(1944a). According to this investigation there are three effects
of blanching that account for the displacement of intercellular
air. First, the heat expands the air rapidly and much of it moves
out along the intercellular spaces towards a cut surface.
Secondly, heating kills the cells and allows the cell sap to
escape from the killed cells to the intercellular spaces causing
a change in the appearance and juiciness of the tissue. Thirdly
heat softens the cell walls so that they bend and give under the
compressional force of surface tension. Upon cooling the blanched
tissue, the gases contract and the air is replaced by cell sap
that leaks from the killed cells. In the case of white potato
tissue, intercellular air is relatively small in volume and so
its displacement has little effect upon the appearance of the
finished product. According to Crafts (1944b) the opaqueness of
raw potato is due to the refraction of light by starch grains,
rather than to gas-filled intercellular space. Different effects
may be obtained by different heating procedures.

Crafts (1944a) pointed out if blanching has not been
thorough, the air bubbles may reform and if the walls are not
sufficiently plastic, the air bubbles will remain in the finished
product making it opaque.

1.3.5   Histological Changes in Tissue
1.3.5.1 Changes in potato tissue

Heating of potato tissue has been extensively studied.
It is well known that heat produces remarkable changes in potato
tissue due to denaturation of proteins, and gelatinisation of
the starch.

The behaviour of potato tissue on heating is complex and
depends on a number of factors including variety and maturity as
well as processing conditions.

Various workers have attempted to explain the way in which heat influences the tissues, and several views have been put forward. At the beginning, it was believed that starch generally affects potato tissue by causing distension of the cell wall due to the swelling starch granules when potato is heated beyond the gelation temperature of the starch.

According to this view a 'swelling pressure' was assumed to cause rupture of the cell wall or rounding off of the cells, thereby causing rupture of the middle lamella and separation of the cells. This hypothesis appears as a solidly established fact in many publications, (Whittenberger, 1951; Reeve, 1954b; Bettelheim and Sterling, 1955; Reeve, 1967; Talburt and Smith, 1975). Microscopic observations of rounded and separated cells in cooked potato tissue as a result of the swelling of the gelatinized starch have been frequently cited as evidence of this mechanism (Reeve, 1954a; Burton, 1966).

An alternative interpretation was suggested by Hoff (1972), who in his study on starch swelling pressure of cooked potato described the way in which heat affects the tissue and the mechanism of cell separation in the following manner. As potato tissue is heated from room temperature to the boiling point, the potato which consists mostly of water, will increase approximately 4% in volume. As a result of this increase in volume considerable shear stresses both radial and tangential will be generated in the potato interior, dependent on the tensile strength of the cell wall, the module of elasticity and on the turgor pressure that existed when heating was initiated.

Under certain circumstances, the limit of elasticity of the middle lamella and the cell wall which varies with temperature will be exceeded and the results will be cell separation and cell rupture. But if the elasticity limit is not exceeded, neither cell separation nor cell rupture will occur.

According to this view a number of factors that influence
the strength of the cell wall and the middle lamella have to be
considered. These factors include the content of calcium and
organic acid, cell size, starch content, starch retrogradation,
diffusion of amylose, age and storage time. A number of these fac-
tors have been recognised in some publications (Reeve, 1954b;
Bettelheim and Sterling, 1955; Barrios et al., 1961; Wager,
1963).

1.3.5.2 Changes in carrot tissue

Priestley (1979) has given extensive reviews on the effect
of heat on carrot tissue. It is well known that the mechanical
properties of carrot tissue that reflect the firmness, depend
largely upon the structure arrangement and the chemical composi-
tion of the cell walls (Sterling, 1968; Paulus and Saguy, 1980).

There are two views regarding the physical effect of heat
on the softening of carrot tissue and the structure of the cell
wall. These include: the loss of rigidity in the individual
cell walls (softening of interlamellar layer) and the easy sepa-
ration of cell walls, (Sterling, 1959; Sterling and Shimazu, 1961).

1.4 Blanching Process
1.4.1 Blanching

Blanching is regarded as an important and necessary prelimi-
nary step in the preparation of vegetables and some fruits prior
to freezing, canning or drying. Blanching is usually accomplished
by heating the plant tissue rapidly to the required temperature,
holding it at this temperature for a definite period of time and
then either rapidly cooling the blanched tissue or passing it
immediately to the next stage of the process without delay.

The form and objective of heat applied during the blanching process varies according to the type of blanching process and the final processing to be carried out. Blanching prior to freezing, drying or irradiation is used primarily to inactivate enzymes, whereas blanching prior to canning is used to remove tissue gases, soften the tissue, inactivate enzymes and to increase the temperature of the tissue. Hot water blanching prior to frying is used both to destroy enzyme activity and to leach out reducing sugars and other chemical constituents responsible for the production of poor colour and flavour.

1.4.2 Blanching Applications

Apart from the above particular applications, the general characteristics and reasons for blanching are:

1. To inactivate enzymes or to destroy enzyme substrates which would contribute to undesirable changes in colour, flavour, odour or nutritive value during processing and storage of the food (Lee, 1958).
   Oxidative and other chemical reactions are also inhibited. The more heat resistant enzymes in vegetables, which serve as an index of blanching adequacy, are catalase and peroxidase.

2. To remove intercellular gases which might cause the excessive build-up of pressure in the can during heat processing, and to reduce the can corrosion by reducing the oxygen content of can headspace gases and to aid the attainment of adequate headspace vacua during canning (Adam et al., 1942).

3. To soften and shrink the food so reducing weight and volume resulting in higher drained weights and facilitating packing in a container (Adam and Stanworth, 1941).

4. To act as a preliminary cleaning stage and reduce the load of microorganisms present on surfaces.
   Microbial destruction is not a primary objective of the

blanching process for canning but can be a key factor in reducing the microbial load in frozen products.

5. To improve the texture especially in dehydrated foods by maintaining the capability for adequate reconstitution in the vegetable tissues which are to be dehydrated.

6. To improve the colour and flavour of the canned vegetables and setting the natural colour of certain products, for example during blanching of carrot, the carotenoids become dissolved in small intracellular oil droplets and in this way they are protected from oxidative breakdown during dehydration (Duckworth, 1966).

Against these desirable characteristics blanching may lead to:

1. Leaching out of the water-soluble nutrients (sugar, protein and minerals) into the blanch medium (Horner, 1936; Lee, 1958).

2. Loss of the heat sensitive vitamins (Vitamins B_1 and C).

3. Loss of the desirable flavour constituents from the food.

The leaching out of reducing-sugars may be used to control product colour in the potato industry (Mitchell and Rutledge, 1973).

Because various types of vegetables differ in size, shape, thermal properties, maturity and the natural level of their enzymes, blanching treatments have to be established on an experimental basis.

With potato, blanching time may vary from 2-12 minutes depending upon the temperature used, size of piece, product load in the blancher, uniformity of heat distribution in the blancher and variety and maturity of the potato being processed (Talburt and Smith, 1975).

1.4.3 Methods of Blanching

The most common methods of blanching in commercial operation
are those which convey product through steam and those which
convey product through water. The former method being favoured
in Continental Europe and the USA and the latter in Britain.

Hot water blanching involves passing the food at a controlled
rate through hot water for the required time and temperature. In
most modern factories, continuous systems are used and are usually
of the following types: immersion blancher, tube or pipe blancher,
rotary blancher, hydrostatic blancher and thermoscrew blancher.

Water blanching also can be conducted on a batch basis by
simply dipping a batch of products in hot water at the desired
temperature and time.

The main disadvantages of hot water blanching are the direct
contact with food which leads to high loss of water soluble
nutrients, the scrupulous sanitation requirements to avoid
microbial build-up, and the large volumes of high quality water
needed. The leaching of water soluble materials also results in
high BOD (Biochemical Oxygen Demand) blancher effluents. Lee (1958)
reported that conventional blanching of vegetables (peas and beans)
in general can cause losses as high as 40% for minerals and cer-
tain vitamins, 35% for sugar and 20% for protein.

The leaching loss can be reduced by allowing soluble solids
from the food to accumulate in the blanching water until the
desired concentration is obtained. This is called 'serial water
blanching'. Alternatively two blanchers in series may be used
for their maximum leaching and for more effective control of the
product colour and texture, for greater flexibility and to
increase the capacity of the plant. More than two blanchers and
many combinations of high and low water temperatures may be used
to obtain the desired colour and texture in the finished product.

. Water blanchers using recycled hot water are more efficient in the use of energy than steam blanchers. In addition the recycling of hot water within a processing system is more energy efficient than a single-pass operation which continually heats cold water and discards it (Swartz and Carroad, 1979). In the recycling system not only water and energy conservation can be achieved, but also a higher-solids product would result with more dilute effluent.

In steam blanching the blanchers are designed on the principal of using a conveyor to transport a thin layer of food through a steam chamber and subjecting it to jets of saturated steam at atmospheric or low pressure from above and below. The steam blanchers are commonly of the following types: thermoscrew blancher, vibratory spiral blancher-cooler and in can steam blanching. Continuous steam type blanchers are mechanically more complex than are the hot water type and occupy more floor space than water blanchers for comparable capacity. Steam blanching causes much less loss of soluble solids by leaching than water blanching but the cleaning effect on the food is reduced so that an 'after washer' is necessary.

There are some other methods of blanching also available, but these methods have been used experimentally or to a limited extent in commercial operation. These methods are: Individual Quick Blanching (IQB), Microwave blanching, Electronic blanching, Hot gas blanching, and Fluidized-bed blanching.

IQB is a new concept in blanching and it is a modified three stage steam blanching processing. It is claimed by Lazar et al. (1971) to reduce both the volume and strength of blancher effluent, improving the nutritional values (controlling blanching losses), and texture of processed vegetable and uniform heat treatment.

Microwave blanching has been investigated but few commercial units are in operation. Microwave in combination with hot water or steam has been suggested by Dietrich et al. (1970), Huxsoll et al. (1970), and Chen et al. (1971). Microwave blanching has some applications with fruits and vegetables and offers several advantages such as microbiological cleanliness, no effluent and low losses of nutrients, but the high capital costs make it much more expensive than conventional blanching.

Blanching of vegetables by a dielectric heating system was suggested by Reynolds (1951), by using a high-frequency field, heat inside the food will be generated by molecular stress. It is claimed that dielectric heating reduces the blanching time to about 20 seconds and gives improved texture, colour and vitamin retention. The disadvantage of a dielectric system is that it imposes restrictions on the thickness and character of the product, since the food to be blanched is part of the power generating electrical circuit. Foodstuff thicknesses of less than 0.025m are considered practical in the dielectric system.

Robe (1973) and Ralls et al. (1973) have successfully applied hot gas blanching to spinach and other vegetables. Hot gases at 150°C are circulated through and around the vegetables which are conveyed through the gas chamber on a stainless steel belt. It is claimed that hot gas blanching reduces the volume of waste water effluent to less than 1% compared to steam or hot water blanching. The other characteristics are better nutrient retention and better product colour, but there may be high weight losses due to evaporation. Since partial dehydration can be accomplished in hot gas blanching, the method is particularly well suited to products that are subsequently to be dried. Mitchell et al. (1968) claimed that heating in a fluidized bed offers a possible means for achieving uniform short-time blanching. In this process the vegetable is subjected to an updraft of gas of high velocity to cause the bed to behave as a fluid.

From the above one can conclude that the main problems concerning blanching are: firstly in ensuring uniform heat treatment and second in controlling blanching losses and the effluent disposal dfficulties caused by these. Also one can conclude that a good blanching process should have a high heat efficiency, maintain product quality, occupy little space and have little or no liquid effluent. Based on these considerations, commercial steam blanchers are criticized for allowing steam to be wasted at the inlet and outlet and for increasing effluent by condensation on uninsulated walls. In addition, steam blanchers occupy more floor space than water blanchers for comparable capacity.

Although water blanching has been shown to be more effective for heat transfer into the product and to be less expensive in both capital equipment and operating costs, it is criticized for a greater tendency to leach solids from the product than steam blanching. Water blanchers with recycled hot water are more efficient in the use of energy than steam blanchers.

Individual quick blanching has shown promise for decreasing blancher effluent and giving uniform heat treatment as well as maintaining high yield and product quality.

Microwave blanching although it has no effluent, the large capital cost and low energy efficiency make it much more expensive than conventional blanching.

Superheated steam and high frequency electrical heating have not been considered satisfactory from an operational or economic standpoint. Hot gas blanching reduces the effluent to a negligible quantity, but requires more energy than steam blanching and may cost 2-10 times as much.

Based on the work of Bomben (1977), the energy efficiency of a conventional steam blancher is 5%, a hydrostatic steam blancher 27%, vibratory spiral blancher 85% and a water blancher 60%.

When the operational costs of the above blanchers are compared to those of a conventional water blancher the low capital cost of the water blancher makes it the most economical choice.

2.   MASS AND HEAT DIFFUSION THEORY

2. MASS AND HEAT DIFFUSION THEORY

2.1 The Diffusion Model and Prediction of Apparent Diffusion Coefficient

The mass transfer process is characterized by the general type of equation:

$$\text{Rate of mass transfer} = \frac{\text{driving force}}{\text{resistance}}$$

This equation shows that in order to transfer a property such as mass, a driving force is needed to overcome the resistance. In the blanching of vegetables, the two contributions to the total resistance to mass transfer are the surface resistance due to convection and the internal resistance due to mass diffusion. These two can be represented by Fick's first and second laws together with a mass balance at the interface (surface):

$$\frac{dc}{dt} = D_a \frac{d^2 c}{dx^2} \qquad (2.1)$$

and

$$-D_a \frac{dc}{dx} = K (C - C_o) = \frac{1}{A} \cdot \frac{dN}{dt} \qquad (2.2)$$

at x = a (surface)

where: D_a = diffusion coefficient ($m^2 s^{-1}$)

A = total surface area for mass transfer (m^2)

C = solute concentration at any point in the sample (%)

C_e = concentration of the (blanch) medium %

K = surface mass transfer coefficient, $kg\ m^{-2}\ s^{-1}$

N = mass diffusing, (kg)

t = blanch time (s)

x = any position in the sample where the concentration is C (m).

Equation (2.1) expresses the rate of accumulation of mass at a given point in the medium. The second equation gives the rate of diffusing per unit area of a medium in terms of the diffusion coefficient and the concentration gradient across the medium. Equation (2.1) is a general expression for mass diffusion in one dimension.

To obtain equations for mass diffusion in the form of cylindrical or spherical coordinates, equation (2.1) can be expressed as:

$$\frac{dc}{dt} = D_a \left(\frac{d^2c}{dr^2} + \frac{1}{r} \cdot \frac{dc}{dr}\right) \tag{2.3}$$

for infinite cylinder, and

$$\frac{dc}{dt} = D_a \left(\frac{d^2c}{dr^2} + \frac{2}{r} \cdot \frac{dc}{dr}\right) \tag{2.4}$$

for a sphere,

where: r is the distance from the centre.

The solution to these equations is given by Newman (1931a) for the three geometric shapes of slab of infinite extent, cylinder of infinite length and a sphere. The average concentration is obtained after integration with respect to position as a function of time for given values of surface mass transfer coefficient, all in non-dimensionalised form.

It was assumed that:

1. There was no chemical reaction in the system.
2. The initial concentration was uniform throughout the sample of the vegetable.
3. The concentration of the (blanching) medium was constant and uniform.

If there is sufficient agitation of the blanching liquid, then the surface resistance becomes small because at maximum agitation the mass transfer coefficient (K) becomes large and the relative resistance (m) approaches zero according to:

$$m = \frac{D_a}{ka}$$

Thus it can be assumed that the total resistance to mass diffusion is due to only the 'internal' resistance. We then require only the solution to Fick's second law. This is given by Newman (1931b) for the geometrical shapes, slab of infinite extent, cylinder of infinite length, and sphere, with the average concentration obtained after integration with respect to position as a function of time, again in non-dimensionalised form as follows:

Slab:

$$E = \frac{\bar{C} - C_o}{C_1 - C_o} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left[-(2n+1)^2 \left[\frac{D_a t}{a^2} \right] \right.$$

$$\left. \left[\frac{\pi}{2} \right]^2 \right] = E_x \qquad (2.5)$$

Sphere:

$$E = \frac{\bar{C} - C_o}{C_1 - C_o} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left[-n^2 \left[\frac{D_a t}{a^2} \right] \pi^2 \right] = E_s \qquad (2.6)$$

Cylinder:

$$E = \frac{\bar{C} - C_o}{C_1 - C_o} = 4 \sum_{n=1}^{\infty} \frac{1}{R_n^2} \exp \left[- \left[\frac{D_a t}{a^2} \right] R_n^2 \right] = E_r \qquad (2.7)$$

where R_n is the root of $J_o(x) = 1 + \sum_{n=1}^{\infty} (-1)^n \frac{x^{2n}}{(2n)^2!} = 0$

where the first ten values are:

n	1	2	3	4	5	6	7	8	9	10
R_n	2.4048	5.5201	8.654	11.792	14.931	18.071	21.212	24.352	27.493	30.635

and here:

a = characteristic linear dimension; half the diameter for a
cylinder and sphere, half the thickness for a slab (m).

$\overline{C}$ = average solute concentration in the (blanched) sample at
time t, (%)

C_1 = uniform initial (cell sap) solute concentration in the fresh
(unblanched) sample, (%)

J_0 = the Bessel function of order zero

n = number of roots.

and $\dfrac{D_a t}{a^2} = \tilde{t}$, a non-dimensional time.

Newman (1931b) by using the principle of superposition
showed mathematically how the solution for a slab of infinite
extent can be used to obtain the solution for diffusion in two
directions x and y (rectangular bar) three directions, x, y and
z (cubes) and a cylinder of finite length.

If the values of E_x, E_y or E_z are each used for diffusion
between a pair of parallel faces, then the solution for diffusion
from the x and y faces in a rectangular bar is

$$E = f\left(\frac{D_a t}{x^2}\right) \, f\left(\frac{D_a t}{y^2}\right) = E_x E_y \qquad (2.8)$$

For diffusion from all three faces, x, y and z in cubes:

$$E = f\left(\frac{D_a t}{x^2}\right) \, f\left(\frac{D_a t}{y^2}\right) \, f\left(\frac{D_a t}{z^2}\right) = E_x E_y E_z \qquad (2.9)$$

and for diffusion from a short cylinder of length x and radius r

$$E = f\left(\frac{D_a t}{x^2}\right) f\left(\frac{D_a t}{r^2}\right) = E_x E_r \qquad (2.10)$$

It may be seen that E is dimensionless and expresses in a sense the fraction of leachable solute in a blanched material. The magnitude of E ranges from unity to zero; thus $E = 1.0$ for any unblanched material. The value of E reduces to a fraction during the course of blanching. The right hand side of the equations 2.5, 2.6, 2.7 is a rapidly converging series. If D_a and a are constant, E will nearly be a linear function of the blanching time on a semilogarithmic coordinate.

Newman (1931b) developed these solutions for drying applications over a wide range of concentrations and presented the results as a set of tables. In the case of blanching vegetables the concentrations are much smaller and near to zero. The solutions were therefore recalculated at much smaller increments in the range of concentrations applicable to the blanching of vegetables, using the first ten terms for the three series. These are shown in Tables 2.1, 2.2 and 2.3, for various values of $\left(\frac{D_a t}{a^2}\right)$ for a slab of infinite extent, sphere and cylinder of infinite length, (see Appendix I for the computer program used in the calculation).

From these data, graphs as illustrated in Figures 2.1, 2.2 and 2.3 were prepared showing

$$\frac{\bar{C} - C_o}{C_1 - C_o}$$

as a function of $\tilde{t}$ for values of $\frac{D_a t}{a^2}$ in the ranges, 0 - 0.01, 0 - 0.04 and 0 to 0.20.

To calculate the apparent diffusion coefficient (D_a),

$$E = \frac{\bar{C} - C_o}{C_1 - C_o}$$

$\tilde{t}$ $[= \dfrac{D_a t}{a^2}]$	Slab E_x, E_y or E_z	Cylinder E_r	Sphere E_s
0.0002	0.9774	0.9528	0.9306
0.0004	0.9734	0.9456	0.9198
0.0006	0.9698	0.9388	0.9098
0.0008	0.9663	0.9324	0.9004
0.0010	0.9631	0.9264	0.8915
0.0012	0.9601	0.9207	0.8831
0.0014	0.9572	0.9152	0.8752
0.0016	0.9544	0.9100	0.8677
0.0018	0.9518	0.9051	0.8605
0.0020	0.9493	0.9004	0.8537
0.0022	0.9469	0.8953	0.8471
0.0024	0.9446	0.8914	0.8408
0.0026	0.9424	0.8872	0.8348
0.0028	0.9402	0.8832	0.8290
0.0030	0.9381	0.8792	0.8234
0.0032	0.9361	0.8754	0.8179
0.0034	0.9342	0.8717	0.8127
0.0036	0.9323	0.8682	0.8076
0.0038	0.9304	0.8647	0.8026
0.0040	0.9286	0.8613	0.7978
0.0042	0.9269	0.8580	0.7932
0.0044	0.9251	0.8547	0.7886
0.0046	0.9235	0.8516	0.7842
0.0048	0.9218	0.8485	0.7798
0.0050	0.9202	0.8455	0.7756
0.0052	0.9186	0.8425	0.7715
0.0054	0.9171	0.8396	0.7674
0.0056	0.9156	0.8368	0.7635
0.0058	0.9141	0.8340	0.7596
0.0060	0.9126	0.8313	0.7558
0.0062	0.9112	0.8286	0.7521
0.0064	0.9097	0.8260	0.7484
0.0066	0.9083	0.8234	0.7448
0.0068	0.9070	0.8208	0.7413
0.0070	0.9056	0.8183	0.7378
0.0072	0.9043	0.8158	0.7344
0.0074	0.9029	0.8134	0.7310
0.0076	0.9016	0.8110	0.7277
0.0078	0.9003	0.8086	0.7244
0.0080	0.8991	0.8063	0.7212
0.0082	0.8978	0.8040	0.7181
0.0084	0.8966	0.8017	0.7149
0.0086	0.8954	0.7995	0.7119
0.0088	0.8941	0.7973	0.7088
0.0090	0.8930	0.7951	0.7059
0.0092	0.8916	0.7929	0.7029
0.0094	0.8906	0.7907	0.7000
0.0096	0.8894	0.7887	0.6971
0.0098	0.8883	0.7866	0.6943
0.0100	0.8872	0.7845	0.6915

TABLE 2.1: Values of $\tilde{t}$ $[= \dfrac{D_a t}{a^2}]$ for various values of E $[= \dfrac{\overline{C} - C_o}{C_1 - C_o}]$ in the range of 0 to 0.010 for the geometrical shapes: slab of infinite extent, sphere, and cylinder of infinite length

$\tilde{t}\ [= \dfrac{D_a t}{a^2}]$	Slab	Cylinder	Sphere
	$E_x,\ E_y$ or E_z	E_r	E_s
0.002	0.9493	0.9003	0.8536
0.004	0.9286	0.8612	0.7978
0.006	0.9125	0.8312	0.7557
0.008	0.8990	0.8063	0.7212
0.010	0.8871	0.7845	0.6914
0.012	0.8763	0.7650	0.6651
0.014	0.8664	0.7473	0.6414
0.016	0.8572	0.7369	0.6198
0.018	0.8486	0.7157	0.5998
0.020	0.8404	0.7014	0.5812
0.022	0.8326	0.6879	0.5639
0.024	0.8251	0.6751	0.5475
0.026	0.8180	0.6630	0.5321
0.028	0.8111	0.6513	0.5175
0.030	0.8045	0.6402	0.5036
0.032	0.7981	0.6295	0.4904
0.034	0.7919	0.6192	0.4778
0.036	0.7859	0.6093	0.4657
0.038	0.7800	0.5997	0.4541
0.040	0.7743	0.5904	0.4429
0.042	0.7687	0.5814	0.4322
0.044	0.7633	0.5726	0.4219
0.046	0.7579	0.5641	0.4119
0.048	0.7527	0.5559	0.4023
0.050	0.7476	0.5478	0.3930

TABLE 2.2: Values of $\tilde{t}\ [= \dfrac{D_a t}{a^2}]$ for various values of $E\ [= \dfrac{\bar{C} - C_o}{C_1 - C_o}]$

in the range of 0 to 0.050 for the geometrical shapes: slab of infinite extent, sphere, and cylinder of infinite length

$\tilde{t} \ [= \dfrac{D_a t}{a^2}]$	Slab E_x, E_y or E_z	Sphere E_s	Cylinder E_r
.0002	.9773	.9305	.9527
.0004	.9784	.9198	.9455
.0006	.9697	.9097	.9887
.0008	.9663	.9003	.9328
.0020	.9493	.8536	.9003
.0040	.9286	.7978	.8612
.0060	.9125	.7557	.8312
.0080	.8990	.7212	.8063
.0100	.8871	.6914	.7845
.0200	.8404	.5812	.7014
.0300	.8045	.5036	.6402
.0400	.7743	.4429	.5904
.0500	.7476	.3930	.5478
.0600	.7236	.3508	.5105
.0700	.7014	.3143	.4772
.0800	.6808	.2825	.4470
.0900	.6614	.2544	.4195
.1000	.6431	.2295	.3941
.1100	.6257	.2072	.3707
.1200	.6091	.1873	.3489
.1300	.5931	.1694	.3286
.1400	.5778	.1532	.3096
.1500	.5630	.1387	.2918
.1600	.5487	.1256	.2751
.1700	.5349	.1137	.2595
.1800	.5215	.1030	.2447
.1900	.5085	.0932	.2309
.2000	.4959	.0845	.2178
.2100	.4836	.0765	.2055
.2200	.4718	.0693	.1939
.2300	.4600	.0628	.1830
.2400	.4487	.0569	.1727
.2500	.4377	.0515	.1629
.2600	.4270	.0467	.1538
.2700	.4165	.0423	.1451
.2800	.4063	.0388	.1370
.2900	.3964	.0347	.1293
.3000	.3867	.0314	.1220
.3100	.3773	.0285	.1151
.3200	.3681	.0258	.1087
.3300	.3591	.0234	.1025
.3400	.3503	.0212	.0968
.3500	.3418	.0192	.0913
.3600	.3334	.0174	.0862
.3700	.3253	.0157	.0814
.3800	.3174	.0142	.0768
.3900	.3096	.0129	.0725
.4000	.3021	.0117	.0684
.4100	.2947	.0106	.0645
.4200	.2875	.0096	.0609
.4300	.2805	.0087	.0575
.4400	.2737	.0079	.0543

.4500	.2670	.0071	.0512
.4600	.2605	.0064	.0483
.4700	.2541	.0058	.0456
.4800	.2479	.0053	.0430
.4900	.2419	.0048	.0406
.5000	.2360	.0043	.0383
.5100	.2302	.0039	.0362
.5200	.2246	.0035	.0341
.5300	.2192	.0032	.0322
.5400	.2138	.0029	.0304
.5500	.2086	.0026	.0287
.5600	.2035	.0024	.0271
.5700	.1986	.0021	.0256
.5800	.1937	.0019	.0241
.5900	.1890	.0017	.0228
.6000	.1844	.0016	.0215

TABLE 2.3: Values of $\tilde{t}$ $[= \dfrac{D_a t}{a^2}]$ for various values of

E $[= \dfrac{\overline{C} - C_o}{C_1 - C_o}]$ in the range 0 to 0.600 for the

geometrical shapes: slab of infinite extent, sphere, and cylinder of infinite length

was first evaluated from the experimental data, then the corres-
ponding value of $\tilde{t}$ was obtained from the graph of

$$\tilde{t} \left(= \frac{D_a t}{a^2} \right) \quad \text{versus} \quad E \left(= \frac{\overline{C} - C_o}{C_1 - C_o} \right)$$

for the appropriate shape.

By equating the value of $\tilde{t}$ to $\dfrac{D_a t}{a^2}$, the value of diffusion coeffi-
cient (D_a) was determined.

During blanching in a finite volume of water, the concentration
in the blanch medium C_o varies from C_{01} at the beginning of blanching
to C_{0t} at the end of blanching. Therefore C_o was approximated by
the arithmetic average:

$$C_o = \frac{C_{01} + C_{0t}}{2}$$

With blanching of potato tissue the concentration of solids and
sugars were considered to be as follows:

$$C_1 = \frac{M_o}{W}$$

$$\overline{C} = \frac{M_t}{W}$$

and

$$C_o = \frac{M_w}{W_w}$$

where: M_o = weight of solids or sugar at time $t = 0$ in unblanched
potato

W = weight of free water in potato

M_t = weight of solids or sugar at time $t = t$ in blanched
potato

M_w = weight of solids or sugar at time $t = t$ in blanch water

W_w = weight of blanch water.

FIGURE 2.1: Plot of E for slab, infinite cylinder and sphere versus $\tilde{t}$ in the range 0 to 0.010 for evaluation of the diffusion coefficient (D_a)

43

1.0

0.9

0.8

Slab

$E = \dfrac{\bar{c} - c_o}{c_1 - c_o}$

0.7

Cylinder

0.6

0.5

Sphere

0   0.01   0.02   0.03   0.
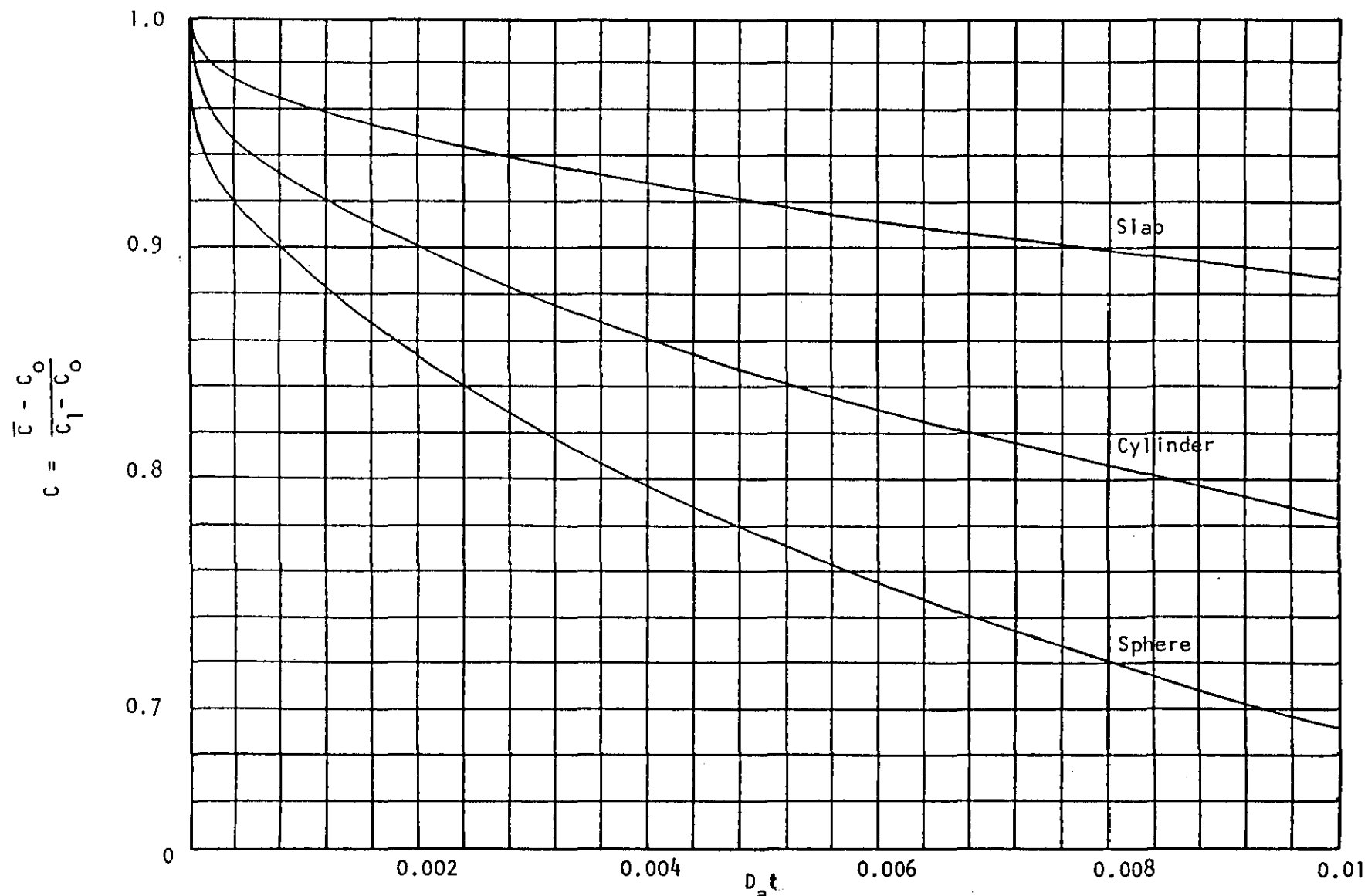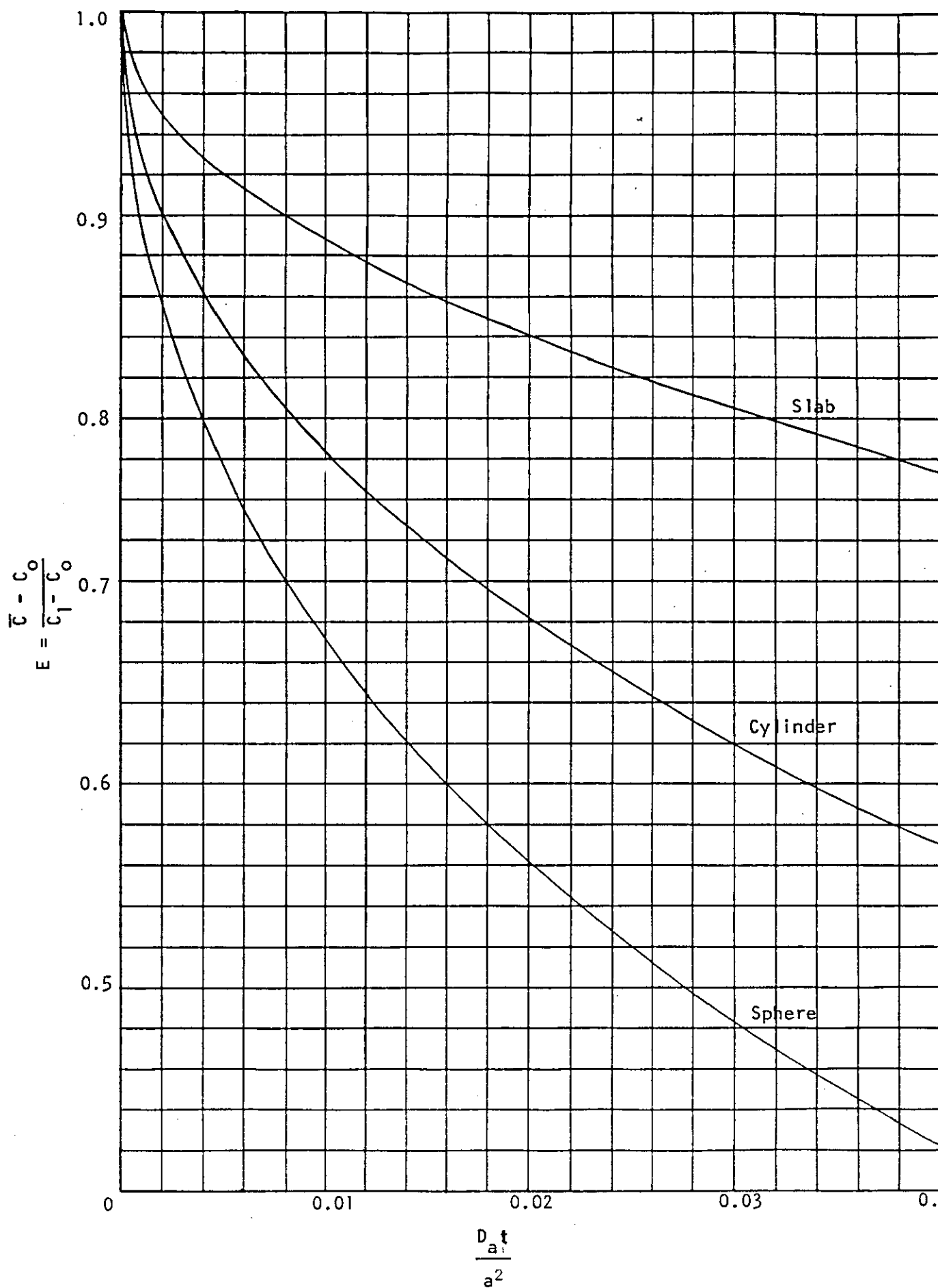
$$\dfrac{D_a t}{a^2}$$

FIGURE 2.2: Plot of E for slab, infinite cylinder and sphere versus $\tilde{t}$
in the range 0 to 0.040 for evaluation of the diffusion
coefficient (D_a)
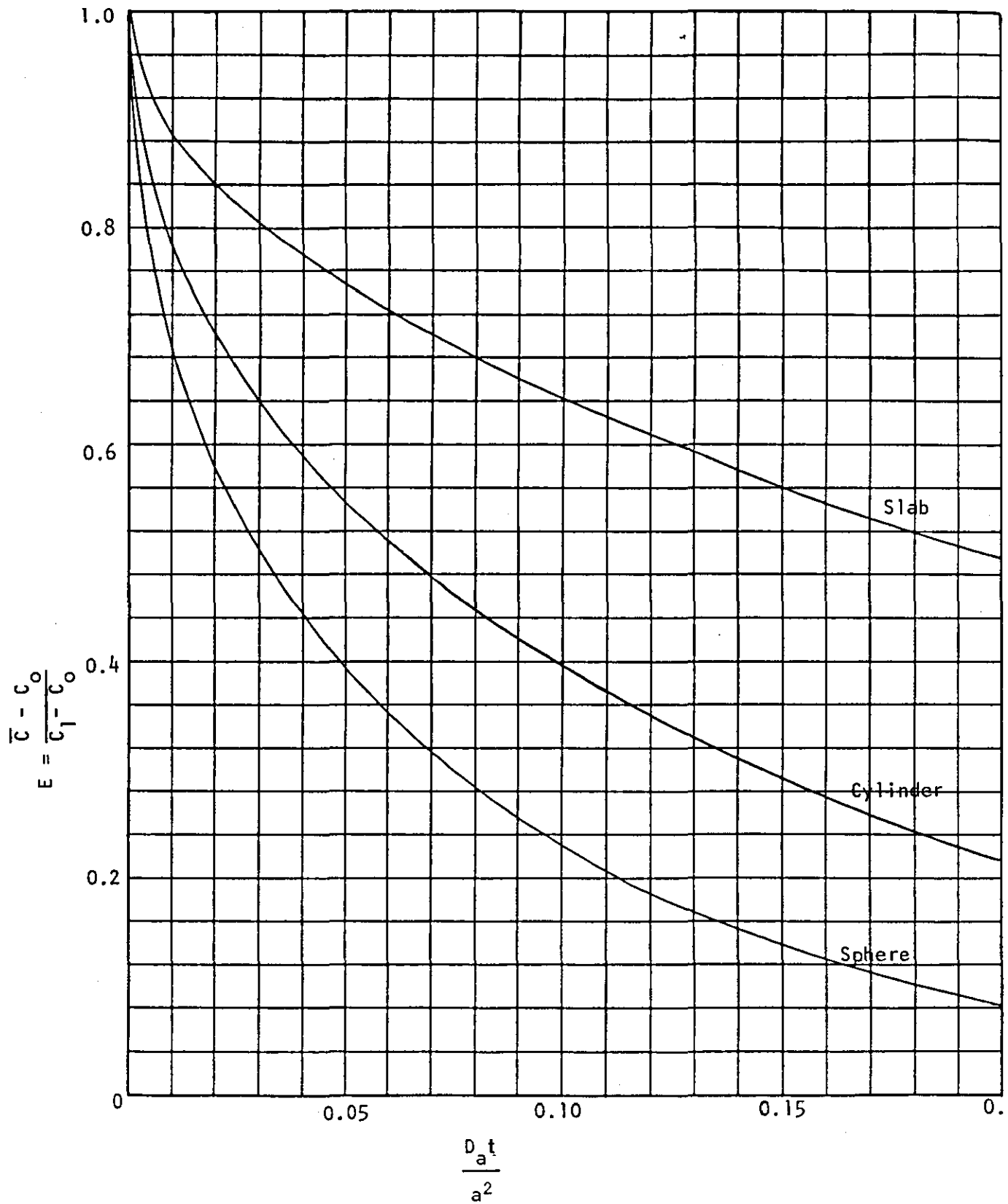
FIGURE 2.3: Plot of E for slab, infinite cylinder and sphere versus $\tilde{t}$ in the range 0 to 0.20 for evaluation of the diffusion coefficient (D_a)

2.2 Arrhenius Theory and the Activation Energy Prediction

The most common and generally valid assumption is that temperature-dependence of the diffusion coefficient (D_a) will follow the Arrhenius equation (Geankoplis, 1972). This behaviour can be expressed as:

$$D_a = D_o \exp \left(- E_a/RT\right) \qquad (2.11)$$

where: D_o = constant, $(m^2 \ s^{-1})$

E_a = activation energy, kJ mol$^-$

R = universal gas constant $(8.314 \ J \ k^{-1} \ mol^{-1})$

T = absolute temperature, (^oK)

This equation (the Arrhenius equation) indicates that a plot of $\ln D_a$ versus the reciprocal of absolute temperature $(\frac{1}{T})$ gives a linear relationship (straight line) as shown in Figure 2.4.
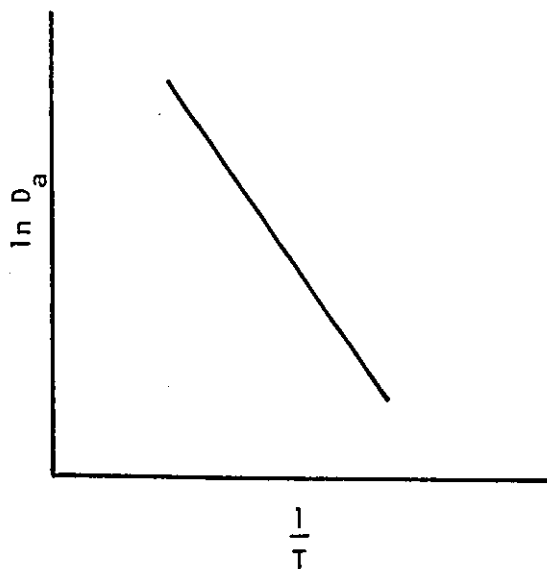
FIGURE 2.4: Relation between $\ln D_a$ and $\frac{1}{T}$

The activation energy, (E_a), is generally derived from the slope of the plot of $\ln D_a$ vs $\frac{1}{T}$, (which is the activation energy divided by the gas constant R), according to the following equation:

$$E_a = - SR \qquad (2.12)$$

where S is the slope of the straight line and E_a and R have the same meaning as before.

E_a may be determined in the following manner; taking logarithms of both sides of equation 2.11:

$$\ln D_a = \ln D_o - \frac{E_a}{RT} \qquad (2.13)$$

The constant D_o can be estimated by letting D_a be D_{a1} at temperature, T_1 then

$$\ln D_o = \ln D_{a1} + \frac{E_a}{RT_1} \qquad (2.14)$$

Substituting equation 2.14 into equation 2.13 gives:

$$\ln \frac{D_a}{D_{a1}} = \frac{-E_a}{R} \left(\frac{1}{T} - \frac{1}{T_1}\right) \qquad (2.15)$$

$$= \frac{-E_a}{R} \left[\frac{(T_1 - T)}{T_1 T}\right] \qquad (2.16)$$

Thus if experimental values of D_a at two or three temperatures are available, then one could extrapolate the straight line and predict the diffusion coefficients at other temperatures.

Labuza and Riboh (1982) indicated that practical or theoretical errors may arise from this type of extrapolation due to the heterogeneity of the food sample causing a sampling error, and the sample itself may contain substances interfering with the analysis.

2.3 Prediction of Apparent Thermal Diffusivity

Unsteady state or transient heat conduction is the most widely encountered situation during heating and cooling of food materials. For the unsteady state condition, the temperature distribution in a body is given by Fourier's general law of heat conduction in the form of a partial differential equation as follows:

$$\frac{d}{dx}\left(K_o \frac{dT}{dx}\right) + \frac{d}{dy}\left(K_o \frac{dT}{dy}\right) + \frac{d}{dz}\left(K_o \frac{dT}{dz}\right) + q$$

$$= \rho \cdot Cp \cdot \frac{dT}{dt} \tag{2.17}$$

where: K_o = thermal conductivity of the material W/m°K

T = temperature, °K

q = internal heat generation, W/m^3

Cp = specific heat, kJ/kg°K

ρ = density of the material, kg/m^3

t = time, sec

x,y,z = coordinate directions

By considering a food material with the following characteristics:

1. Thermal conductivity, K_o is uniform and constant.
2. No internal heat generation.

Equation 2.17 reduces to:

$$\frac{dT}{dt} = \alpha \left[\frac{d^2T}{dx^2} + \frac{d^2T}{dy^2} + \frac{d^2T}{dx^2}\right] \tag{2.18}$$

where:

$$\alpha = \frac{K_o}{\rho \, Cp} \quad \text{is the thermal diffusivity } (m^2.sec^{-1}).$$

The equivalent Fourier's equation for cylindrical coordinates i.e. for an infinite cylinder with only a radial temperature gradient is:

$$\frac{dT}{dt} = \alpha \left[\frac{1}{r} \cdot \frac{d}{dr}\left(r \frac{dT}{dr}\right)\right] \tag{2.19}$$

where r is the distance from the centre.

For spherical coordinates, Fourier's equation of conduction is:

$$\frac{dT}{dt} = \frac{\alpha}{r^2} \left[2r \frac{dT}{dr} + r^2 \frac{d^2T}{dr^2}\right] \tag{2.20}$$

Where conditions are such that the temperature difference between the heating or cooling medium and the food surface is negligible, and where the surface temperature is maintained at the temperature of the heating or cooling medium, then it can be assumed that the surface thermal resistance is negligible, $\frac{1}{hA_1} = 0$ since this condition implies a large heat transfer coefficient, h, at the surface of the food. This condition arises in a well agitated medium.

The calculation is more complex for the case of a small heat transfer coefficient where there is a finite temperature

difference and the surface thermal resistance is large. If the initial and boundary conditions of the food material are that it has a uniform initial temperature and the surface temperature remains constant at the heating or cooling medium temperature, then the solution to the above heat conduction differential equation for the central temperature history of the three elementary shapes, the infinite slab, the infinite cylinder and the sphere will be as given by Schneider (1974) in dimensionless form:

Slab:

$$\frac{T_t - T_s}{T_o - T_s} = \frac{4}{\pi} \ [e^{-(\frac{1}{4})\pi^2 t} - \frac{1}{3} e^{-(\frac{9}{4})\pi^2 t} + \frac{1}{5} e^{-(\frac{25}{4})\pi^2 t} - \ldots]$$

(2.21)

Cylinder:

$$\frac{T_t - T_s}{T_o - T_s} = 2 \ [\frac{e^{-R_1^2 t}}{R_1 J_1(R_1)} + \frac{e^{-R_2^2 t}}{R_2 J_1(R_2)} + \ldots]$$

(2.22)

Sphere:

$$\frac{T_t - T_s}{T_o - T_s} = 2 \sum_{n=1}^{\infty} (-1)^{n+1} \exp \ [-n^2\pi^2(\frac{\alpha t}{r^2})]$$

(2.23)

where: T_t = the centre temperature at time (t)

T_o = the uniform initial temperature of the vegetable

T_s = the temperature of the heating or cooling medium.

$J_1(R_1)$ is the first order Bessel function of R_1.

$R_1, R_2, R_3, \ldots R_n$ are the roots of the zero-order Bessel function.

A graphical solution for these equations is given by Schneider (1974). In this graphical solution the relationship between $\ln \frac{T_t - T_s}{T_o - T_s}$ and $\frac{\alpha t}{r^2}$ gives straight line graphs from which the

thermal diffusivity α can be calculated.

   To calculate the thermal diffusivity the value of $E = \dfrac{T_t - T_s}{T_o - T_s}$ was first calculated from the experimental results.

Then by using the Schneider chart (Figure 2.5) a value for $\tilde{f} = \dfrac{\alpha t}{r^2}$ was obtained. Finally the thermal diffusivity α was determined by solving::

$$\tilde{f} = \frac{\alpha t}{r^2}$$

where r is the characteristic linear dimension i.e. half the thickness for a slab, half the diameter for a cylinder and sphere (m).
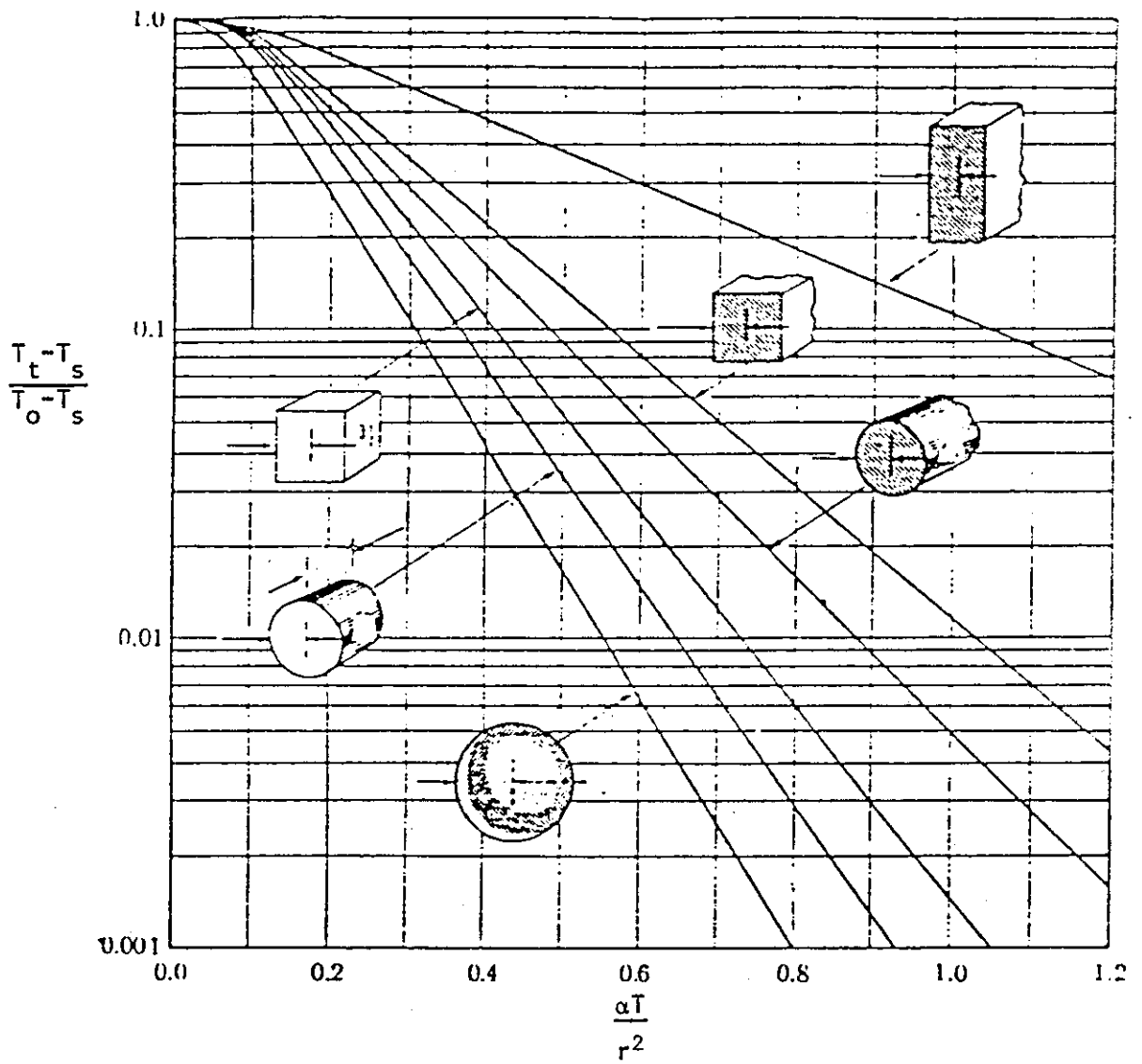
FIGURE 2.5: Central temperature history in an infinite plate, an infinite square bar, an infinite cylinder, a cube, a finite cylinder and a sphere, with all surfaces maintained at T_s (after Schneider, 1974)

3. LITERATURE SURVEY

3. LITERATURE SURVEY

The survey includes relevant work relating to the water
blanching of vegetables, the diffusivity of nutrients, and heat
transfer in vegetables.

The survey was divided into three sections: firstly diffusi-
vity and activation energy in food systems, secondly heat diffusion
in vegetable tissue and thirdly mass transfer during water blanching
of vegetables.

3.1 Diffusivity and Activation Energy in Food Systems

3.1.1 Diffusion Coefficients of Nutrients and Water in Food Systems

Knowledge of mass transfer and diffusivity of nutrients
through vegetable tissues during processing is becoming an impor-
tant factor in the food industry as the characteristics of the final
product, process simulation and equipment design become increasingly
dependent on the rate of mass diffusion. While there is some informa-
tion in the literature on the application of Fick's law to predict
the diffusivity of components in foodstuffs, very few studies have
examined the diffusivity and mass transfer properties of vegetables
as functions of time, temperature, concentration and other factors.

Steward (1930) studied the diffusion of certain solutes (glucose
and potassium phosphate) through membranes of living tissue of
potato and red beet. The results indicated that the diffusion
coefficient of glucose through various living plant tissues is of
a lower order than that of glucose in water. The diffusion coeffi-
cient of glucose was found to be 0.217×10^{-11} m^2 s^{-1} through turgid
beet root and 0.10×10^{-11} m^2 s^{-1} through unplasmolysed potato tissue.
It was stated that the rate of diffusion of solutes through living

tissues is much slower than the rate in aqueous solution apparently due to the resistance of living protoplasm itself. Also it was indicated that the lower diffusion rate of potassium phosphate $(0.220 \times 10^{-12}$ m^2 $s^{-1})$ was probably due to the electrical effects on the walls of capillary spaces.

Becker and Sallans (1955) estimated apparent diffusion coefficients (D_a) for water at several temperatures during drying of wheat kernel which was considered as spherical in shape, and found that D_a was related to temperature by an Arrhenius type equation:

$$D_a = D_o \exp \left(- \frac{E_a}{RT}\right)$$

In the temperature range 20 to 80°C the diffusion coefficients were found to lie between 0.069×10^{-10} and 2.77×10^{-10} m^2 s^{-1}. The diffusion coefficient was also found to be independent of moisture content in the important range 12-30% water. However, no attempt had been made to study the effects of relative humidity, air velocity, or reduction of atmospheric pressure.

Fish (1958) accurately measured the diffusion of water by adsorption and desorption in potato starch gel and scalded potato, at moisture contents ranging from 0.7 to 44% (wet basis). The diffusion coefficient was found to decrease very markedly with decreasing moisture content especially below 30% moisture. Also it was found that diffusion of water in scalded potato was controlled by the migration of water through the starchy part of the material. He suggested that the slow transport of water in dry starchy material is associated with the loss of rotational freedom of the water molecules. The coefficient for diffusion of water in scalded potato and starch gel are shown in Table 3.1 as functions of moisture content.

TABLE 3.1: Variation of diffusion coefficients of water (D_a) with water content in scalded potato and starch gel (after Fish, 1958)

Starch Gel		Scalded Potato	
Moisture Content %	D_a at 25°C $m^2 s^{-1}$	Moisture Content %	D_a at 25°C $m^2 s^{-1}$
0.8	0.0011×10^{-11}	9	0.10×10^{-11}
6.3	0.015×10^{-11}	10	3.0×10^{-11}
14.1	0.36×10^{-11}	15	7.0×10^{-11}
80.0	2.4×10^{-11}	-	-

Duckworth and Tobasnick (1960) showed by the use of autoradiography that sulphite applied to strips of root vegetables (potato, carrot), in scalding solutions diffuse through the volume of the strip during subsequent dehydration. Movement of sulphite appeared to be rather more rapid in carrot than in potato with a slightly higher concentration for both cases in the centre of the strip than at the periphery. The results appeared to lend some support to the suggestion that the phenomenon of the brown centre during drying might be due to an inward diffusion of the browning reactants themselves, due to formation of a concentration gradient resulting from the more rapid removal of water from the surface layers.

In another study Duckworth and Smith (1961) examined the diffusion of glucose during potato and carrot dehydration using similar methods. Strips of potato and carrot were soaked in a solution containing glucose labelled with C-14 until the distribution of the labelled glucose was uniform through the material. The strips were then dehydrated either with or without a preliminary blanch in boiling water. In blanched potato and carrot strips, glucose accumulated in the centre of the dehydrated product while in unblanched potato strips it accumulated peripherally.

The contrast between the behaviour of glucose in scalded and unscalded potato is probably due to the difference in form of the starch in the two cases. In the unscalded strips the temperature of the material did not rise sufficiently high during drying to cause gelatinisation of the starch. The starch grains therefore remained intact throughout the drying. The results also confirmed that the predominant direction of diffusion of solutes during the dehydration of scalded strips of potato and carrot is towards the centre of the piece.

Duckworth (1962) reported on the relation between moisture content and diffusion of solutes in dried vegetable tissue. In order to examine the extent to which diffusion of solutes can take place at different moisture levels, he applied labelled glucose to carrot and potato pieces and stored them for several months at various relative humidities. Subsequently he found the diffusion rate of labelled glucose in dried carrot and potato decreased with the decreasing of initial moisture content. Unfortunately the presentation of the results did not allow calculation of the diffusion coefficients.

Saravacos and Charm (1962) reported diffusion coefficients of the order of 10^{-9} to 10^{-10} m^2 s^{-1} for water in the air drying of potato slabs and other fruits and vegetables at atmospheric pressure in the range of moisture content 0.1 to 1.0 (g moisture/g dry matter). The diffusivity of water in potato slabs was found to increase with temperature and the values were: 2.58×10^{-10} m^2 s^{-1} at $54^{\circ}C$, 3.94×10^{-10} m^2 s^{-1} at $60^{\circ}C$, 4.37×10^{-10} m^2 s^{-1} at $65^{\circ}C$ and 6.36×10^{-10} m^2 s^{-1} at $69^{\circ}C$. They also found a strong temperature dependence from which they calculated an activation energy of 52.3 kJ/mol for diffusion. The results suggested that moisture transfer during the falling-rate period in potato was by molecular diffusion.

Nakayama and Jackson (1963) measured the diffusion coeffi-
cient of tritiated water (H^3 H^1 O^{16}) at four agar gel concentrations
and found that D_a was related to concentration by a linear regression
equation from which a value D_a = 2.41 ± 0.055 x 10^{-9} m^2 s^{-1} was
determined for the diffusion of tritiated water in ordinary water.
This value agrees with the results of Wang et al.(1953),
2.44 ± 0.057 x 10^{-9} m^2 s^{-1} which were determined by using a
diffusion capillary technique. However in 1% agar solution the
diffusion coefficient of water was reduced to a value of
2.2 x 10^{-9} m^2 s^{-1} from a value of 2.4 x 10^{-9} m^2 s^{-1} in pure water.

Zagrodszki and Kubiak (1963) described a method for measuring
the diffusion coefficient of sugar in beet tissue. The method was
based on measuring the D_a of sugar between known solutions through
a diaphragm made of the beet tissue. The measurements were carried
out for different diaphragm thicknesses (0.2 - 0.6 cm), different
temperatures (60 to 75°C) and different speeds of water flow
(1-12 cm.s^{-1}). The mean D_a values of sugar at 60, 65, 70 and 75°C
were found to be: 6.75 x 10^{-10} m^2 s^{-1}, 7.6 x 10^{-10} m^2 s^{-1},
9.25 x 10^{-10} m^2 s^{-1} and 1.05 x 10^{-9} m^2 s^{-1} respectively.

Silin (1964) reported values for diffusion coefficients of
sucrose, raffinose and non-sugar substances through beet cells at
temperatures of 20°C and 70°C. He found that most of the non-sugar
solutes diffuse more quickly than the sucrose, while proteins
(colloids) diffuse much more slowly, due to the large molecular
weight. The diffusion coefficients of sucrose were 4.28 x 10^{-10} m^2 s^{-1}
and 1.24 x 10^{-9} m^2 s^{-1} at 20 and 70°C respectively. While the
diffusion coefficients of albumen were 1.02 x 10^{-11} m^2 s^{-1} at 20°C
and 2.95 x 10^{-11} m^2 s^{-1} at 70°C.

Wood (1966) studied the diffusion of sodium chloride in pork
muscle, using a system in which the total salt uptake by the muscle
was plotted versus (time)$^{\frac{1}{2}}$ to give a straight line. He found that
the rate of salt diffusion did not depend on the muscle fibre
direction. The diffusion coefficients at -2°C and 25°C were:

0.12 x 10^{-9} and 0.36 x 10^{-9} m^2 s^{-1} respectively. Freezing the muscle at -20°C was found to have no effect on the diffusion coefficient subsequently determined at -2°C.

Wood (1966) in the above paper also calculated the diffusion coefficient of sodium chloride in pork muscle (0.40 x 10^{-9} m^2 s^{-1}) from the results of Wistreich et al. (1960) and found it to be independent of the brine concentration.

Del Valle and Nickerson (1967) used a similar method for fish muscle and found that the diffusion coefficients for sodium chloride were not constant but depended upon the salt concentration and the temperature. The diffusion coefficients at 5 and 25°C were: 0.65 x 10^{-9} and 1.25 x 10^{-9} m^2 s^{-1} respectively.

Urie and Shahbenderian (1968) studied the desalination process of pickled gherkins based on a model for salt diffusion from an equivalent sphere into a solution. They found that the rate of desalination appeared to be controlled by simple diffusion with a 1.35 x 10^{-9} m^2 s^{-1} diffusion coefficient. Also it was found that stirring of the leaching solution had little effect on the rate of leaching, and the skin of the gherkin offered negligible resistance to diffusion.

In a more fundamental work Paulus (1972) used radioactive isotopes to study the ion uptake and transport in potato tissue. In his experiments the osmotic pressure of the tissue was higher than that of the surrounding solution. Under these conditions there was, in addition to diffusive transport of ion, an osmotic flux of water. He calculated the diffusion coefficients for several ions (Cs, Sr, Zr and Ce) using an empirical equation and found the diffusion coefficients for these ions ranged from 5.0 x 10^{-10} m^2 s^{-1} for caesium to 5.0 x 10^{-12} m^2 s^{-1} for cerium.

Geurts et al. (1974) studied the transport of sodium chloride and water during the salting of cheese. They considered the penetration of salt into the cheese and the outward migration of water as an impeded mutual diffusion process. Diffusion coefficients of salt in the moisture in the cheese were found to be: 2.31×10^{-10} m^2 s^{-1}, while that of salt in pure water was 1.16×10^{-9} m^2 s^{-1}. They suggested that the lower value of diffusion coefficient may have been due to local viscosity increases, reduction in cheese volume and obstructions to diffusion due to tortuosity of the pores.

Stahl and Loncin (1979) used the one dimensional solutions of Fick's second law to predict diffusivity (D_a) in potato, and found that the apparent diffusivity of cyclohexanol in potatoes is strongly dependent on the variety. For varieties high in water content (86%) the diffusivity was as much as 6.0×10^{-10} m^2 s^{-1} at 20°C. The corresponding diffusivity of cyclohexanol in water was 8.7×10^{-10} m^2 s^{-1} at the same temperature. The influence of temperature on diffusion coefficient (D_a) showed that D_a obeyed an Arrhenius type equation with a 35.7 kJ/mol activation energy.

In a more recent and practical study Lathrop and Leung (1980) studied the leaching of Vitamin C from peas during blanching. They found that the leaching of Vitamin C was controlled primarily by diffusion. The diffusivity for leaching of Vitamin C out of peas at 85°C was found to be 1.4×10^{-8} m^2 s^{-1} based on Vitamin C retention after two minutes of water blanching. They suggested that the higher value of diffusion coefficient may be due to the higher temperature used.

Fick's law in terms of moisture content for diffusion out of spheres was successfully applied by Suarez et al. (1980) to describe the drying of grain sorghum. It was found that the diffusion coefficient of water was independent of moisture content in the approximate range of 21-6% (dry basis) moisture content. At 60 and

$50^{\circ}C$ the diffusion coefficients were 4.0×10^{-11} m^2 s^{-1} and 2.9×10^{-11} m^2 s^{-1} respectively. An Arrhenius type temperature dependency of moisture diffusivity was found, from which the energy of activation was estimated to be 31.4 kJ/mol. The authors attributed the lower value of activation energy to the way that the material moisturised, since the diffusivities of rewetted materials were different from that of the naturally moist one.

Desai and Schwartzberg (1980) predicted the diffusion coefficients of sodium chloride in 0.046m diameter, 0.00255m thick potato slices and 0.025m diameter, 0.2m long pickled cucumbers during a two-stage counter current leaching process. The predicted D_a values for pickles and potatoes were calculated by respectively treating the pickles as infinite cylinders and the potatoes as infinite slabs. The D_a values were found to be 0.42×10^{-9} m^2 s^{-1} and 1.4×10^{-9} m^2 s^{-1} for potato and pickled cucumber respectively after 30 minutes.

Kozempel et al. (1981) showed that the leaching of soluble solids, glucose, potassium, magnesium and phosphorus from potato in hot water blanching can be predicted by using a mathematical model when diffusion is the rate controlling step. The diffusivity of these soluble solids, at 77°C were found to be 7.6×10^{-9}, 1.13×10^{-7}, 1.18×10^{-8} and 1.08×10^{-8} m^2 s^{-1} respectively. Although the model was developed for 0.95 cm french fry cut potatoes, they concluded that it was applicable to other types and cuts of other vegetables.

A model based upon diffusion as the rate controlling step in blanching was also used successfully by Kozempel et al. (1982) to correlate and predict the loss of water soluble vitamins from potato as a function of the process parameters. The diffusivity values for ascorbic acid, thiamin, riboflavin and niacin of french fries 0.95 cm thick at 77°C were estimated to be 9.56×10^{-9} m^2 s^{-1}, 3.61×10^{-9} m^2 s^{-1}, 3.36×10^{-9} m^2 s^{-1} and 7.93×10^{-8} m^2 s^{-1} respectively.

In similar experiments Bressan et al. (1981 and 1982) used a mass transfer model to measure the effective diffusion coefficient of total solids and lactose from small cured cottage cheeses during washing at several temperatures. At temperatures of 25, 35, 50 and $58^{\circ}C$ the effective diffusion coefficients were: 3.40×10^{-10} m^2 s^{-1}, 3.96×10^{-10} m^2 s^{-1}, 5.02×10^{-10} m^2 s^{-1} and 5.54×10^{-10} m^2 s^{-1} respectively. An empirical correlation for diffusivity of total solids as a function of temperature was found to be:

$$D_a = (0.0658T + 1.72) \times 10^{-10}$$

where D_a is in m^2 s^{-1} and T is in $^{\circ}C$.

The diffusion coefficient values for lactose at $25^{\circ}C$ $(3.8 \times 10^{-10}$ m^2 $s^{-1})$ are uniformly larger than those of the associated total solids values, indicating that the whey proteins are more significantly influencing the diffusion of total solids than are the salts and low molecular weight components.

Califano and Calvelo (1983) proposed a mathematical model for heat and mass transfer with a simultaneous chemical reaction to analyse the influence of blanching at moderate temperatures on the reducing sugar content of the potato. Potato spheres of 2.25 cm diameter were blanched in a container filled with distilled water at a controlled temperature and stirring was strong enough to secure uniformity of heat transfer coefficient. The apparent diffusion coefficient obtained was found to be changed with temperature according to the Stokes-Einstein equation:

$$D_G = KT/\mu_w$$

where D_G, is the apparent diffusion coefficient of reducing sugar in potato, μ_w is the water viscosity at temperature T and K is constant.

At 60°C with simultaneous reducing sugar generation, the D_a
value was 11.3×10^{-10} m^2 s^{-1} . When the simultaneous generation
of sugar was not taken into account, the result led to
$D_a = 4.95 \times 10^{-10}$ m^2 s^{-1} at 60°C.

The described phenomenon of reducing sugar generation became
less important at temperatures higher than 75°C because of the
simultaneous destruction of the enzymes.

3.1.2 Activation Energy for Diffusion in Food Systems

The diffusion process is influenced by the movement of mole-
cules and ions. In a liquid or solid system these molecules are
subjected to a considerable force holding them together. There-
fore they are not free to move as in the gas system. In such
systems molecules can only diffuse or move if they have sufficient
kinetic energy to overcome the forces holding them to adjacent
molecules, and to push other molecules out of the way. The energy
necessary to do this is the 'activation energy' (E_a).

Becker and Sallans (1955) found that the energies of activation
for diffusion of moisture in two different samples of wheat kernel
of 10.3% and 9.6% moisture content (dry basis) were 61.6 kJ/mol
and 54.1 kJ/mol. Since the only difference between the two samples
was a time lapse of 6 months, it was stated that the decrease in
energy of activation was due to chemical or physical changes taking
place during storage.

Fish (1958) found that the increase of the diffusion coefficient
of water in gelled starch with increasing water content, was mainly
caused by a decrease of E_a from 41.0 kJ/mol at a water content of
0.74% to 18.8 kJ/mol at a water content of 44.5%. Activation
energies for water diffusion in various food materials during
drying was also reported and they are given in Table 3.2.

TABLE 3.2: Activation energies (E_a) for water diffusion in food materials

Material	E_a kJ/mol	Moisture Content (dry basis) gm/gDW	References
Sugar beet root	28.9		Vaccareza et al. (1974)
Wheat	54.0-61.1	0.12-0.30	Becker and Sallans (1955)
Tobacco leaf	18.0		Chen and Johnson (1969)
Rice: (bran)	44.8		Steff and Singh (1980)
(starchy endo-sperm)	28.5	0.34-0.13	
Tapioca root	22.6		Chirife (1971)
Sorghum	31.4	0.21-0.06	Suarez et al. (1980)
Fish muscle	29.7	0.1	Jason (1958)

Thijssen and Kerkhof (1977) reported activation energies for physical properties at high water activities as given in Table 3.3 (overleaf).

Stahl and Loncin (1979) obtained an activation energy of 35.7 kJ/mol for cyclohexanol diffusion in potato tissue, which is about twice as much as for diffusion in water. This indicated that mass transfer in potatoes may also be influenced by cell walls and membranes. Saravacos and Charm (1962) came to the same conclusion, and attributed the high value of activation energy for water diffusion in potato tissue to the resistance of the potato to moisture transfer that is due to the presence of cell walls and other non-starchy materials.

TABLE 3.3: Activation energies at high water activities of physical
            properties and reactions.
            (After Thijssen and Kerkhof (1977))

Property	E_a kJ/mol
Physical properties	2.1 - 209.3
Water vapour pressure	41.9
Water diffusion coefficient	8.4 - 41.9
Heat transfer coefficient	2.1 - 29.3
Viscosity water (20°C)	0.008
Viscosity glucose (25°C)	200.9
Enzyme reaction	16.7 - 62.8
Chemical reaction	62.8 - 502.4
Hydrolysis	62.8 - 108.9
Maillard browning	104.7 - 209.3
Protein denaturation	334.9 - 502.4

Activation energies related to texture softening during
cooking of three varieties of carrot were found by Paulus and Saguy
(1980) to be 117.2, 113.0 and 92.1 kJ/mol for Rubika, Rothild and
Kundulus varieties respectively. However they did not explain why
the energy of activation of the Kundulus variety was significantly
lower than those of the Rubika and Rothild varieties.

Califano and Calvelo (1983) reported an activation energy for
reducing sugar generation during warm water blanching of potato
in the range of 60-70°C. The E_a was 41.8 kJ/mol. This value seems
comparable with those reported by Ikemiya and Deobald (1966);
(30.3 - 30.9 kJ/mol) in the range 30-70°C for the enzymic generation
of reducing sugars in similar biological systems.

3.2 Heat Diffusion in Vegetable Tissue

The thermal properties, namely thermal diffusivity, thermal conductivity and specific heat are of great importance in establishing the energy requirements of a particular heating or cooling process. Values of thermal properties of foods are essential in predicting, designing and optimising many processes involving heat transfer, such as freezing, canning, drying, cooking and blanching. Some of these thermal properties have been determined in the freezing region of some foods, but in the heating and cooking region, these properties are not readily available in terms useful for design parameters (Matthews and Hall, 1968).

The scarcity of literature data and lack of information on the thermal properties of some vegetables, especially potato, during heating (blanching), suggested that there was a need for the determination of such data. Dickerson and Read (1968) have shown that the calculation of heat transfer rates in food requires the following knowledge:

1. Thermal properties of the food.
2. Geometry of the food.
3. Thermal processing conditions:
    a) temperature of the heat source
    b) initial temperature of the food
    c) temperature difference between heat source and food surface.

3.2.1 Thermal Diffusivity

In the heating and cooling of food materials, unsteady-state or transient heat conduction is the most widely encountered situation which involves the accumulation or depletion of heat within the the body so that the temperature distribution changes with time. Thermal diffusivity α is a measure of the quantity of heat absorbed by a material for a given temperature change, and further indicates

the ability of the material to conduct heat to adjacent molecules. In terms of other thermal properties, thermal diffusivity is defined as the ratio of thermal conductivity, K_o, to the product of specific heat, Cp, and density, ρ,

$$\alpha = \frac{K_o}{\rho \; Cp} \quad m^2 s^{-1}$$

Values of thermal diffusivity are required to predict temperature history curves of food during various heating or cooling processes.

Thermal diffusivity for apple, orange, grapefruit and squash has been reported by Gane (1936). The thermal diffusivity was calculated from the time-temperature data using Gurney-Lurie charts. The unit surface conductance was assumed to be large so that $\frac{k}{h} \simeq 0$. The thermal diffusivity values were 1.26×10^{-7}, 1.21×10^{-7}, 1.32×10^{-7} and 1.26×10^{-7} m^2 s^{-1} for apple, grapefruit, squash and orange respectively.

Based on time-temperature relationships involved in the transfer of heat in the unsteady state for several fruits and vegetables, Kethley et al. (1950) applied the graphical method of Gurney and Lurie to calculate the thermal diffusivity of these foods for the temperature range 27 to -18^oC (the usual cooling range in the freezing of fruits and vegetables). The average values of thermal diffusivity were found to range from 1.20×10^{-7} for peach flesh to 1.50×10^{-7} m^2 s^{-1} for apple flesh. The thermal diffusivity of Irish potato was 1.21×10^{-7} m^2 s^{-1}.

Since the fruits and vegetables used in these experiments were subjected to temperatures sufficiently low to freeze 95% or more of their water content, the average thermal diffusivity of these foods might be expected to be a function of both liquid and solid water (ice) and would be similar to the thermal diffusivity of water in the temperature range of 0 to 27^oC which is 1.43×10^{-7} m^2 s^{-1} (Mohsenin, 1980).

Matthews and Hall (1968) used the method of finite differences to determine the thermal diffusivity of Excel potatoes. It was found that the thermal diffusivity decreased linearly with storage time (at 4°C) according to the relation:

$$\alpha = [6.327 \times 10^{-3} \ (1.126 \times 10^{-4} \ \times \text{test date})] \times 0.25806 \ m^2 s^{-1}$$

A correlation between maximum temperature and thermal diffusivity of potato based on experimental results was given as:

$$\alpha = [-1.962 \times 10^{-2} + (2.617 \times 10^{-4} \times T) - (8.500 \times 10^{-7} \times T^2)]$$

$$\times 0.25806 \ m^2 \ s^{-1}$$

According to this correlation, as temperature increased, thermal diffusivity increased up to a maximum value at 68°C ($9.75 \times 10^{-8} \ m^2 s^{-1}$) and then decreased with higher temperature. The maximum values of diffusivity which occurred in the 68 to 74°C range suggests that maximum diffusivity was related to the starch gelatinisation of the potato.

Wadsworth and Spadaro (1969) reported an experimental determination of the thermal diffusivity of sweet potatoes during immersion heating in a constant temperature water bath. It was shown that the apparent thermal diffusivity during heating increased with temperature from a value of $1.03 \times 10^{-7} \ m^2 \ s^{-1}$ at 27°C to a maximum value of $2.22 \times 10^{-7} \ m^2 \ s^{-1}$ at 74°C and then decreased to a value of $1.55 \times 10^{-7} \ m^2 \ s^{-1}$ at 90°C. An approximation of the variation of thermal diffusivity with temperature during immersion heating from 27 to 90°C was given by the expression:

$$\alpha = [0.30 \times 10^{-2} + 0.10 \times 10^{-4} \times T + 0.50 \times 10^{-7} \times T^3 -$$

$$0.55 \times 10^{-9} \times T^4] \times 0.25806 \ m^2 \ s^{-1}$$

It was believed that the rapid increase in α between 65 and 74°C was due to the gelatinisation of sweet potato starch which occurs in that temperature range. The decrease in α above 74°C was probably due to the softening and separation of the cells.

Rao et al. (1975) used the line-source method for the simultaneous measurement of the thermal conductivity and thermal diffusivity of process varieties of squash and white potato at ambient temperature. The average thermal diffusivities for potato were: $1.70 \times 10^{-7} \ m^2 \ s^1$ at about 82% moisture content with a standard deviation of 9.0% from the mean, while that for the squash was $1.55 \times 10^{-7} \ m^2 \ s^{-1}$ with a standard deviation of 6.3%. The magnitudes of thermal diffusivity of potatoes are higher than those reported by Matthews and Hall (1968) which ranged between 9.59×10^{-8} and $1.41 \times 10^{-7} \ m^2 \ s^{-1}$. The high thermal diffusivity was attributed to the high moisture content (82%) and to the Excel potatoes used by Matthews and Hall (1968) which were stored for several months causing the thermal diffusivity to decrease.

The thermal diffusivities of five states of sweet potato materials (solid potato, plain puree, and three types of pureed potato with varying amounts of starch, corn, syrup, and milk) for three processing temperatures using uniform sized samples were determined by Crumpton and Threadgill (1977). The results indicated that there was a significant difference in thermal diffusivity with respect to retort temperature and to the states of sweet potato materials. The diffusivity differed according to the states, with a range of $1.29 \times 10^{-7} \ m^2 \ s^{-1}$ for solid to $1.39 \times 10^{-7} \ m^2 \ s^{-1}$ for plain puree. The plain puree and the solid were highly significantly different from each other, and from the three puree mixes which were not significantly different from each other, and had an average

diffusivity of 1.33 x 10^{-7} m^2 s^{-1}. Retort temperatures had an effect on thermal diffusivity but this effect was less than the effect of state of material on thermal diffusivity. The diffusivities for the 116°C, 132°C and 149°C retort temperature were 1.32 x 10^{-7}, 1.33 x 10^{-7} and 1.36 x 10^{-7} m^2 s^{-1} respectively.

3.2.2 Specific Heat

In food heating processes, specific heat is a very important unit as it indicates the amount of heat required to bring the food material to the desired temperature. Specific heat is defined as the heat capacity of a body per unit mass of the body (Mohsenin, 1980).

$$Cp = \frac{Q}{M\Delta T} \quad kJ/kg^{\circ}K$$

where M is the mass of the material and Cp is specific heat.

The ratio of the heat supplied Q to the corresponding temperature rise ΔT is defined as the heat capacity of a body. The need for specific heats of food materials has been realised for some time and the influence of water on thermal properties of food has been given great attention. This is because moisture content changes considerably during many processing operations, and because there is normally a substantial difference between the thermal properties of water and the other constituents. Many formulae have been suggested to determine the specific heat of food from its moisture content.

In 1892, Siebel introduced a formula to measure the specific heat from the moisture content. His formula relied on the assumption that specific heat is an additive property. He suggested that the specific heat above freezing point for high moisture content foods

like fruits, vegetables and meat could be calculated from the following equation:

$$Cp = [0.008M + 0.20] \times 4.1868 \text{ kJ/kg}^{\circ}\text{K}$$

where M is the water content of the food material in percent wet basis and 0.20 is a constant assumed to be the specific heat of the dry solid.

Earle (1966) reported that if the percentage of water in a foodstuff is known, then the specific heat of the foodstuff above freezing can be estimated from:

$$Cp = [\frac{M}{100} + \frac{0.2 \ (100-M)}{100}] \times 4.1868 \text{ kJ/kg}^{\circ}\text{K}$$

Charm (1971) obtained the relationship:

$$Cp = 1.0 \ X_w + 0.3 \ X_s + 0.5 \ X_f$$

to calculate specific heat of food from its composition, where X_w, X_s and X_f are the weight fractions of water, solids and fat respectively.

Lamb (1976) based on the data of Earle (1966) and Charm (1971) gave the following approximation to calculate the specific heat:

$$Cp = [0.65M + 0.35] \times 4.1868$$

where Cp is in kJ/kg$^{\circ}$K and M is on a wet weight basis.

Due to the high moisture content, many investigators found that the specific heat of vegetables and fruits as calculated from Siebel's

equation varies very little from the experimental values.

Hood (1961) measured the specific heat of cucumbers using
the method of calorimetry. He reported a value of 4.091 kJ/kg^{o}K
compared to 4.053 kJ/kg^{o}K calculated from Siebel's equation at
96% moisture content.

Frechette and Zahradnik (1968) used calorimetry to measure
the specific heat of apples. They found the specific heat of
McIntosh apples to be 3.77 kJ/kg^{o}K as determined experimentally
and 3.73 kJ/kg^{o}K as calculated using the average water content of
86%.

Yamada (1970) has reported on the measurement of specific
heat of potato using the method of liquid calorimetry. He found
that the moisture content had a marked influence on the specific
heat of potato. The specific heat varied from 2.072 kJ/kg^{o}K at
22% moisture content to 3.65 kJ/kg^{o}K at 83% moisture content.
Furthermore the relation between the specific heat and the moisture
content indicated that the best fitting equations are:

$$Cp = [0.216 + 0.780 \ W] \times 4.1868 \ (W > 0.50)$$

$$Cp = [0.393 + 0.437 \ W] \times 4.1868 \ (0.50 > W > 0.20)$$

In general there is very little data available on the specific
heat of potato.

Specific heat measurements of citrus fruits using the method
of mixtures have been reported by Turrell and Perry (1957).
The specific heat of freshly picked orange, lemon and grapefruit
were found to vary very little: 3.663, 3.735 and 3.705 kJ/kg^{o}K
respectively due, as expected, to the water content. To find the
effect of water content, they determined the specific heat of
orange at different moisture contents. The regression of specific
heat of orange with water content was:

$$Cp = [0.00601M + 0.347] \times 4.1868$$

The method of mixtures was also used by Sharma and Thompson (1973) to measure the specific heat of grain sorghum at five different moisture levels between 2 and 29%. The method consisted of determining the temperature change of water contained in a calorimeter at $4.5^{\circ}C$ where a grain sample at approximately $24^{\circ}C$ was dropped into the calorimeter. A regression equation for the relationship between specific heat and moisture content in the range of 2-30% wet basis was reported to be:

$$Cp = [0.3337 + 0.0077M] \times 4.1868$$

3.2.3 Thermal Conductivity

Thermal conductivity, K_o, is a physical property of the material through which heat is transferred. The thermal conductivity of a substance can be defined as the amount of heat flow per unit area per unit time when the temperature decreases by one degree in unit distance. In mathematical form, the thermal conductivity K_o (w/m$^{\circ}$K) is the proportionality factor in the Fourier's law for heat conduction.

$$Q = K_o A \frac{dt}{dl}$$

where Q is the quantity of heat flow (W), A is the area for heat transfer (m^2) and $\frac{dt}{dl}$ is the temperature gradient $(\frac{K}{m})$.

A most notable feature of food materials is their extremely low values of thermal conductivity compared to metals. This difference in thermal conductivity is due to differences in the abundance of free electrons. In metals the electrons transmit most of the heat energy, whereas in foods, where water is the main constituent,

the free electron concentration is low and the transfer mechanism
involves primarily vibration of atoms and molecules. Another
striking feature is that since the food materials are not homo-
geneous and vary in cellular structure, composition and air
content, the variations in thermal conductivity are greater than
those of the non-biological materials. One of the earliest works
reported on the measurement of thermal conductivity of fruits and
vegetables is that by Gane (1936). The thermal conductivity was
calculated from the relation:

$$\alpha = \frac{k_o}{\rho \ Cp}$$

where α is thermal diffusivity, k_o thermal conductivity, Cp specific
heat and ρ is density. Thermal conductivity for apple, orange, and
grapefruit was 0.4154, 0.4154 and 0.3981 W/m°K respectively.

Kethley et al. (1950) estimated the average thermal conductivity
of certain fruits and vegetables deduced from experimental values
of thermal diffusivity and the average apparent specific heat
between -18 and 27°C. These values varied from 1.0557 W/m°K for
Irish potato to 1.3499 W/m°K for strawberries. The average thermal
conductivities of these foods were also calculated for the tempera-
ture range 26.6 to 0°C. These values varied from 0.4846 to 0.5884 W/m°K
and compared favourably with the average value of 0.6057 W/m°K for
water in this same temperature range.

Thermal conductivity of citrus fruit was determined by Turrell
and Perry (1957) using a mathematical model and time-temperature
data. The values of k_o, for grapefruit, lemon, orange (Valencia)
and orange (Washington Naval) were 0.3267, 0.4398, 0.490 and
0.410 W/m°K. The lower conductivity of grapefruit was attributed
to the thicker rind or peel of the grapefruit compared to lemon
and orange. The authors suggested that since a large portion of
rind volume is taken up by air and CO_2, the thermal conductivity of
the rind should be lower than that of the pulp or the edible tissue.

The dependence of thermal conductivity of potato on moisture content and temperature has been reported by Yamada (1970). The thermal conductivity was measured by the method of the unsteady state heat conduction of a sphere. The values of thermal conductivity of potato at 76% moisture content ranged from 0.485 W/m^{o}K at 10°C to 0.556 W/m^{o}K at 75°C. The relation between the thermal conductivity and moisture content showed that the decrease in the moisture content was accompanied by a decrease of the thermal conductivity.

Sweat (1974) measured the thermal conductivity of several fruits and vegetables using a miniaturised thermal conductivity probe. As expected, he found a high correlation between thermal conductivity and water content for all the materials used except apples, apparently due to the large amount of air space which reduces thermal conductivity.

Based on the high correlation between water content and thermal conductivity, a regression equation was proposed to calculate the thermal conductivity of high moisture content food as follows:

$$k_o = 0.00493 \ W + 0.148$$

where k_o is in W/m^{o}K and W is in percent.
Some of the results are shown in Table 3.4 (overleaf).

The method of line heat source was used by Rao et al. (1975) to measure the thermal conductivity of white potatoes and squash. The potatoes employed in this study were Katahdin, Russet Burbank, Monona, Norchip and Kennebec varieties. At the probability level of 5 percent, the thermal conductivities of the five varieties of potatoes studied were found to be significantly different. The values of thermal conductivity varied between 0.533 W/m^{o}K for the Katahdin variety to 0.571 W/m^{o}K for Russet Burbank variety at 82% moisture content. The thermal conductivity values of three varieties of

TABLE 3.4:   Thermal conductivity of selected fruits and vegetables
(After Sweat, 1974)

Material	Water Content % w.b.	Temperature °C	Thermal Conductivity W/m°K
Apple (green)	88.5	28	0.422
Beet (red)	89.5	28	0.601
Carrot	90.0	28	0.605
Cucumber	95.4	28	0.598
Turnip	89.8	24	0.563

squash studied were not found to be significantly different when
variations in moisture content were taken into consideration.

3.3 Mass Transfer During Blanching of Vegetables

3.3.1 Diffusive Loss of Sugar in Relation to Colour of Potato Chips

Diffusing out of reducing sugar is of particular importance in the potato industry. In the manufacture of potato chips, french fries and dehydrated potato, the reducing sugar content is closely related to the colour of the final product. It is widely known that when potatoes are processed, a maillard or non-enzymic browning reaction can take place between sugar, especially reducing sugars, and amino acids, producing an undesirable brown colour at the surface of the potato strip (Schwimmer et al., 1957; Townsend and Hope, 1960; Hoover and Xander, 1961 and Smith, 1975).

Control of colour in the potato chips industry is necessary to obtain a standard product and in general light-coloured chips are preferred. In comparing a large number of sugar determinations with colour of chips, Wright and Whiteman (1951) found that chips with the most desirable colour came from potatoes averaging 0.18 percent reducing sugar. A level of 0.4 percent has been found to be the upper limit conducive to a satisfactory product (Wright and Whiteman, 1954). Smith (1955) found that in most instances acceptably coloured chips were made from potatoes of less than 0.2 percent (FWB) reducing sugars.

Habib and Brown (1957) also found a high correlation between light coloured chips and low reducing sugar content of the tubers.

Hawkins et al. (1958) found a critical concentration of 0.4 percent reducing sugars above which chips were dark brown and not acceptable in flavour. Burton (1962) reported that potatoes with 1.22 percent reducing sugar content produced chips much too dark, but those with 0.25 percent had a good light colour.

Mitchell and Rutledge (1973) stated that potatoes containing about 0.2% reducing sugar usually produced chips with the desired

golden brown colour, but with higher levels of reducing sugars the product tended to be unattractively dark with a burnt flavour.

Reducing sugar content of potatoes depends upon variety (Smith, 1969; Mills, 1964), maturity (Miller, 1972; Smith, 1957), storage and cultural conditions (Clegg and Chapman, 1962; Harvey 1962, Talburt and Smith, 1975). Glucose, fructose and sucrose comprise the major sugars in the potato (Schwimmer et al., 1954). Of these, the reducing sugars, because of the non-enzymic browning reaction during processing, have the most effect on the colour of chips (Habib and Brown, 1957). The reducing sugar content of potato is naturally low, but during low temperature storage (0 to 4.$^\circ$C), reducing sugars accumulate and often the finished fried product will be darker than desired.

Smith (1975) mentioned three processes which occur in potatoes during storage: (i) respiration, which utilizes sugars by converting them into carbon dioxide and water, (ii) conversion of starch to sugar by amylolytic enzymes, and (iii) conversion of sugar to starch, by starch-synthesizing enzymes. Hanes (1940) attributed the conversion of reducing sugar to starch to the activity of the enzyme, phosphorylase. According to Arreguin-Lozano and Bonner (1949), phosphorylase is equally active in potatoes from all storage temperatures and it does not attack starch in potatoes stored at high temperatures. This is attributed to the formation of an inhibitor of phosphorylase at high temperatures which disappears at low storage temperatures. Potatoes differ according to variety in the rate at which reducing sugar accumulates in cool storage, and the rate at which it is converted when the temperature is raised. Such differences may also be influenced by maturity, pre-storage conditions as well as storage temperature. Low storage temperatures (below 4°C) are necessary for slowing sprouting and dehydration. The importance of storage temperature on the processing quality of potato has been recognised by many authors.

Sweetman (1930) showed that chips made from tubers stored between 0 and 2.8°C were darker than those made from potato stored at 4.4-12.8°C. The changes in colour were correlated with changes in sugar content under different conditions of storage. Peacock et al.(1931), Wright et al.(1936) also found that the colour of potato chips when made from tubers stored at 15.6 or 21°C was most desirable, and that as storage temperatures decreased to 4.4,2.2 and 0°C, the brown colour of the chips became more intensified.

Stevenson and Cunningham (1961) found that potato varieties vary considerably in their ability to accumulate reducing sugars during storage. They stated that varieties which accumulate large percentages of reducing sugars during low temperature storage and cannot be reconditioned at 20-25°C were unsuitable for chip proces- sing. Hyde and Morrison (1964) found that storage at 4.4°C resulted in accumulation of reducing sugars whereas storage at 21°C caused little change in reducing sugars. Also they found that phos- phorylase activity was greater at 4.4°C than at 21°C. They concluded that since the phosphorylase enzyme catalyzes the breakdown of starch, it could be a factor influencing sugar accumulation and chip colour of potatoes stored at 4.4°C.

Smith (1975) considered that 10 to 12.8°C is the ideal storage temperature for potatoes to be processed into chips or french fries. He stated that although sugar may accumulate at these temperatures it will not be appreciable unless stored for long periods. Partial removal or lowering of sugar contents by storing the potato tubers at temperatures of 10-16°C or above is a fairly standard practice, but such a practice introduces major problems with sprouting, dehydration and rotting. In the processing and production of french fries control of the chip colour is possible by using water blanching as a means of lowering the reducing sugar level of the potato tuber.

Hot water blanching in the range of 60 to 80°C prior to frying is used to leach out reducing sugars and other chemical constituents responsible for the production of off-colours and flavours, in french fries.

Patton (1948) described a process of leaching the reducing sugar from potato slices before frying. The potato slices were immersed in a hot aqueous solution of alkaline salt such as calcium chloride, calcium sulphamate and magnesium chloride in 0.1 to 0.005 molar concentrations for various times before frying. He found that immersing potato slices in 0.25 percent calcium chloride for three minutes at a temperature just below the boiling point, leached sufficient browning reactants to give light coloured chips after frying.

Whiteman (1951) found that potato slices soaked in slightly acidulated water (0.044 percent hydrochloric acid) at 62.8^oC for two minutes just before frying gave chips acceptable in colour and flavour.

Dexter and Salunkhe (1952a) showed that great improvement in chip colour resulted from short treatment of slices with hot water. Pontiac potato slices were immersed for 1.5 minutes in water at 70^oC followed by soaking for various times in cold water at room temperature. Chemical analysis (Table 3.5) showed a considerable removal of proteins as well as sugars. In 15 minutes of extraction practically all of the reducing sugars, about 27% of the protein and about 7% of dry matter were removed. When the slices were soaked in cold water without hot water treatment, the total solids lost were about one-third as much as in 15 minutes soaking after a hot treatment was given, while sugar and protein loss was reduced to about one-tenth. From the size of potato cells and the thickness of the slices, it was suggested that this loss was largely due to the contents of the cut cells on the face of each slice.

Townsley (1952) obtained satisfactory chip colour when potato slices were soaked in water for 5-7 minutes at $67-73^oC$. However some flavour was lost as a result of such treatment due to leaching out of sugar, nitrogenous compounds and other constituents of the potato.

TABLE 3.5: Analyses of extracts and tuber slices after immersion in hot water and soaking in cold water. (After Dexter and Salunkhe, 1952a)

Period of extraction in cold water, minutes	Total Solids %	Protein %	Total Sugar %	Reducing Sugar %	Non-Reducing Sugar %
	Analyses of the extracts				
0-15 (following hot treatment)	1.21	0.49	0.21	0.12	0.09
15-30	0.72	0.27	0.12	0.10	0.02
30-60	0.54	0.19	0.08	0.04	0.04
Total (sum of above) 0-60	2.47	0.95	0.41	0.26	0.15
Cold (0-60 no hot treatment)	0.40	0.06	0.02	0.02	0.00
	Analyses of tuber slices				
0 (direct from potato)	18.5	1.77	0.56	0.41	0.15
0-15 (following hot treatment)	-	-	0.11	0.00	0.11
15-30 (following hot treatment)	-	-	0.00	0.00	0.00
30-60 (following hot treatment)	-	-	0.01	0.00	0.01
Cold 0-60 (no hot treatment)	-	-	0.53	0.38	0.15

    Dexter and Salunkhe (1952b) attempted to improve chip colour by treating potato slices with various chemical solutions so that reducing sugar might be removed by diffusion without excessive leaching of other desirable constituents of potato. Pontiac potato slices were treated for 1.5 minutes with water, hydrochloric acid pH 1.9 (about 0.05%), or phosphoric acid pH 1.9 at 23.9°C or 48.9°C, after which they were extracted with water at the same temperature for 3.5 minutes. The results (Table 3.6) showed that soaking and washing

TABLE 3.6: Treatment of potato slices
            (After Dexter and Salunkhe, 1952b)

Sample	Analysis of Extracts				Analysis of extracted slices	
	Total solids extracted as		Protein extracted as		Total sugar	Reducing sugar
	% Slices	% Solids	% Protein	% Slices	% Slices	% Slices
Water 23.9°C	0.91	4.32	5.49	0.156	1.88	0.10
Water 48.9°C	1.19	5.69	10.98	0.313	1.44	0.08
Hydrochloric acid 23.9°C	1.06	5.06	9.68	0.275	1.75	0.05
Hydrochloric acid 48.9°C	1.34	6.40	13.16	0.375	1.27	0.00
Phosphoric acid 23.9°C	1.30	6.22	9.00	0.256	1.57	0.04
Phosphoric acid 48.9°C	1.61	7.68	13.49	0.384	1.35	0.00
Unextracted slices	TS % 20.92		TP % 2.85			

in water at 23.9°C for 5 minutes removed 4.3% of the solids and this was increased to 5.7% by raising the temperature to 48.9°C. Acidification of the water resulted in further increases in the solids extracted. In a more or less parallel way, extraction of protein was increased either by raising the temperature or by acidification. Losses of dry matter in the potato slices, owing to the most severe acid treatment were 7.7% of the total solids or 3.36% more than that with washing with water at room temperature. In any case, this method which involved only the control of temperature or acid concentration or both appears well adapted to remove reducing sugars without great loss of other soluble constituents.

Mitchell and Rutledge (1973) found that the rate of leaching of reducing sugar in water was greatest at 73°C and satisfactory crisps were produced from Kennebec potatoes with up to 0.4% reducing sugar. This was attributed to the increase in permeability of the tissue associated with thermal breakdown of cell membranes and the absence

of a diffusion resistance caused by gelling of the starch. Yields and compositions of potato slices and crisps leached at 73°C are given in Table 3.7. Potatoes with more than 0.4% reducing sugars were judged unsatisfactory since the length of time required for leaching the reducing sugars at 73°C also removed the desirable constituents (flavour, nitrogenous compounds and vitamins) and a poor quality crisp resulted.

TABLE 3.7: Relative yield and composition of potato slices and crisps
            (After Mitchell and Rutledge, 1973)

Quality	Time of Leaching (min) at 73°C			
	0	1	3	7
Yield after leaching	100.0	100.4	100.0	98.4
% solids after leaching	21.0	19.2	17.8	16.9
% yield of crisps	30.1	30.2	31.1	31.8
% oil in crisps	30.2	36.4	42.8	46.8

3.3.2 Diffusive Loss of Nutrients During Blanching of Carrot Tissue

Horner (1936-1937) noted that during water blanching of certain fresh vegetables (peas, beans, carrots and potatoes) considerable loss of potassium and phosphates occurred with all vegetables. Shrinkage of the vegetables accompanied by a reduction in weight also took place. Calcium was absorbed by the vegetables during blanching, and the amount depending upon the nature of the vegetables, the hardness of blanching water and the time of blanching. In the following blanching processes peas (3 minutes at 100°C), beans (3 minutes at 82°C), carrots (7 minutes at 100°C) and potatoes (5 minutes at 100°C), the percentage gain in calcium oxide (CaO) and losses in potassium oxide (K_2O), phosphorous pentoxide (P_2O_5) and

weight, are as shown in Table 3.8. Unfortunately the author did not give information on the samples' size, initial weight and sample to water ratio which are important in calculating the diffusivity, nor did he explain the way by which potassium and phosphate were lost.

TABLE 3.8: Gain in calcium and loss in potassium and phosphates contents during blanching (After Horner, 1936-1937)

Vege-tables	Loss in wt %	Composition						Loss		Gain
		Raw			Blanched					
		K_2O %	P_2O_5 %	CaO %	K_2O %	P_2O_5 %	CaO %	K_2O %	P_2O_5 %	CaO %
Peas	6.5	0.295	0.257	0.0199	0.192	0.235	0.0302	39	20	52
Beans	2.2	0.337	0.085	0.104	0.208	0.088	0.124	40	-	19
Carrots	9.0	0.072	0.051	0.0432	0.067	0.048	0.0521	16	15	21
Pota-toes	0.0	0.552	0.109	0.0118	0.502	0.099	0.0157	9	9	33

Horner (1939) also studied the effects of cooking, blanching, and canning on the mineral constituents of peas, beans, carrots, potato and spinach. The constituents studied were: calcium, magnesium, potassium, phosphates and chloride. Blanching of carrots and potatoes were carried out at 100°C for 7 and 5 minutes respectively. The results indicated that when water of appreciable hardness was used, the calcium content of the vegetables increased, but the other inorganic constituents decreased. The total losses on canning and cooking were of approximately the same magnitude. The presence of common salt in the canned material has little or no effect on the distribution of the inorganic constituents between the solid and liquid portions of the can. Therefore he concluded that it is not possible to diminish the losses in canned material by adjusting the composition of the covering liquid. Results for the mineral loss

and gain from carrot and potato are shown in Table 3.9. The
mechanism by which these changes occurred in potato and carrot
blanching were not given.

TABLE 3.9: % gain (+) or loss of mineral constitutents during
blanching, cooking and canning.
(After Horner, 1939)

Vegetables	Constituent	% Gain or Loss		
		Blanching	Canning	Cooking
Carrot	Calcium	+9	1	6
	Magnesium	21	27	28
	Potassium	15	42	44
	Phosphorus	3	34	24
Potato	Calcium	+30	+72	-
	Magnesium	25	45	-
	Potassium	11	44	-
	Phosphorus	11	18	-

The changes occurring during the blanching of vegetables (peas, beans,
carrots, potatoes, parsnips, swedes and brussel sprouts) for 1, 3 and
6 minutes in water and for 3 minutes in steam have been reported by
Adam et al. (1942). The ratio of water to solids during blanching was
3 to 1 and the blanching temperature was 100°C. The retention of
the chief nutritive substances, and the principal physical changes
were studied. The results indicated that small units of large surface
area, such as fresh peas and sliced or diced roots, retained a lower
proportion of their nutritive materials than do the larger units such
as whole roots and the starchy seeds, see Tables 3.10, 3.11 and 3.12.
Small units of large surface area retained 65-81% of their sugars,
50-68% of their vitamin C, 70-83% of their mineral substances and
78-86% of their protein, the larger roots and starchy seeds retained
79-90% of their sugars, 67-78% of their Vitamin C, 92-98% of their

TABLE 3.10: Composition of Carrots
(After Adam et al., 1942)

Carrot Type	Total Solids %	Sugars %	Ash %	Protein %	Ascorbic Acid mg per g
Carrots, whole	10.3	4.8	0.31	1.1	0.057
Carrots, sliced	10.5	5.5	0.42	1.2	0.055
Carrots, diced	9.9	6.4	0.44	1.2	0.050

TABLE 3.11: Retention of nutritive substance during blanching,
a, b, c and d refer to water-blanching treatments of
1, 3 and 6 min and 3 min blanching in steam
(After Adam et al., 1942)

Carrot Type	Sugar %				Protein %				Vitamin C %			
	a	b	c	d	a	b	c	d	a	b	c	d
Carrots, whole	98	86	82	89	90	90	90	91	84	64	56	68
Carrots, sliced	80	73	58	74	70	73	70	74	78	70	61	78
Carrots, diced	-	87	73	83	77	75	79	93	77	62	54	80

TABLE 3.12: Physical changes produced by blanching
(After Adam et al., 1942)

Carrot Type	Weight compared with unblanched weight				Volume compared with unblanched volume			
	a %	b %	c %	d %	a %	b %	c %	d %
Carrots, whole	98.4	96.9	95.6	98.5	98.0	95.9	94.4	98.4
Carrots, diced	98.8	97.7	98.3	99.8	97.8	95.4	95.9	100.0

protein and 84-92% of their mineral substances. They concluded that blanching causes a reduction in the weight of vegetables through expulsion of water-soluble cell contents and a reduction in volume, through expulsion of gases and contraction or collapse of the tissues.

The effect of blanching conditions on the yield and properties of the dehydrated product have been studied in detail by Gooding and Tucker (1955). They observed that as the concentration of solutes in the blanch medium rose, the loss of solutes from the carrot became less. Also they found that as the soluble solids concentration increased from about 1% to 4.5% the yield of dehydrated product increased by about 30%. A comparison between the standard strips of 3/16 in x 5/16 in cross section and strips of 3/32 in x 5/16 in cross-section showed that when blanched in liquor of high soluble solids concentration (3-5%), the thinner strips suffered about 50% greater loss than the thicker strips, and gave a yield of dehydrated product some 10-15% less. But when steam blanching was substituted for water blanching, the yields of thin strips were similar to those of the thicker strips.

Gooding (1956) also studied the role of blanching media like steam and water (on the factory scale) on the quality and yield as well as the keeping quality of the dehydrated material. The yield and losses during processing of carrot are shown in Tables 3.13 and 3.14. The loss of solids by blanching in steam was substantially less than during water blanching. Carrots blanched in steam were found to be more susceptible to discolouration while those blanched in water became unpalatable due to excessive leaching losses.

In carrot blanched at high blanch liquor concentrations a caramelised flavour occurred and the storage life at 37°C was sharply reduced. This was explained by the suggestion that the reducing leaching at higher blanch liquor concentrations was leaving in the tissue a higher concentration of easily caramelised substances and

a higher concentration of the substances that take part in the browning reactions during high temperature storage.

TABLE 3.13:   Losses of soluble solids during processing (strips 3/16 in x 5/16 in)
(After Gooding, 1956)

Soluble solids content as % of dry matter			% loss of soluble solids		Loss of soluble solids as % of dry matter originally present	
Raw Carrot	a*	b**	a	b	a	b
66.4	63.0	64.9	13.8	6.3	9.2	4.3

* (a) scalded in liquor containing 3.4% soluble solids

** (b) scalded in steam

TABLE 3.14:   Yields and losses during processing
(After Gooding, 1956)

Treatment	Strip size in	Yield as % of trimmed carrot	Yield as % of dry matter entering stripper	Losses during processing as % of dry matter entering stripper	
				Total	Scalding
Water scalded (liquor with soluble solids content (3-5%)	3/16x 5/16	8.42	86.6	13.9	11.9
	3/32x 5/16	7.21	76.0	24.0	17.4
Steam scalded at 98-100°C	3/16x 5/16	9.84	88.1	11.9	8.5
	7/32x 5/16	10.21	88.6	11.4	6.1

Sistrunk (1969) studied the influence of blanching on colour, firmness and carbohydrate changes in canned carrots. Two varieties of carrots, Scarlet Nantes and Highlight Hybrid were peeled, sliced and blanched for 1.5, 3 or 6 minutes at 71°C, 79.4°C or 87.8°C. The results showed that the total sugars increased as blanch time increased at 71 and 79.4°C. Conversely, starch content decreased indicating that part of the increase in sugar resulted from the transformation of starch. Also when the time of blanch at 71°C was increased, water-soluble pectin decreased and Calgon-soluble pectin increased. This could be due to the effects of pectin methyl esterase which is activated by low temperature. Table 3.15 shows the effect of blanch time and temperature on the quality of carrot. He concluded that with a blanch treatment of 71°C carrots were firmer and more moist and contained more carbohydrates than carrots blanched at higher temperatures. This was attributed to the thermal degradation of cellular structure at high temperature, which results in a decrease in firmness and turgidity.

TABLE 3.15: Effect of blanch time and temperature on the quality of carrot (After Sistrunk, 1969)

Blanch Treatment		% Total Sugars	% Starch	% Water Soluble pectin	% Calgon soluble pectin
Temperature °C	Time min				
71	1.5	8.61	2.02	0.811	0.215
71	3	9.03	1.34	0.783	0.283
71	6	9.51	0.65	0.766	0.301
79.4	1.5	8.63	1.02	0.738	0.251
79.4	3	8.90	0.87	0.764	0.269
79.4	6	9.23	0.33	0.756	0.221
87.8	1.5	8.85	0.36	0.764	0.265
87.8	3	8.59	0.33	0.765	0.218
87.8	6	8.19	0.23	0.811	0.181

Dan and Jain (1971) reported a new blanching medium for dehydration of red coloured Asiatic type carrots. Bright red Asiatic carrots were washed, peeled, shredded and blanched in steam, boiling water and sugar solutions of varying concentration (2-10 Brix) for 5-15 minutes. The results of blanching carrot shreds for 5 minutes in varying concentrations of sugar solutions (between 0 and 10 Brix) showed that there was an increase in the total soluble solids of the medium when the initial Brix was less than that of fresh carrots (i.e. 4.5 Brix), due to leaching out of soluble solids from the shreds into the medium.

In the case of media of initial Brix higher than that of the shreds, there was uptake of sugar by the shreds from the medium. The blanching medium of 4.6 Brix for carrot shreds was considered as optimum because of the minimal changes in the total soluble solids of the shreds as well as the blanching medium. Blanching in plain water caused maximum leaching loss to the shreds lowering the total soluble solids to 1.4 Brix. The results are summarised in Tables 3.16 and 3.17. The retention of reducing sugars in the shreds was found to be dependent on the concentration of the sugar in the blanching medium and the time of blanching. They concluded that blanching in water resulted in maximum leaching losses from the carrot shreds, while use of sugar solutions and steam blanching induced little leaching loss.

The loss of ascorbic acid, riboflavin, thiamin and carotene in carrots using different blanching methods of live steam and hot water were studied by Mirza and Morton (1974). The time taken to blanch the carrot was checked by the time taken to inactivate the enzyme peroxidase (2 min for steam blanching and 3.5 min at 100°C for water blanching). They found that steam blanching gave better retention of water soluble vitamins in carrots than water blanching. Carotene content showed some increases on blanching and this was probably due to the leaching of water soluble solids whereas carotene, being insoluble, was retained.

TABLE 3.16: Effect of sugar concentration in blanching media on total soluble solids, dry matter and reducing sugars in carrot shreds blanched for 5 minutes (After Dan and Jain, 1971)

Blanching medium (sugar solution)		Blanched Shreds		
°Brix		Dry matter %	°Brix	Retention of reducing sugars %
Initial	After blanching			
0.0	0.4	3.92	1.4	39.96
2.2	2.4	6.55	3.7	21.29
4.6	4.5	8.91	5.8	Not dtd.
6.8	6.4	11.0	7.7	16.20
9.2	8.6	13.19	9.1	15.69

TABLE 3.17: Effect of blanching medium and blanching time on total soluble solids (TSS) and the % retention of reducing sugars in carrot shreds (After Dan and Jain, 1971)

Blanching Medium			Blanching time (min)	Blanched Shreds			
Type	TSS of medium °(Brix)			Dry matter %	TSS °(Brix)	Retention of sugars %	
	Initial	After Blanching				Reducing	Total as invert
Water	0.0	0.8	5	4.90	1.4	34.9	30.4
	0.0	0.9	10	4.87	1.2	32.1	28.3
	0.0	1.0	15	5.37	1.1	30.6	27.9
Sugar solu-tion	4.7	5.4	5	11.48	5.9	14.9	81.4
	4.7	5.3	10	11.62	6.1	15.3	81.1
	4.7	5.3	15	11.94	6.3	15.9	81.5
Steam at atmos-pheric pressure	-	-	5	7.54	5.1	94.0	87.7
	-	-	10	8.26	5.1	94.3	86.6
	-	-	15	8.26	5.1	95.2	86.6

Thermal destruction of carotenoids by blanching and cooking of carrot, and leaching of soluble solids during processing of carrot were examined by Baloch et al. (1977) in an attempt to explain the apparent increase in carotenoid content during processing. Results given in Table 3.18 showed a positive relationship between the apparent increase in carotenoid content and leaching loss. Increases in carotenoid contents were obtained when results were calculated on a dry weight basis for the leached material, but when the results were calculated on a water insoluble solids basis, no such increase in carotenoid content was apparent. Therefore they suggested that leaching of soluble solids is a major factor responsible for the apparent increase in the carotenoid content of carrot during processing. Several workers have also found leaching losses to be responsible to a great extent for such increases during processing of carrot (Lee, 1945; Della Monica and McDowell, 1965).

TABLE 3.18: Effect of leaching of soluble solids on carotenoid content of processed carrot (After Baloch et al., 1977)

Treatment	Loss in soluble solids (% dry wt basis)	Increase in carotenoid content (% drywt basis on leached material)
Unblanched	-	-
Blanched	2.7	9.1
Water dipped	6.9	26.1
Detergent dipped	7.5	29.1
Water washed	11.9	48.2
Detergent washed	14.5	58.0
Water dipped at $75^{\circ}C$	8.1	27.9

Guerrant et al. (1947) and Weckel et al. (1962) also found leaching losses of water soluble solids resulted in such apparent increases in carotenoid content during blanching and processing.

In a more detailed study, Selman and Rolfe (1979) carried out laboratory scale experiments to demonstrate the main mechanisms by which weight changes and solute loss occurred in immature pea seeds and carrot root tissue during blanching in water. Samples of vegetable tissue were blanched in 80 ml distilled water at temperatures from 20 to 97°C for periods not exceeding 25 minutes. The results showed that loss of solutes by diffusion appeared to be influenced largely by the initial solute concentration of the cell sap, whereas the overall tissue weight loss appeared to be governed largely by the initial cell volume, inherent cell turgor pressure and the elasticity of the cell walls.

3.3.3 Diffusive Loss of Nutrients During Blanching of Potato Tissue

Gooding (1956) made a comparison on a factory scale between scalding of vegetables in water and in steam at 98-100°C and the effects of these processes on the yield, quality and storage life of the products. The results for potato (Table 3.19) showed that when thicker strips (3/16 x 5/16 in) of potato were used, the total loss of dry matter was 13.0% with water scaling and 7.4% during steam scalding (the increase in yield resulting from steam blanching was 6.2%), and when thinner strips were used (1/8 x 5/6 in), water scalding led to an increase in loss (17.9), but with steam scalding the yield was almost exactly the same as that obtained from the thicker strips. On the other hand he found that steam blanching did lead to the expected reduction in high-temperature storage life. He recommended that if steam blanching was to be used in the manufacture of dehydrated potato it would be necessary to ensure that the raw vegetable had a low content of reducing sugar. Also he recommended adequate washing before scalding to remove superficial starch which led to slimness in the cooked potato.

TABLE 3.19:   Yields resulting from water and steam scalding
              (After Gooding, 1956)

Strip Dimension inch	Variety	Water Scalding		Steam Scalding	
		Yield as % of trimmed potato	% Recovery of dry matter	Yield as % of trimmed potato	% Recovery of dry matter
3/16x5/16	King Edward	16.1	87.0	17.1	92.6
1/8x5/16	" "	15.6	82.1	17.2	92.4

The leaching of solutes and the sloughing (disintegration of the outer layers) of potato tuber tissue were investigated by Davis et al. (1973).   Slices of tissue from low (1.075-1.078) and high (1.092-1.094) specific gravity tubers were soaked in distilled water (100 g/250 ml) at room temperature for 0, 1, 2, 3, 4 and 6 hours. Then the pH, electrical conductivity, total solids, potassium, phosphorus and citric acid content of the soak water were analysed. They noted that all constituents studied diffused into the water during the soak periods. After 6 hours the average amount of materials in the soak water were: total solids 23%, phosphorus 68%, phytic acid 55%, potassium 71%, total ash 62%, total nitrogen 56%, calcium 35% and magnesium 50%.   The greatest losses from the slices occurred in the first 2-3 hours and were similar for both specific gravity groups. The decrease in the amount of citric acid in the soak water after reaching maximum value 67% after 3 hours soaking was attributed to either a concentration gradient effect or to metabolism of the acid. The effect of soaking on composition of potato is shown in Table 3.20. They also found that the decrease in sloughing was highly correlated ($P < 1\%$) with the length of soak period, the increase in electrical conductivity of the soak water, and with the leaching of all constituents measured.

TABLE 3.20:   Effect of soaking on sloughing and composition of
Russet Burbank potato tissue (After Davis et al., 1973)

Specific Gravity	Soak Period hr	Cooking potato weight g	Total solids g/100g	Total nitrogen mg/100g	Total ash mg/100g	Electrical conductivity mg KCl/1
Low 1.075-1.078	0	22	20.4	440	817	0
	1	57	17.1	307	600	1000
	2	89	16.9	230	487	1277
	3	109	16.5	177	440	1623
	4	114	16.1	163	360	1742
	6	120	15.9	130	297	1928
High 1.092-1.095	0	15	23.4	293	890	0
	1	56	20.4	200	697	1120
	2	84	19.3	183	597	1420
	3	95	18.8	157	533	1530
	4	108	18.3	157	427	1775
	6	114	17.7	170	350	1993

The effects of various unit operations of commercial potato
processing plants on proteins and vitamin content of the products
were investigated by Augustin et al. (1979a). The investigation
included processing lines for potato granules and flakes as well as
dehydrated slices and dices. They pointed out that in general, protein
and vitamin retentions were lowest at any point where potatoes were
exposed to high temperature for prolonged periods of time.

In the granule process, total retention values over the entire
process varied from 9% for thiamin to 83% for protein and vitamin B6
(Table 3.21). Ascorbic acid and folic acid retention were below the
50% level. The relatively low retention values for ascorbic acid and
folic acid during water blanching were believed to be due to a combination

TABLE 3.21: Percent overall nutrient retention during commercial
potato granule production (After Augustin et al., 1979a)

Treatment	Pro-tein %	Ascor-bic acid %	Thia-min %	Ribo-flavin %	Nia-cin %	Folic acid %	Vita-min B6 %
Water blanching	91	86	94	103	90	69	91
Cooling	88	81	98	83	91	68	85
Steam blanching	87	79	84	92	80	60	79
Mixing and mashing	90	43	9	119	74	42	81
Conditioning	89	42	7	105	73	43	79
Dehydration	83	45	9	125	78	48	83

of leaching as well as to their sensitivity to heat. They observed
that riboflavin values increased significantly during the granule
process. It was hypothesized that the increase in riboflavin reten-
tion was due to the presence of lipids interfering with the analysis.
During the flake operation, water blanching and the drum drying
operation resulted in the greatest reduction of retention values.
Thiamin retention was a relatively high 64% during the production
of potato flakes. The manufacture of dehydrated slices and dices
showed the lowest retention values of all the dehyrated potato
products investigated. Overall retention values ranged from 4% for
thiamin to 85% for protein (Table 3.22). The low values found with
thiamin were not the results of heat inactivation or leaching, but
were due to the interaction of this nutrient with sulphites.

With the exception of ascorbic acid, retention losses were
significantly greater during water blanching than during dehydra-
tion. They concluded that the nutrient retention is significantly
reduced during commercial dehydration of potato, with the exception
of thiamin which is completely destroyed during the granule process
as well as in the slice and dice operation, and ascorbic acid which

is retained at roughly the 40% level, all nutrients are retained at the 50% or higher level.

TABLE 3.22: Percent overall nutrient retention during commercial potato slice and dice operation (After Augustin et al., 1979a)

Treatment		Pro-tein %	Ascor-bic acid ·%	Thia-min %	Nia-cin %	Folic acid %	Vitamin B6 %
Slices	Water blanching	88	70	95	82	70	80
	Dehydration	85	40	4	73	58	72
Dices	Water blanching	95	.68	97	88	79	90
	Dehydration	86	38	4	80	69	84

Augustin et al. (1979b) also investigated the nutritional effects of the various unit operations in commercial processing plant of frozen potato products. The investigation involved a processing line for french fries and pre-formed patties. In general, the total retention values were highest with protein, thiamin and niacin, and the lowest with ascorbic acid and folic acids (Table 3.23). Differences between total retention and retention during water blanching in general were insignificant. Retention values with small cut ($\frac{1}{4}$ in) french fries were lower than those of the large ($\frac{1}{2}$ in) size cut. This was probably due to differences in leaching losses of some nutrients as a result of different volume to surface area ratios of the two sizes cut.

With the exception of the case of ascorbic acid in preformed patties, water blanching was found to be the major cause of nutrient reduction during commercial frozen french fry production. The overall retention values found ranged from a low of 53% for ascorbic acid in preformed patties to a high of 90% for Vitamin B in preformed patties also. The results (Table 3.24) also show that the

TABLE 3.23: Percent retention of nutrients during commercial processing (After Augustin et al., 1979b)

	Large sized French fries [a]		Small sized French fries [a]		Preformed patties [a]	
	Total	Water Blanching	Total	Water Blanching	Total	Water Blanching
Protein	85[b](12.0)[c]	89(6.2)	81(8.5)	81(12.7)	90(4.4)	97(7.0)
Ascorbic acid	69 (14.4)	75(10.2)	61(20.3)	69(22.0)	53(26.6)	80(6.3)
Thiamin	80 (11.4)	80(9.3)	81(16.8)	88(5.9)	88(9.9)	96(5.6)
Niacin	84 (1.25)	85(8.0)	74(13.6)	78(18.4)	90(18.2)	93(7.9)
Vitamin B_6	78 (12.5)	79(12.0)	74(11.9)	77(19.0)	91(12.8)	92(9.6)
Folic acid	66 (19.4)	69(19.5)	65(23.3)	66(21.1)	73(16.2)	81(13.2)

a Number of plants sampled; b % retention; c Coefficient of variation

TABLE 3.24: Comparative percent retention of nutrients in potatoes during water and steam blanching (After Augustin et al., 1979b)

Nutrients	Water Blanching %	Steam Blanching %
Protein	81	94
Ascorbic acid	69	89
Thiamin	88	90
Niacin	78	93
Vitamin B6	77	97
Folic acid	66	93

retention values of steam blanching were significantly greater than those of water-blanching.

The loss of Vitamin C and solids from potato strips after soaking-blanching at temperatures from 25-80°C for periods up to 30 minutes, after par-frying (at 185°C for 90 sec), frozen storage

and after finish frying (at 185°C for 90 sec) were determined by
Boushell and Potter (1980). Vitamin C was lost during soaking-
blanching at 25 to 80°C to the extent of 2.7-68% of the initial
Vitamin C level, and the rate of this loss was increased with the
use of higher blanch temperatures. In most cases the rate of
Vitamin C loss was greater during the first 10 minutes of the
blanching than in subsequent minutes. The loss of Vitamin C was
attributed to both heat destruction and leaching. Additional losses
due to finish-frying were high and exceeded those due to water
blanching. Final Vitamin C levels were as low as 9.2% of the original.
However, soaking-blanching did not significantly affect the solids or
fat content of potato strips, but both processes of frying were found
to increase the total solids content of the strips. This effect of
frying on solids content was due to water evaporation and oil
absorption.

Effect of boiling at 100°C for 10, 20 or 40 min or blanching
for 2 min at 100°C in distilled water on retention of L-ascorbic
acid, thiamin and riboflavin of peeled and unpeeled potato and
other vegetables was investigated by Salib et al. (1980). Generally
they found that boiling resulted in greater decreases of vitamin
content than blanching, and vitamin retention decreased as boiling
time increased. Also the retention of vitamins in vegetables boiled
in acidic solution pH6 was higher than in alkaline solution pH8 and
after boiling in distilled water.

Kozempel et al. (1982) reported a significant loss of nutrients
from 0.95 cm french fries cut potato in hot water blanching at 77°C
for 16 min. These nutrients were: ascorbic acid, thiamin, riboflavin,
niacin and some amino acids, glutamic acid, aspartic acid, valine,
phenylalanine, arginine, methionine and tryptophan. Based on the
assumption that vitamin losses in potato are due to leaching, a
model based upon diffusion as the rate controlling step in leaching
was successfully used to correlate and predict the loss of the
vitamins. Also, the authors suggested that most of the losses of
amino acids may be due to leaching of the free amino acids from the potato.

3.4 Conclusions

From the review of the literature on the blanching of
vegetables (carrot and potato), it appears that most of these
studies report only losses or retention under selected conditions
and do not give information on the losses as functions of tempera-
ture, time, concentration, dimension and other properties. Rela-
tively few studies have involved the sugar and solids losses from
carrot and potato tissue, and in most cases little consideration
has been given to the mechanisms of loss involved. There is also
little evidence to show whether the variability of raw materials,
supposedly of the same tissue type, have any significant effect
on loss rate.

In literature concerned with the study of diffusion coefficient
of nutrients during processing, there seems to be a lack of informa-
tion on the diffusion coefficients of solute and sugar from carrot
and potato. Most workers seem more concerned with the evaluation
of the diffusion coefficients rather than the actual mechanism
involved. However, in very general terms, it appears that diffusion
coefficient is governed by the process temperature, medium concentra-
tion and the diffusing substance size, and very few studies have
examined the diffusion coefficients as function of these properties.

3.5 Objectives of this Research

The first objective of this work was to examine the mechanisms
of solute loss from both carrot tissues (non-starchy food) and
potato tissues (starchy food) during water blanching, using the
same parameters as those found in the literature survey, i.e. to
study the effects of blanch temperature, blanch time, blanch medium
concentration, dimensions of tissue to be blanched, tissue to
blanch water ratio, and post-blanching cooling process. The next
objective was to apply Fick's law of diffusion to describe the rate
of solute loss during blanching and to estimate values for diffusion

coefficients (D_a) under various conditions of tissue size, blanch time, temperature and concentration of the blanch medium. One objective of this study was to study the diffusivity of reducing sugars out of potato during laboratory scale and industrial scale blanching and to determine if the diffusion model obtained from laboratory data could be used to correlate and predict the loss of reducing sugars on an industrial scale.

As the water blanching of vegetable involves simultaneous heat and mass diffusion and as a knowledge of the thermal properties of vegetables (thermal diffusivity, thermal conductivity and specific heat) are necessary in order to predict heating or cooling rates during processing, the work was extended to ascertain the relative importance of heat diffusion during blanching.

4. MATERIALS AND EXPERIMENTAL METHODS

4. MATERIALS AND EXPERIMENTAL METHODS

4.1 Laboratory Scale Blanching

4.1.1 Carrot Blanching Studies

4.1.1.1 Raw material and sample preparation

The carrots (<u>Daucus</u> <u>carota</u>, variety Chanetenay) used in this work were supplied by the National Vegetable Research Station, Wellesbourne.

Commercial samples of carrot roots purchased from a local supermarket were also used in this study for comparative purposes.

The carrots were sorted to select those with a length of 0.12 to 0.15 m and a diameter of 0.025 to 0.035 m before storage at $5-6^{\circ}C$ in paper sacks.

Cylindrical samples 0.06 m long and 0.006 m diameter were cut longitudinally from the carrot tissue by using a No 3 size cork borer.

The cylinders were trimmed by a scalpel to the required length. This effectively 'infinite' cylinder was chosen because of the availability of a formal solution for unsteady state diffusion and the similarity to the shape of a whole carrot. Several cylinders were cut from a number of carrot roots and placed in a covered petri dish to minimise the evaporation from the surface during the short delay prior to use.

After the carrot cylinders were prepared, they were mixed together to minimise the variation in composition and then used immediately for blanching.

Samples consisted of two cylinders (approximately 0.005 kg) for each blanch time. The samples were carefully blotted with absorbent paper to remove the surface cell sap before being weighed. Samples from both cortex and core were used separately in this work and the preparation was the same.

4.1.1.2 Blanching apparatus

The blanching apparatus consisted of a large glass vessel of 0.45 x 0.29 m diameter and 29 litre capacity. The blanch media used was either distilled water or sucrose solutions. In order to maintain a constant concentration in the blanch medium and to effect an infinite volume, the vessel was filled with 27 litres of the blanch medium.

The temperature of the blanch medium was thermostatically controlled to $\pm 0.5^{\circ}C$ by a sensitive thermostat connected to an immersion heater. The blanch medium was constantly agitated by an impeller to maintain a uniform concentration and temperature distribution at the surface of the carrot sample.

Evaporation from the surface of the blanch medium was minimised by a number of plastic spheres of about 0.015 m diameter floating on the surface (see Figure 4.1).

4.1.1.3 Blanching procedure

Cotton thread was passed diametrically through the centre of each carrot cylinder with a fine needle so that two carrot cylinders of each sample were suspended in a horizontal fashion and were about 0.10 m apart. The cylinder samples were presented, with no pre-treatment to the blanch medium in such a way that several samples of two cylinders each fixed on threads of cotton were suspended vertically from cross bars fixed at the top of the vessel.

Thermostat
control devices

Electronic
thermometer

Impeller

Plastic
spheres

Immersion
heater

Blanching
medium

Potato
cylinder
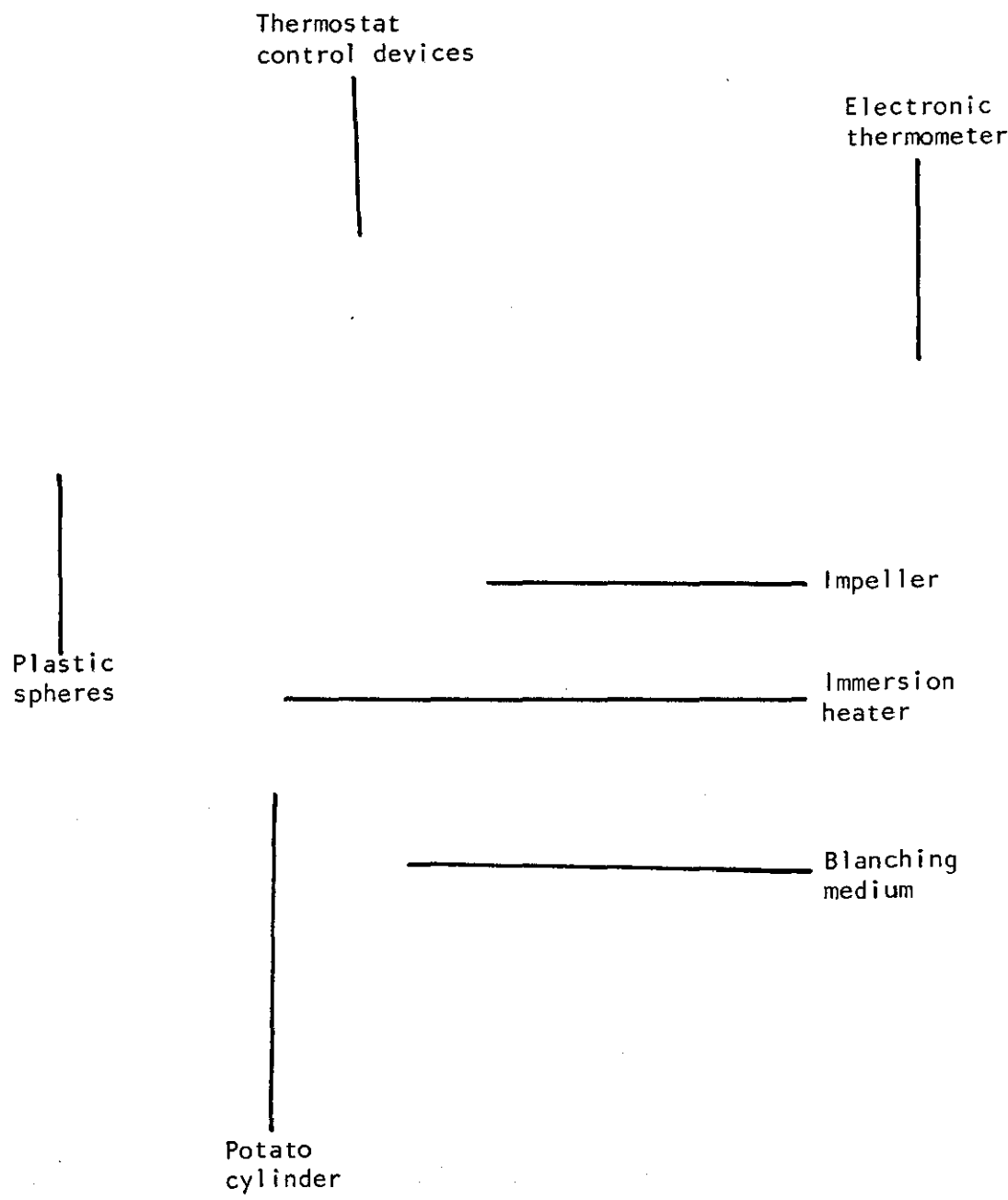
FIGURE 4.1:   Blanching medium
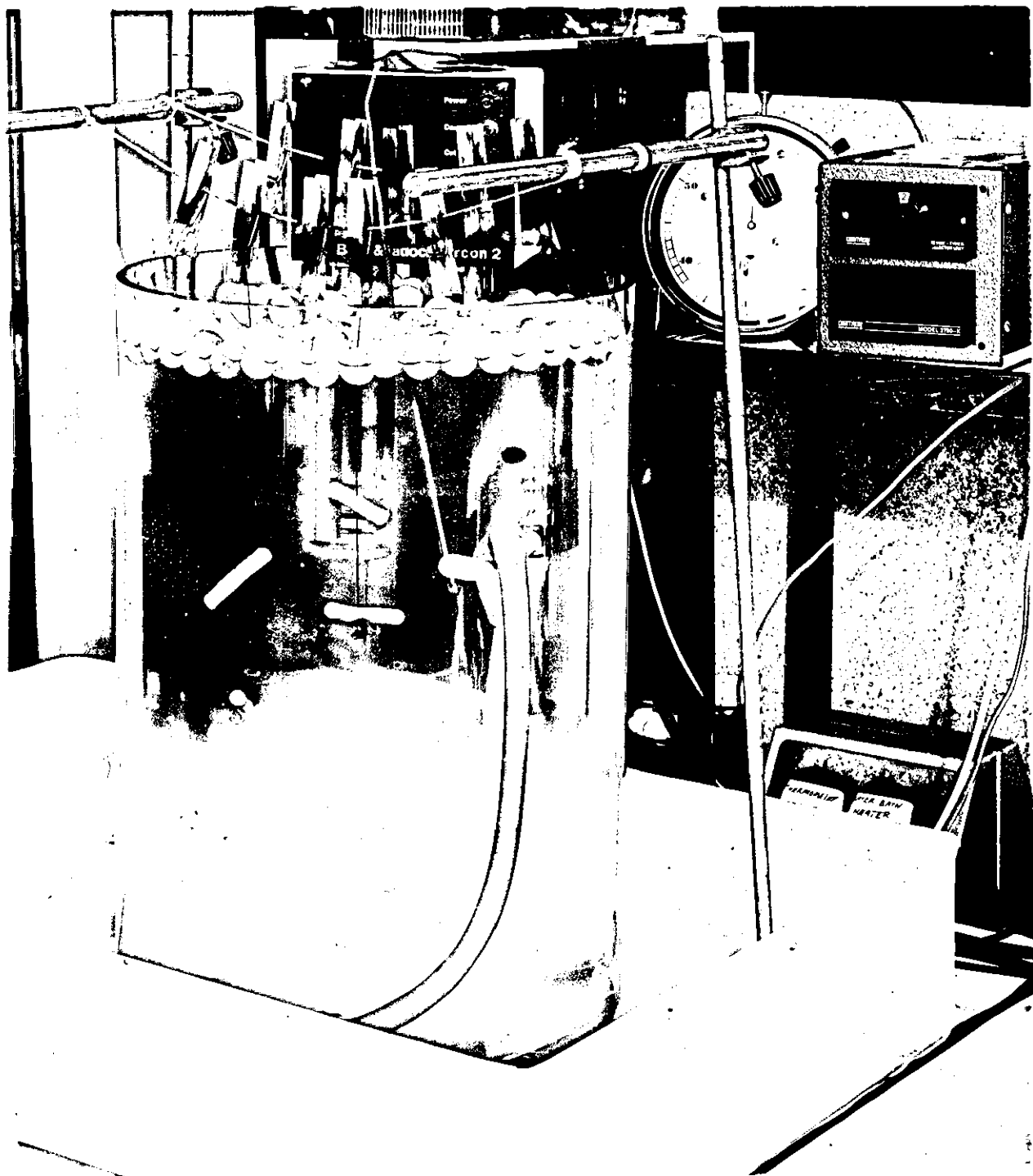
A small weight was attached to the bottom of the thread to prevent the cylinders from floating and getting entwined with other samples present in the vessel.

The blanching time was recorded from the time the carrot cylinders were immersed into the blanching medium. After the required blanch time the samples were removed from the vessel, lightly blotted with absorbent paper to remove drops of free liquid, separated from the cotton thread and placed in a closed petri dish.

One cylinder in each sample was used to determine the total weight loss and the dry matter and the other one was used for the determination of the cell sap concentration.

A post-blanch cooling procedure was not incorporated unless specifically stated.

4.1.2 Potato Blanching Studies

4.1.2.1 Raw material and sample preparation

Fresh new potatoes (HomeGuard and Maris Bard varieties) were supplied by Thorolds of Loughborough and potatoes of the Record variety were supplied by an industrial company.

Record potatoes were used only with sugar studies. The potatoes were stored in paper sacks at 10-15°C. Whole potatoes to be blanched were removed from store and washed in water and dried.

Samples were prepared by dicing the whole potatoes into 1 cm cubes (unless otherwise stated). Cubes were chosen because they were easy to obtain from potato. Cubes were cut from the pith area only. Quantities of cubes from at least 5-7 potatoes were prepared and thoroughly mixed to ensure uniformity, and placed in a covered beaker to minimize the evaporation from the surface.

The cubes were then immediately used for blanching.

A sample of 9 cubes (10.50g $\pm$ 0.30g) was used for each blanch time. This method of preparation was used to minimise the variation in composition among the cubes of the potatoes.

4.1.2.2 Blanching apparatus

The blanching technique was developed from that described by Selman and Rolfe (1979). The samples of vegetables were blanched in distilled water in a 250 ml beaker. The temperature of the blanch water was maintained by using an electrically heated hot plate set at the required temperature and a bunsen burner.

The drop in blanch temperature caused by addition of the sample to the water was minimised by placing the beaker over a bunsen flame for 20 seconds before returning the beaker to the hot plate.

The blanch water in the beaker was agitated by a magnetic stirrer at constant rate (120 rpm). The evaporation of water during blanching was minimized by covering the beaker with a lid of aluminium foil. A thermometer was kept inside the beaker to check any change in temperature of water during blanching.

4.1.2.3 Blanching procedure

Samples of potato tuber of approximately 10.50 $\pm$ 0.30g (9 cubes) were blanched in a 250 ml beaker containing 50 ml distilled water to give a ratio of sample to water during blanching of approximately 1:5 (unless otherwise stated).

Nine cubes of potato were added in one lot to the blanch water with no pre-treatment. The blanching time was varied from 120-1800 sec. The blanching time was recorded from the time the potato cubes were dipped into the blanching medium. After the required blanch time, the potato cubes were drained out over a

funnel and blotted lightly between two pieces of absorbent paper in a standard manner to remove surface moisture before being placed in petri dishes and then weighed after it was cooled.

The blanch water was collected in a glass dish and dried to constant weight at 95-100°C in a circulated air oven.

No post-blanching cooling was used in this procedure unless otherwise stated. The potato cubes were handled with care and in a standard manner during the procedure.

4.2   Industrial Scale Blanching

4.2.1   Raw Material and Sample Preparation

Medium size Record potatoes (0.05 - 0.07 m) diameter were kept stored at 10°C until use. The mean value of dry matter content was 22.2 ± 0.8.

The potatoes were sliced mechanically in most cases trans-versely to the main axis, and cut into slices (0.065 m length and 0.059 m width) with a thickness of 0.147 ± 0.025 cm.   At least three measurements of the thickness were made at different points of each piece with a dial micrometer (13 pieces were used) (see Appendix II).

4.2.2   Sampling and Operating Procedure

A similar study to that developed on the laboratory scale was conducted on the factory scale (commercial operation).   Potato samples were collected from various stages of a processing line. Samples of blanch water were also collected (see Appendix VIII).

A flow chart for the processing line and the sampling points are shown in Figure 4.2.   The potato samples were collected from

FIGURE 4.2: Diagrammatic representation of process layout and sampling points

P = Potato sample point

W = Water sample point
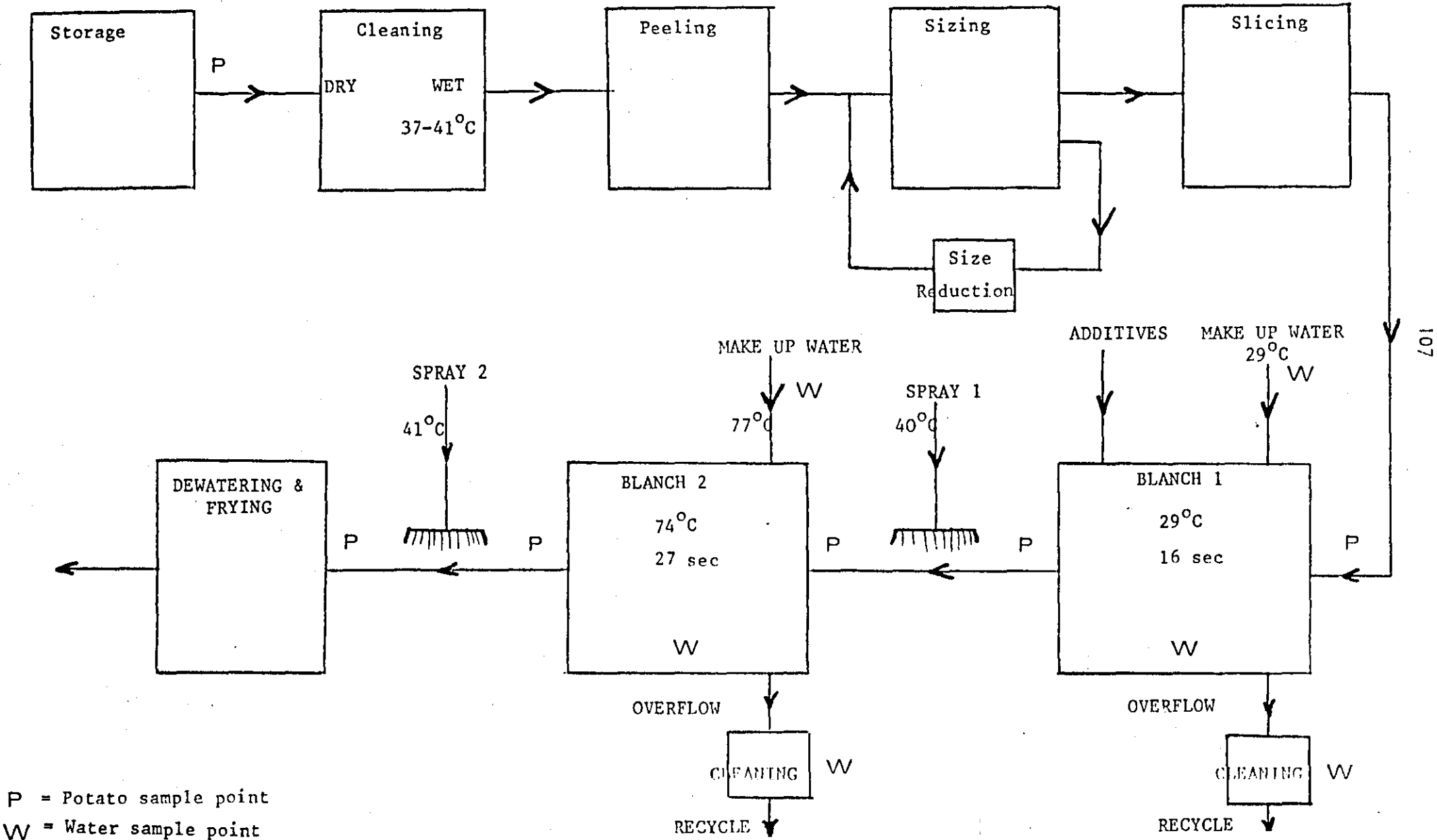
six points along the processing line; (1) at the store, (2) after slicing, (3) after washing at $29^{o}C$ for 15-17 sec, (4) before the hot blanching, (5) immediately after hot blanching (27 sec at $74^{o}C$), (6) after water spraying at $41^{o}C$.

Blanch water samples were collected from each of the following points:

1. from the wash water in blanch 1;
2. from the make up water 1;
3. from the overflow in blanch 1;
4. from the blanch water in blanch 2;
5. from make up water 2;
6. from the overflow in blanch 2.

The parameters investigated were total and reducing sugar content, total, soluble and suspended solids and dry matter content for both potato slices and blanch waters.

The potato slices and blanch waters were sampled in duplicates of approximately 300 g each for every sampling point as shown in Figure 4.2.

Following the removal of samples from the line, each sample was put inside a glass jar, and labelled. The samples were transported to the laboratory and then stored at $5^{o}C$ until the analysis. Within three days of sampling,part of each sample was used for dry matter determination, solids loss measurement and sugar extraction. The extracted samples were stored at $5^{o}C$ until used for the sugar analysis. The remaining part of each sample was also stored at $5^{o}C$ for further analysis.

4.3 Analytical Procedures

4.3.1 Measurement of Sample Weight

When the sample preparation was finished, samples of nine cubes of potato or one cylinder of carrot for each blanch time were carefully and lightly blotted with absorbent paper to remove the surface moisture.

The samples were then quickly placed in a closed dish and weighed.

After a given blanch time, the samples were sieved over a funnel and quickly blotted in the same way and placed in a closed dish and then weighed after cooling.

4.3.2 Measurement of Dry Matter Content

The dry matter content of the fresh vegetable tissue was estimated by drying samples of 0.005kg approximately (4 cubes of potato or 3 cylinders of carrot) in a vacuum oven at $70^{o}C$ and 13.33 kN m^{-2} pressure (100 mm) to constant weight.

The dry matter content of blanched samples was estimated immediately after draining, blotting and weighing of blanched cubes or cylinders. Samples of blanched potato cubes or carrot cylinder were cut into thin slices to enhance drying and dried in the same way in a vacuum oven.

4.3.3 Measurement of Cell Sap Concentration

Total soluble solids content (cell sap concentration) was measured using an Abbe refractometer calibrated with sucrose solutions w/w at $20^{o}C$. The cell solution was obtained from the sample by pulping the sample with a pestle and mortar and then squeezing out by hand into a small dish. The calibration curve is as shown in Figure 4.3.
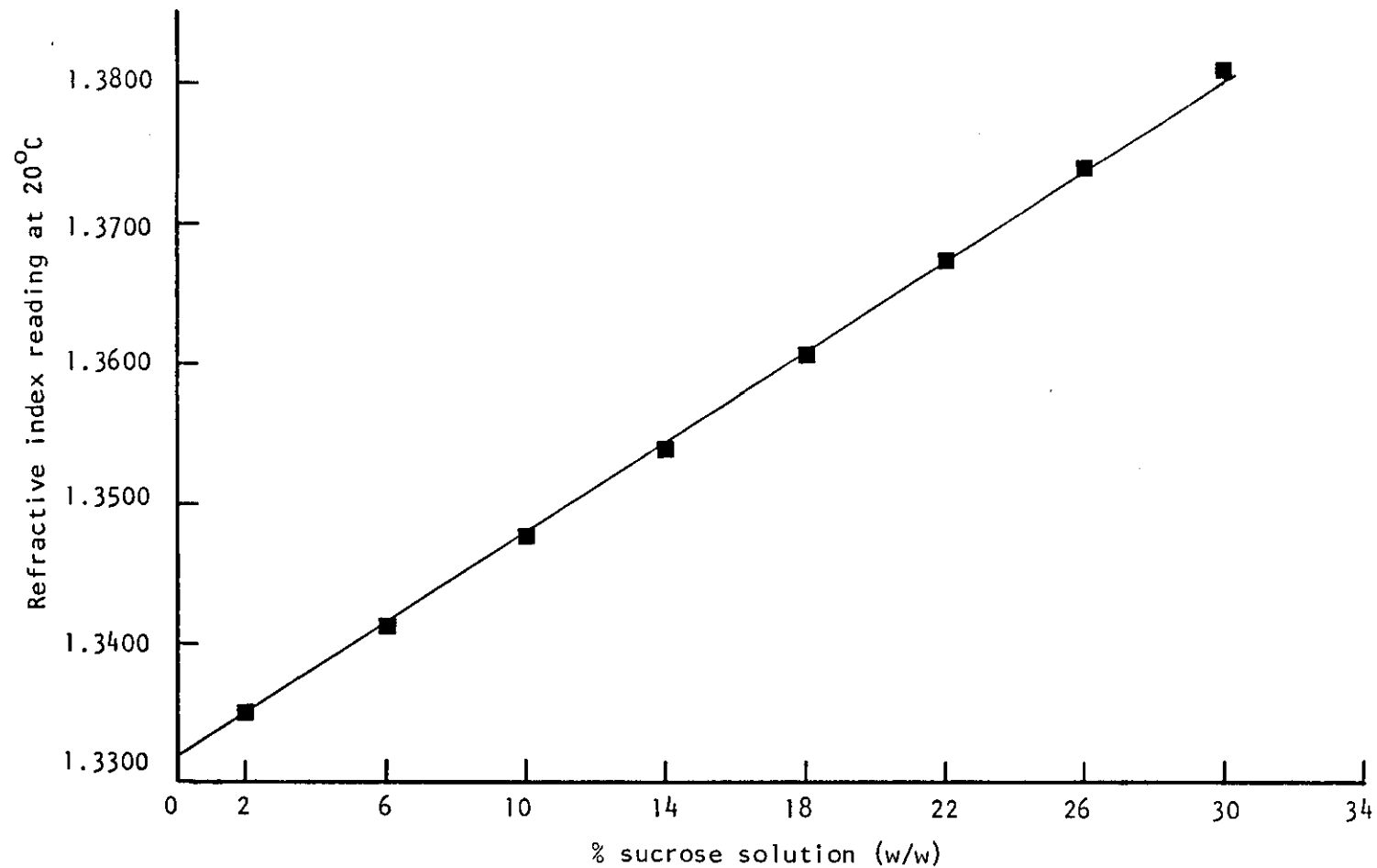
FIGURE 4.3: Calibration graph of refractive index vs % sucrose solution (w/w) at 20°C

4.3.4 Measurement of Total Solids in the Blanch Water

After blanching, the potato cubes were sieved over a funnel and removed. The blanch water was collected in a glass dish and dried to constant weight at 95-100°C in a circulated air oven.

The percentage of solids lost from the tissue sample into the blanch water was calculated as follows:

$$\text{\% solids lost into blanch water} = \frac{\text{weight of solids in blanch water}}{\text{initial fresh weight of tissue sample}} \times 100$$

For soluble solids, the blanch water was filtered through No 541 Whatman filter paper and dried to constant weight. The soluble solids were calculated from the difference between the total and insoluble solids.

4.3.5 Method for Varying the Initial Moisture Content of the Tissue

In order to see how the initial moisture content of fresh tissues influenced the losses of solids and weight changes during blanching, the initial water content of fresh tissue was varied. The water content of fresh tissues was decreased by allowing water to evaporate from samples at 30°C in a circulated air oven for different times, and increased by allowing samples to take up water during immersion in distilled water at 20°C for various times. The resulting changes in fresh weight and cell sap solute concentration were then measured as shown before (Selman and Rolfe, 1979).

4.3.6 Alcohol Insoluble Solids (AIS) Determination

The AIS was measured using the method of Moyer and Holgate (1948). Samples of 20g of macerated material were transferred to a 100 ml measuring cylinder and then blended with 80 ml 85% ethanol for 60 sec using a 'Silverson' homogeniser. The solids were then filtered through No 41 Whatman filter paper using a Buchner funnel. The residue after filtration was then dried to constant weight in an air oven at 95-100°C. AIS content was used as a maturity characteristic of the tissues.

4.3.7 Determination of Sugar Content

The total and reducing sugar contents (and sucrose by difference) of the blanched potato and blanch water were determined using the method of Cronin and Smith (1979). The method was chosen because a rapid procedure was required for the analysis of a large number of samples. Solutions of glucose covering the concentration range 50-500 μg/ml were prepared in 85% methanol and used to construct the standard calibration graph, see Figure 4.4. The sugar content was calculated as follows:

Analysis of potato samples before and after blanching:

Sugar in potato sample % =

$$= \frac{\text{Reading from graph μg/ml} \times D \times 10^{-6} \times 100}{\text{Initial weight of potato sample}}$$

= g of sugar/100 g of fresh weight.

Analysis of blanch waters:

Sugar lost into blanch water % from the potato sample

$$= \frac{\text{Reading from graph μg/ml} \times D \times 10^{-6} \times 100}{\text{Initial weight of potato sample}}$$

= g of sugar lost into blanch water/100 g of initial fresh weight of potato sample
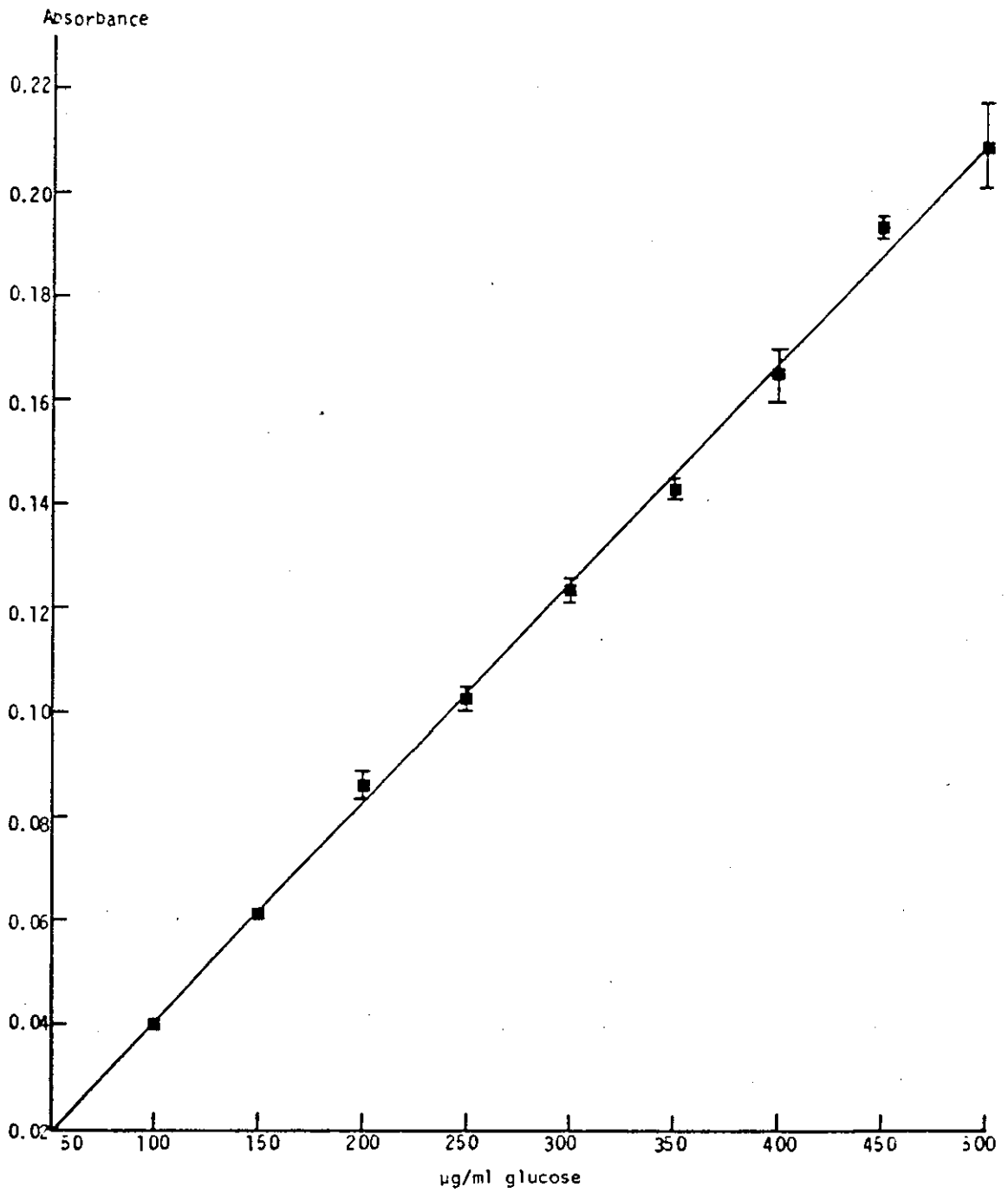
FIGURE 4.4: Calibration graph showing glucose (µg/ml) versus absorbance for the Unicam SP 500 spectrophotometer at a wavelength of 520 nm

D = is the dilution factor

4.3.8 Free Water Content Measurement

The water which is removed by using a forced convection oven at 100-105°C is called the total water content. The free water content is defined as:

'Total water' content - 'Bound water' content

=   'free water' content

In the vegetable tissue most of the sugar and other soluble materials are present in solution in the free water of the tissue, Kuprianoff (1958). So a measure of free water content was required. The free water content was calculated from the measurement of the concentration before and after addition of a known amount of water to a potato sample as follows.

The concentration before adding water to the sample was first measured:

$$C_1 = \frac{m}{W_1} \tag{4.1}$$

This was followed by the measurement of concentration after adding water to the sample

$$C_2 = \frac{m}{W_1 + W_2} \tag{4.2}$$

where: m = amount of soluble solids in sample

W_1 = unbound water (free water)

W_2 = amount of water added

C_1 = concentration of sample (refractometric solids of cell sap)

C_2 = concentration of sample after known amount of water is added.

Then by solving equations 4.1 and 4.2, equation 4.3 was obtained from which the free water content of the potato sample was calculated:

$$W_1 = \frac{W_2 \, C_2}{C_1 - C_2} \qquad\qquad (4.3)$$

The concentration of the tissue C_1 and C_2 was measured by using an Abbe refractometer.

4.4 Transient Temperature Distribution Studies

4.4.1 Raw Materials and Sample Preparation

The potatoes used in this study were the Record variety (see Materials section). The potatoes were removed from storage before use and allowed to equilibrate with room temperature to ensure uniform temperature distribution in the potato. A cylindrical section of potato tissue was cut from the central area of the tuber (pith) by using a sharp cork borer size number (10). One cylinder sample was taken from a single potato along the major axis. The cylinder was 0.015 m in diameter and 0.07 m in length so that the ratio of the length to the diameter of the sample was high.

By choosing a high ratio of length to radius and by insulating the ends of the cylinder, a good approximation to the infinite cylinder was attained, i.e. the radial condition only.

4.4.2 Temperature Measurement Apparatus

Figure 4.5 shows a schematic diagram of the apparatus used for measuring temperature distribution in the potato sample. The thermocouples were carefully passed through the upper cork insulation of the apparatus, so that the thermocouple wires passing through the cork lay in the central axis of the apparatus.
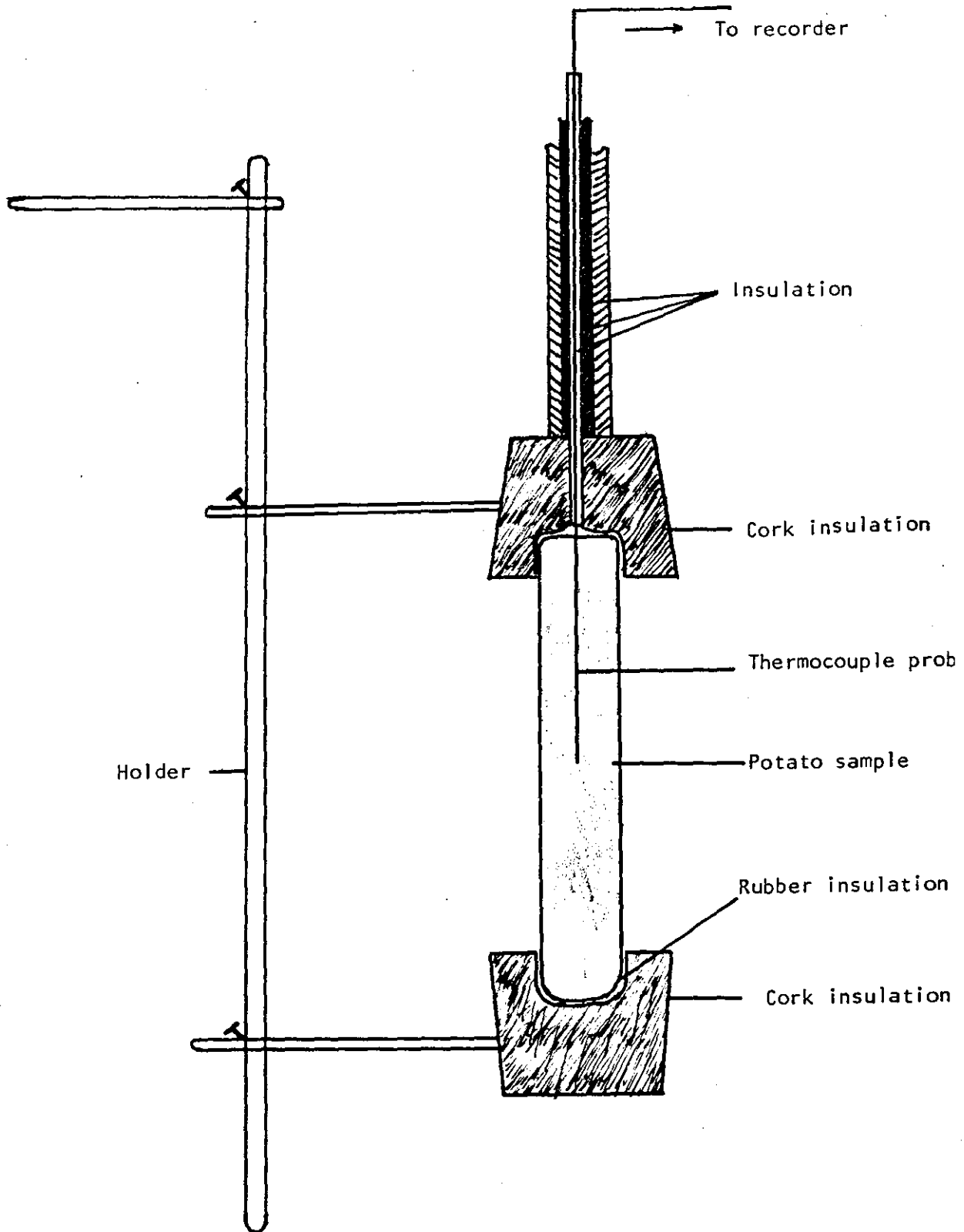
FIGURE 4.5: Apparatus used to measure the temperature distributio in potato during heating and cooling

The thermocouple probe was positioned at the mid-point of the central axis, about 0.035 m from the cork insulation. The apparatus was then mounted on a holder. The assembled apparatus was placed in a constant temperature water bath at 20°C and allowed to attain bath temperature. After attaining the desired initial uniform temperature, the assembled apparatus was then transferred quickly to a second constant temperature water bath (heating medium), see Figure 4.6. The temperature at the centre of the sample was recorded as a function of time by a digital temperature recorder (one-point flat bed chart recorder) using paper moving at 0.025 m/min speed. The potato sample remained in the bath until the measured temperature was within 0.2°C of the water bath temperature. After each sample was heated, it was cut open to check that the thermocouple had been at the centre. Temperature measurements from samples in which the thermocouple was not found at the centre were discarded. All experiments at the same conditions were repeated at least three times.

4.4.3 Thermocouples

Nickel chromium vs nickel aluminium thermocouples, enclosed in 0.0015 m diameter stainless steel sheaths were used to measure the temperature distribution inside the potato cylinders.

Three thermocouples were used, one for measuring the temperature at the centre of the potato cylinder, one for measuring the temperature of the water bath and one for measuring the temperature of the cooling water bath.

4.4.4 Water Bath

A well agitated constant temperature ($\pm$ 0.5°C) water bath was used to heat or cool the potato samples. The capacity of the water bath was sufficient to prevent any drop in water temperature during immersion. Evaporation from the surface of the water bath was

Thermostat
and
immersion
heater

Electronic
thermometer

Impeller

Thermocouple

Assembled
apparatus

Heating medium

Chart
recorder

Constant
temperature
water bath

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FIGURE 4.6 :   Temperature distribution measurement apparatus
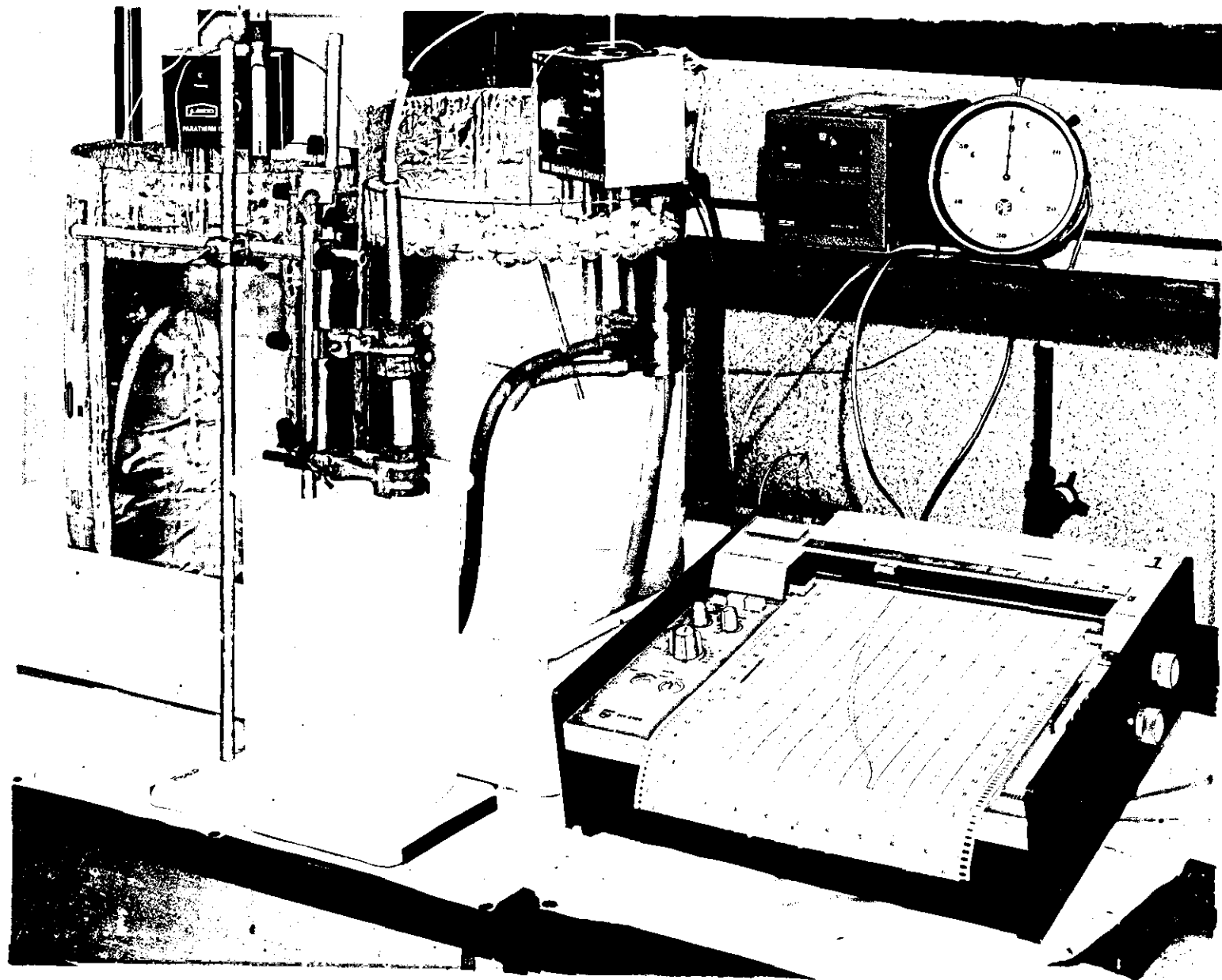
minimised by a layer of plastic spheres. The length and width of the bath was 0.45 x 0.29 m and the height was 0.29 m. The total water content was 27 litres.

4.4.5 Experimental Parameters

The parameters investigated were:

1. Heating temperature
2. Cooling temperature
3. Cooling time.
4. Heating time
5. Cylinder diameter
6. Agitation rate

Seven water bath temperatures during heating were selected to cover a wide range of temperatures below and above the gelatinisation temperature range of starch in potato. The temperatures used were: 30, 40, 50, 60, 70, 80 and $90^{\circ}C$. The temperature of the water bath during cooling was $20^{\circ}C$. The heating and cooling time varied from 0 to 900 sec. The diameter of potato cylinders studied ranged from 0.015 m to 0.027 m.

4.5 Specific Heat Studies

4.5.1 Method and Measurement

The method of mixtures (Mohsenin, 1980) was employed in this investigation using a Dewar flask calorimeter.

Figure 4.7 shows the schematic diagram of the calorimeter used to determine the specific heat. The calorimeter was first filled with 250 ml distilled water at constant temperature with one of the thermocouples placed inside the water. A cylindrical sample of potato 0.022 m diameter and 0.06 m in length was cut from the potato by means of cork borer size number 15. After weighing

To thermometer

Lid

Stopper

Thermocouples

Hook

Vacuum jacket

Water

Potato sample

Dewer flask

Beaker

Stirrer
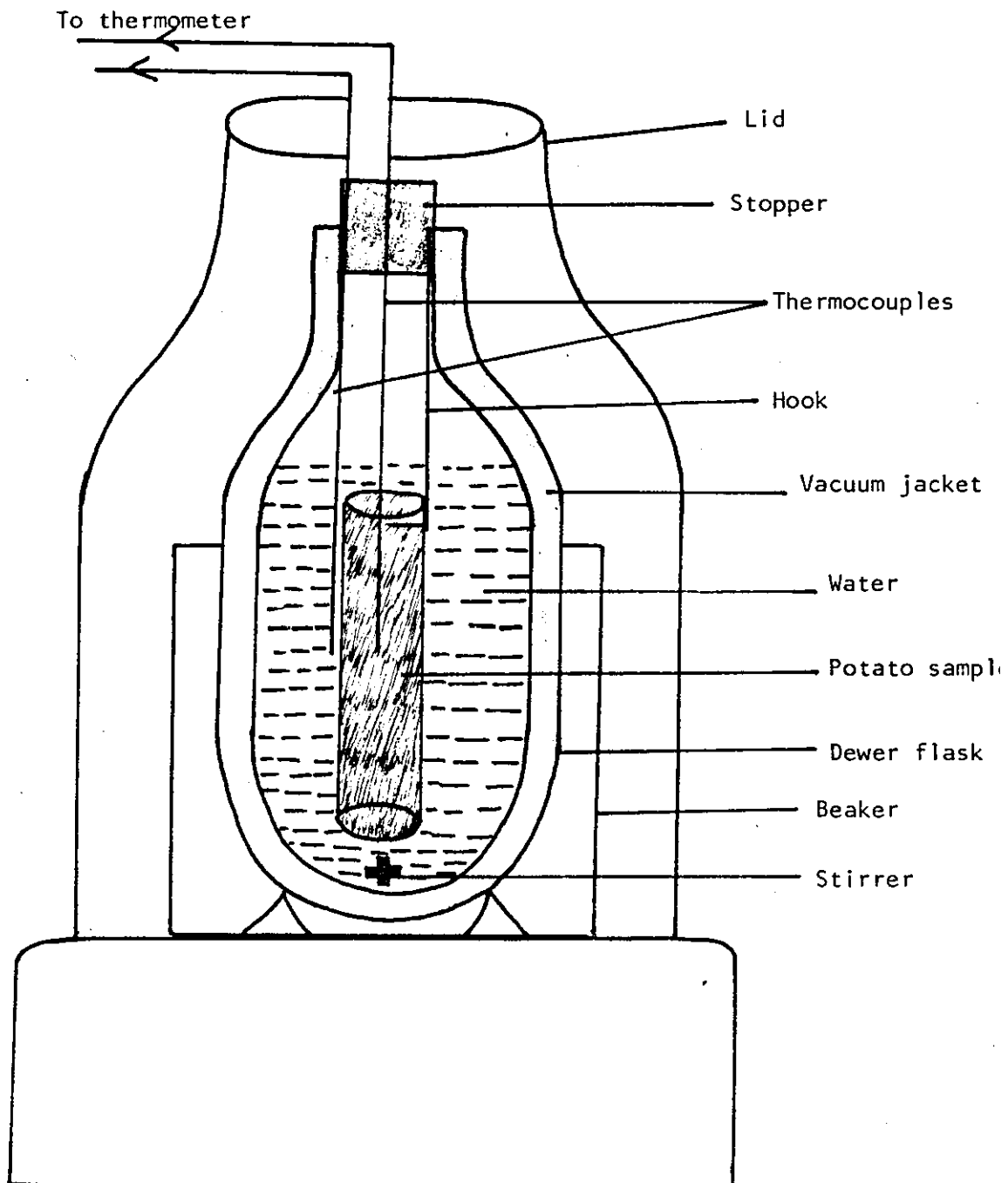
FIGURE 4.7: Diagram of calorimeter used to measure the specific heat of potato cylinders

the sample, the initial centre temperature was measured by a thermocouple. When a constant initial temperature was observed for both sample and water, the potato sample was immersed in the calorimeter in such a way that the cylindrical sample was hanging inside the water from a hook. The lid was closed immediately to reduce heat leakage. The final temperature of water and potato sample were recorded when equilibrium was reached between the water and potato. This procedure was repeated at least four times.

The specific heat was measured at temperatures ranging from 30 to $90^{\circ}C$ and at moisture contents ranging from 70 to 80%.

4.5.2 Specific Heat Calculation

The specific heat of the potato was calculated from the following heat balance equation:

$$Cp \ Mp \ (t_p - t_e) = C_w \ M_w \ (t_e - t_w) \tag{4.4}$$

$$Cp = \frac{C_w \ M_w \ (t_e - t_w)}{Mp \ (t_p - t_e)} \tag{4.5}$$

where: Cp = specific heat of sample,   kg/kJK
         $*C_w$ = specific heat of water,   kg /kJK
         t_e = equilibrium temperature, $(^{\circ}C)$
         t_w = initial water temperature, $(^{\circ}C)$
         t_p = initial sample temperature, $(^{\circ}C)$
         M_w = weight of added water,   (g)
         Mp = weight of potato sample   (g)

* See Appendix IV

The accuracy of this method is dependent on maintaining the temperature of the water in the calorimeter significantly the same

and minimizing the heat exchanges between the calorimeter and its surrounding environment, so the calorimeter was covered with a lid during the test, and the thermal leakage from the calorimeter was measured by running the procedure with water only and the temperature difference with time was recorded, see Appendix III.

To correct the error resulting from the thermal leakage of the calorimeter, a correction factor was incorporated in calculating the specific heat values. This correction factor was added to the equilibrium temperature on both sides of the energy equation. Where k_f is the correction factor, then the heat balance equation 4.5, becomes:

$$Cp = \frac{C_w M_w \left[(t_e + k_f) - t_w \right]}{Mp \left[t_p - (t_e + k_f) \right]} \qquad (4.6)$$

The energy added by stirring was assumed to be negligible. k_f values were obtained from Appendix III at the given temperatures.

4.6 Thermal Conductivity Calculation

The thermal conductivity was determined by the thermal diffusing method. The thermal diffusing method is an indirect method for measuring thermal conductivity. According to this method, thermal conductivity is defined as:

$$\alpha = \frac{K_o}{\rho \, Cp} \qquad (4.7)$$

where: α = thermal diffusivity m^2 sec^{-1}

K_o = thermal conductivity W/m^{o}K

ρ = density kg/m^3

Cp = specific heat of the sample J/kg^{o}K

If the thermal diffusivity, specific heat and density of the potato sample are measured, then the thermal conductivity can be calculated from the above equation (see Appendix x for density data).

4.7 Heat Transfer Coefficient Calculation

The heat transfer coefficient was calculated from the following equation:

$$\frac{1}{Nu} = \frac{K_o}{ha}$$ (4.8)

$$Nu = \frac{1}{K_o/ha} = \frac{ha}{K_o}$$ (4.9)

where: Nu = Nusselt number

h = heat transfer coefficient

K_o = thermal conductivity

Nusselt number, Nu, was obtained from Newman charts, Figure 4.8 by solving:

$$X = \frac{\alpha t}{a^2}$$ (4.10)

and

$$Y = \frac{T_t - T_s}{T_o - T_s}$$ (4.11)

from the experimental results, where

α = thermal diffusivity

t = heating time

a = radius of the cylinder sample

$$Y = \frac{T_t - T_s}{T_o - T_s}$$

$$Nu = \frac{ha}{ko}$$
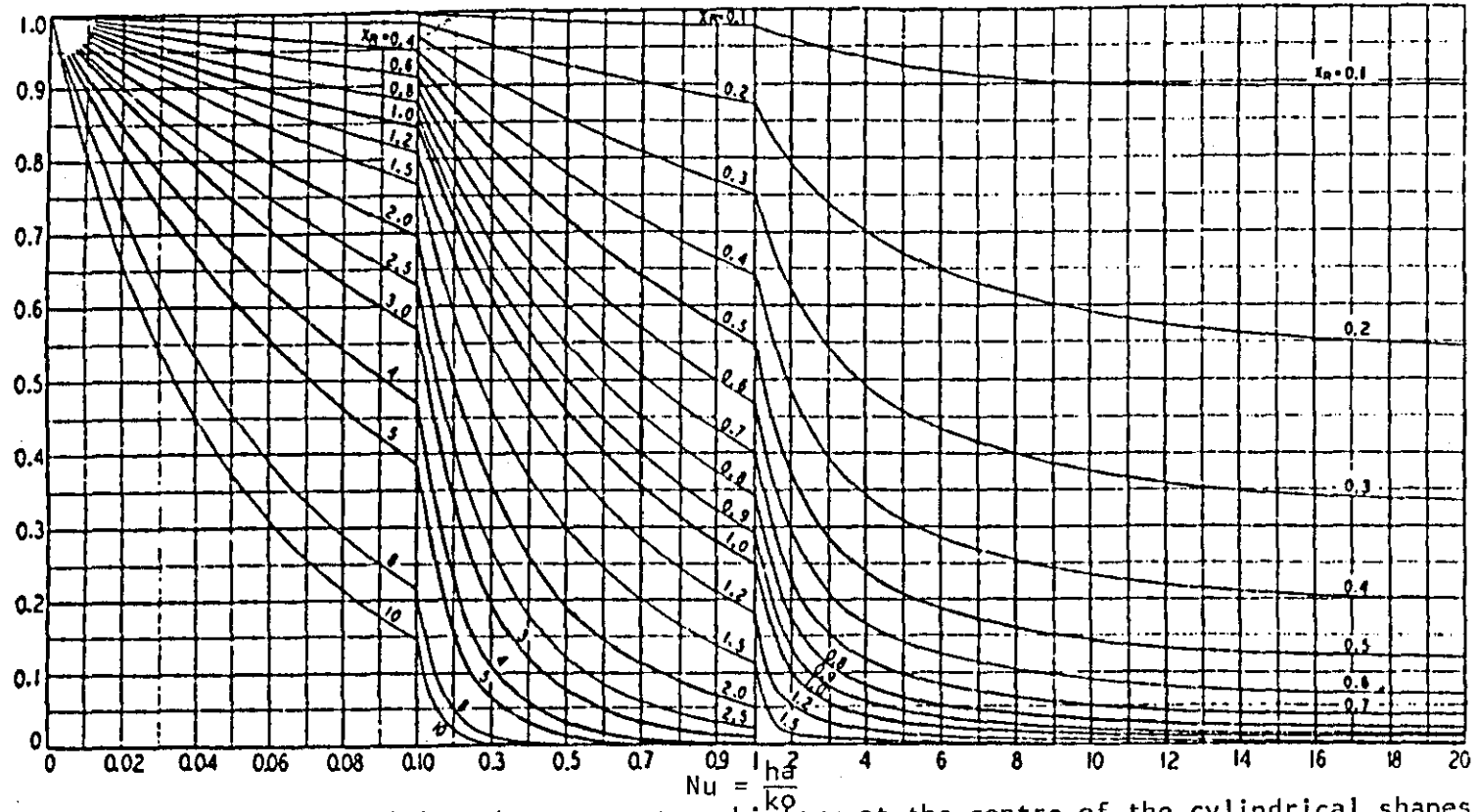
FIGURE 4.8: Chart for determining the temperature history at the centre of the cylindrical shapes (after Newman, 1936)

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T_t = centre temperature of the sample at time t

T_s = temperature of the heating medium

T_o = the initial uniform temperature of the sample

5. RESULTS AND DISCUSSION

5. RESULTS AND DISCUSSION

5.1 Mass Transfer During Blanching

5.1.1 Effect of Blanch Temperature

5.1.1.1 Carrot tissue

An experiment was first carried out to study the changes in fresh weight and cell sap concentration which occurred when cylinders of fresh carrot root tissue (cortex and core) were immersed in water for 300 and 900 sec over the temperature range of 20-90°C. The results are summarized graphically in Figures 5.1, 5.2 and 5.3. Figure 5.1 shows that at the lower temperatures between 20-50°C a weight gain was recorded as a result of water uptake by osmosis due to the diffusion pressure deficit of the cells. This water uptake increased with temperature up to 40°C to give a high weight gain (7.7%) at this temperature. As the temperature was raised above 40°C, a point was reached at which the osmotic properties of the cytoplasmic membrane became critical. From this point onward the rate of water uptake began to decrease and continued to do so as temperature increased. When the temperature was high enough to destroy the semi-permeability of the cytoplasmic membrane and its osmotic properties, then a weight loss was observed. This temperature occurred between 50 and 60°C. As the temperature increased from 60 to 90°C, the rate of weight loss increased to reach maximum values of 6% at 90°C after 300 sec blanching and 8.3% at 80°C after 900 sec.

The weight loss recorded between 60-90°C, is due to both loss of water and to the increase in solute loss as a result of cytoplasmic membrane disorganization, and cessation of the osmotic properties of the membranes. The rate of weight loss appears to be increased with increasing blanch temperature, but a slight weight gain was recorded between 80-90°C after 900 sec blanching, which
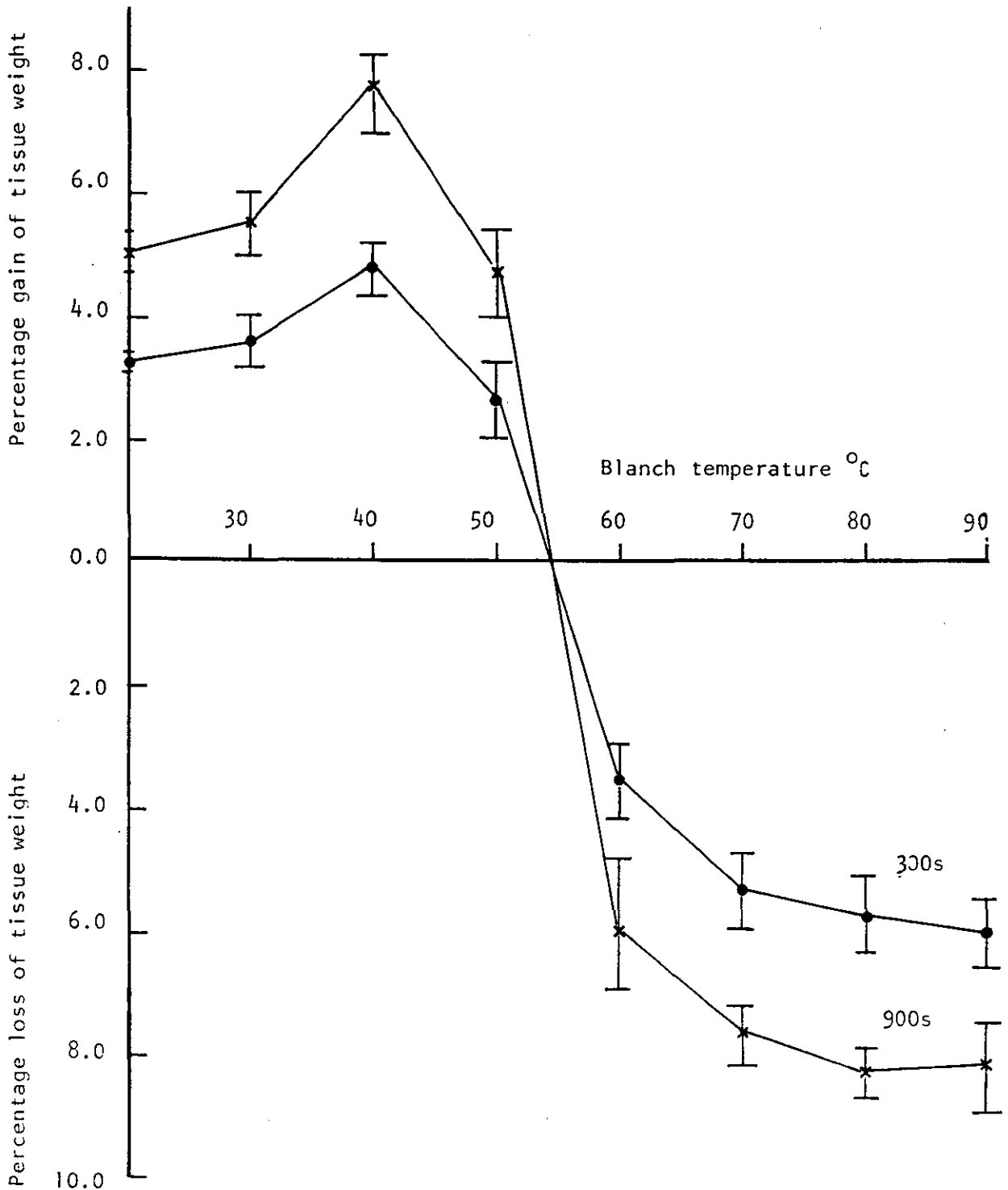
FIGURE 5.1 : Percentage tissue weight changes of carrot cortex
cylinders blanched for 300 and 900 s at the given
temperature (mean of two duplicated replicates)
O, 300 s, X, 900 s

indicates that water diffusion from the blanch medium into the carrot tissue is taking place at this stage. The trend for both blanching for 300 sec and 900 sec is similar, but the amount of weight gain and loss at the given temperature is different. The difference in the rate of weight loss obtained at 60, 70, 80 and 90°C after 300 and 900 sec may be due to the rate of heat penetration into the tissue and to the rate of disorganization of the cytoplasmic membrane, which will vary with time and temperature of the blanching. The high values of weight loss recorded at 80 and 90°C demonstrate the rapid rate of heat penetration at these temperatures which disorganized the cytoplasmic membranes very fast rendering the tissue completely permeable in a few seconds. Figures 5.2 and 5.3 show a slow gradual decrease in cell sap solute concentration with temperature up to 50°C and then followed by a high rate of cell sap concentration decrease up to 90°C. Some of the solutes lost into the blanch water below 50°C would be expected to come from the tissue surface cells ruptured during the preparation and cutting of sample tissue cylinders.

The trend for both core and cortex is similar, both exhibiting a decrease in cell sap solute concentration with temperature, but the rate of cell sap concentration decrease from the core is lower than that from the cortex. This difference may arise in part to initial concentration differences between the tissues, and to structural differences between the tissue. Cell sap solutes (expressed as sucrose concentration) in the unblanched carrots were generally less in the core (7.8%) than the cortex (9.5%).

The typical variation of cell sap concentration between cylinders cut from eight Chantenay carrots cortex is shown in Appendix V. The number of cylinders that could be cut from one carrot without defect varied from two to five. Cylinders taken from different positions within the cortex gave the same cell sap concentration. Solute content of the cell sap ranged from 7.8 to 10.4% with the mean for all 27 cylinders being 9.1 $\pm$ 0.2% (as sucrose).
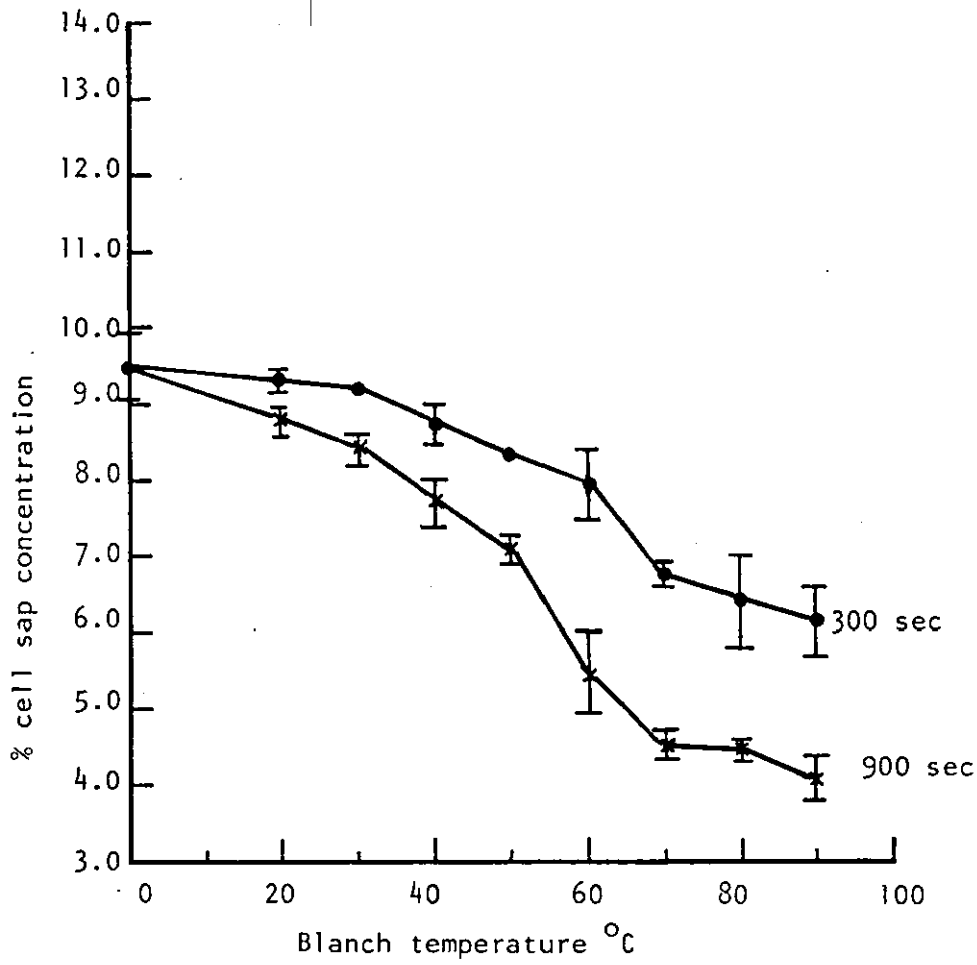
FIGURE 5.2: Percentage of cell sap concentration of carrot
cortex cylinders blanched for 300 and 900 sec at
the given temperature (mean of two duplicated
replicates). 0, 300 s, X, 900 s.
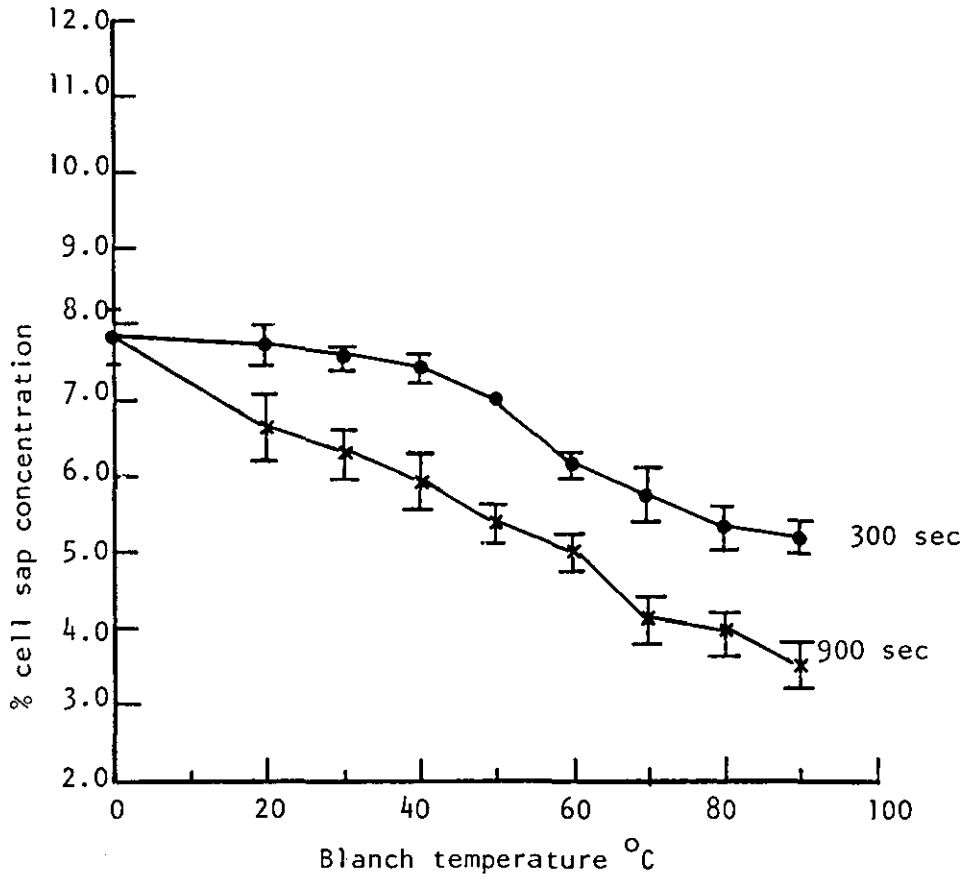
FIGURE 5.3:   Percentage cell sap concentration of carrot
core cylinders blanched for 300 and 900 s at
the given temperature (means of two duplicated
replicates). 0, 300 s, X, 900 s.

5.1.1.2 Potato tissue

A similar experiment was carried out to study the changes in fresh weight and solute losses which occurred when cubes of Home Guard potato tissue were immersed in water for 900 sec over the range 20-90°C. The results are summarized in Figure 5.4. At temperatures between 20-50°C, the amount of water absorbed osmotically by potato tissue was higher than that in the case of carrot root tissue. Above 50°C a weight loss was recorded which reached a maximum value at 65°C. Above 65°C weight loss decreased up to 90°C. This decrease in weight loss indicates that the starch gelatinization which occurred above 60°C caused some water uptake by the cells. During heating of potato tissue above 50°C, the starch granules within the cell of the tissue begin to swell and when the starch gelatinization temperature is reached (60-70°C), the starch granules swell rapidly, and the resulting starch gel will occupy the greater part of the cell volume setting up a certain imbitional force which is assisting water uptake. It is known that during gelatinization, the starch granule absorbs large quantities of water, equivalent to several times its own weight. The solute losses show a gradual increase with temperature up to 65°C then reduced up to 70°C and started to increase again up to 90°C. The solute loss between 65 and 70°C was expected to be influenced by the inward water movement. The solute loss between 20 and 50°C was higher than the loss from carrot tissue and in part due to the loss of starch from the damaged cells on the surface of the tissue during cutting. However the amount of solute lost from the potato tissue was smaller than that from carrot tissue due to differences in the cell sap solute content of the tissues which were 4.5% in potato and 9.5% in carrot.

Figure 5.5 shows that the pattern of tissue weight changes from Record potatoes is different from that of Home Guard potatoes with respect to time. The weight loss reached a maximum value at 60°C after 600 sec then decreased up to 90°C. These changes suggest that the presence of the starch in high amount in Record
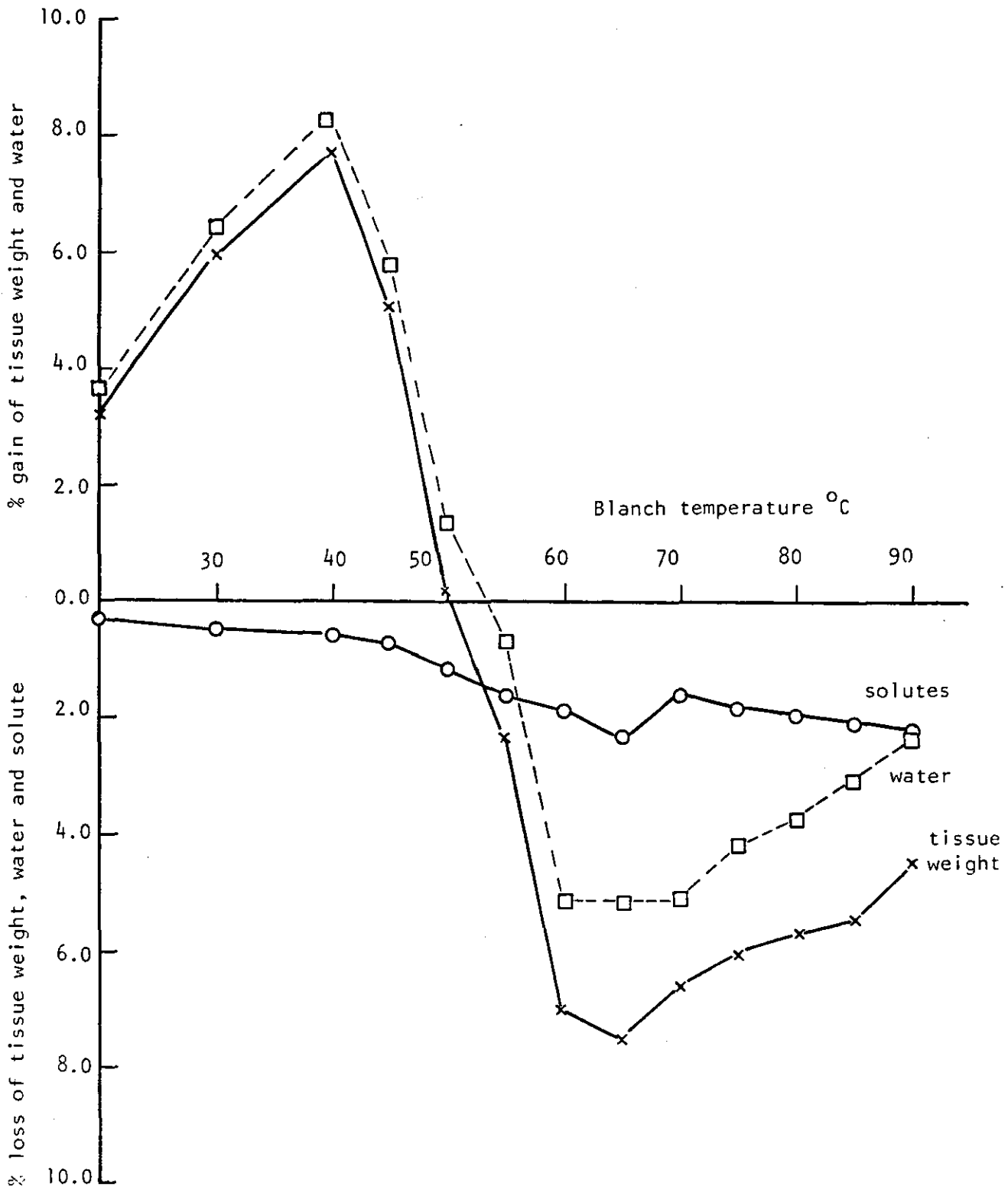
FIGURE 5.4 :   Percentage tissue weight changes and solute loss from
samples of Home Guard potato cubes blanched for 900 s at
the given temperature (means of four replicates).
0, solutes, X, tissue weight,□,water.

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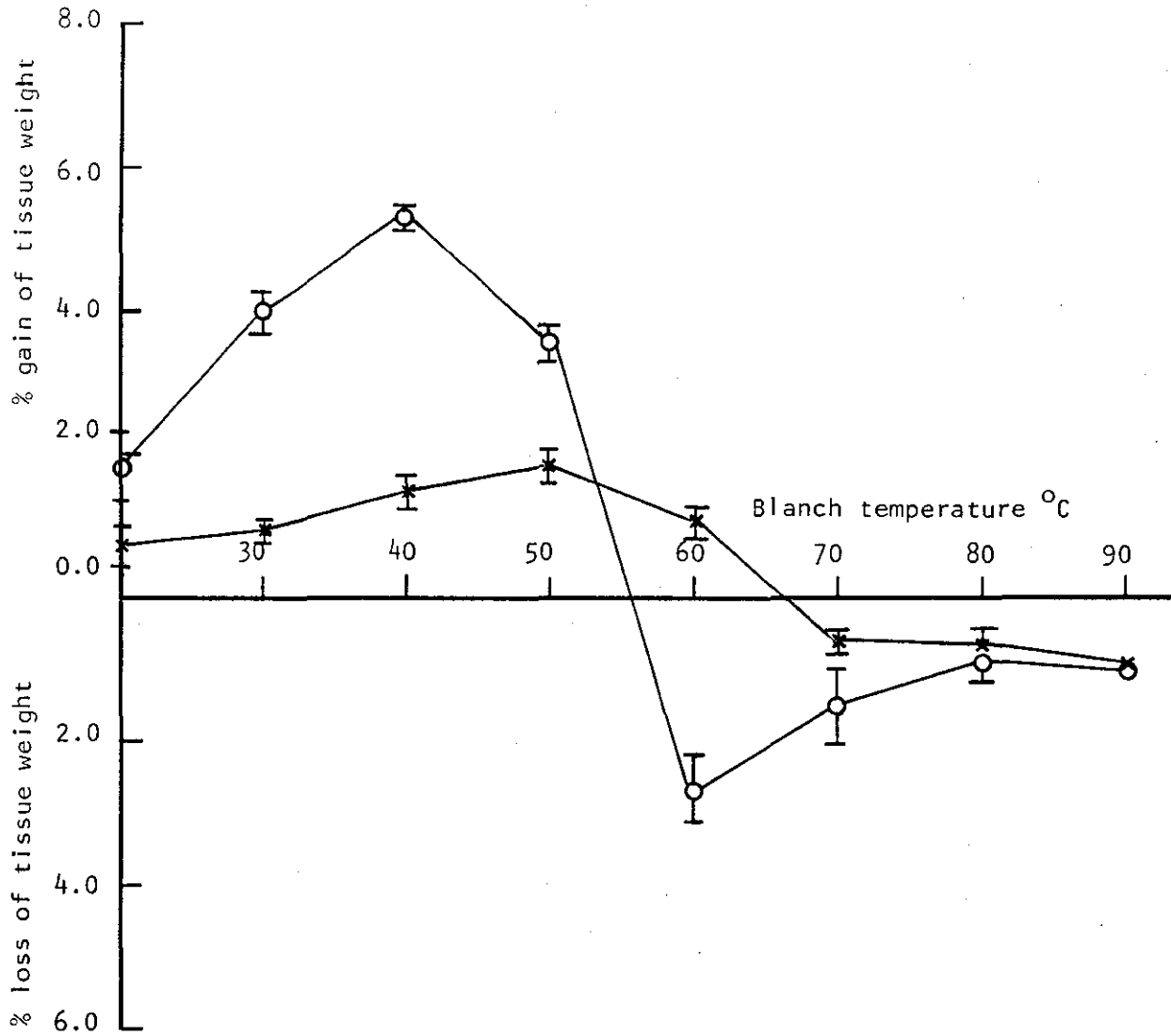
FIGURE 5.5: Percentage tissue weight changes of Record potato cubes
samples blanched for 120 and 600 s at the given temperatures
(means of two replicates). 0, 600 s, X, 120 s.

potato retards the loss of water from the cell at temperatures above 60°C due to imbibition of some water in the gelatinization process. Also it is possible that the gelatinization of starch in old potatoes (mature) is more significant than in the new potatoes which contain less starch. In fact the alcohol insoluble solids content of Record potatoes (14.5%) was higher than that of Home Guard potatoes (11.1%).

5.1.2 Effect of Blanch Time
5.1.2.1 Carrot tissue

An experiment was conducted to investigate the changes in fresh weight and dry matter which occurred when cylinders of carrot root tissue (core and cortex) were blanched in water at 70°C over the time interval 120-1800 sec. The cortex and core tissue shows a weight loss with time during blanching at 70°C, see Figure 5.6. For the first 300-600s the rate of weight loss for both core (0.014) and cortex (0.011) was greater than after 600s when the rate tailed off to an approximate steady increase (0.001). It appears that the loss of weight during the first 300-600s is controlled by expulsion of cell contents into the blanch medium as a result of loss of turgor. Selman and Rolfe (1979) also found that weight loss during the first 120 sec arose primarily from the contraction of the tissue on loss of cell turgor. The steady weight losses after this time suggest that the weight loss is entirely controlled by the diffusion of solutes and water. The weight loss after 1800 sec was higher for the core (9.8%) than the cortex (8%) possibly due to the high water content of the core tissue.
Figure 5.7 shows the effect of both blanch time (120-1800 sec) and temperature (50-90°C) on tissue weight change of cortex tissue. As expected a weight gain was recorded at 50°C between 120-1800s due to water uptake by osmosis as the temperature was still low enough to keep the cytoplasmic membranes and the osmotic properties of the cells intact. At higher temperatures the pattern of weight loss was similar, but with increasing temperature, weight losses
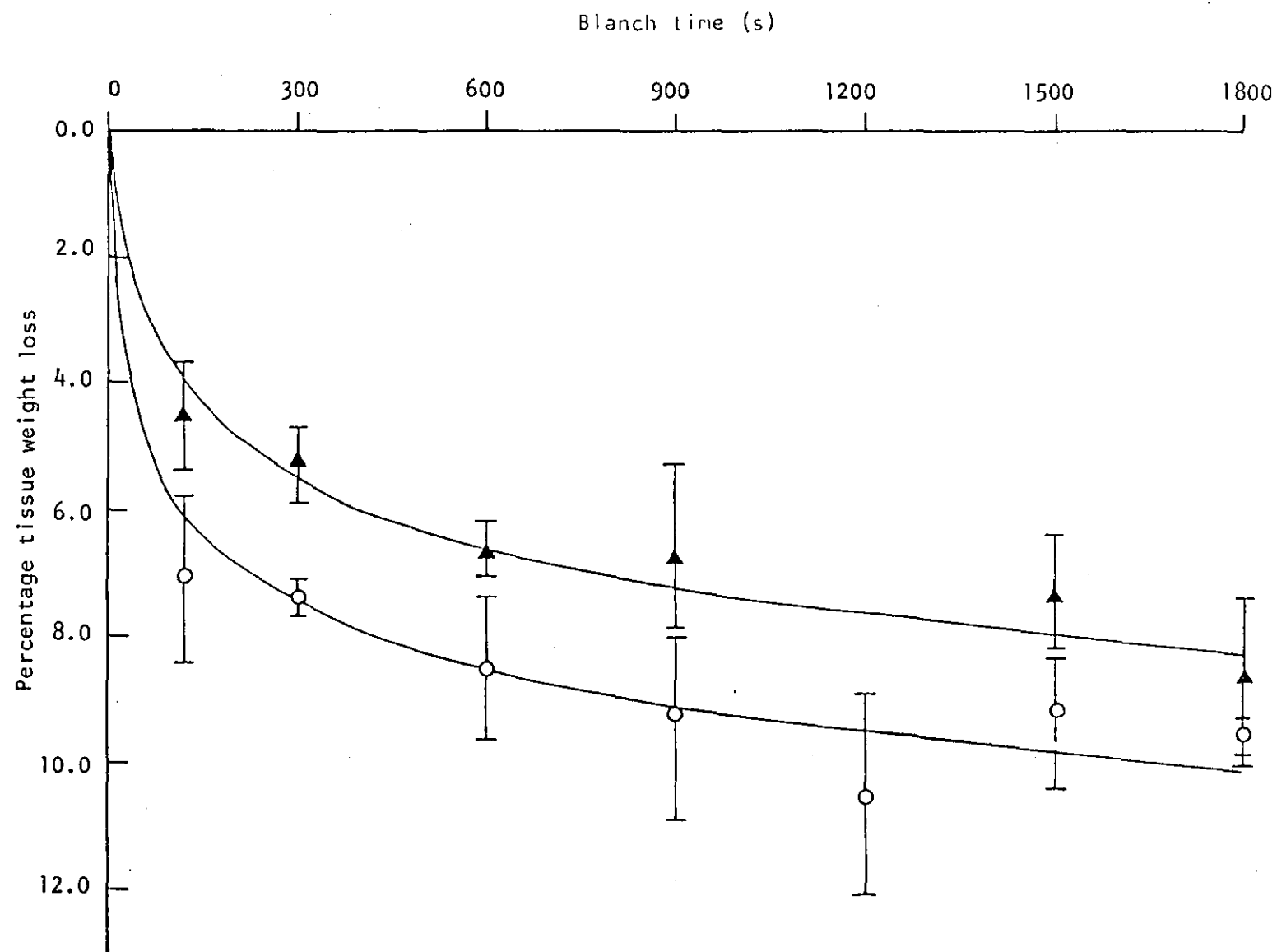
FIGURE 5.6:   Percentage loss of tissue weight from carrot cortex and core cylinder samples after the given
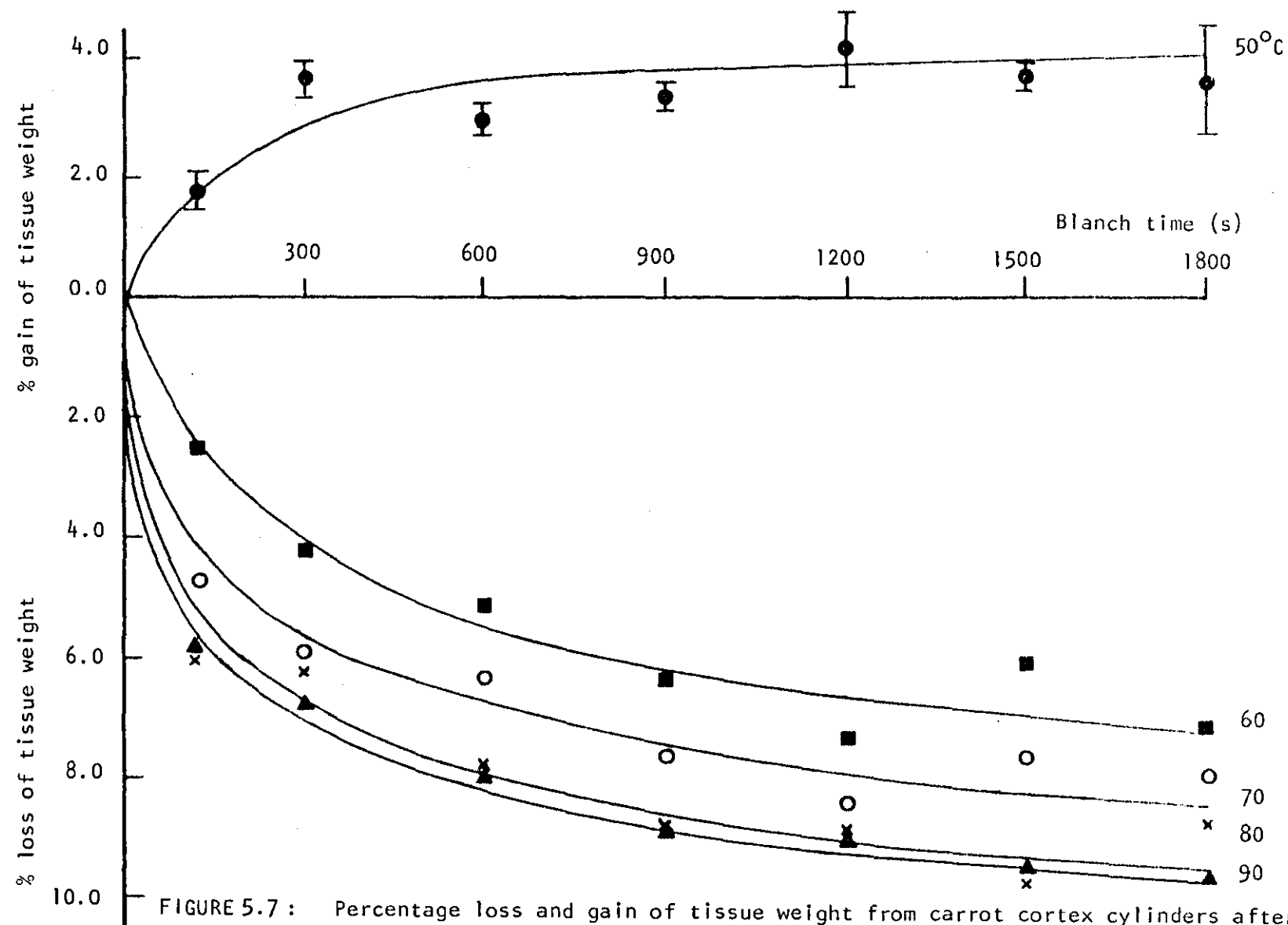
FIGURE 5.7 : Percentage loss and gain of tissue weight from carrot cortex cylinders after the given blanch time at 50, 60, 70, 80 and 90°C (means of two duplicated replicates). ●. 50 ■ .60. ○. 70. X. 80. ▲ 90

tended to increase during the first 600 sec, which resulted in a greater overall loss at each subsequent blanch time.

Figures 5.8 and 5.9 show that the dry matter content of both the cortex and core decreased with the increase in blanching times. The rate of decrease in both cases was higher between 0-600 sec than the time thereafter, when the decrease tailed off. This also indicated that loss of solids during the first 600 sec occurred by expulsion of cell contents into the blanch medium. The decrease in dry matter after 600 sec was largely due to the diffusion of solids from the carrot tissue into the blanch medium. As the concentration gradient decreased with blanch time, then the diffusion rate of solids slowed. The difference between the loss trend from core and cortex was negligible. The losses of dry matter solids from carrot cortex during blanching at 60, 70, 80 and $90^\circ C$ for 120-1800 sec are shown in Figure 5.10. As expected the dry matter solids behaved in a similar fashion as before, decreasing with the increase of both blanch temperature and time.

5.1.2.2 Potato tissue

Similar experiments were carried out to study the changes in fresh weight and solute losses which occurred when cubes of potato tissue were blanched in water at 60, 70, 80 and $90^\circ C$ over the time interval 120-1800s. The results are summarised in Figures 5.11, 5.12, 5.13 and 5.14. These figures show an increase in the solute loss with time. The rate of this increase, increases with use of higher temperatures except at $60^\circ C$, where the rate of solute loss is higher than that at 70, 80 and $90^\circ C$. In all cases the solute loss was greater during the first 300 sec of blanching. The loss of both weight and water also increased more rapidly during this first 120-300 sec of blanching. This suggests that the weight loss from potato tissue during the first 300 sec arises from the expulsion and expression of solutes and water on loss of cell turgor. After this time the rate of weight loss at 80 and $90^\circ C$ starts decreasing with blanch time (see Figures 5.13 and 5.14) due largely to the
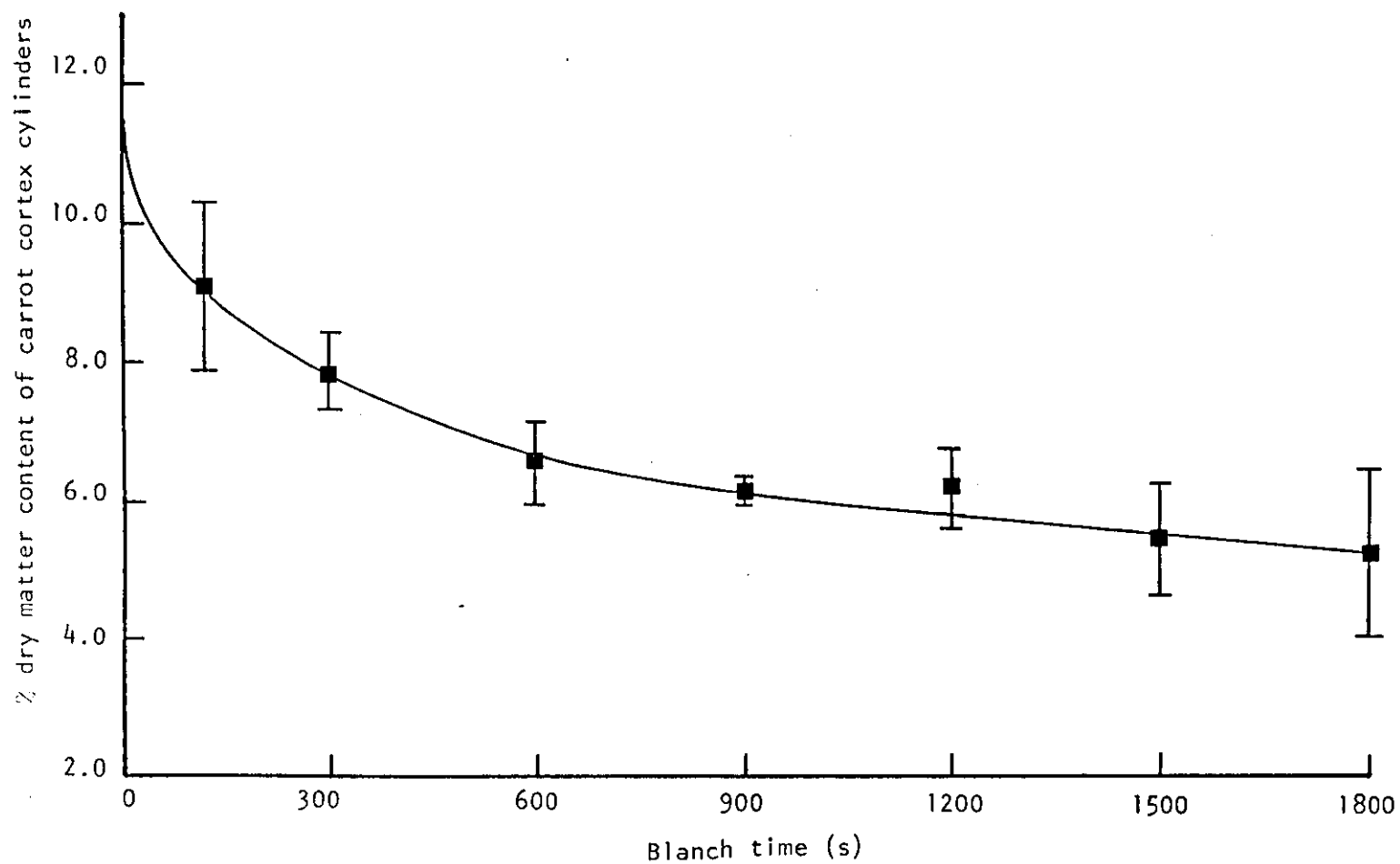
FIGURE 5.8 : Percentage dry matter of carrot cortex cylinders after the given blanch time at 70°C (means of two duplicated replicates)
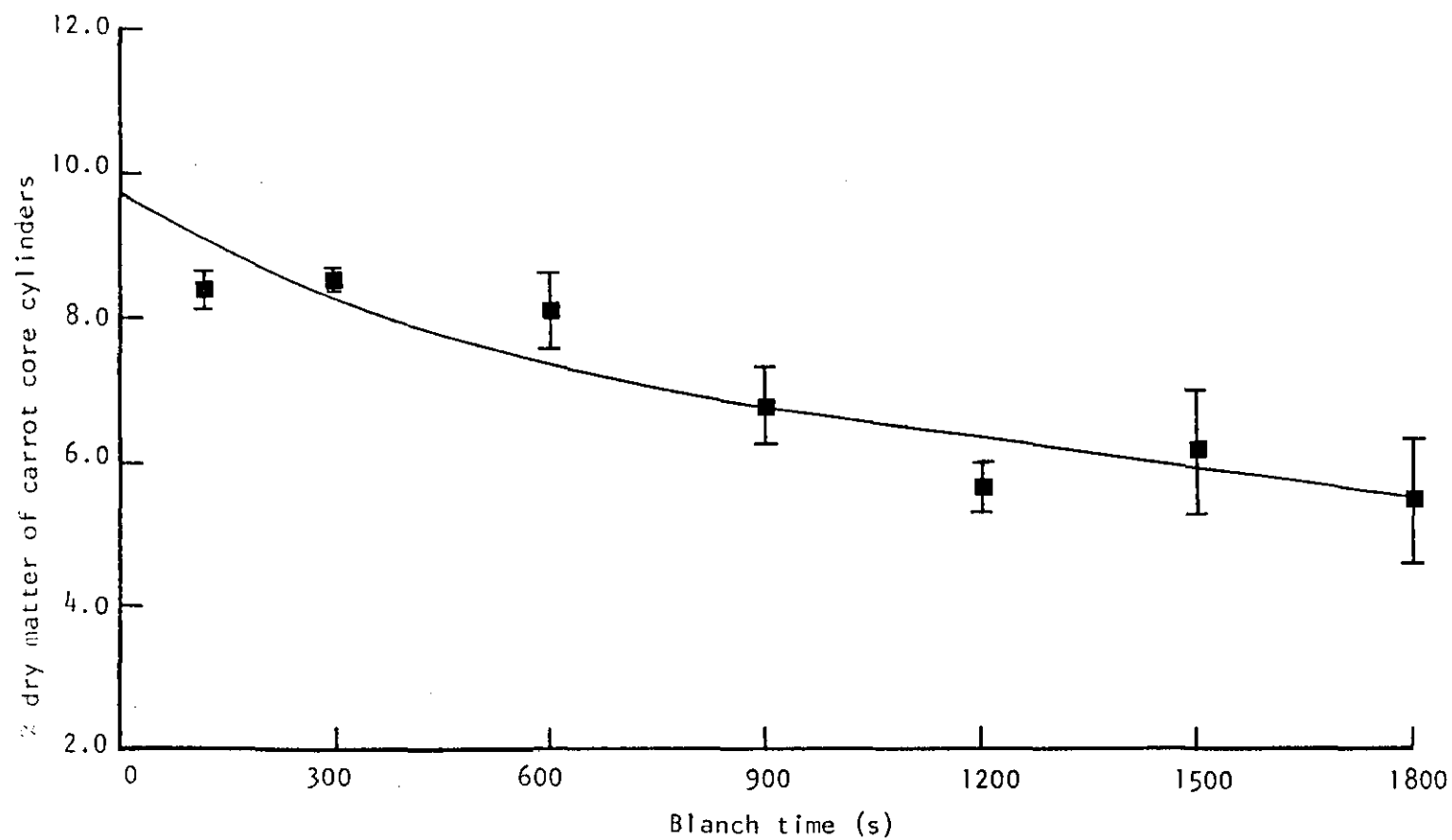
FIGURE 5.9:   Percentage dry matter of carrot core cylinders after the given blanch time at $70^{\circ}C$
(means of two duplicated replicates)
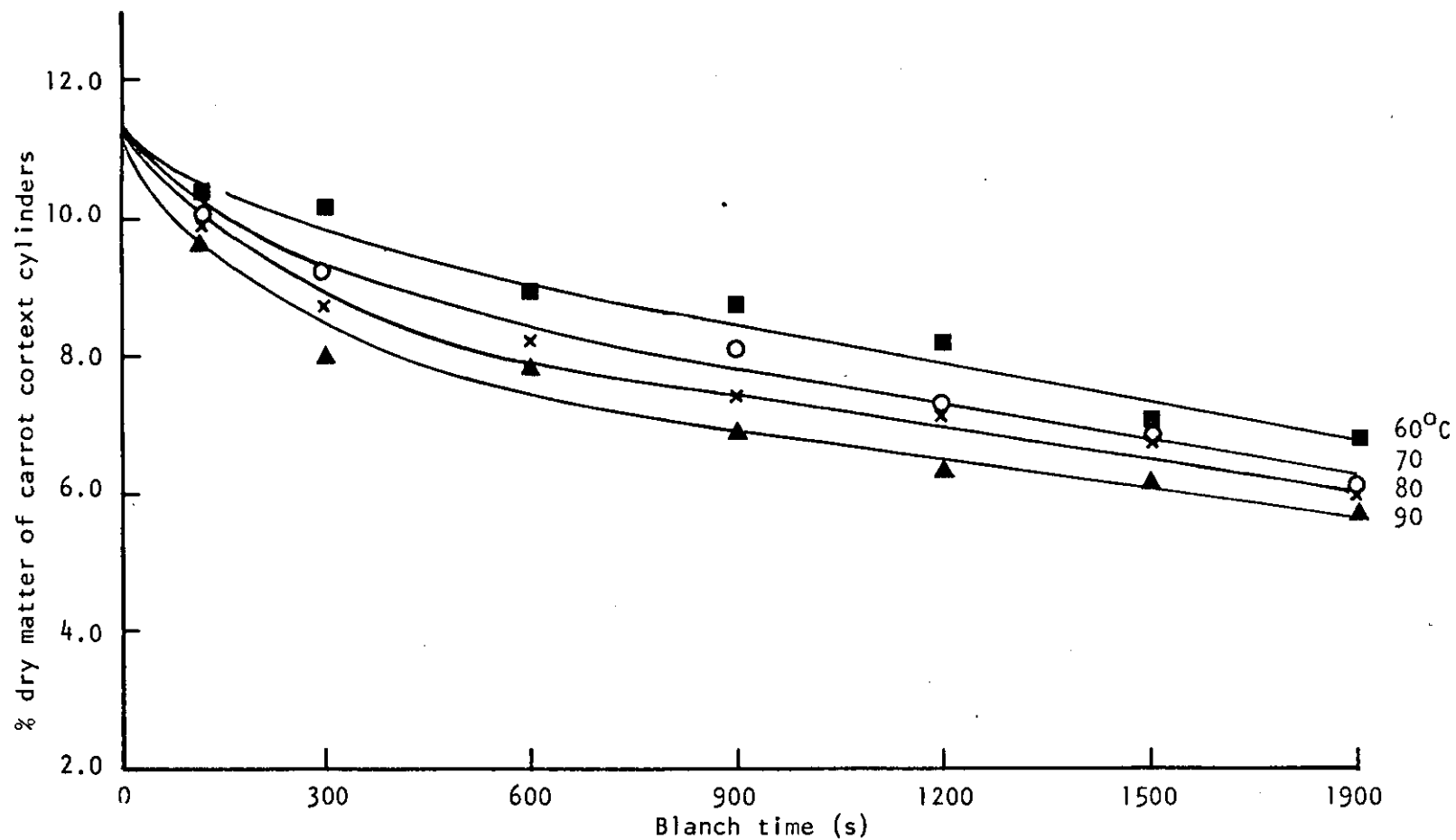
FIGURE 5.10: Percentage dry matter of carrot cortex cylinders after the given blanch time at 60, 70, 80, and 90°C. (Means of two duplicated replicates) ■ , 60, 0, 70°C, X, 80°C, ▲ , 90°C

retention of some water within the cell during starch gelatiniza-
tion which is accelerated by increasing the temperature and time.
The gelatinization of potato starch during blanching at $70^{\circ}C$
(Figure 5.12) seems to make little contribution to the retention
of water in the tissue.

During blanching at $60^{\circ}C$ (Figure 5.11) the trend was not
the same as at 70, 80 and $90^{\circ}C$. For the first 120 sec of blanching
there was a weight gain which was as expected due to uptake of water
through the intact cytoplasmic membranes, but after this time, the
cells death and the expulsion of cell contents caused a high rate
of weight loss which reached a maximum value (10.2%) after 1800 sec.
However the high solute loss at $60^{\circ}C$ (2.9%), which is higher than
at 70, 80 and $90^{\circ}C$, suggested that an enzymic reaction might be
initiated by this temperature causing internal generation of sugar
from starch, and thus increasing the fraction of solutes in the
medium. In a work performed on the changes of sugar content in
potatoes during blanching at 60-75$^{\circ}C$, Califano and Calvelo (1979)
found evidence that besides the mass transfer to the bath there
exists an internal generation of reducing sugars due to an enzymic
hydrolysis of starch. Another mechanism could be attributed to
cell wall pressure, if the degree of cell content expulsion depends
on the cell wall pressure or the amount of distension of the cell
wall at the time the membranes are disorganised. Therefore as the
potato tissue at $60^{\circ}C$ absorbed water up to 2% (tissue weight) during
the first 120 sec, then one can expect a higher loss of water and
solute after the cytoplasmic membranes are disorganised and turgor
lost.

Comparison between Figures 5.15 and 5.7 indicates that the
patterns of change occurring in carrots were different from those of
potato tissue. The presence of starch in potato tissue seems to have
great influence on these changes involving water. However, in general
the potato starch gelatinization had little effect on solutes loss.
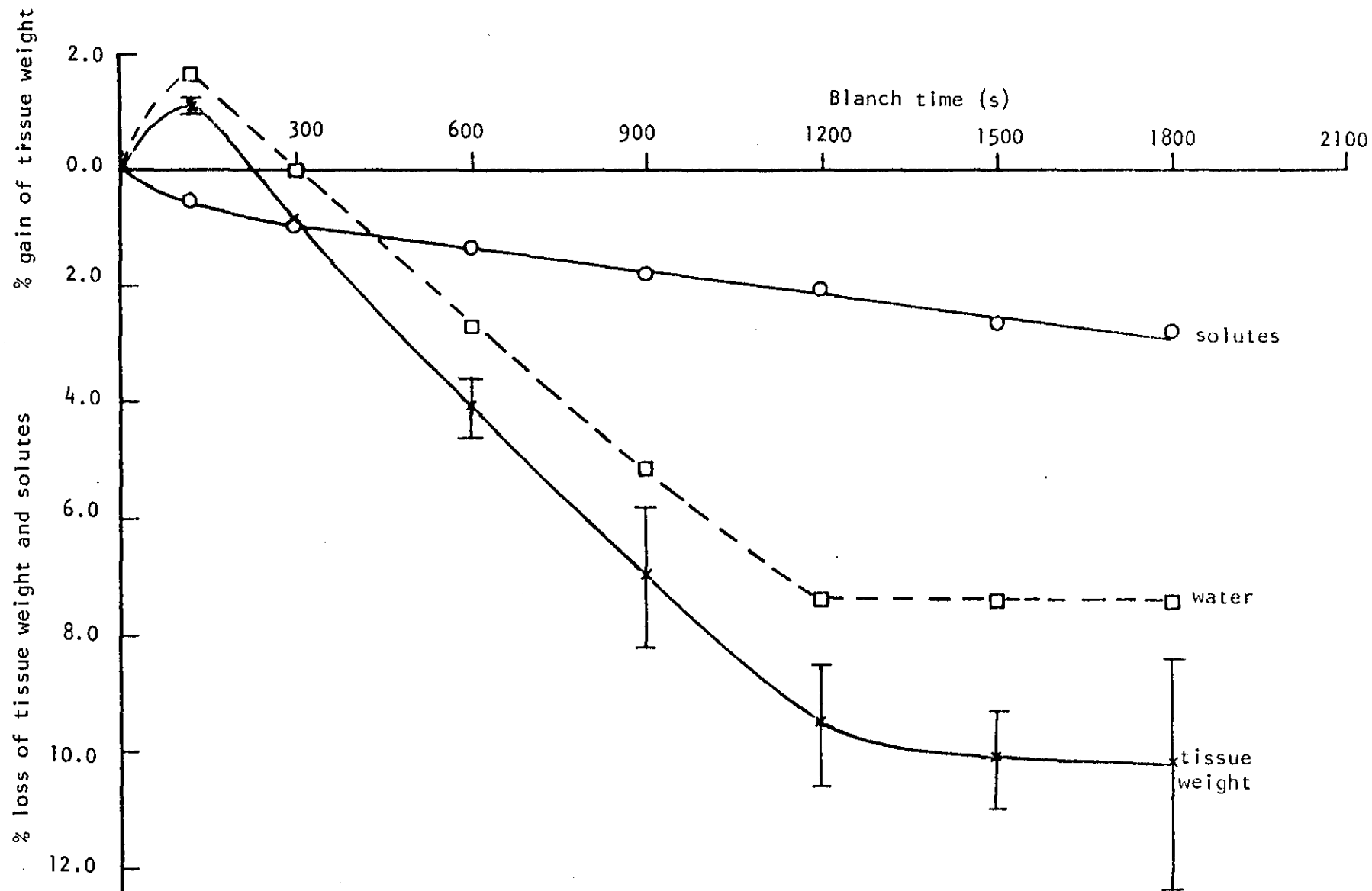
FIGURE 5.11: Percentage loss of tissue weight, solutes, and water (by difference) from Home Guard potato cubes after the given blanch time at 60°C (means of four replicates) 0, solutes, □, water, X, tissue
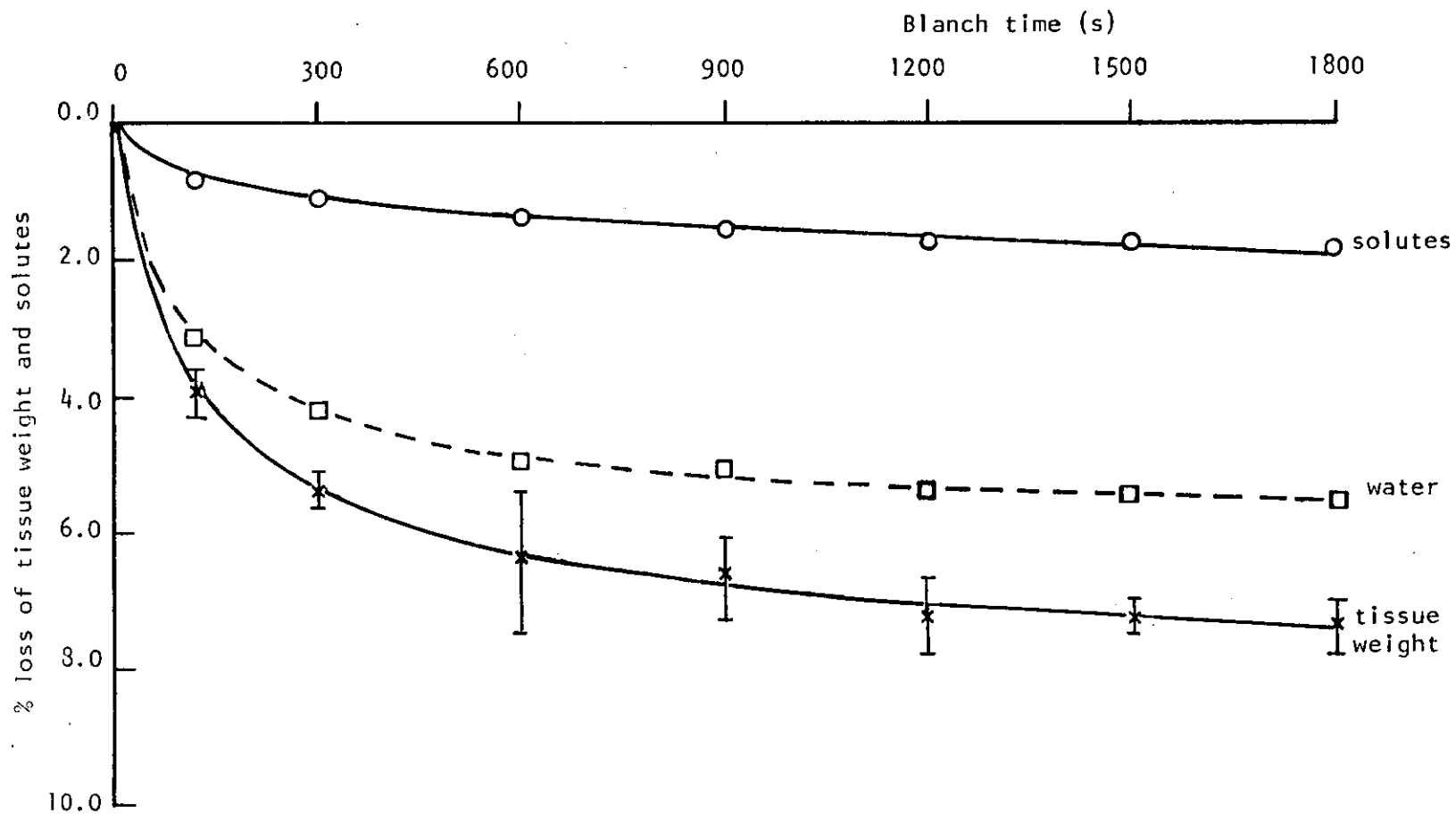
FIGURE 5.12: Percentage loss of tissue weight, solutes and water (by difference) from Home Guard potato cubes after the given blanch time at 70°C. (Means of four replicates), 0, solutes, □ , water, X, tissue weight
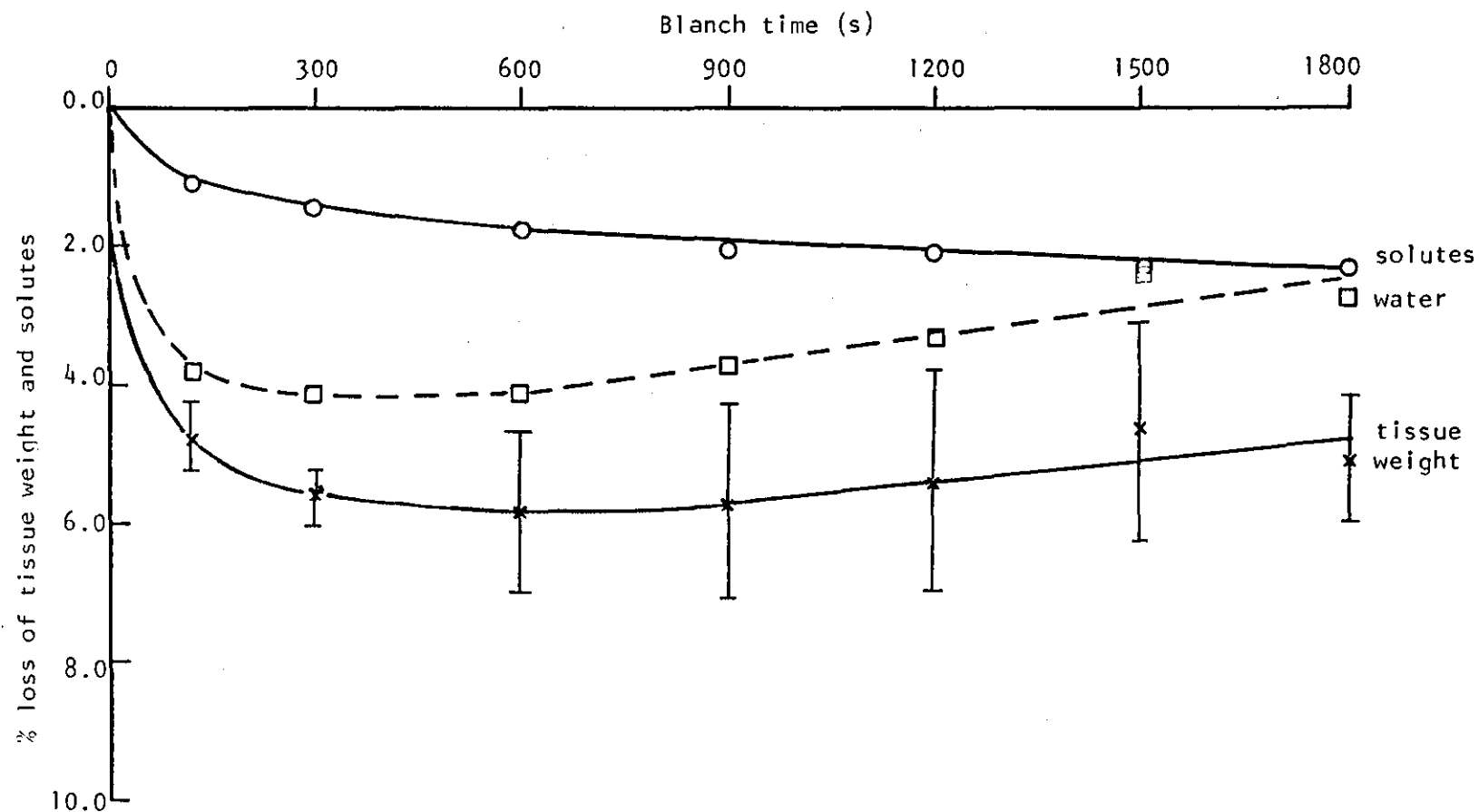
FIGURE 5.13: Percentage loss of tissue weight, solutes and water (by difference) from Home Guard potato cubes after the given blanch time at 80°C (means of four replicates). 0, solutes, □ , water, X, tissue weight
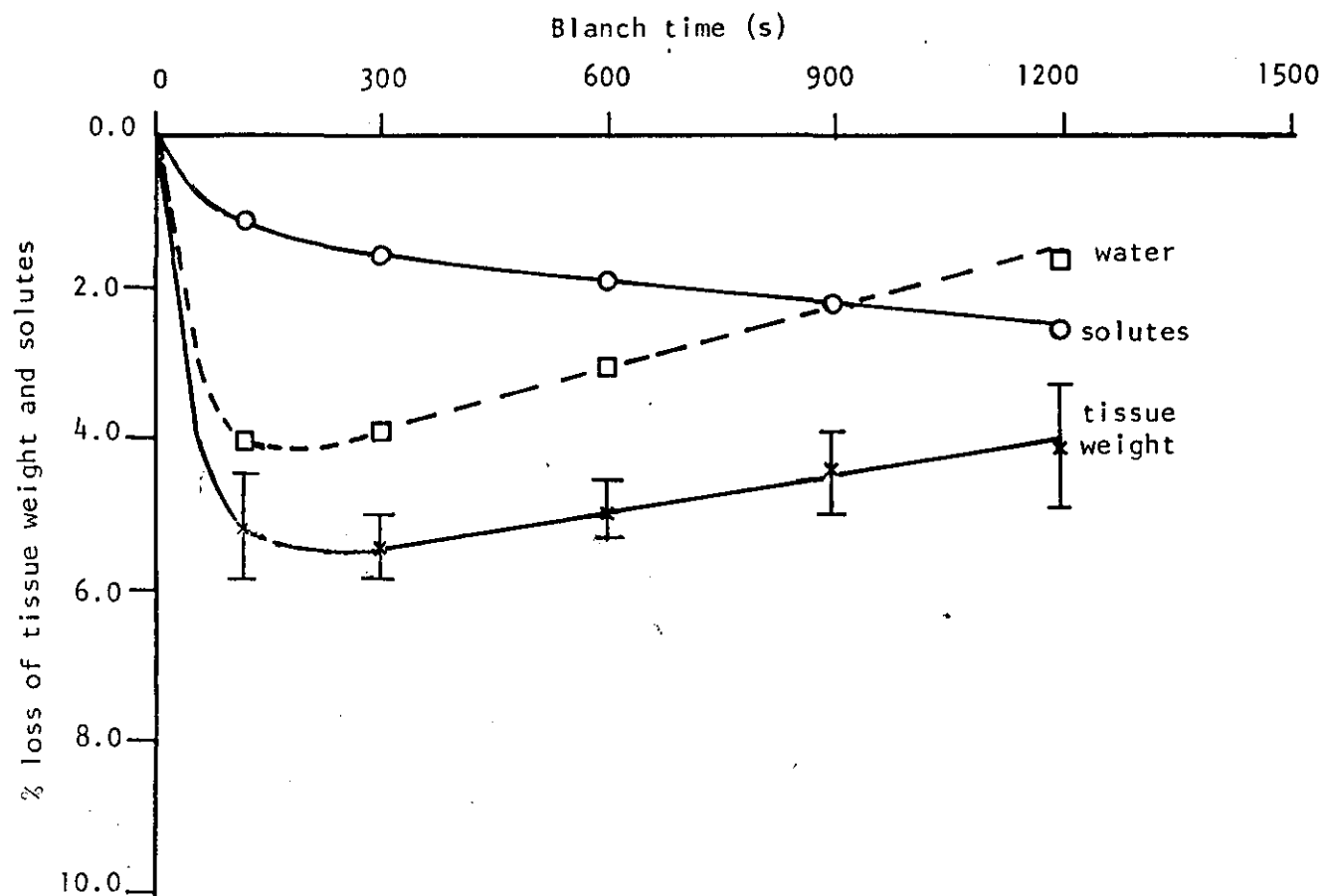
FIGURE 5.14: Percentage loss of tissue weight, solutes and water (by difference) from Home Guard potato cubes after the given blanch time at 90°C. (Means of four replicates), 0, solutes, □ , water, X, tissue weight
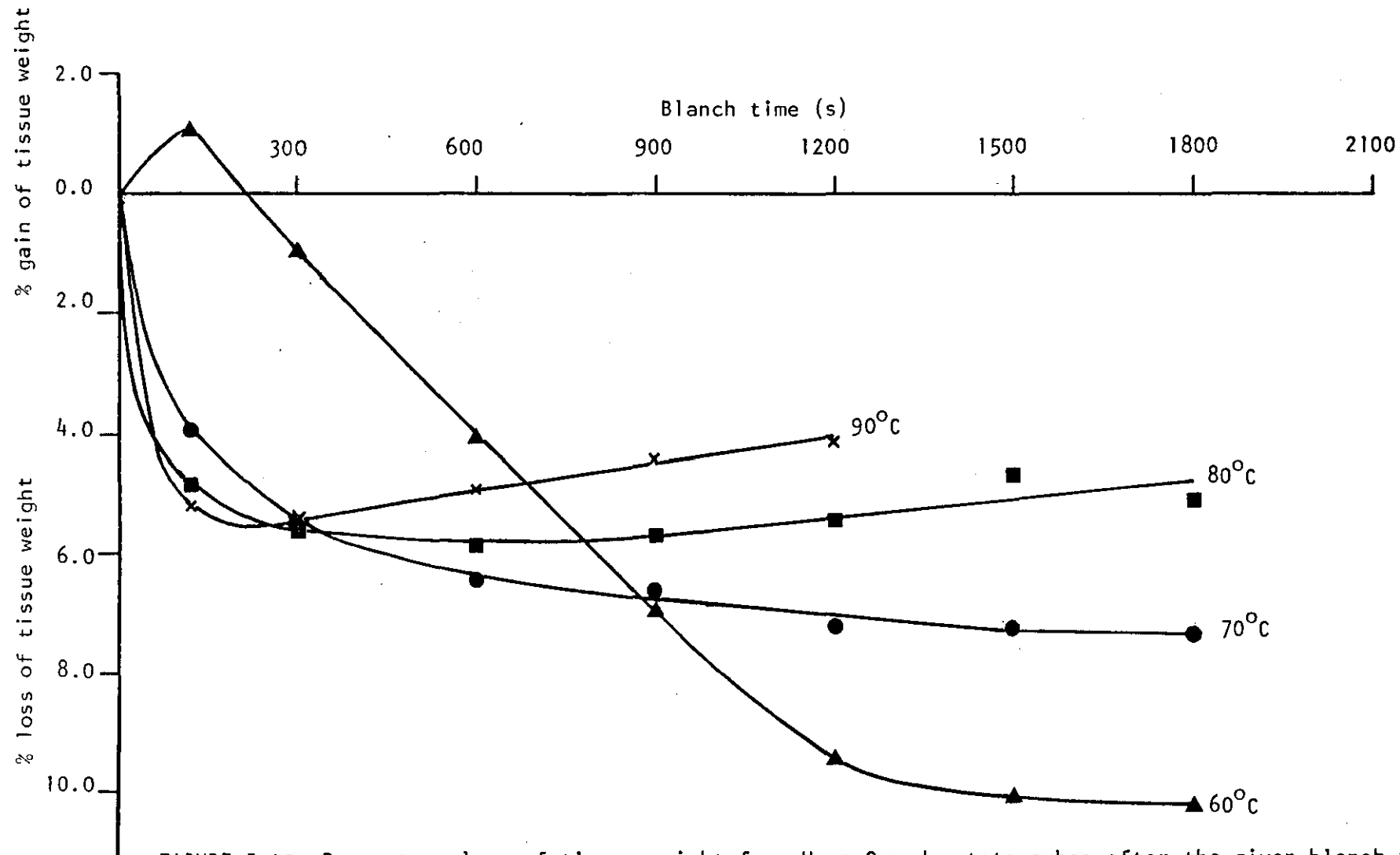
FIGURE 5.15: Percentage loss of tissue weight from Home Guard potato cubes after the given blanch time at 60, 70, 80 and 90°C (means of four replicates), ▲, 60, ●, 70, ■, 80, X, 90.

5.1.3   Effect of Initial Water Content (Turgor) on Losses During Blanching

5.1.3.1   Carrot tissue

An experiment was made to study the effect of initial water content (cell wall pressure) on losses during blanching. Samples of core and cortex tissue of a wide range of different initial water contents were prepared as described in the method section, 4.3.5, and the fresh weight change, cell sap concentration and dry matter solids losses were recorded after blanching for 900 sec at $70^{\circ}C$. The results are summarised in Figures 5.16, 5.17, 5.18 and 5.19.

Figures 5.16 and 5.17 show that ·. increasing the initial water content of a sample above its fresh level before blanching, resulted in a higher weight loss than that from fresh carrot samples. Similarly, decreasing the initial water content of fresh carrot samples resulted in a smaller weight loss than that from the fresh samples. Selman and Rolfe (1979) suggested that such weight losses are more likely to be related to the change in tissue volume (i.e. influenced by the initial cell volume and the inherent cell turgor pressure). A weight gain was recorded after 8-10% water removal from the fresh carrot sample. This weight gain suggests that water removal from the tissue cells by dehydration had caused the cell walls to shrink inwards by the contracted cytoplasm and vacuole. Thus on disorganization of the cytoplasmic membranes by blanching at $70^{\circ}C$, it would be expected that water will diffuse into the cell causing the tissue volume to expand resulting in a weight gain. The pattern for both core and cortex tissues was the same. However the prepared core tissue gave a higher weight loss than the cortex, mainly due to the higher initial water content of the core tissue.

In a second experiment, prepared carrot cortex tissue of three different initial water contents (111.0, 100.0, 91.0) were blanched at $70^{\circ}C$ for 120-1800 sec to study the effect of time. The changes are shown in Figure 5.18. The results in Figure 5.18 indicated that
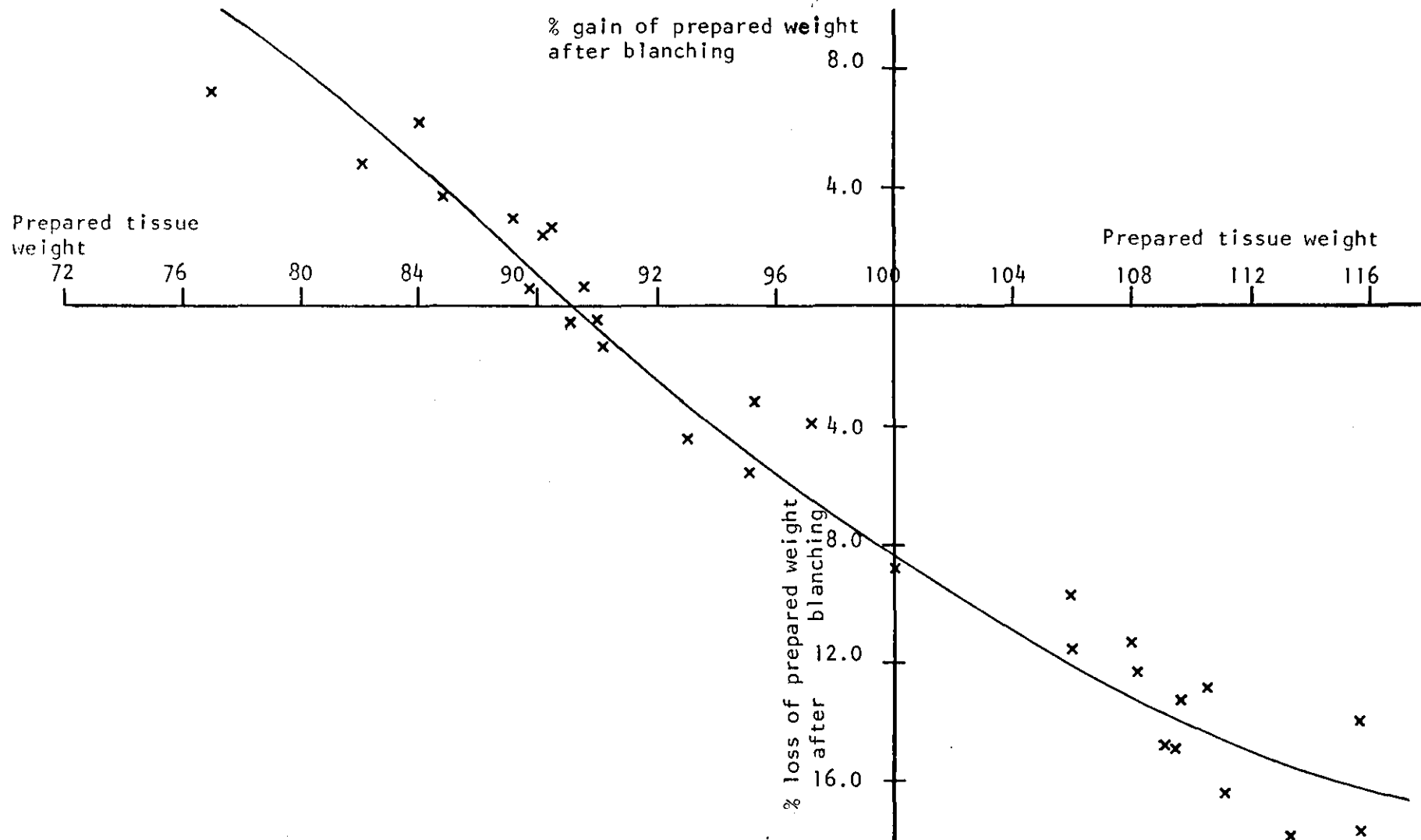
FIGURE 5.16: Percentage change of prepared tissue weight of carrot core cylinder samples blanched for 900 s at 70°C (points from four replicates)
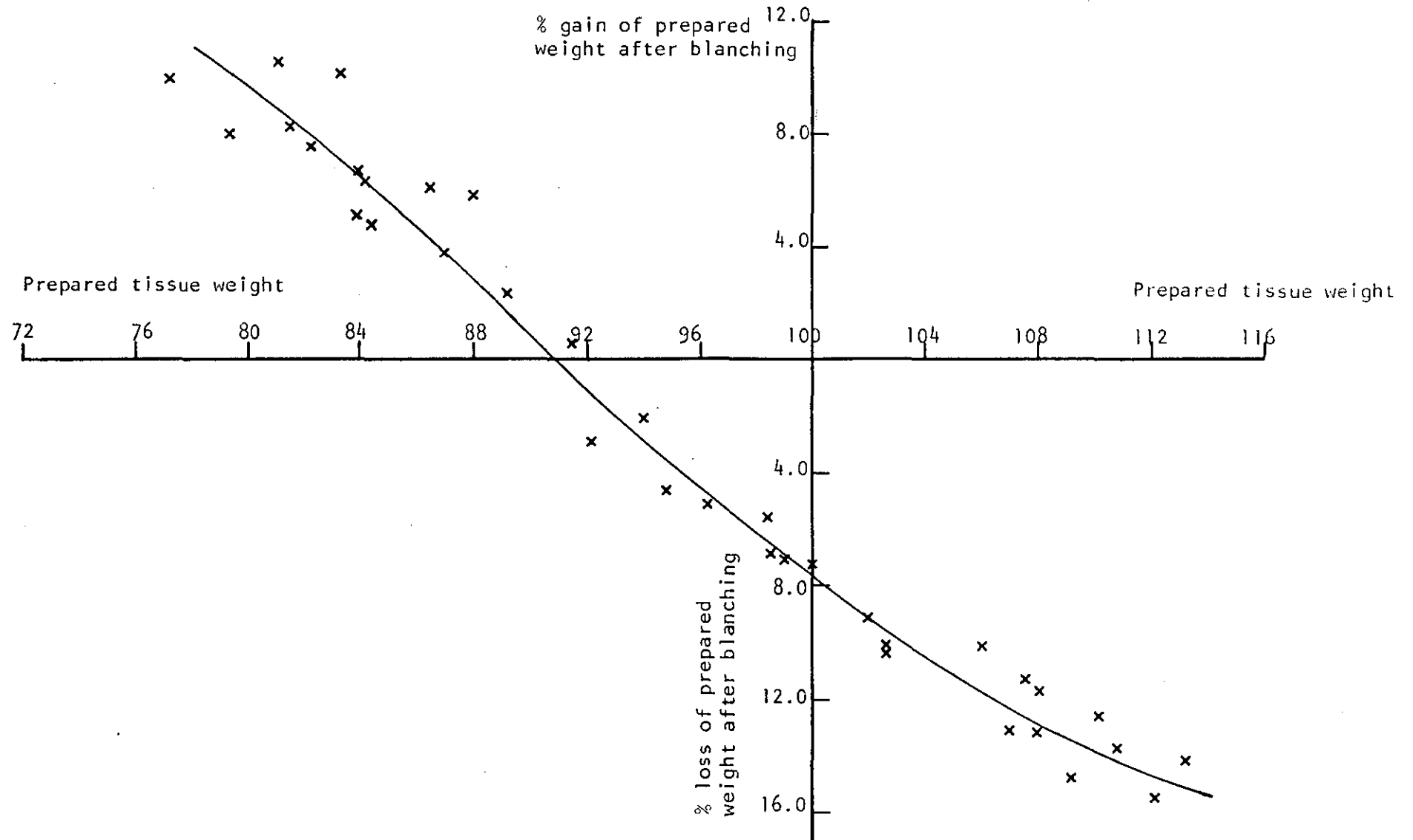
FIGURE 5.17: Percentage change of prepared tissue weight of carrot cortex cylinder samples blanched for 900 s at 70°C (points from four replicates)
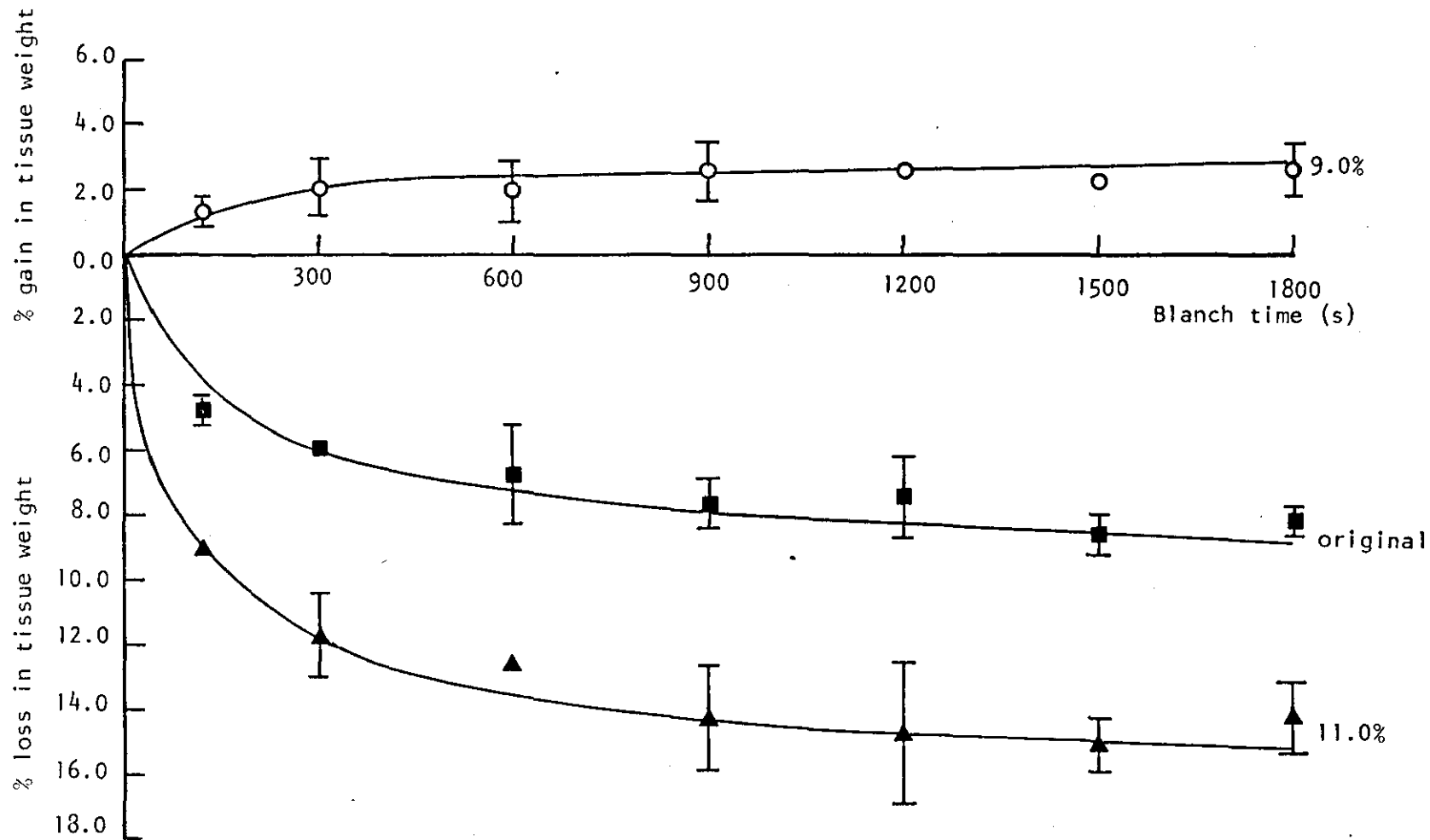
FIGURE 5.18: Percentage weight change of prepared carrot cortex tissue after the given blanch time at 70°C (means of four replicates)
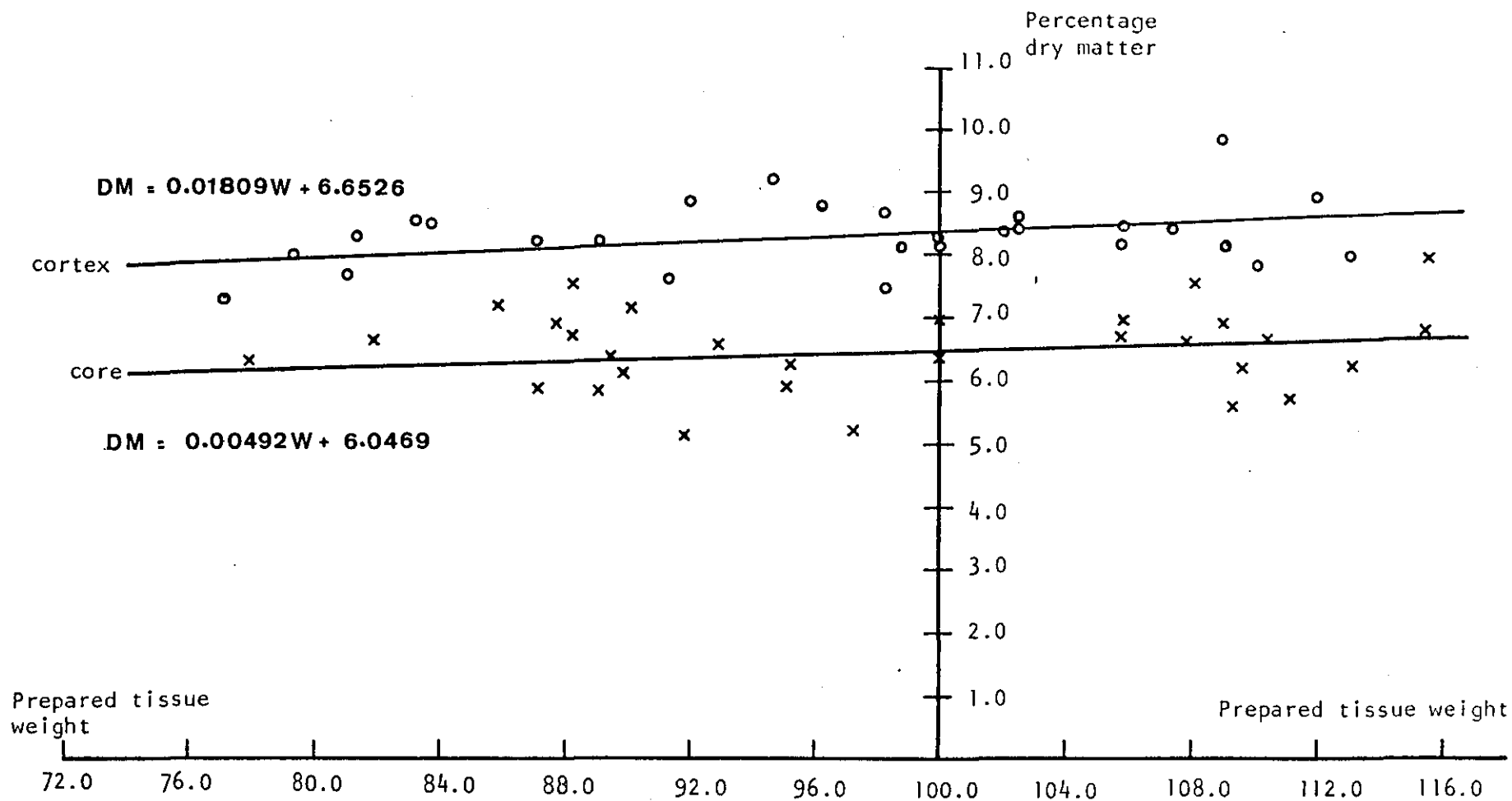
FIGURE 5.19: Percentage change in dry matter solids of prepared tissue of carrot cortex and core blanched at 70°C for 900 sec (points from four experiments)

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the weight loss is correlated positively with initial water content of the tissue. By removing 9% of the water content of the tissue, a weight gain of 2.3% occurred up to 1800 sec, due to diffusion of water into the cell, as the cell solute concentration would be higher than that of the blanch medium, and due to tissue volume changes. As expected, increasing the water content of the carrot tissue up to 11% of its fresh water content resulted in high weight loss (14.3%) after 1800 sec due to contraction of the distended cell wall which forced out the cell solution. These results show the effect of the initial water content on weight change following the disorganization of cell membranes. Also the results confirm that on disorganization of the cytoplasmic membranes by blanching, weight loss arose from the contraction of tissue cells under the influence of cell wall pressure.

The effect of the initial water content of the core and cortex tissue on the dry matter solids changes during blanching at $70^{\circ}C$ for 900 sec is shown in Figure 5.19. The dry matter solids loss for both core and cortex appear to decrease as the initial water content of the tissue was increased. This is due to the fact that the high solids concentration in the cells of tissues having low water content, is causing a concentration gradient to the blanch medium which is higher than in the case of tissue having high water content, see Figures 5.20 and 5.21. So on blanching at $70^{\circ}C$ for 900 sec, the loss is higher from the tissue of low initial water content as the loss of solute and water is controlled by diffusion only at this stage. These results agreed reasonably well with those reported by Selman and Rolfe (1979). The pattern was similar and the solute losses were positively correlated with the initial water content of the tissue.
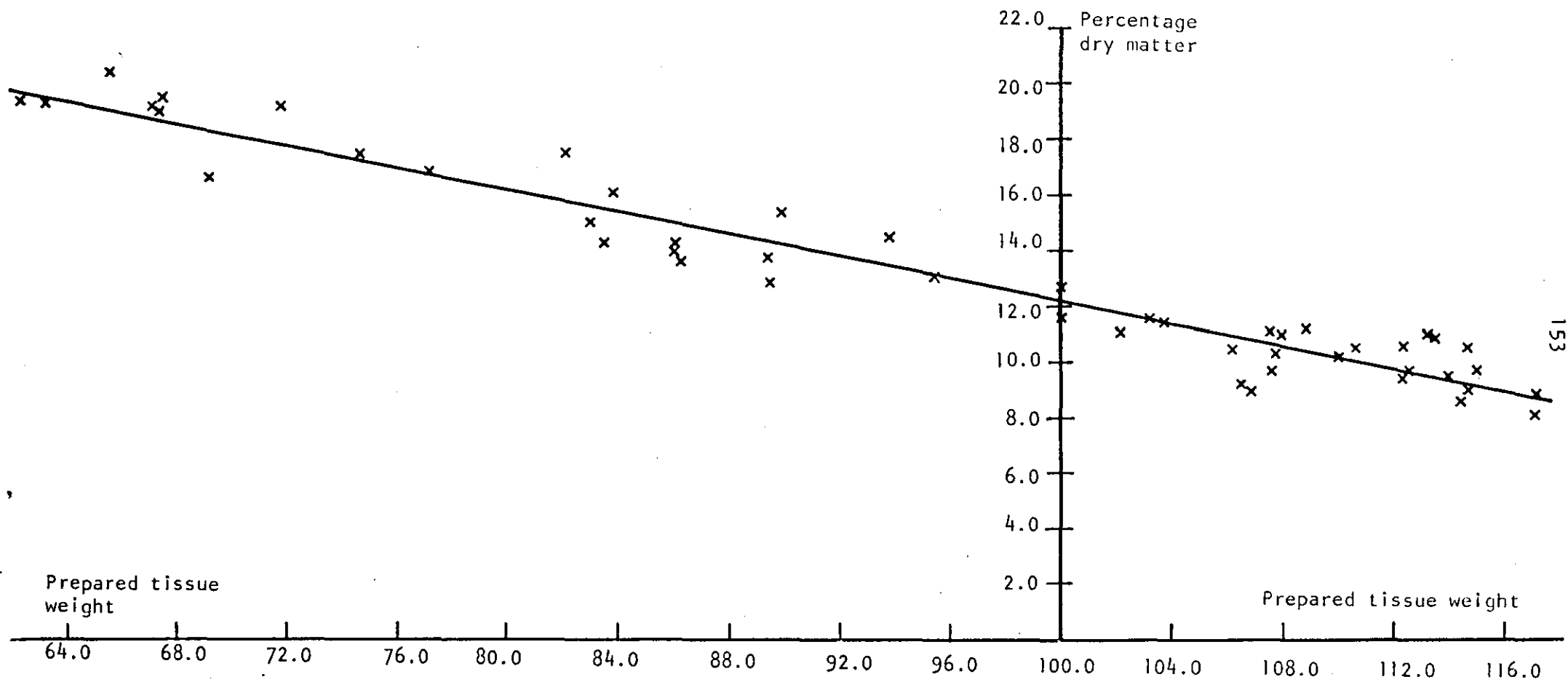
FIGURE 5.20: Variation of dry matter solids with initial water content of prepared carrot cortex tissue (points from four experiments)

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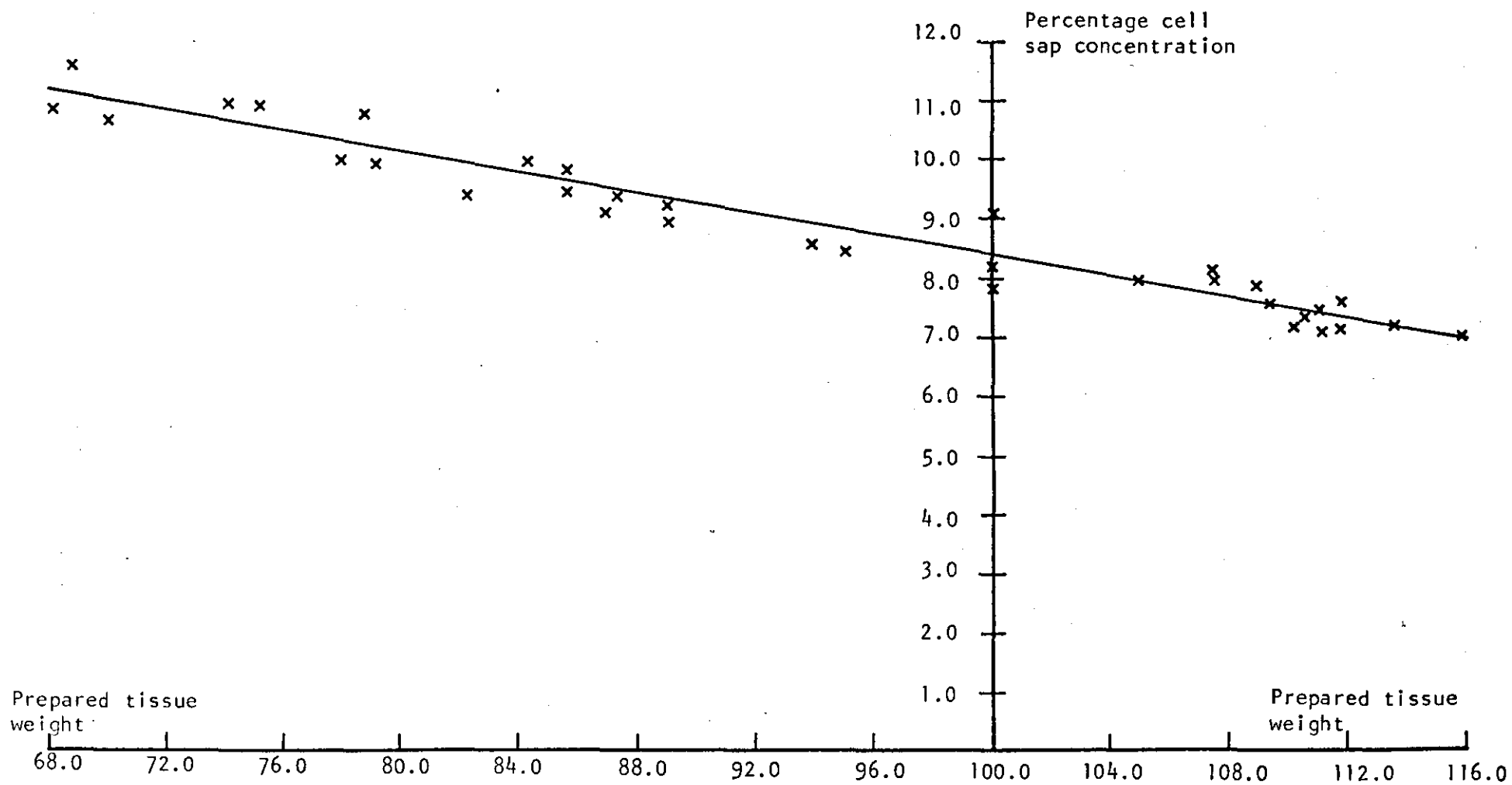
FIGURE 5.21: Variation of cell sap concentration with initial water content of the prepared carrot cortex tissue
(points from four experiments)

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5.1.3.2 Potato tissue

Potato tissue covering a wide range of initial water contents were prepared as described for carrot, and the potatoes were blanched for 900 sec at $70^{o}C$. The resulting fresh weight changes and solute losses are shown in Figure 5.22. A similar pattern to the weight changes exhibited by carrot tissue samples was obtained with potato. An increase in the prepared tissue weight up to 106% of the fresh weight resulted in an almost equivalent increase in weight loss after blanching, but prepared tissue weights of higher than 106% did not give equivalent increases in weight loss after blanching. This may be due to some water uptake by the potato tissue during blanching caused by gelatinization of starch. However prepared tissue weights of less than 92% gave a greater increase in weight gain than the carrot gave after blanching under the same conditions. The solute losses seem to be positively changed with initial water content of the tissue, i.e. the loss increased with decreasing water content of fresh tissue. This increase in solute loss was expected since the removal of water from the tissue increased the solute concentration inside the cell (see Figure 5.23). This increase in solute concentration in the cells, however, produced a high concentration gradient between the cell and the blanch medium. Thus on disorganization of the cytoplasmic membranes by blanching at $70^{o}C$, solute diffused out of the cells in large amounts since the movement of solutes was entirely controlled by diffusion at this stage.

5.1.4   Effect of Blanch Medium Concentration
5.1.4.1 Carrot tissue

An experiment was carried out to study the changes in tissue weight and dry matter content during blanching of cortex cylinders at $70^{o}C$ for 120-1800 sec in different concentrations of sucrose (0, 3, 9 and 15% w/w). Figure 5.24 shows that in 15% and 3% sucrose blanching medium a weight loss occurred. Also it showed that the
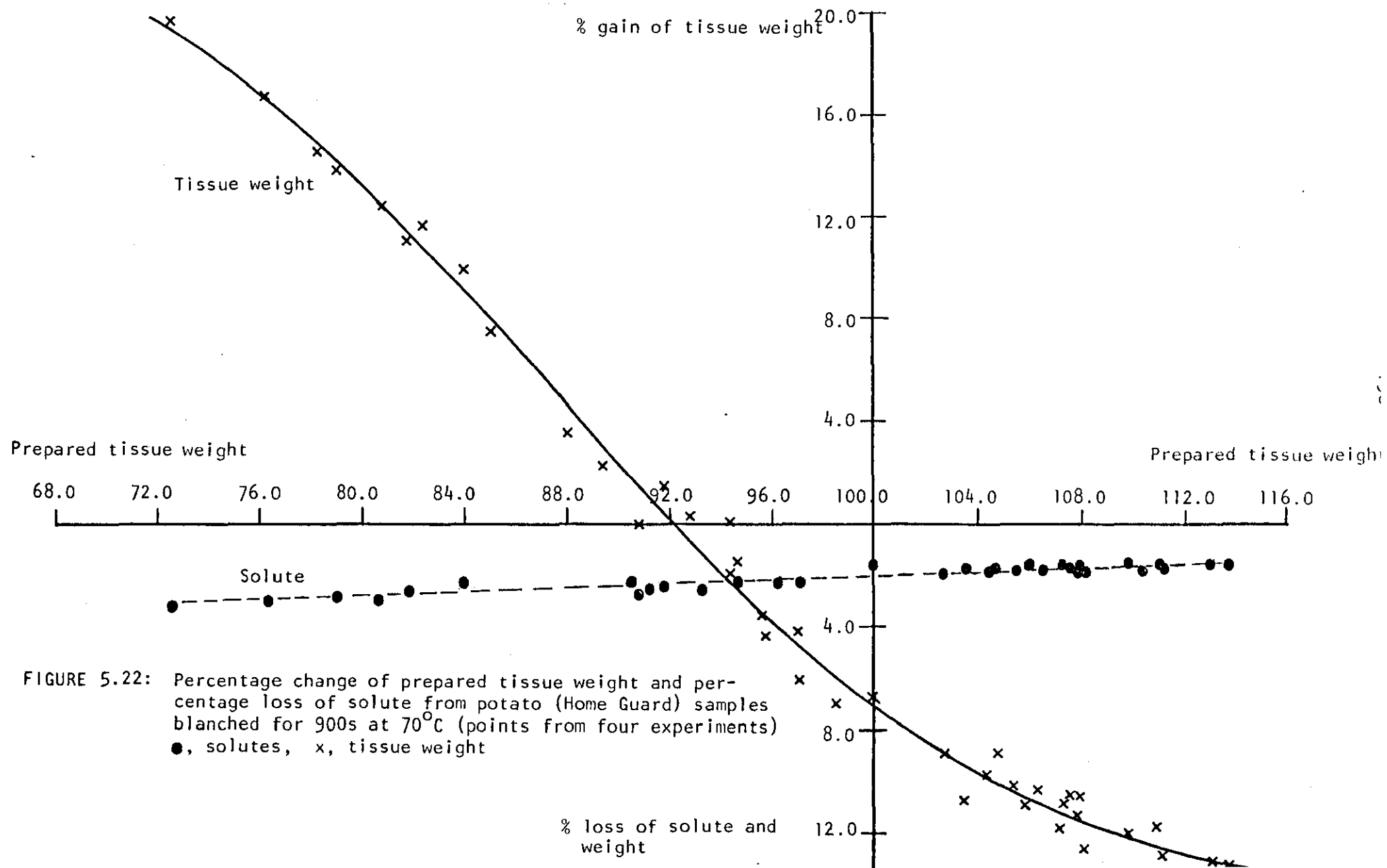
FIGURE 5.22: Percentage change of prepared tissue weight and percentage loss of solute from potato (Home Guard) samples blanched for 900s at 70°C (points from four experiments) ●, solutes, x, tissue weight
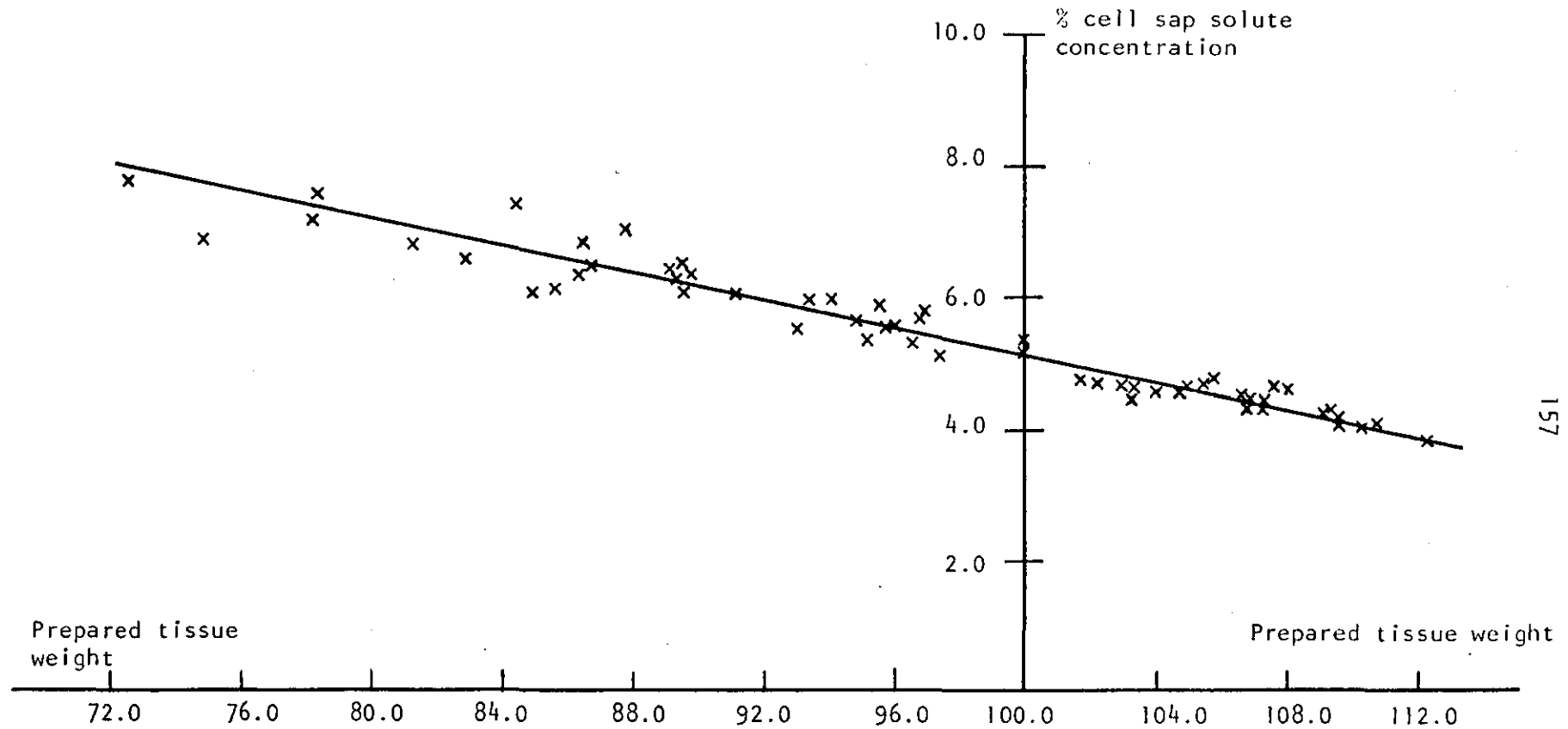
FIGURE 5.23: Variation of cell sap concentration with initial water content of the prepared Home Guard potato (points from four experiments)

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cortex tissue blanched in 15% sucrose had a higher rate of weight loss than the cortex blanched in 3% medium. The rate of weight loss in both media was higher during the first 900 sec before it tailed off to an approximately constant value. In 15% sucrose, the water concentration in the cell tissue was greater than in the blanch medium causing the water to diffuse from the cells into the blanch medium and leading to a high weight loss. In 3% sucrose water diffusion from the blanch medium into the tissue was expected as a result of the water concentration in the tissue being lower than in the blanch medium, but the results showed a slight weight loss which contradicts an expected weight gain. The reason could be that the amount of solute lost from the tissue was higher than the water absorbed, and thus a net weight loss occurred. In 9% sucrose no net change of tissue weight was expected at different blanch times as the concentration of the blanch medium and the cell tissues were approximately equal, so there would be no significant diffusion gradient in either direction. The reason why the rate of weight loss decreased after 900 sec must be because the water concentration in the tissues decreased, the concentration gradient between the tissue and medium became small, and so only a small amount of water diffused out. A weight gain was observed with blanching in water. This again shows a contradiction to an expected weight loss as shown in Figure 5.6. The weight gain could be due to the fact that the tissue used contained low initial water content (i.e. small cell volume) and therefore on blanching will uptake water (see Section 5.1.3.1).

Figure 5.25 shows the changes in dry matter solids during blanching in different sucrose concentrations. In 15% sucrose, there was an increase in dry matter solids content of the tissue with time. This was expected due to diffusion of sucrose from the blanching medium into the tissue, as the concentration of sucrose in the blanch medium was higher than the concentration of tissue cell sap (8.7%). The same occurred in 9% sucrose but the overall dry
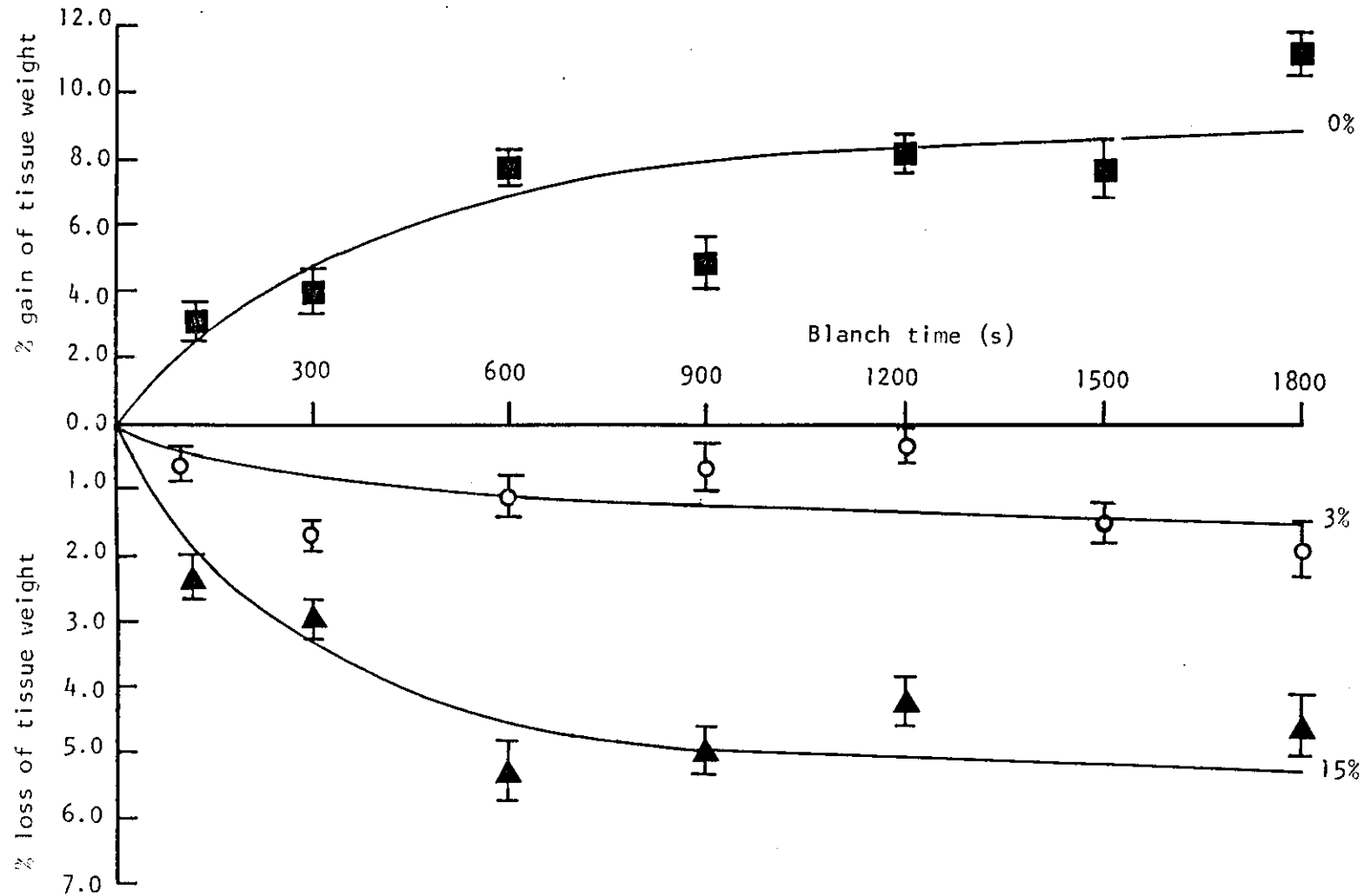
FIGURE 5.24: Percentage loss and gain of tissue weight from carrot cortex cylinder after given blanch time at 70°C in 0, 3 and 15% w/w sucrose solutions (means of two duplicates replicates) ■, 0%, 0, 3%, ▲, 15%
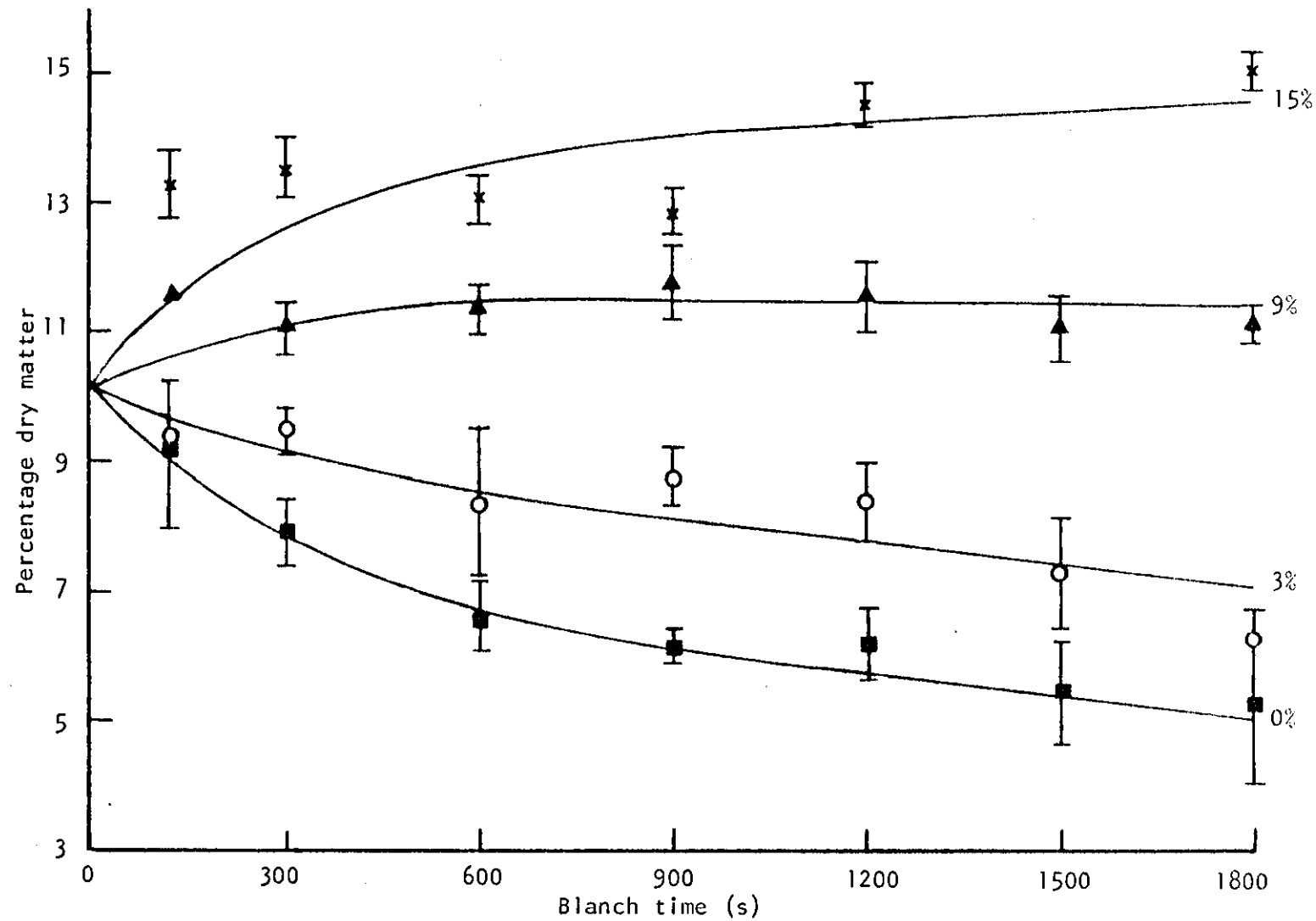
FIGURE 5.25: Percentage dry matter of carrot cortex cylinders after the given blanch time at 70°C in 0, 3, 9 and 15% sucrose solutions w/w (means of two duplicated replicates), X, 15%, ▲, 9%, 0, 3% and ■, 0%

matter solids gain was very small due to the isotonic concentra-
tion of the cell sap and the blanching medium. As expected, in 3%
sucrose there was a dry matter solids loss. This is because the
concentration of sucrose in the medium was lower than the concen-
tration of solutes in the cell tissues.

5.1.5 Effect of Post-blanch Cooling

Most of the previous work carried out on blanching of vegetables
included post-blanching cooling as an integral part of the blanching
process, and most of the measurements on weight change and solute
loss were recorded after this cooling. Therefore the weight changes
and water and solutes losses resulting from cooling were examined
using water and air cooling for different times and temperatures.

5.1.5.1 Carrot tissue

A post-blanching cooling process on carrot cortex tissue was
carried out at $20^{o}C$ in water for 300 and 900 sec after blanching
at $70^{o}C$ for 120-1800 sec in water. The results are summarised in
Table 5.1. A decrease in weight loss was observed when the carrot
tissue was blanched and then cooled in water. However the amount
of weight loss decreased as the time of cooling increased from 300
to 900 sec. This is due largely to the uptake of water during the
cooling process from the medium. The cooling process also resulted
in small solute loss (see Section 5.2.5).

5.1.5.2 Potato tissue

Post-blanch cooling of Maris Bard potato was carried out in
two ways: (1) water cooling, (2) air cooling. Potato samples
were blanched at $70^{o}C$ for 600 sec and then cooled in water or air
for different times and temperatures.

The results are summarised in Figures 5.26, 5.27 and Table 5.2.
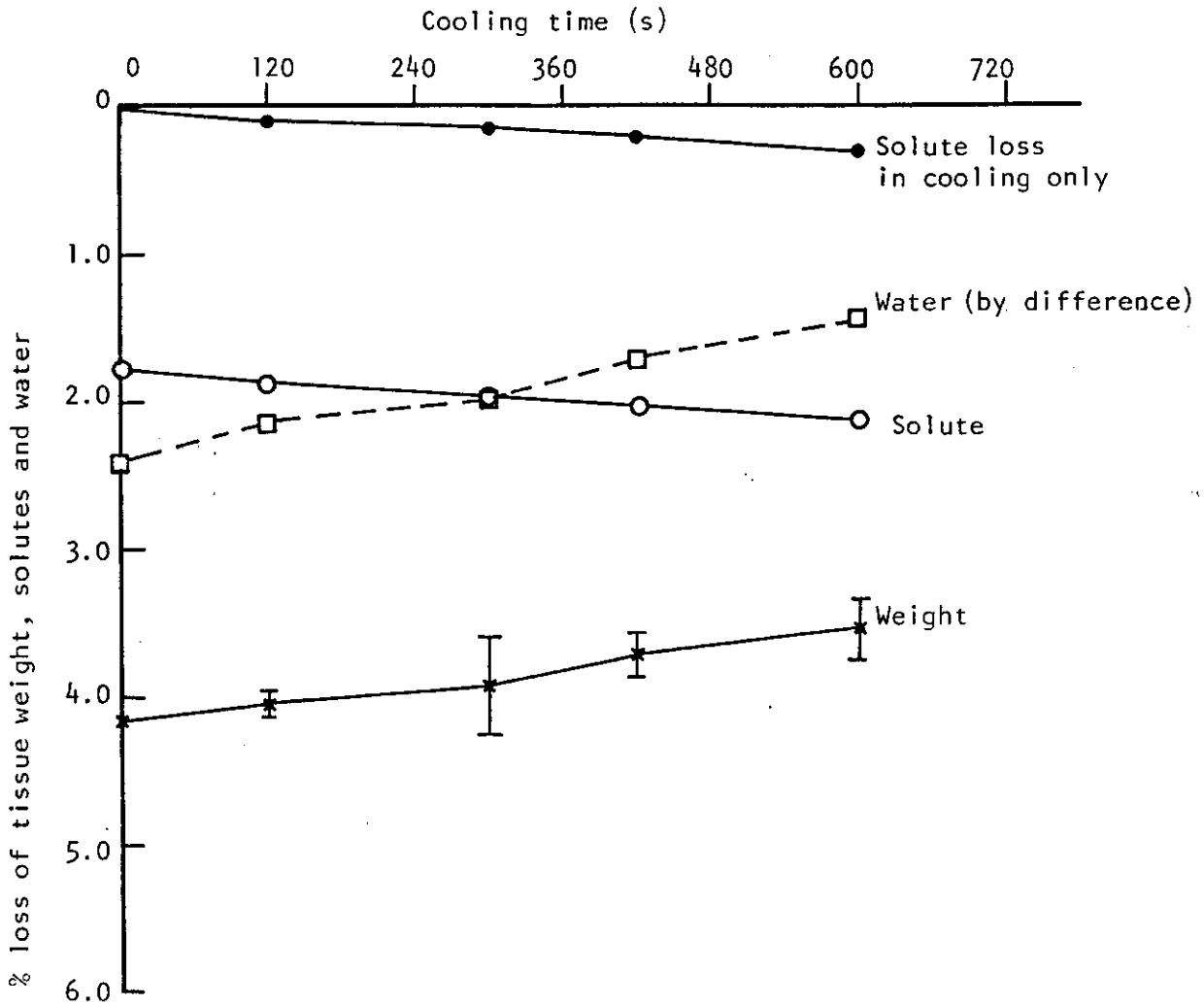
FIGURE 5.26: Effect of post-blanch cooling in water at 20°C for 120-600s on changes in weight, water and solute loss from Maris Bard potato after 600 sec blanching at 70°C (means of three repeats)
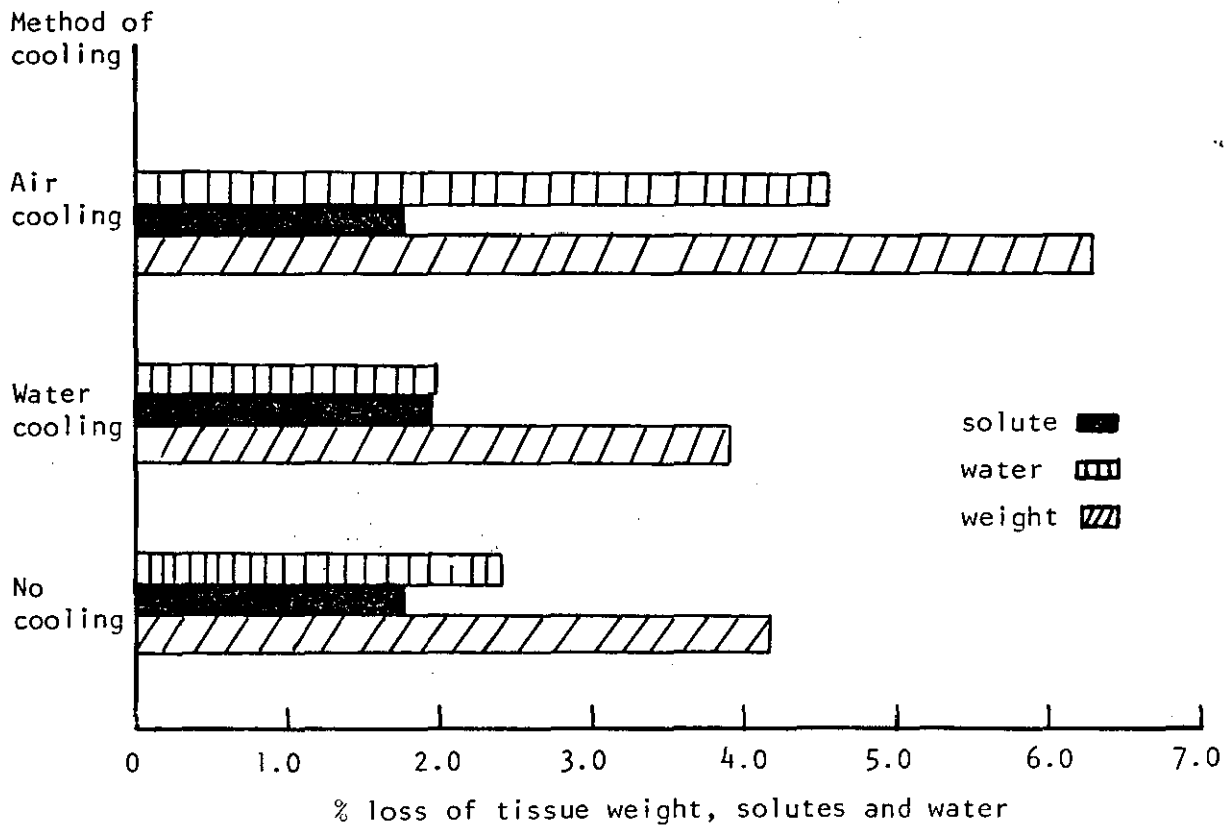
FIGURE 5.27: Effect of blanching at 70°C for 10 min and post-blanch cooling for 300s · in water at 20°C and in air at 22°C on weight changes, solute and water loss from Maris Bard potato tissue (mean of three repeats)
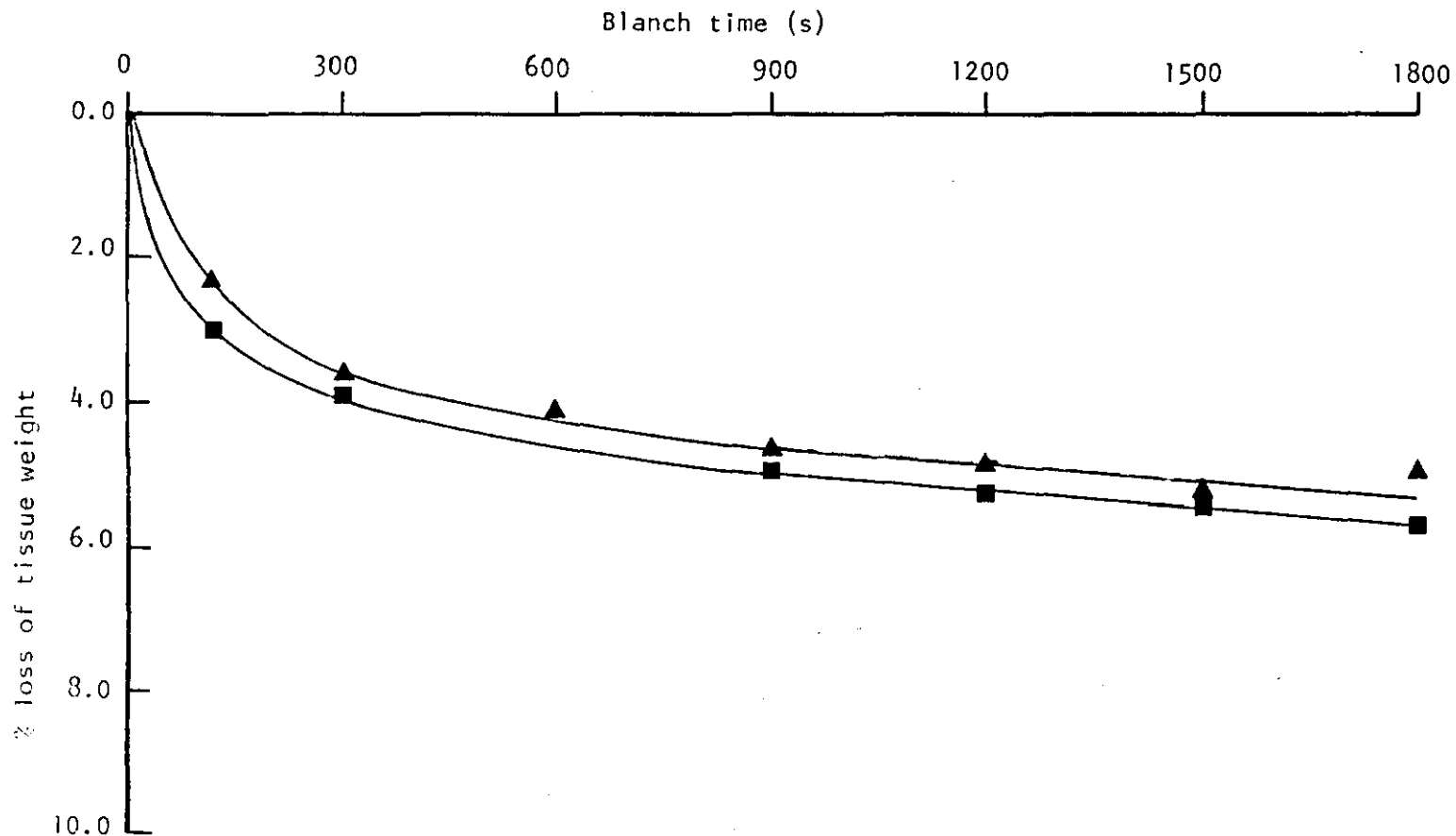
FIGURE 5.28: Effect of post-blanch cooling in water at 20°C for 300s   on weight loss from Maris Bard potato tissue after blanching for .600s   at 70°C (means of three replicates), ▲ , blanching and post blanch cooling, ■ , blanching without cooling

TABLE 5.1: Effect of post-blanching cooling in water at 20°C for 300 and 900 sec on the weight loss from carrot cortex after blanching at 70°C (means of four replicates)

Blanch Time (sec)	Blanch Temp. (°C)	Cooling Temp. (°C)	Percentage weight loss during blanching only	Percentage weight loss during blanching and post-blanching cooling in water for 300s	Percentage weight loss during blanching and post-blanching cooling in water for 900s
120	70	20	4.8	4.7	2.9
300	70	20	5.9	5.3	3.2
600	70	20	7.3	6.7	5.6
900	70	20	7.7	6.9	6.4
1200	70	20	8.4	7.2	6.9

TABLE 5.2: Effect of post-blanching cooling in air at room temperature (22°C) for 120-600 sec on the weight, solute and water loss from Maris Bard potato tissue after 600 sec blanching at 70°C (means of three replicates)

Blanch temperature (°C)	Blanch time (sec)	Cooling temperature (°C)	Cooling time (sec)	Percentage weight loss after blanching and post-blanching cooling in air	Percentage solutes loss after blanching and post-blanching cooling in air	Percentage water loss after blanching and post-blanching cooling in air
70	600	22	120	5.6	1.7	3.9
70	600	22	300	6.3	1.76	4.5
70	600	22	600	7.3	1.78	5.5

The results of Figure 5.26 show small solute losses during the post-blanch cooling in water which increased with increasing cooling time. A water uptake was also recorded during this process which reduced the overall weight loss. It was observed that cooling by air at room temperature $22^{O}C$ after blanching at $70^{O}C$ (Table 5.2) caused a greater weight loss than the other methods due to evaporation of water from the surface. Figure 5.27 shows a comparison between post-blanch cooling in air and water at $22^{O}C$ for 300 sec after 600 sec blanching at $70^{O}C$. Cooling for 300 sec in water resulted in a slightly smaller weight loss (0.3%) than that blanched and weighed without cooling. The water uptake due to cooling was (0.4%). The (0.1%) difference was accounted for by further solute loss during cooling. Although air cooling resulted in the same solute loss as without cooling (1.7%), it resulted in a 2.1% water loss due to evaporation which resulted in a higher overall tissue weight loss of 6.3%.

In a second experiment samples of potato were blanched at $70^{O}C$ for 120-1800 sec followed by cooling in water at $20^{O}C$ for 300 sec. The results are shown in Figure 5.28. This shows again a weight loss decrease with water cooling due to some water uptake from the cooling medium.

5.1.6   Effect of Dimension
5.1.6.1   Carrot tissue

The effect of carrot sample diameter on the changes in weight and dry matter were also investigated. Cylinders of Nameless carrot cortex having diameters of 0.005, 0.006 and 0.007m were blanched for several times up to 1800 sec at $70^{O}C$. The results are shown in Figures 5.29 and 5.30.

The weight loss increased with decreasing cylinder diameter, being 9.8%, 8.5% and 8.0% after 1800 sec blanching at $70^{O}C$ for samples having 0.005, 0.006 and 0.007m diameters respectively.
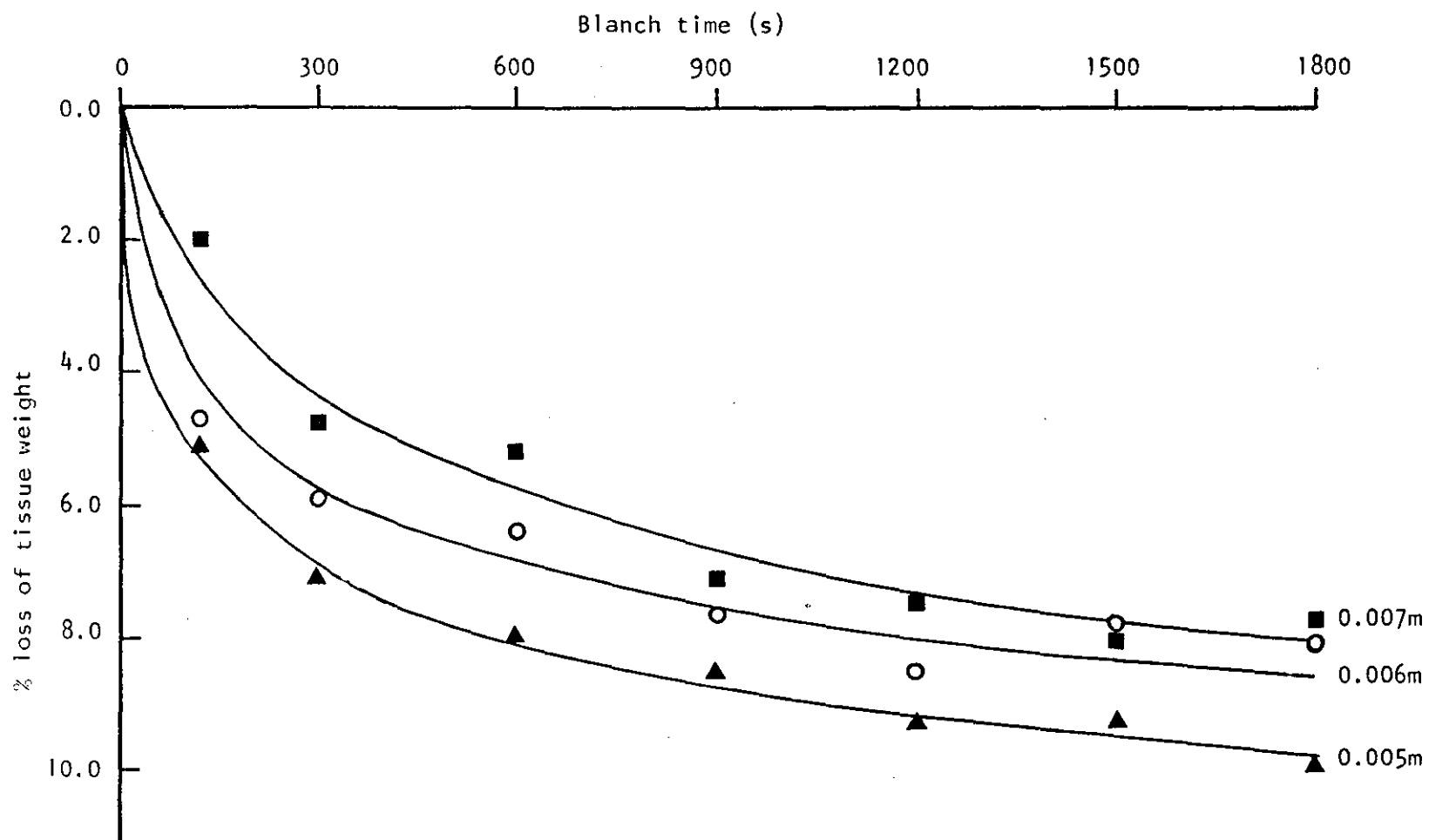
FIGURE 5.29: Percentage loss of tissue weight from carrot cortex cylinders of 0.005, 0.006 and 0.007 m diameter after the given blanch time at 70°C (means of two duplicate replicates) ■, 0.007, 0, 0.006, ▲, 0.005
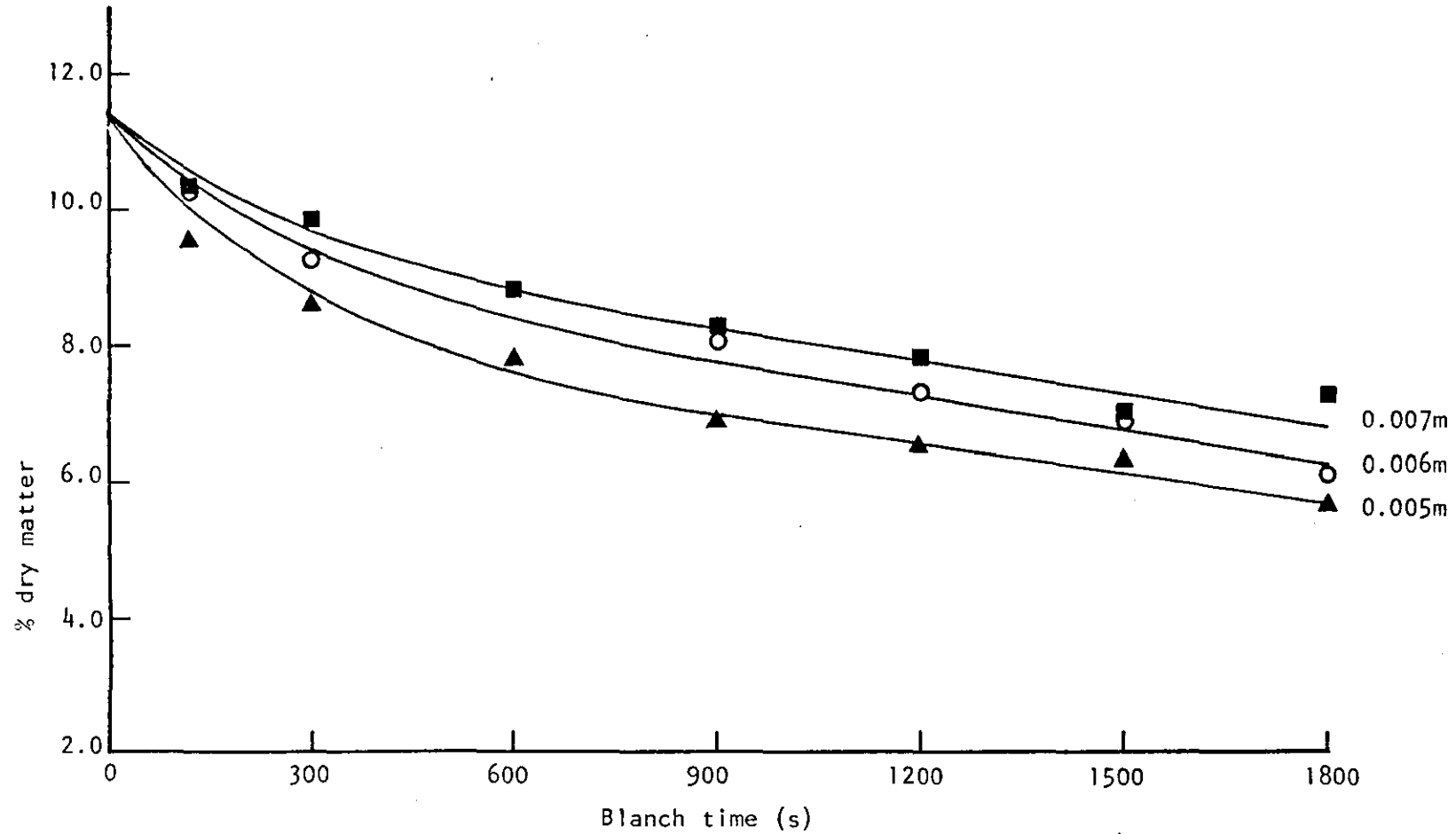
FIGURE 5.30: Dry matter of carrot cortex cylinders of 0.005, 0.006 and 0.007m diameter after the given blanch time at 70°C (means of two duplicated replicates), ■, 0.007, 0, 0.006, ▲, 0.005

With the smaller diameter, the short distance that the solute and water need to travel to reach the surface of the tissue seem to make a large contribution to the high weight losses into the blanch medium. As expected the results in Figure 5.30 show that the dry matter solids loss increases with decreasing of the diameter. Again the trend was the same as before reflecting high dry matter solids loss during the first 900 sec before decreasing to a steady rate.

5.1.6.2 Potato tissue

A similar experiment was carried out with cubes of Maris Bard potato tissue to study the effect of sample dimension (0.01, 0.012, 0.014 and 0.018m) on the changes in tissue weight during blanching at 70°C for 120-1500 sec. The results are shown in Figure 5.31. Figure 5.32 shows the change in weight and solute losses from potato cubes of 0.006, 0.010, 0.012, 0.014 and 0.018m dimension during blanching at 70°C for 900 sec.

The pattern of changes in tissue weight (Figure 5.31) were similar to that of carrot, losses increasing with decreasing sample dimension, but the amount of weight lost from potato was lower than that lost from carrot. For example after 1200 sec blanching at 70°C, the weight losses were 9.3% and 7.5% from carrot cylinders having 0.005 and 0.007m diameter respectively, while the losses were 5.2% and 4.4% for potato cubes having dimensions of 0.01 and 0.018m respectively. This was largely because of water retention within the potato tissue due to starch gelatinization. From Figure 5.32 it seems that the amount of water retained within the tissues increased with decreasing cube size from 0.018 to 0.010m, being 3% and 2.7% respectively after 900 sec blanching. This could be due to the fact that since heat can penetrate the centre of the smaller cubes more rapidly than the larger cubes, more starch gelatinization would occur in a given time and thus more water uptake would result. The high water losses from the 0.006m cubes show a contradiction to the expected increase in water
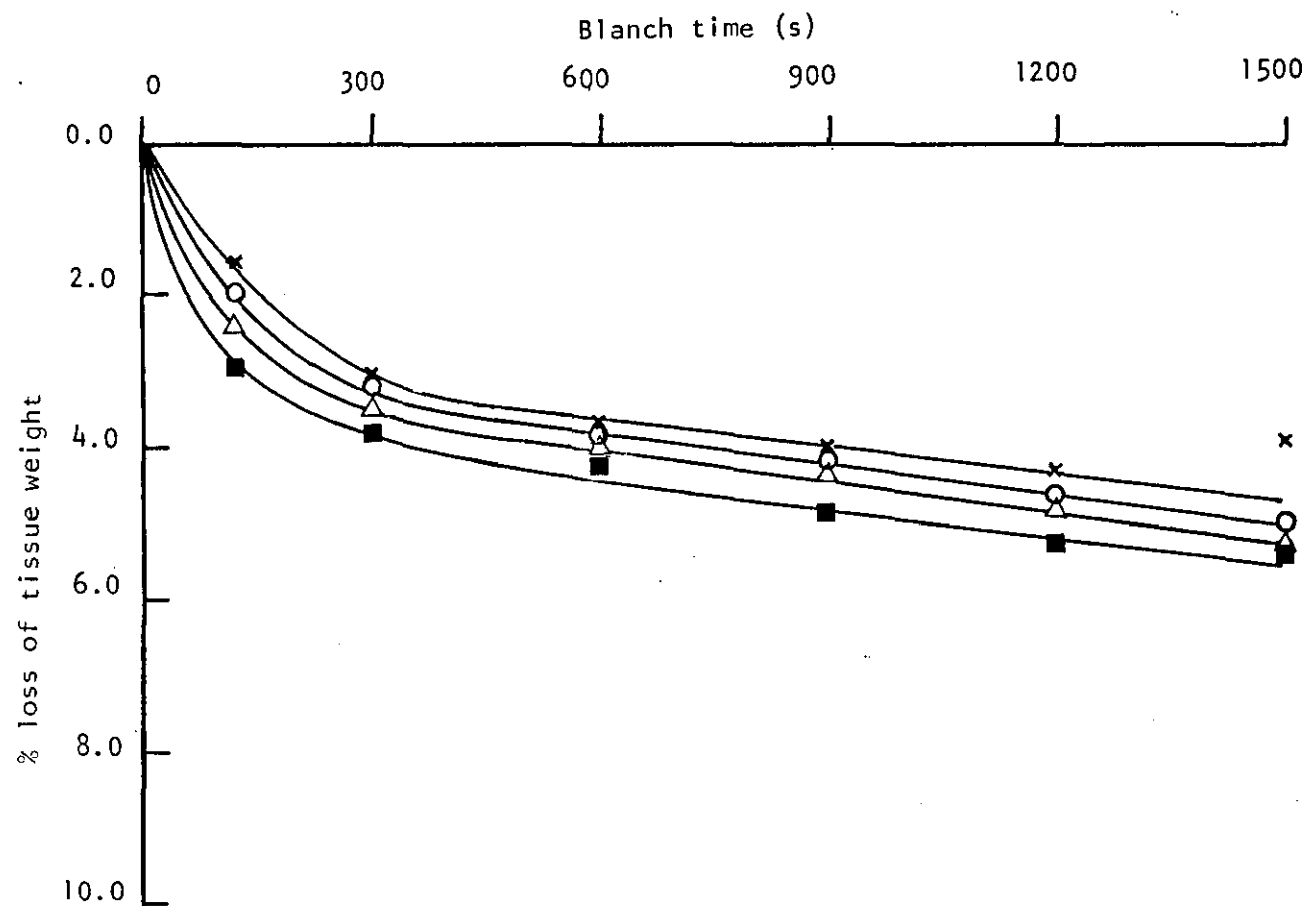
FIGURE 5.31:Percentage loss of tissue weight from Maris Bard potato cubes of 0.018, 0.014, 0.012 and 0.010 m after the given blanch time at 70°C (means of four replicates), X, 0.018m, 0, 0.014, △ , 0.012m, ■ , 0.010m
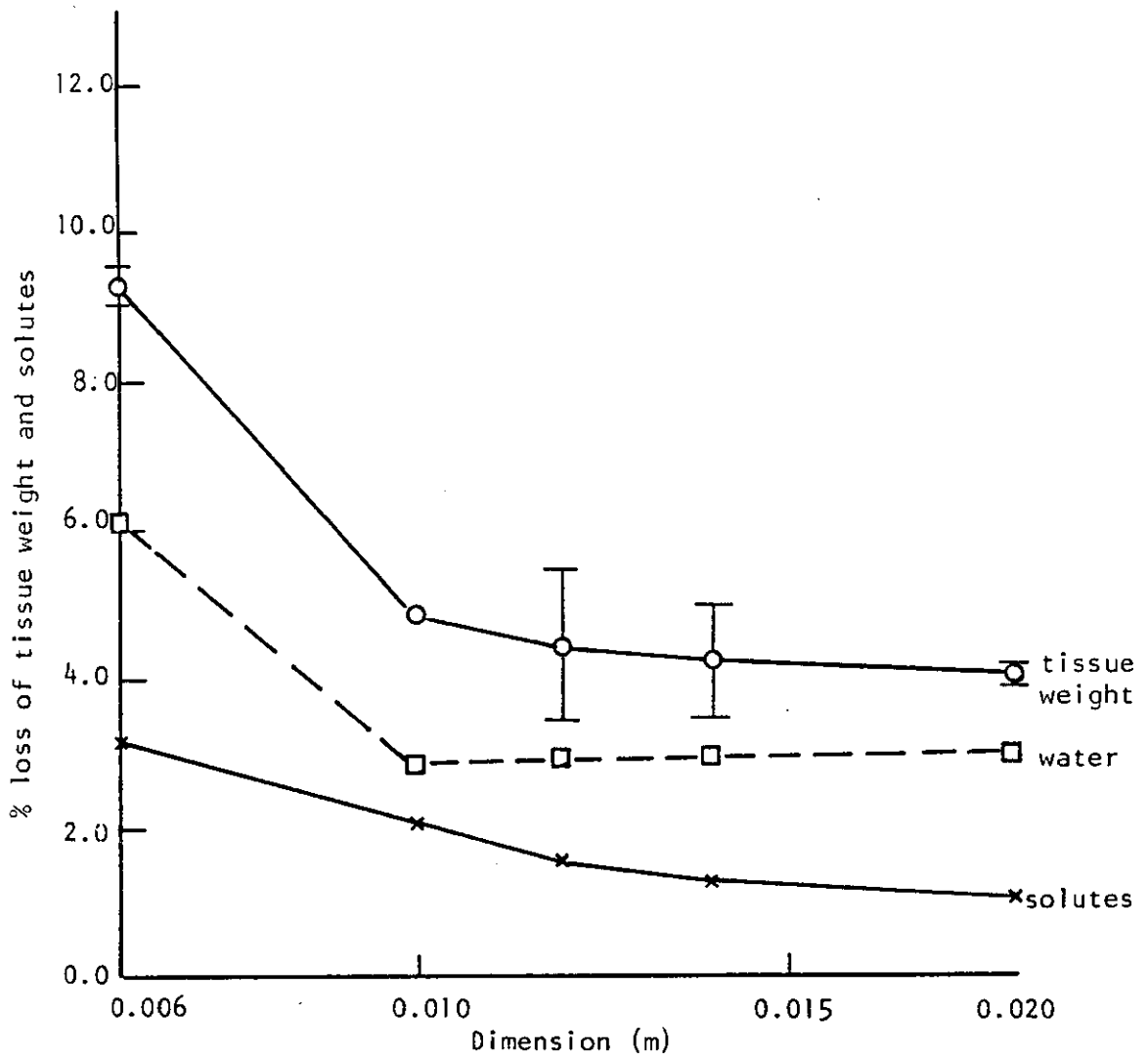
FIGURE 5.32: Percentage loss of tissue weight and water (by difference from Maris Bard potato cubes samples of 0.006, 0.010, 0.0 0.014 and 0.018m blanched for 900s at 70°C. (Means of fo replicates), X, solutes,□, water, 0, tissue weight

retention. It is possible that the expected starch loss from the surface cells ruptured during preparation was very large in the case of the 0.006m cubes which have a large surface area, relative to the volume. Hence the amount of starch remaining within the tissue would be very small. Thus on blanching the amount of water retention by gelatinization of the starch would not be as significant.

5.1.7 Industrial Scale Blanching Process

In the production of potato crisps, a blanching operation is employed to wash the potato slices and to leach out excess quantities of reducing sugars, so that final reducing sugar contents are below 0.1%. The latter aids control of colour in the final product, but additional loss of dry matter may occur in the form of insoluble and other soluble matter. In this study it was possible to take only a small number of potato and water samples to obtain an indication of the performance of this particular industrial process.

5.1.7.1 Total solids content of potato slices and blanch water

The total solids contents of potato slices at various operations are presented in Table 5.3. From an initial content of 22.2% solids, an overall reduction of about 11% occurred as a result of blanching. Blanch 1 and spray 1 accounted for some 5% of the loss, which would arise from the leaching of both soluble and insoluble solids from the large cut surfaces of the potato slices. The water temperatures were too low to inactivate the cell membranes at this first stage. The higher temperatures (above about 50°C) of blanch 2 resulted in a further 6% loss of solids, largely due now to diffusive losses from the dead tissues.

Table 5.4 compares the percentage of solids in the blanch 1 and blanch 2 as well as showing the percentage of solids in the make up water and the overflow for both processes. The total solids

TABLE 5.3: Dry matter contents of potato samples at the various sampling points in the process

Potato Sample Point	Potato dry matter and losses* (%) (FWB)							
	A			B			Average	Losses
	1	2	3	4	5	6		
Ex store (whole)	20.99	22.01	23.12	21.88	22.00	22.91	22.2±0.8	-
Ex slicer	22.84	21.33	-	21.96	22.62	-	22.2±0.7	-
Ex blanch 1	20.74	20.87	-	22.23	21.62	-	21.4±0.7	3.6
Ex spray 1	20.94	20.63	-	20.97	21.76	-	21.1±0.5	5.0
Ex blanch 2	19.39	20.16	-	20.00	19.13	-	19.7±0.5	11.3
Ex spray 2	19.06	20.32	-	18.98	20.95	-	19.8±1.0	10.8

* Percentage losses based on potato composition ex slicer

Soluble solids 6.78%

Moisture content 77.85%

TABLE 5.4: Solids content of the blanching waters (a: total solids, b: soluble solids and c: insoluble solids)

| Water Sample Point | Type of Solids | Solids Loss% | | | | Average |
| | | A | | B | | |
		1	2	3	4	
Blanch 1	a	1.83	1.89	2.61	2.26	2.2 ± 0.4
	b	0.43	0.69	0.41	0.39	0.5 ± 0.1
	c	1.4	1.20	2.2	1.87	1.7 ± 0.5
Overflow 1	a	2.30	4.23	2.42	0.92	2.5 ± 1.4
	b	0.41	0.41	0.40	0.42	0.4
	c	1.89	3.82	2.02	0.50	2.1 ± 1.4
Make up water 1	a	2.25	3.11	2.59	2.08	2.5 ± 0.5
Blanch 2	a	1.50	1.47	1.50	1.45	1.5
	b	1.07	1.16	1.24	0.85	1.1 ± 0.2
	c	0.43	0.31	0.26	0.60	0.4 ± 0.2
Overflow 2	a	1.47	1.46	1.52	1.45	1.5
	b	0.78	0.79	0.80	0.74	0.8
	c	0.69	0.67	0.72	0.71	0.7
Make up water 2	a	1.53	1.52	1.55	1.53	1.5

content of the blanch waters in the first stage was about 2.5%
and for the second stage 1.5%. It is apparent that the insoluble
(75% of total) solids content was much higher in the stage 1 waters
compared to stage 2, as would be expected from the washing out of
starch granules from the cut surfaces.

The soluble solids content of the blanch 2 waters however
was about twice that of the blanch 1 water, as here the temperatures
were high enough to kill the cells and allow leaching of solubles
from the body of the slices. Most of the insoluble material was
therefore lost in blanch 1. There appeared to be some concentrating
of insolubles in the overflow cleaning tank of blanch 1.

5.2 Apparent Diffusion Coefficients for Solute Losses from Carrot Tissue

5.2.1 Effect of Tissue Type (Core and Cortex)

Preliminary work was carried out on Nameless carrots from
which standard cylinders of cortex and core tissue were cut and
then blanched at 70°C for several times up to 1800 sec in water
(see method Section, 4.1.1). Solute concentration in the cell
sap was measured after each blanch time and the results are shown
in Figure 5.33. Cell sap concentration decreased with blanch time.
The trend for both cortex and core was similar both exhibiting the
most rapid decrease in cell sap solute concentration during the
first 300 to 600 sec. In similar studies on carrot cortex Selman
and Rolfe (1979) suggested that losses during the first 5 minutes
were not simply due to diffusion but also to the expulsion of
cell sap as turgor was lost on cell death. The diffusion rate of
solute from both core and cortex tissue into blanch water slowed
between 600 to 1800 sec as the concentration gradient decreased.
The diffusion coefficients (D_a) of carrot cell solutes were
calculated from the curves shown in Figure 5.33 by the method
previously described. The D_a values are given in Table 5.5 as a
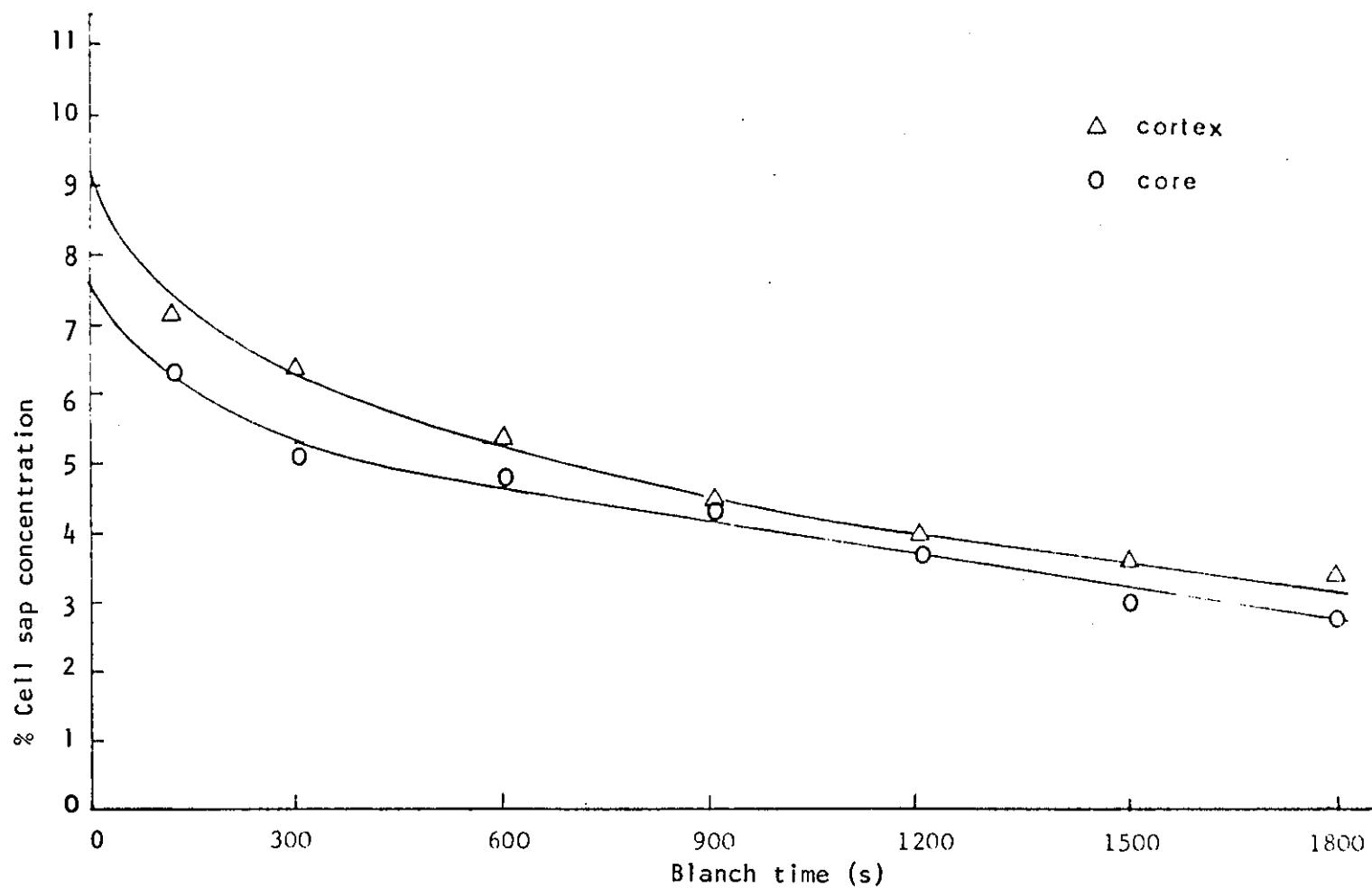
FIGURE 5.33 Percentage Cell Sap Concentration of Nameless Carrot Cortex and Core Cylinders after the Given Blanch Time at 70°C. (Means of two duplicated replicates).

TABLE 5.5: Apparent diffusion coefficients (D_a) of cell solutes of
carrot cylinders when blanched in water under the given
conditions (data from curves in figures 5.33, 5.34, 5.35
and 5.37)

Data from Fig. No	Sample Type	Conditions	Conditions varied from standard*	$D_a \times 10^{10}$ values at the given blanch time in seconds ($m^2 s^{-1}$)							
				120	300	600	900	1200	1500	1800	Mean 600-1800
5.33	Nameless core cortex		Standard	4.50	6.12	5.52	4.84	5.10	5.35	5.70	5.30
			Standard	6.15	6.60	6.62	6.70	6.56	6.06	6.05	6.40
5.35	Cortex	Temperature	60°C	3.75	1.20	2.34	2.10	3.41	3.68	3.82	3.07
			Standard	1.00	2.04	3.42	4.00	4.35	4.35	4.55	4.13
			80°C	1.50	3.30	4.58	5.12	5.72	5.58	5.80	5.36
			90°C	6.98	7.35	7.68	7.62	7.69	7.80	7.34	7.64
5.37	Cortex	Diameter	0.005m	3.07	4.83	5.31	5.14	5.05	4.92	4.80	5.04
			Standard	2.34	4.20	5.25	5.10	5.10	4.86	5.08	5.08
			0.007m	0.96	2.86	4.04	4.76	4.98	5.15	5.21	4.83
5.34	(Chanteney (Cortex	Concentration sucrose	3%)	5.93	7.14	6.33	5.30	4.73	4.62	5.15	5.23
			15%)	19.9	24.3	24.5	22.4	19.5	15.6	13.4	19.1
	(Nameless (Cortex		15%)	4.65	7.50	7.80	6.95	6.30	5.99	6.00	6.61
			20%)	13.5	13.0	11.6	9.50	8.29	7.76	8.30	9.09
Table 5.6	Nameless Cortex	Post-blanch cooling	With cooling(300s)	6.12	5.07	4.91	5.50	4.98	-	-	5.13
			With cooling(900s)	5.95	5.65	4.71	5.55	5.09	-	-	5.12
			Standard	4.95	4.20	4.01	4.90	4.35	-	-	4.42
			Only cooling(300s)	1.2	0.87	0.90	0.60	0.63	-	-	0.71
			Only cooling(900s)	1.00	1.45	0.70	0.65	0.79	-	-	0.70

* Standard conditions: Blanch temperature = 70°C
Blanch medium = distilled water
Carrot cylinder diameter = 0.006m

function of time and tissue type with mean values for D_a during
the period from 600 to 1800 sec. when solute losses appear to
arise solely by diffusion. At 70^oC the mean D_a value for diffusion
of solutes out of core tissue was slightly less than the mean D_a
value for the cortex tissue. These D_a values were $5.30 \times 10^{-10} m^2 s^{-1}$
for core and $6.40 \times 10^{-10} m^2 s^{-1}$ for cortex. This difference may be
due in part to initial concentration differences between core and
cortex tissue and to the variation of biochemical aspects and
structural differences between the tissues. The expulsive losses
during the first 300 sec are reflected in some of the D_a values
given in Table 5.5, which tend to be lower as might be expected
if whole solution is being lost during loss of turgor.

5.2.2   Effect of Blanch Medium Concentration

Cylinders of Chantenay cortex tissue were blanched in three
different concentrations of sucrose solution (3, 9 and 15% w/w)
to give blanch medium concentrations of 6% smaller than, the same
as, and 6% greater than the initial mean cell sap concentration of
8.7%. The changes in the cell sap concentration after blanching
are shown in Figure 5.34. As the cell sap concentration of the
cortex is 8.7%, the 15% sucrose solution causes a high concentration
gradient in favour of the medium and thus sucrose diffused into the
cortex tissue and increased the cell sap concentration. The 3%
sucrose as expected gave the converse effect to the 15% sucrose
since the cell sap concentration of the cortex was higher than the
concentration of the blanch medium. The 9% blanch medium which is
almost isotonic to the initial cell sap concentration of the cortex,
gave very slow rates of diffusion and no net movement in favour of
either direction. This is in agreement with similar observations
reported by Dan and Jain (1971) who blanched Asiatic carrots (4.5%
initial cell sap concentration) for 300 sec at 100^oC in solutions
containing up to 9% sucrose.

FIGURE 5.34 Percentage Cell Sap Concentration of Chantenay and Nameless Carrot Cortex Cylinders after the Given Blanch Time at 70°C in 3, 9, 15, and 20% (w/w) Sucrose Solutions, and Water (from Figure 5.35) (Means of Two Duplicated Replicates).

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The diffusion coefficients calculated from curves for solute movement in the 0,3 and 15% solutions are given in Table 5.5. The D_a value for the 9% solution was indeterminate due to the negligible concentration difference. It is seen from Table 5.5, that the concentration of the blanching medium significantly influences the diffusion rate of the cell sap. Mean D_a values for diffusion of solutes from the 15% sucrose solution were about four times greater ($19.1 \times 10^{-10} m^2 s^{-1}$), than those for the 3% sucrose solution ($5.23 \times 10^{-10} m^2 s^{-1}$). In both solutions D_a decreased with blanch time particularly in the case of the 15% sucrose solution where very small concentration differences existed after 900 sec.

It might be expected that cell sap concentration and blanch water concentration would reach equilibrium at about the same time for both the 15% and 3% conditions. However cell sap concentration rose more rapidly towards an equilibrium in 15% sucrose than did the fall in cell sap concentration toward equilibrium in the 3% sucrose. The higher D_a values observed in blanching in 15% sucrose support this, although it is not clear whether D_a is influenced by the rise of cell sap concentration or vice versa. After 1800 sec cell sap concentration had reached 14% in 15% sucrose and 5.5% in 3% sucrose when in both cases the initial concentration difference was 6%. Compared to the pattern in water, 9% and 3% sucrose, the pattern at 15% appeared to be unexpected. The difference in the 15% curve seems to arise during the first 300 sec blanching, when the changes occurring are not entirely due to diffusion and yet will influence the calculated value of D_a, for if the initial cell sap concentration (C_1) is taken as that recorded after 300 sec blanching (= 12.2%) then D_a at say 1200 sec is $8.7 \times 10^{-10} m^2 s^{-1}$. Similarly if C_1 is taken as that recorded after 600 sec blanching (13.2%) then D_a at 1200 sec becomes $3.8 \times 10^{-10} m^2 s^{-1}$, i.e. more similar to the values of D_a obtained for the other conditions.

However, considering the inherent variability of the carrot materials, it was suggested that the 15% result might simply be a reflection of this, and so bearing in mind the similarity between

the results previously obtained for the Chantenay and the Nameless
carrot cortex cylinders, blanching in 15% sucrose was repeated
and also in 20% sucrose using Nameless carrots of similar charac-
teristics. These results are shown in Figure 5.34. The curves and
D_a values (Table 5.5) are more nearly what might be expected in
relation to the results for water, 9% and 3% sucrose, with a mean
D_a of 6.61 x 10^{-10} in 15% sucrose, and 9.09 x 10^{-10} m^2s^{-1} in 20%
sucrose. It is concluded that the results for Chantenay carrots
at 15% may well have reflected variability in the carrot tissue,
but that D_a is influenced by the blanch medium concentration where
it is higher than the initial cell sap concentration. Typically
a commercial blanch water concentration for carrots might be
about 3-5% during continuous blanching (Gooding, 1956).

5.2.3 Effect of the Blanch Temperature

Cylinders of Chantenay cortex tissue were blanched for several
times up to 1800 sec at 60, 70, 80 and 90°C. The resulting changes
in cell sap concentration are shown in Figure 5.35. A similar
pattern of decreasing cell sap concentration is observed at each
temperature; but with increasing temperature the trend was for a
more rapid decrease in concentration during the first 300 sec which
resulted in a greater overall loss at each blanch time. The
literature data on solids diffusing rates at different temperatures
shows similar behaviour, that is the rate of diffusion increases
with increasing temperature. In most cases, the rate of concentra-
tion decrease slowed noticeably after 600 sec due to the now lower
concentration gradient between the blanch medium and the tissue.

The results for both the cortex of Chantenay and Nameless
carrots at 70°C are very similar, and indicate that different types
of carrots having similar characteristics, such as initial cell sap
concentration, may exhibit a similar pattern of diffusive solute
loss during blanching. The diffusion coefficients for solutes at

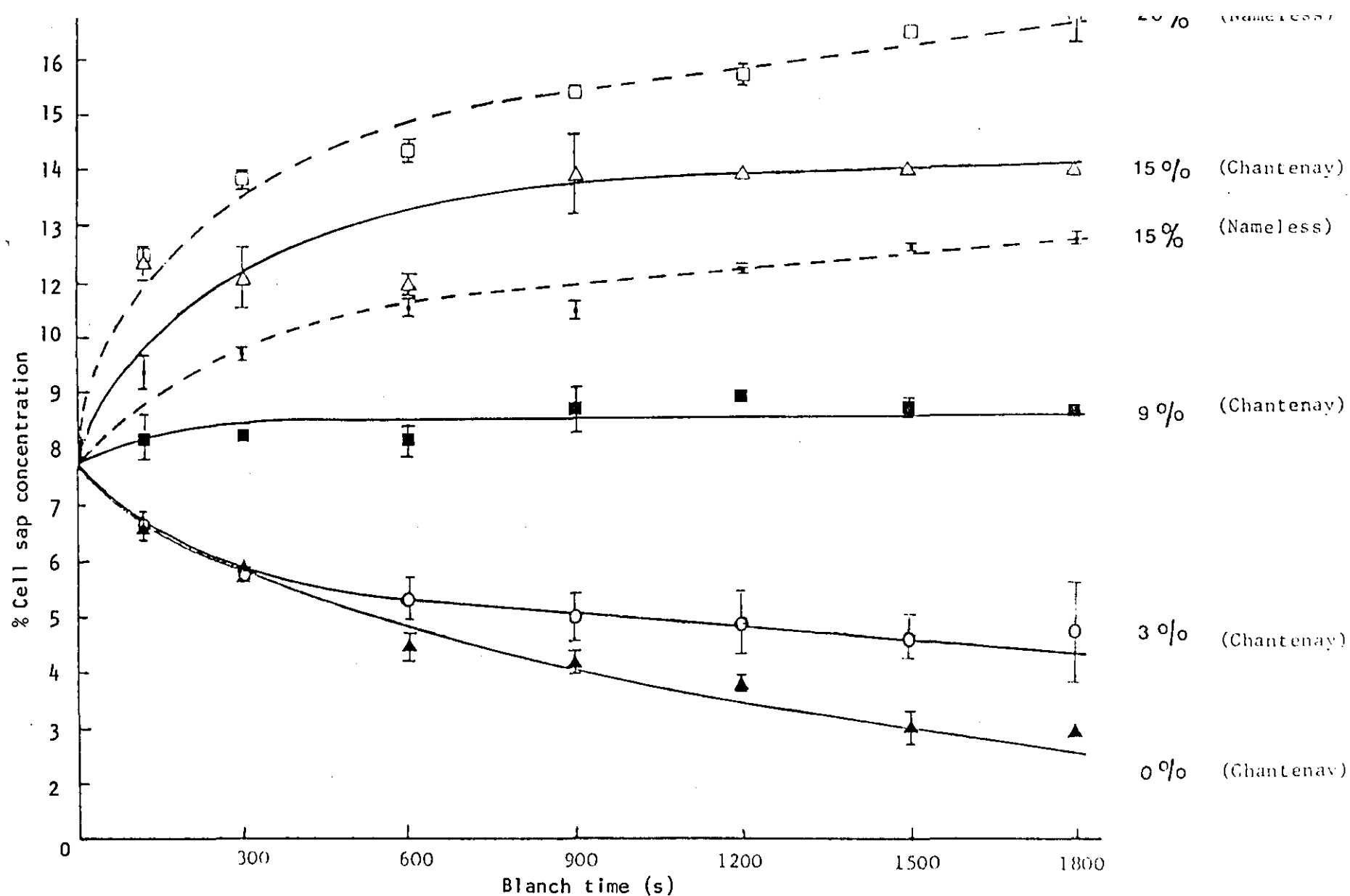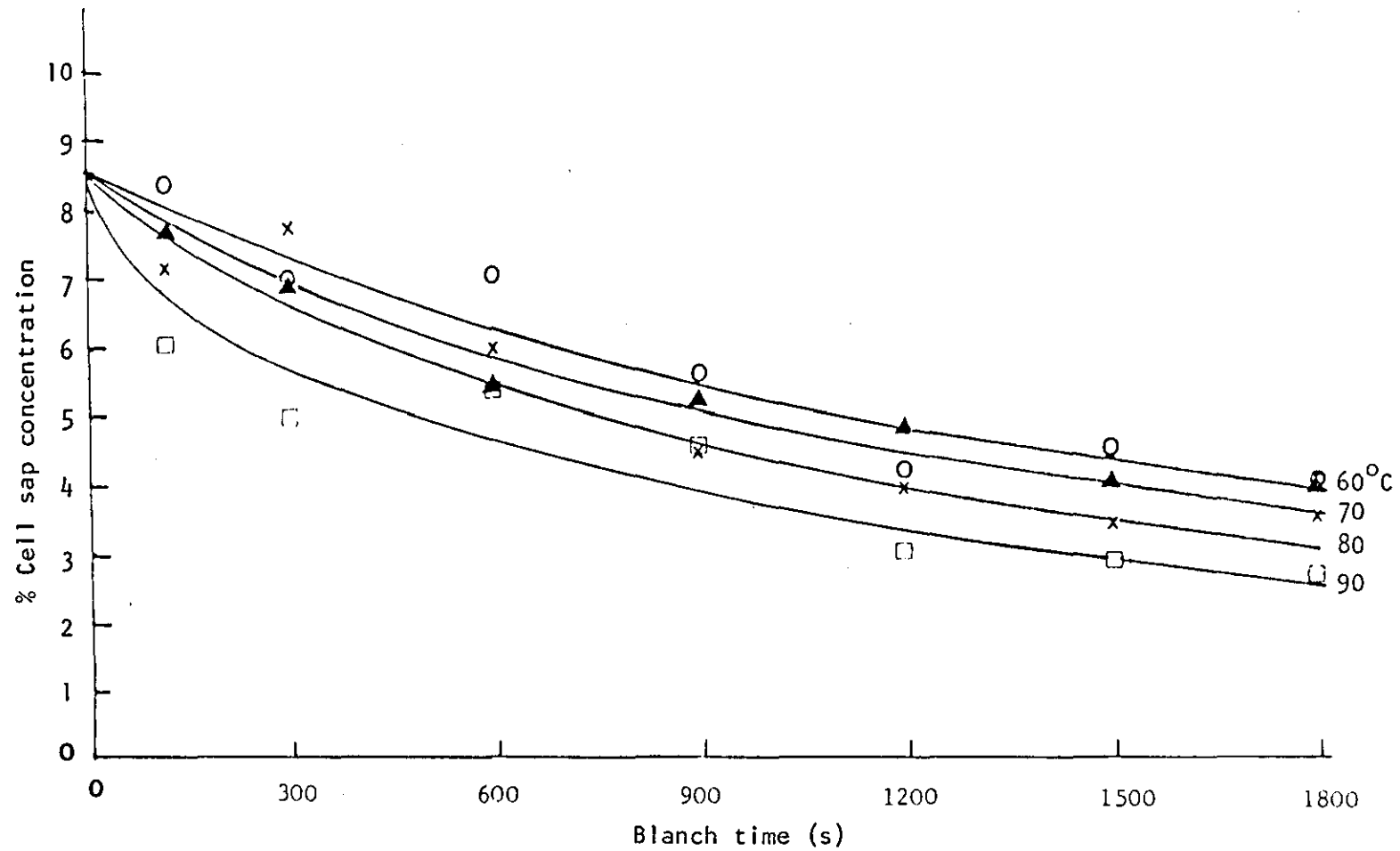Figure 5.35 Percentage Cell Sap Concentration of Chantenay Carrot Cortex Cylinders after the Given Blanch Time at 60, 70, 80, 90°C. (Means of two replicates).

different temperatures calculated from the curves of Figure 5.35 are shown in Table 5.5.

Mean D_a values show that D_a increases with increasing temperature having values of $3.07 \times 10^{-10}\ m^2 s^{-1}$ at $60^{\circ}C$, $4.13 \times 10^{-10}\ m^2 s^{-1}$ at $70^{\circ}C$, $5.36 \times 10^{-10}\ m^2 s^{-1}$ at $80^{\circ}C$ and $7.64 \times 10^{-10}\ m^2 s^{-1}$ at $90^{\circ}C$. These results indicate that diffusion coefficient is dependent on the blanching temperature. The influence of temperature on the diffusion coefficient is plotted in Figure 5.36 as $\ln D_a$ versus $\frac{1}{T}$. The plot shows a linear relationship, which is typical of an Arrhenius type temperature dependency and from which the activation energy was calculated by the following Arrhenius equation:

$$D_a = D_o \exp \left(- \frac{E_a}{RT}\right)$$

The activation energy E_a was calculated to be 28.2 kJ mol^{-1}. This compares well with reported activation energies for other temperature dependent changes occurring in plant foods during processing. Vaccarezza et al. (1974) reported an E_a of 28.9 kJ mol^{-1} for water diffusion during drying of sugar beet, and Suarez et al. (1980) found an E_a of 31.4 kJ mol^{-1} for water diffusion in Sorghum grain drying. Paulus and Saguy (1980) found E_a values of 113.0, 92.1 and 117.2 kJ mol^{-1} for texture change in Rothild, Kundulus and Rubika carrots respectively during cooking.

5.2.4 Effect of Carrot Sample Diameter

The effect of carrot diameter on the D_a values of cell sap was also investigated. Three different Chantenay cortex cylinders having diameters of 0.005, 0.006 and 0.007m were used. These were blanched for several times up to 1800 sec at $70^{\circ}C$. The changes in cell sap concentration are shown in Figure 5.37. The rate of decrease of cell sap concentration appears to increase as cylinder
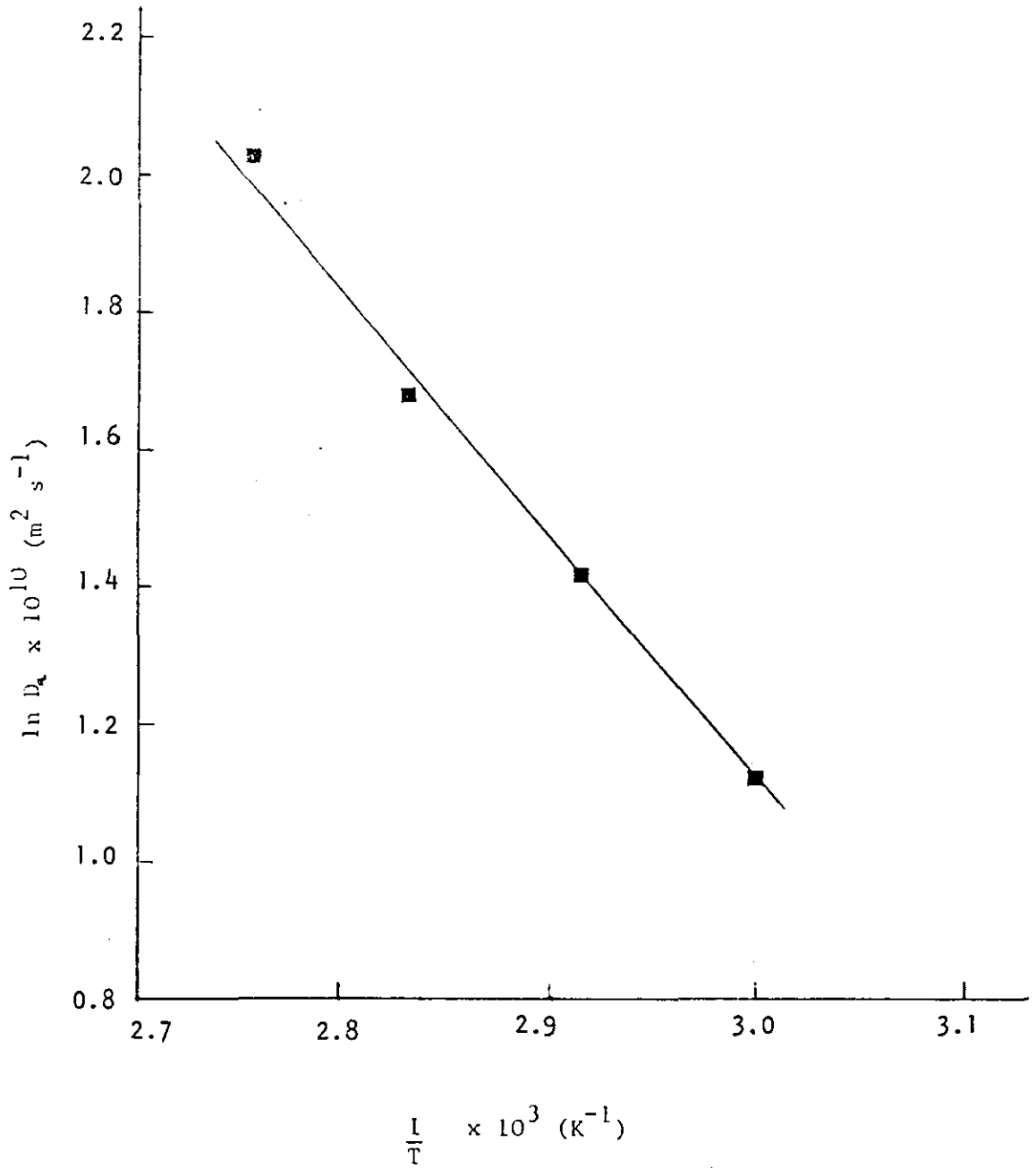
FIGURE 5.36: Graph of ln D$_A$ (Mean Apparent Diffusion Coefficients at 60, 70, 80 and 90°C. from Table 5.5 versus the Reciprocal of Absolute Temperature.
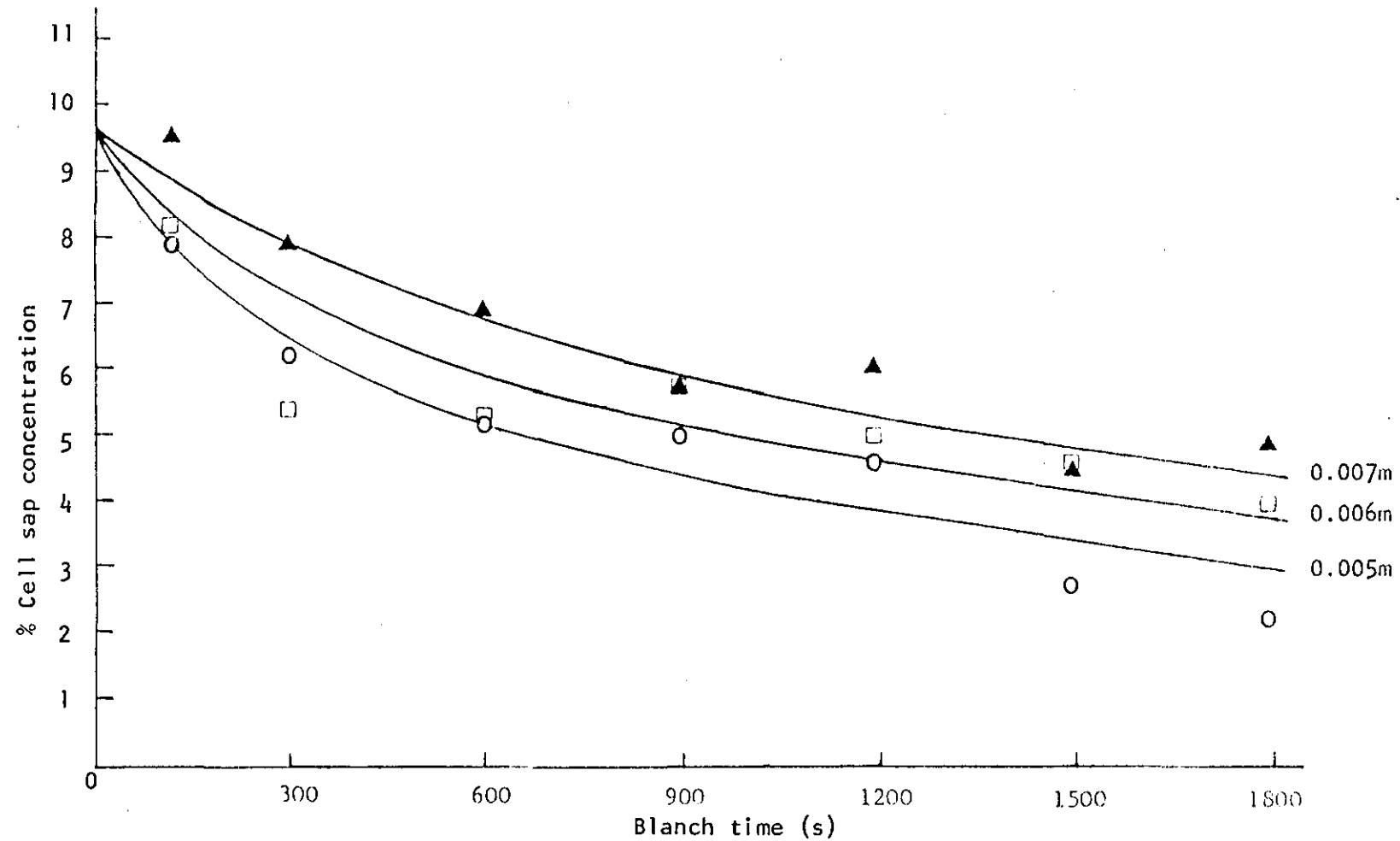
FIGURE 5.37: Percentage Cell Sap Concentration of Chantenay Carrot Cortex Cylinders of 0.005, 0.006, and 0.007 m Diameter after the Given Blanch Time at 70°C. (Means of Two Replicates).

diameter decreases. This indicates that the solute loss increases with decreasing sample diameter. Actual losses of solutes would however be expected to increase with surface area and this is shown to be true. The apparent diffusion coefficients for solutes from the 0.005, 0.006 and 0.007m cortex are shown in Table 5.5. It is seen that the D_a values are influenced by diameter, but only during the first 300 sec blanching, thereafter the D_a values in all three cases were similar with mean D_a values of 5.04×10^{-10}, 5.08×10^{-10} and 4.83×10^{-10} $m^2 s^{-1}$ for the 0.005, 0.006 and 0.007m diameter cylinders respectively. As expected, this indicates that D_a is independent of diameter during the time when solute loss occurs solely by diffusion.

5.2.5 Effect of Post-blanch Cooling

An experiment was carried out to examine the changes in cell sap concentration and diffusion coefficients during post-blanch cooling. Cylinders of Nameless carrot tissue were cooled in water at $20^{o}C$ for 300 and 900 sec after blanching at $70^{o}C$ for several times up to 1200 sec. Cooling times of 300 and 900 sec at $20^{o}C$ were used for industrial reasons. The cell sap concentration changes are shown in Table 5.6. The rate of decrease of cell sap concentration appears to increase with increase in the post-blanch cooling time. The diffusion coefficients, D_a, values as functions of cooling time are given in Table 5.5. This data shows an increase in the D_a values as a result of both blanching and cooling due to the further solute loss during cooling. However the cooling time appeared to have no significant effect on D_a values with mean D_a values of 5.13×10^{-10} and 5.12×10^{-10} $m^2 s^{-1}$ after 300 and 900 sec cooling. The D_a values during the cooling process only was also calculated and found to be 0.71×10^{-10} $m^2 s^{-1}$. This lower value may result from the slower rate of solute loss at the lower temperature and as a result of the movement of water in the opposite direction.

TABLE 5.6: Effect of post-blanching cooling in water at 20°C for 300 and 900 sec on the cell sap concentration changes of carrot cortex after blanching at 70°C (means of three replicates)

Blanch Time (secs)	Blanch Temperature ($^{\circ}$C)	Cell sap conc. changes during blanching only %	Cell sap conc. changes during blanching and post-blanching cooling for 300 sec %	Cell sap conc. changes during blanching and post-blanching cooling for 900 sec %
120	70	7.25	6.25	5.70
300	70	6.80	6.0	5.05
600	70	5.8	5.1	4.75
900	70	4.85	4.35	4.0
1200	70	4.55	4.05	3.7

* 20°C was the cooling water temperature

8.8% was the initial cell sap concentration

5.3 Apparent Diffusion Coefficients for Solute Loss from Potato Tissue

Diffusion coefficients for the leaching of solutes out of potato were calculated. The diffusion coefficients were calculated as functions of temperature, time, dimension, ratio of sample weight to blanch water, potato variety and post-blanch cooling. The solute losses during blanching were used to calculate the diffusion coefficients based on the method described before (Section 2.1).

5.3.1 Effect of Blanch Temperature

Cubes of Home Guard potato tissue were blanched for several times up to 1800 sec at 60, 70, 80 and 90°C. The increase of solute loss as the blanching proceeds at the four temperatures is shown in Figure 5.38. It is seen that solute loss is almost complete after 1800 sec with most of the loss occurring in the first 300-600 sec as with carrot. The results also demonstrate that the mass transfer is more rapid at the higher temperature, which is as expected since diffusivity of solute in water increases with temperature. The apparent diffusion coefficients for solutes, calculated from the results shown in Figure 5.38, are listed in Table 5.7 as a function of time with a mean D_a value of 8.25×10^{-10} $m^2 s^{-1}$ at 60°C, 4.25×10^{-10} $m^2 s^{-1}$ at 70°C, 7.75×10^{-10} $m^2 s^{-1}$ at 80°C and 11.5×10^{-10} $m^2 s^{-1}$ at 90°C. These mean D_a values for solute loss from potatoes were plotted in Figure 5.39 as $\ln D_a$ versus $\frac{1}{T}$. It can be seen that the plot is a straight line of an Arrhenius type relationship from which the activation energy for diffusion was estimated as 41.6 kJ mol^{-1}.

The diffusion coefficients for each temperature and time, Table 5.7, show no difference which would indicate that the solute D_a values are independent of time except at 60°C. The D_a value for solutes at 60°C for 900 sec and longer, appear to be higher than the D_a values for the same time at 70°C, and similar to the D_a values at 80 and 90°C. The increase in D_a values at 60°C could be due to
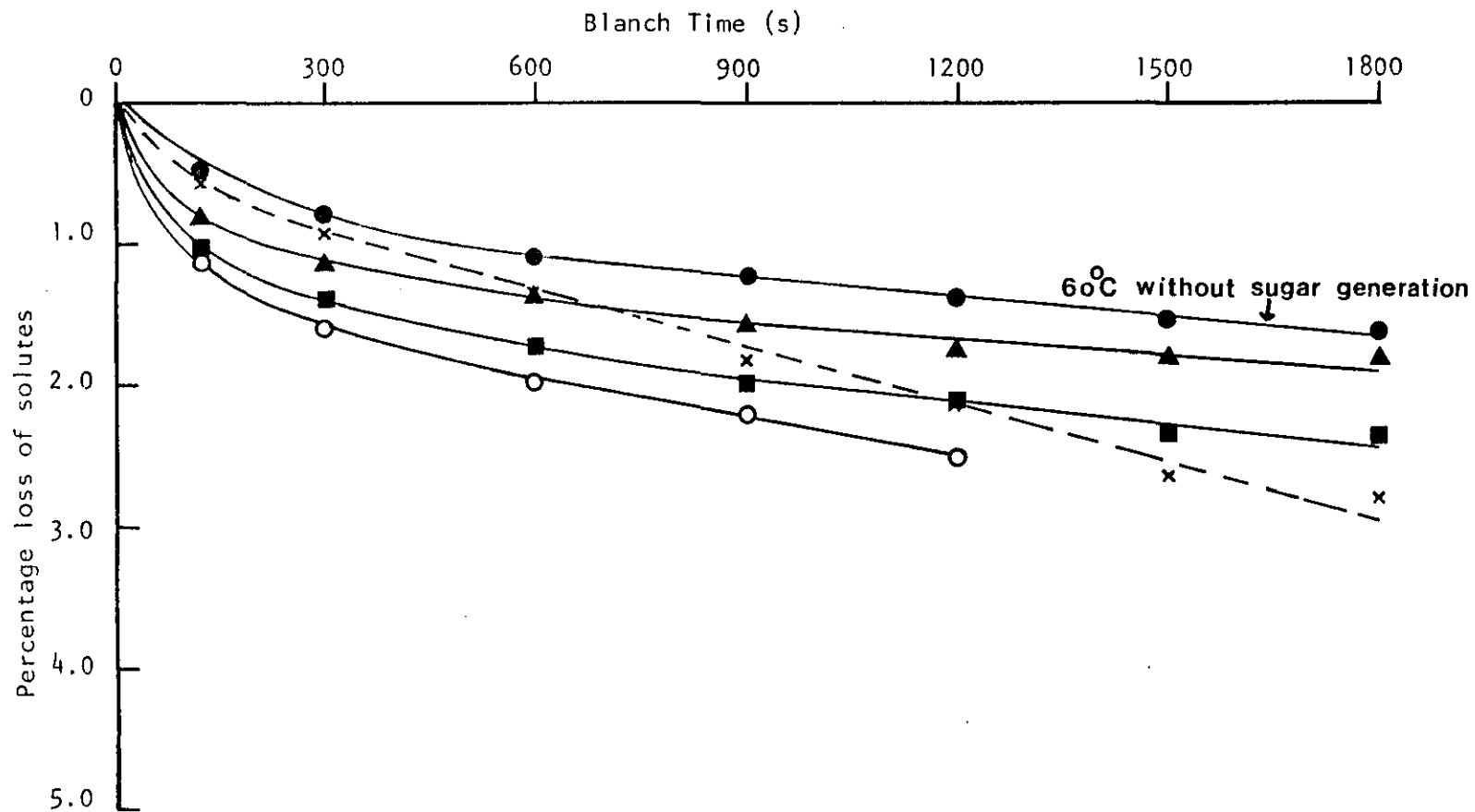
FIGURE 5.38: Percentage solute loss from Home Guard potato cubes after the given blanch time at 60, 70, 80 and 90°C (means of four replicates) x, 60; ▲ , 70; ■ , 80; 0; 90.

TABLE 5.7: Apparent diffusion coefficients (D_a) of solutes of potato cubes when blanched in water under the given conditions (data from curves in figures 5.38, 5.40, 5.41, 5.42 and 5.43)

Data from Fig No.	Sample Type	Conditions	Conditions varied from Standard*	D_a × 10^{10} values (m2 s-1) at the given blanch time (sec)							
				120	300	600	900	1200	1500	1800	Mean 600-1800
5.38	Home Guard Potato	Temperature	60°C	3.33	3.83	4.71	6.72	7.2	11.3	11.3	8.25
			Standard	8.13	6.67	5.0	4.47	4.67	3.85	3.26	4.25
			80°C	13.9	9.83	8.71	8.1	7.46	7.83	6.67	7.75
			90°C	16.7	13.8	11.8	10.7	12.1	-	-	11.5
5.40	Maris Bard Potato	Dimension	Standard	10.9	9.9	7.8	7.2	6.48	6.33	5.83	6.73
			0.012m	7.5	6.9	5.76	5.16	5.12	4.56	4.1	4.94
			0.014m	5.51	6.37	5.72	4.63	5.02	4.70	4.36	4.89
			0.018m	6.08	6.48	5.67	5.28	4.66	5.08	4.95	5.13
5.41	Home Guard Maris Bd Record	Variety	Standard	8.13	6.67	5.00	4.47	4.67	3.85	3.26	4.25
			Standard	10.9	9.9	7.8	7.2	6.48	6.33	5.83	6.73
			Standard	8.33	4.17	4.79	3.89	4.00	3.50	3.47	3.93
5.43	Maris Bard Potato	Ratio of sample to blanch	1:2.5	11.0	9.83	8.13	7.42	6.97	6.67	6.32	7.10
			1:20	11.3	9.78	7.60	7.47	6.29	5.97	5.67	6.60
5.42	Maris Bard Potato	Post-blanch cooling	Standard	11.0	9.92	7.92	7.64	6.56	6.25	5.83	6.84
			With cooling(300s)	11.05	9.97	7.97	7.67	6.61	6.30	5.86	6.88
			Cooling only(300s)	0.05	0.025	0.05	0.025	0.05	0.054	0.033	0.042

*Standard conditions: Blanch temperature = 70°C

Potato cubes dimension = 0.010m

Potato sample to blanch water ratio = 1:5
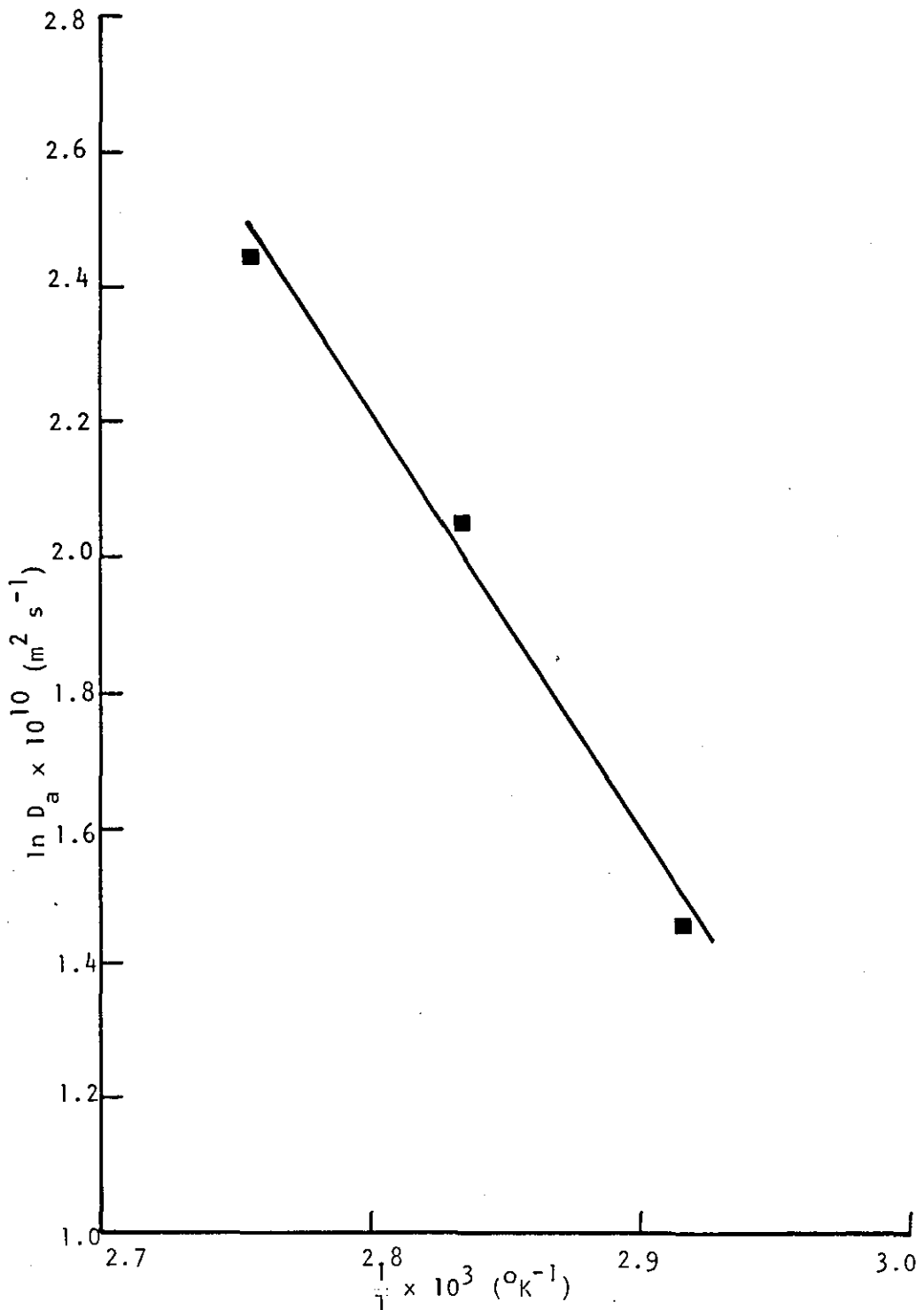
FIGURE 5.39: Graph of ln D_a (mean apparent diffusion coefficients at 70, 80 and 90°C from Table 5.7) versus the reciprocal of absolute temperature

a reducing sugar increase as a result of internal generation of reducing sugars due to enzymic hydrolysis of starch. As seen from Table 5.7 such an increase in reducing sugar only becomes important after 600 sec blanching, as the D_a values increase to 6.72×10^{-10} m^2s^{-1} after 900 sec, and 11.3×10^{-10} m^2s^{-1} after 1800 sec. In order to determine the rate of solute loss at $60^{\circ}C$ without chemical reaction (i.e. where the generation of sugars is not taken into account), the D_a value at $60^{\circ}C$, 2.69×10^{-10} m^2s^{-1} obtained from Figure 5.39, was applied to the diffusion model and the resulting values of $\bar{C}$ (solute loss into blanch water) are shown in Figure 5.38.

5.3.2 Effect of Dimension

Maris Bard potato cubes of 0.01, 0.012, 0.014, 0.018m were blanched at $70^{\circ}C$ for several times up to 1800 sec, and solute losses are shown in Figure 5.40. As expected the solute loss appeared to decrease as the cube size increased. The trend in general was similar to the loss from carrot of different diameters. The diffusion coefficients as functions of time and dimension are given in Table 5.7 as calculated from Figure 5.40. From Table 5.7 it is clear that the dimension has no influence on diffusion coefficients and the mean D_a values in all four cases were similar having **values** 5.13×10^{-10}, 4.89×10^{-10}, 4.94×10^{-10} and 6.73×10^{-10} m^2s^{-1} for 0.018, 0.014, 0.012, 0.010m cubes. This indicates that D_a is independent of the surface area for cubes from 0.012 to 0.018m. D_a values for 0.01m cubes is a little higher than for the other cubes which may have been due to the increase in sugar content during storage, as the measurements on solute loss from 0.01m cubes was carried out three weeks after these on the 0.012, 0.014 and 0.018m cubes. To confirm this a repeat experiment using 0.008 to 0.014m cubes was carried out at $70^{\circ}C$ for 600 sec and the mean D_a values were: 6.42×10^{-10}; 6.28×10^{-10}; 6.16×10^{-10} and 6.61×10^{-10} m^2s^{-1} for solute loss from 0.014, 0.012, 0.010 and 0.008m potato cubes respectively.
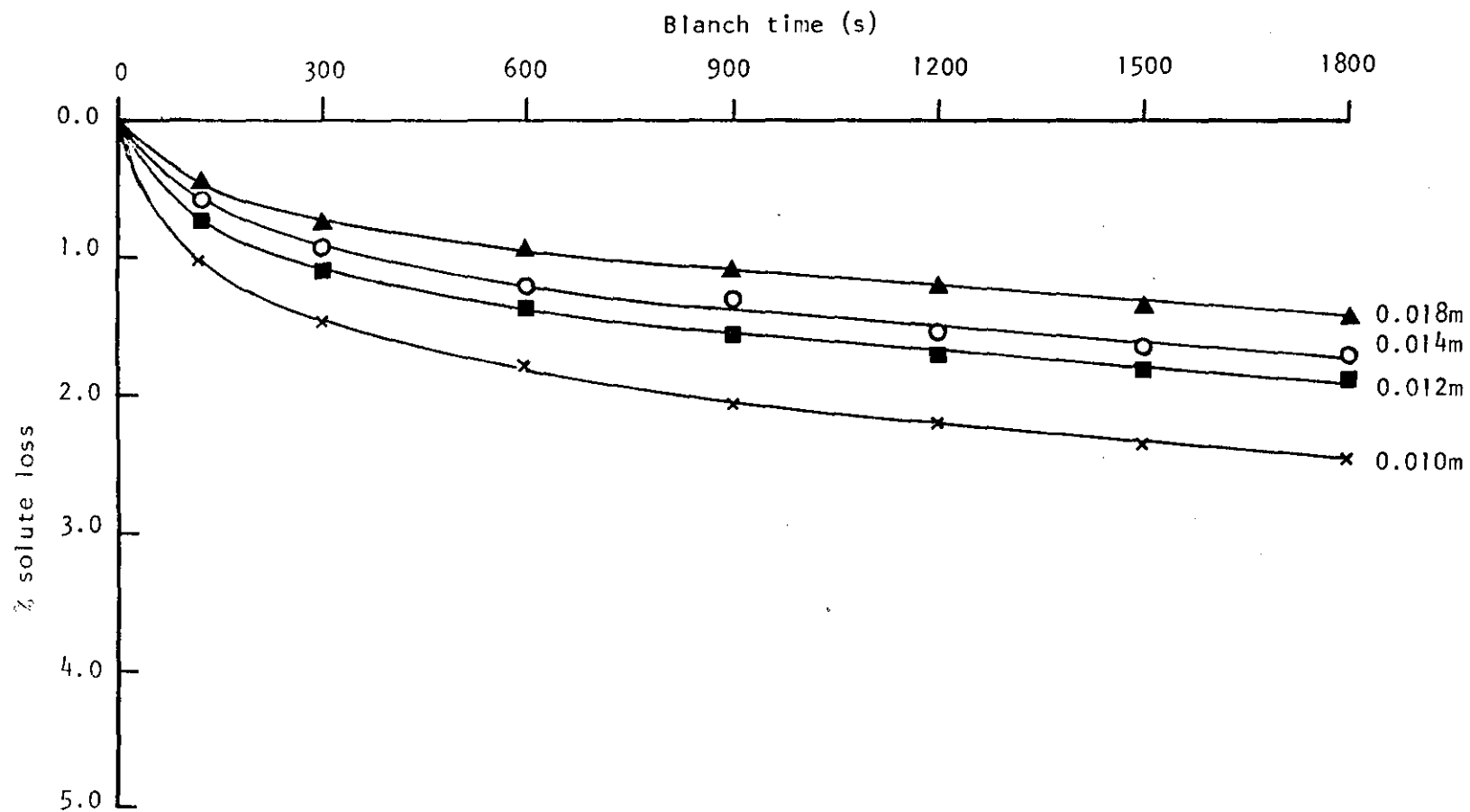
FIGURE 5.40: Percentage solute loss from Maris Bard potato cubes of 0.018, 0.014, 0.012 and 0.010m after the given blanch time at 70°C (means of four replicates) ▲, 0.018m, 0, 0.014m, ■, 0.012, X, 0.010m.

5.3.3 Effect of Potato Variety

Solute loss from three varieties of potatoes (Home Guard, Maris Bard and Record) having 16.9%, 19.3% and 25.0% total solids respectively were examined during blanching at 70°C for several times up to 1800 sec. The results are summarised in Figure 5.41. A similar pattern of solute loss was observed for each variety. Greater solute loss occurred with the variety of higher total solids content. A higher solute loss was noted with Record variety as expected due to the high soluble solids content (6.4%) as compared to 4.7% for Maris Bard and 4.3% for Home Guard. The diffusion coefficients calculated from these results are listed in Table 5.7 with mean values of 3.93×10^{-10} m^2s^{-1} for Record, $4.25 \times 10^{-10} m^2 s^{-1}$ for Home Guard and 6.73×10^{-10} $m^2 s^{-1}$ for Maris Bard. The mean D_a values for solute movement of Maris Bard are larger than the D_a values of Home Guard and Record potatoes, indicating that the sugar and other low molecular weight components have more influence on the D_a values of potato than the other soluble components (proteins and starch). It should be pointed out that the apparent diffusion coefficient of solute in potato is strongly dependent on the composition of the variety. Stahl and Loncin (1979) in their study of the prediction of diffusion in foodstuffs, also found that the apparent diffusivity in potatoes is strongly dependent on variety.

5.3.4 Effect of Post-blanch Cooling in Water

Post-blanch cooling in water at 20°C for 300s was also used in this study to examine its effect on the diffusion coefficient of solutes. Figure 5.42 shows the solute loss during the blanching of potato without cooling, with cooling and during cooling only. The results show a slight increase in solute loss with cooling. The D_a values for solute loss during blanching without cooling and cooling only were calculated separately in order to determine the D_a values for solute loss during blanching with cooling process. These values are presented in Table 5.7 as a function of time and the process.
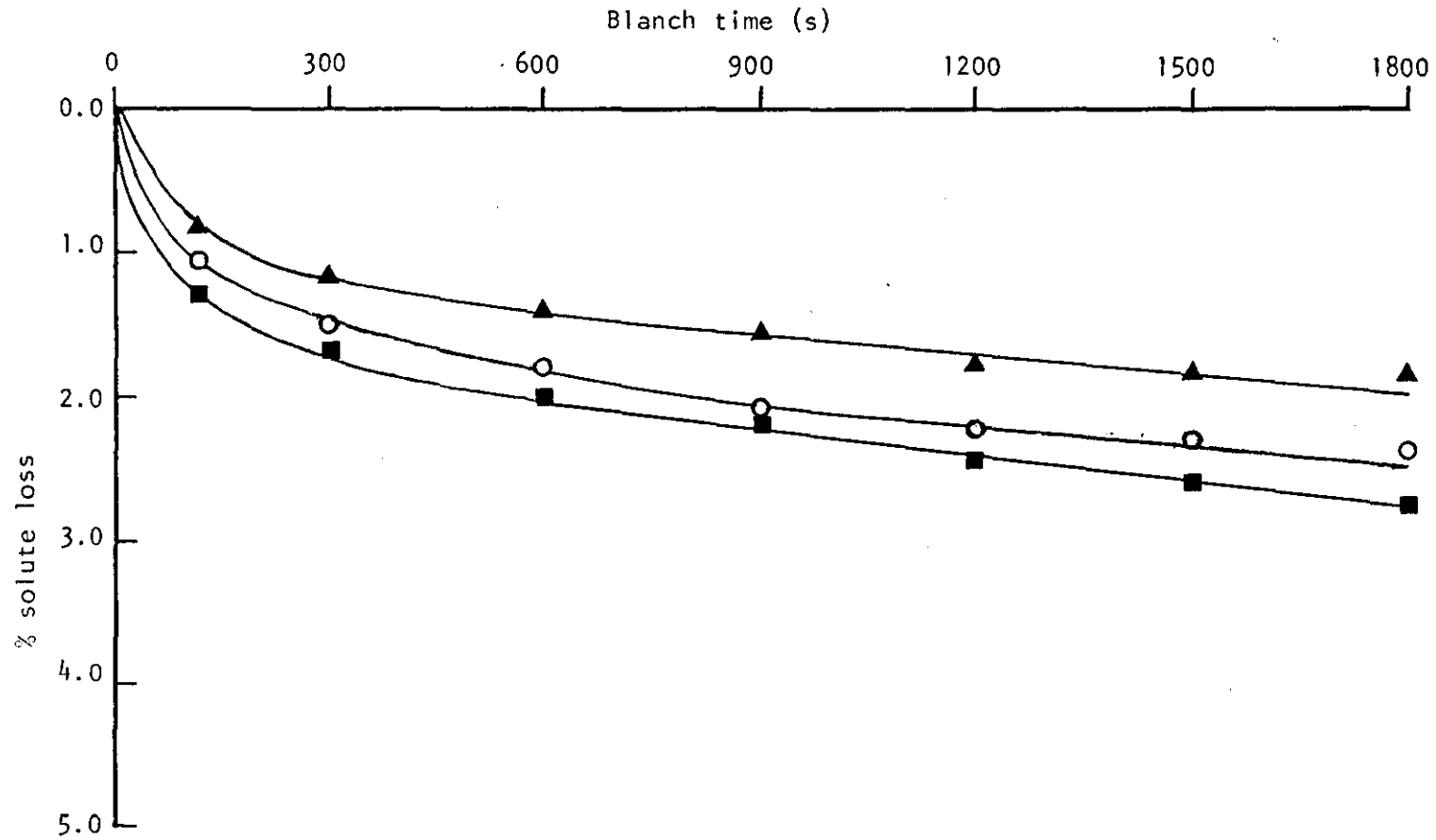
FIGURE 5.41: Percentage solute loss from Home Guard, Maris Bard and Record potato cubes after the given blanch time at 70°C (means of four replicates) ▲, Home Guard, O, Maris Bard and ■, Record potato
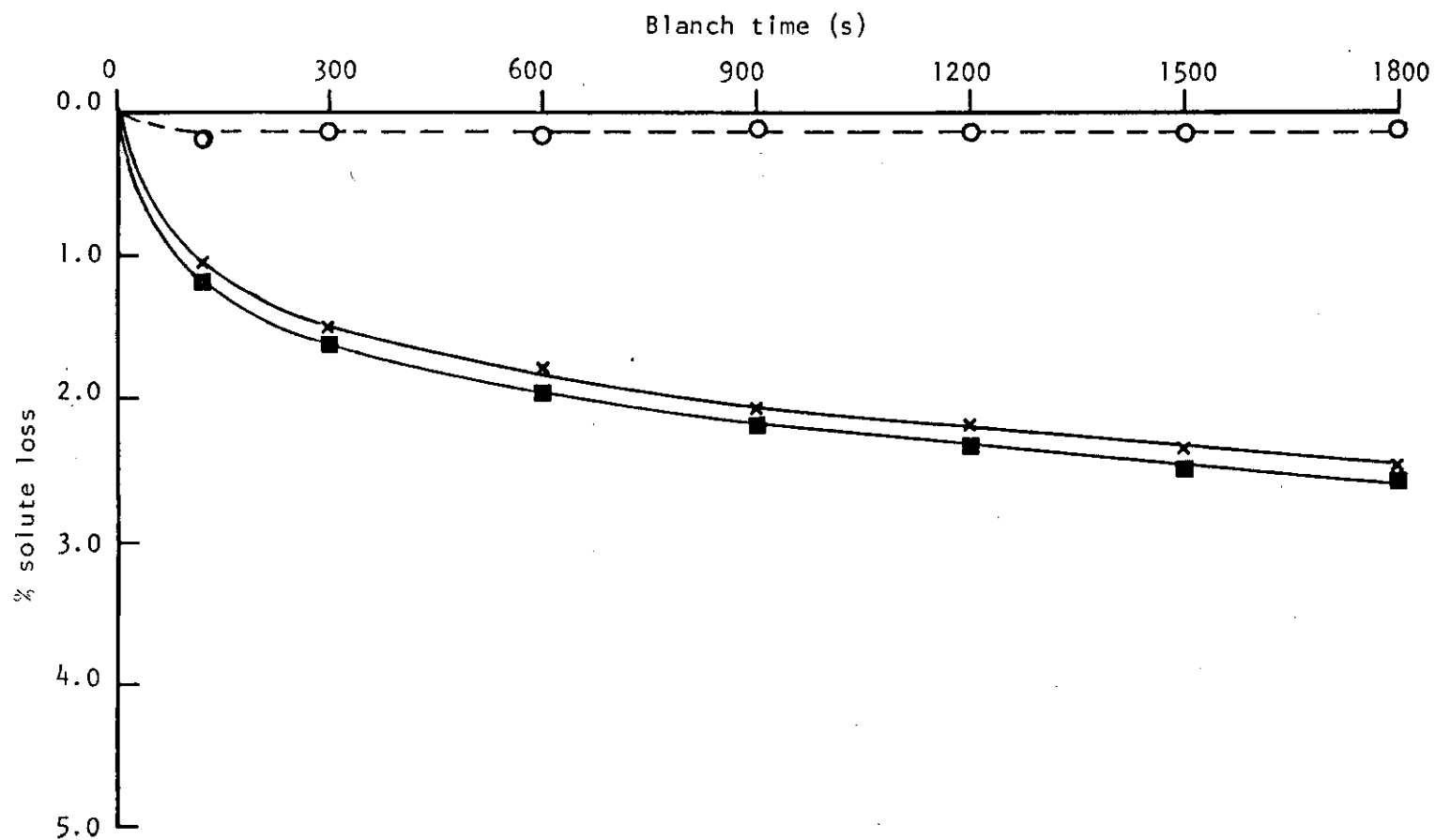
FIGURE 5.42: Percentage solute loss from Maris Bard potato cubes after the given blanch time at 70°C, and cooling for 300 s at 20°C (means of three replicates), 0, solute loss during cooling, X, solute loss during blanching, ■ , solute loss during blanching and cooling

The mean D_a values for solutes during blanching without cooling and blanching with cooling were 6.84×10^{-10} and 6.88×10^{-10} m^2s^{-1} respectively, showing no significant solute transfer during the cooling process. The mean D_a value for solute loss during cooling only was 0.0425×10^{-10} m^2s^{-1}.

5.3.5 Effect of Ratio of Sample to Blanch Water

Ratios of 1:2.5, 1:5 and 1:20 sample weight to water were used. Maris Bard 0.01m potato cubes were blanched in these ratios at 70°C for several times up to 1800 sec. The solute loss at these ratios are shown in Figure 5.43. There was a negligible difference between blanching in 1:2.5, 1:5 and 1:20 on the pattern of solute loss. This was expected as the amount of solute lost into the blanch water was very small, and because the concentration of the blanch medium remained virtually the same in all three cases. After 1800 sec blanching in these three ratios the concentrations of solutes were 0.004, 0.002 and 0.001 g/ml respectively. The diffusion coefficient for solute movement in these three ratios are given in Table 5.7 as a function of time and the ratios of sample weight to blanch water. It is seen that the D_a value in all three cases was similar, with mean D_a values of 7.10×10^{-10} m^2s^{-1} at 1:2.5, 6.73×10^{-10} m^2s^{-1} at 1:5 and 6.60×10^{-10} m^2s^{-1} at 1:20. This indicates that D_a values are constant over such small range of concentration difference.
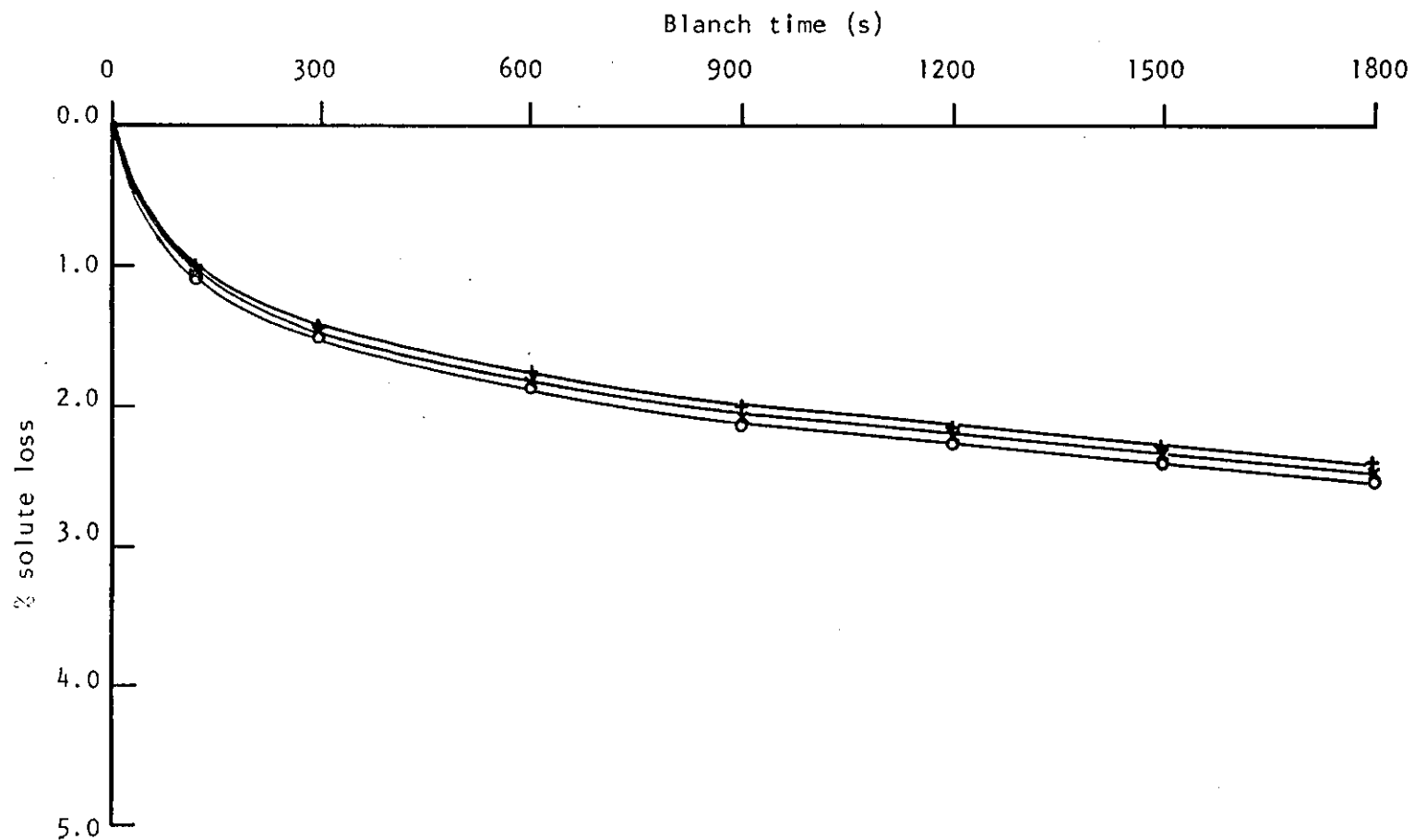
FIGURE 5.43: Percentage solute loss from Maris Bard potato cubes after the given blanch time at 70°C for 1:2.5, 1:5 and 1:20 ratios of sample weight to blanch water (means of three replicates) +, 1:2.5, X, 1:5, 0, 1:20

5.4   Apparent Diffusion Coefficient of Sugar in Potato Tissue

5.4.1   Laboratory Scale

5.4.1.1   Effect of temperature and time

Figures 5.44, 5.45, 5.46 and 5.47 illustrate the changes in percentage of total and reducing sugar in both blanch water and potato with time of blanching at 50, 60, 70 and 80°C. Curves T and R in each figure show the change of average sugar percentage (total and reducing) in the blanched potato with time, and curves T̄ and R̄ show the corresponding change in percentage of sugar lost into the blanch water. In most cases the rate of sugar loss is high in the first 300 to 600 sec before declining to a steady rate of loss. Because of the differences in the initial sugar concentration of potato used in this work as seen in Figures 5.44 to 5.47, non-dimensional graphs were drawn by dividing the concentration after each blanch time for each temperature over the initial concentration. From these non-dimensionalised graphs, Figures 5.48 and 5.49, it can be seen that the diffusing rate of both total and reducing sugar increased with increasing blanch temperature and the trend was the same. Figure 5.52 shows the percentage total and reducing sugars lost into the blanch water after 120 and 600 sec blanching at different temperatures. The pattern of loss for total and reducing sugars was similar with the amounts lost increasing substantially above 50°C. The losses of sugar below 50°C were assumed to arise from the cut surface cells. The losses between 50 and 90°C increased gradually and reached maximum values of 0.106% and 0.082% at 90°C for total and reducing sugars respectively after 600 sec. Reducing the blanch time from 600 sec to 120 sec resulted in a significant reduction in sugar loss. The reduction in losses at 90°C were 0.046% and 0.052% for total and reducing sugars respectively.

Diffusion coefficients (D_a) for movement of reducing sugars, total sugars and sucrose out of potato cubes during blanching in water at 50, 60, 70 and 80°C are presented in Table 5.8. The
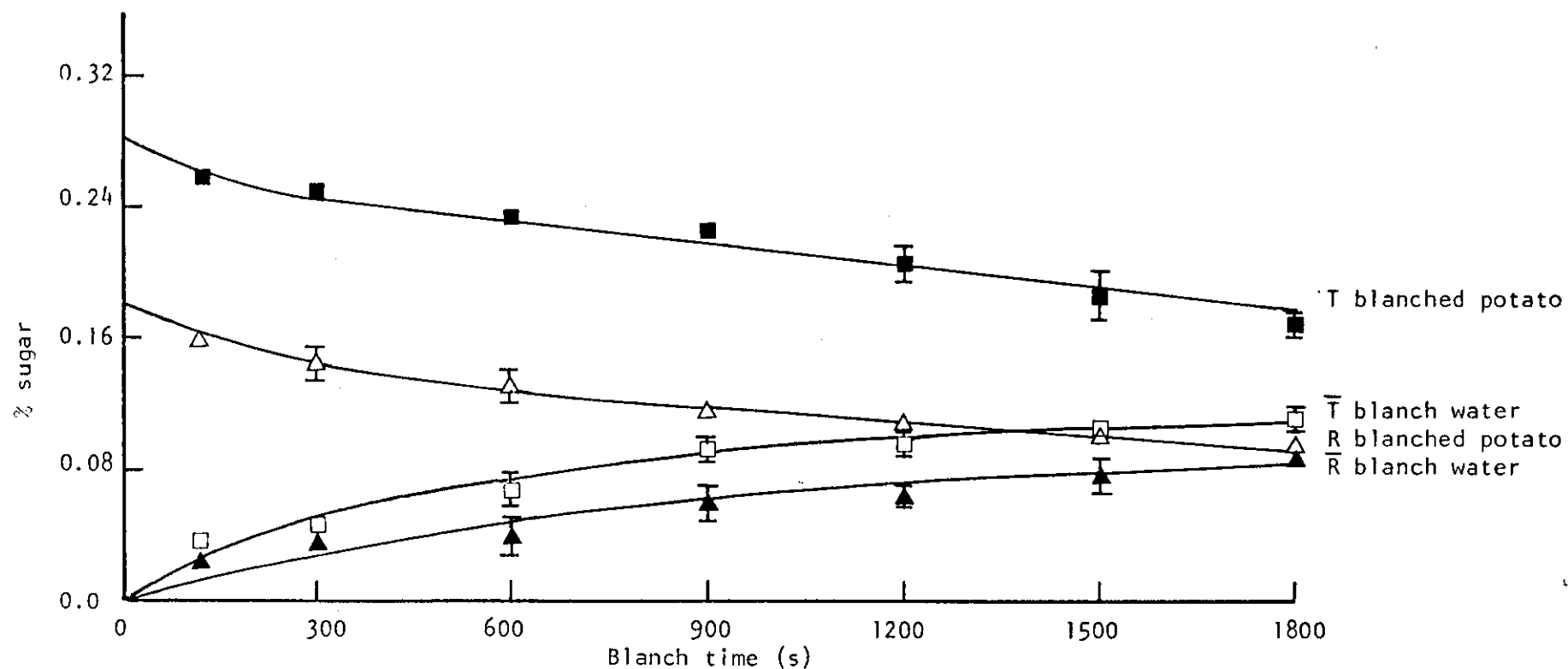
FIGURE 5.44:Percentage of Total (T) and Reducing (R) sugar remaining in Record potato cubes and lost into blanch water ($\overline{T}$, $\overline{R}$) after the given blanch time at 50°C (means of four replicates)
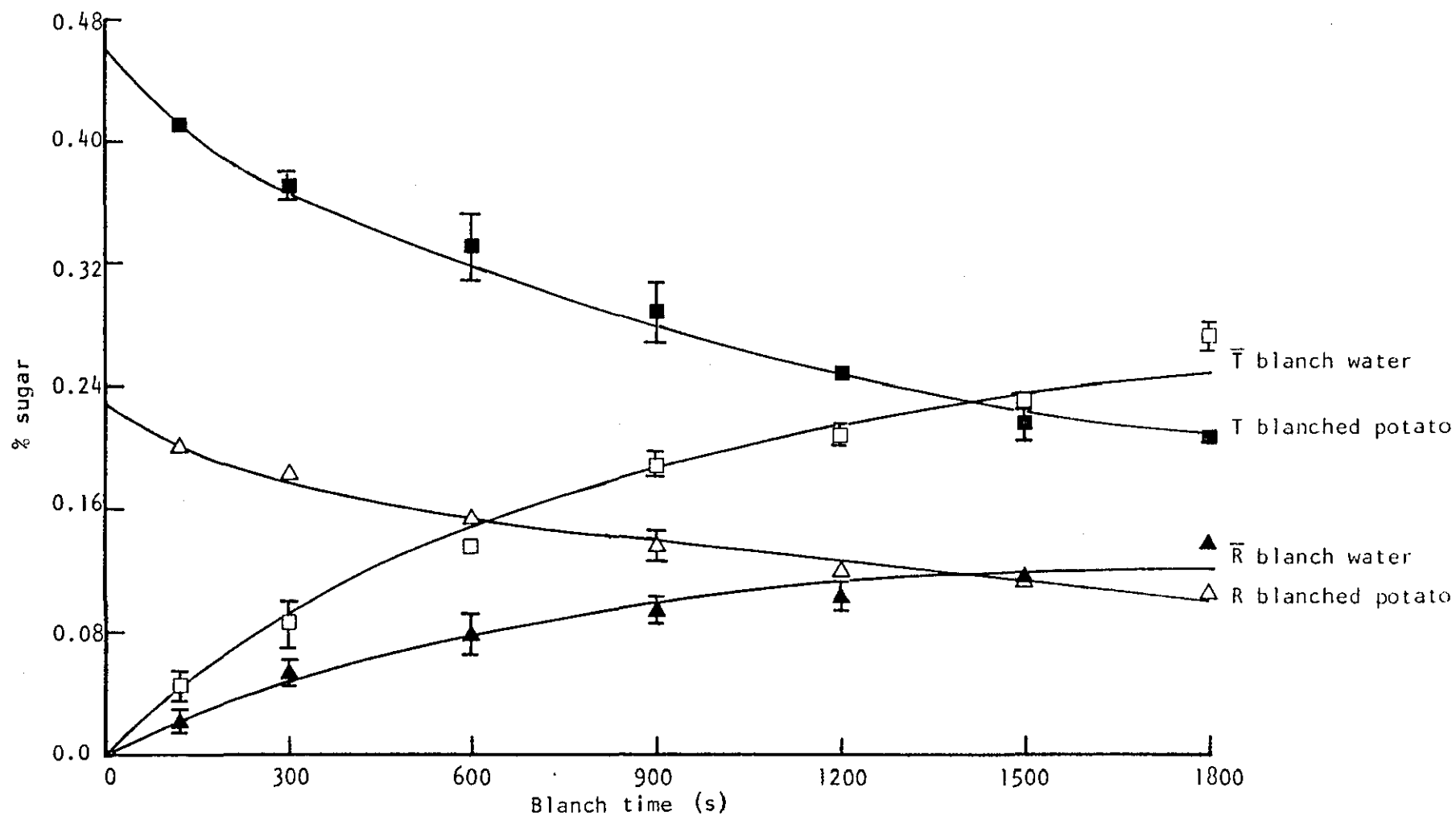
FIGURE 5.45 Percentage of Total (T) and Reducing (R) sugar remaining in Record potato cubes and lost into blanch water ($\overline{T}$, $\overline{R}$) after the given blanch time at $60^{\circ}C$ (mean of four replicates)
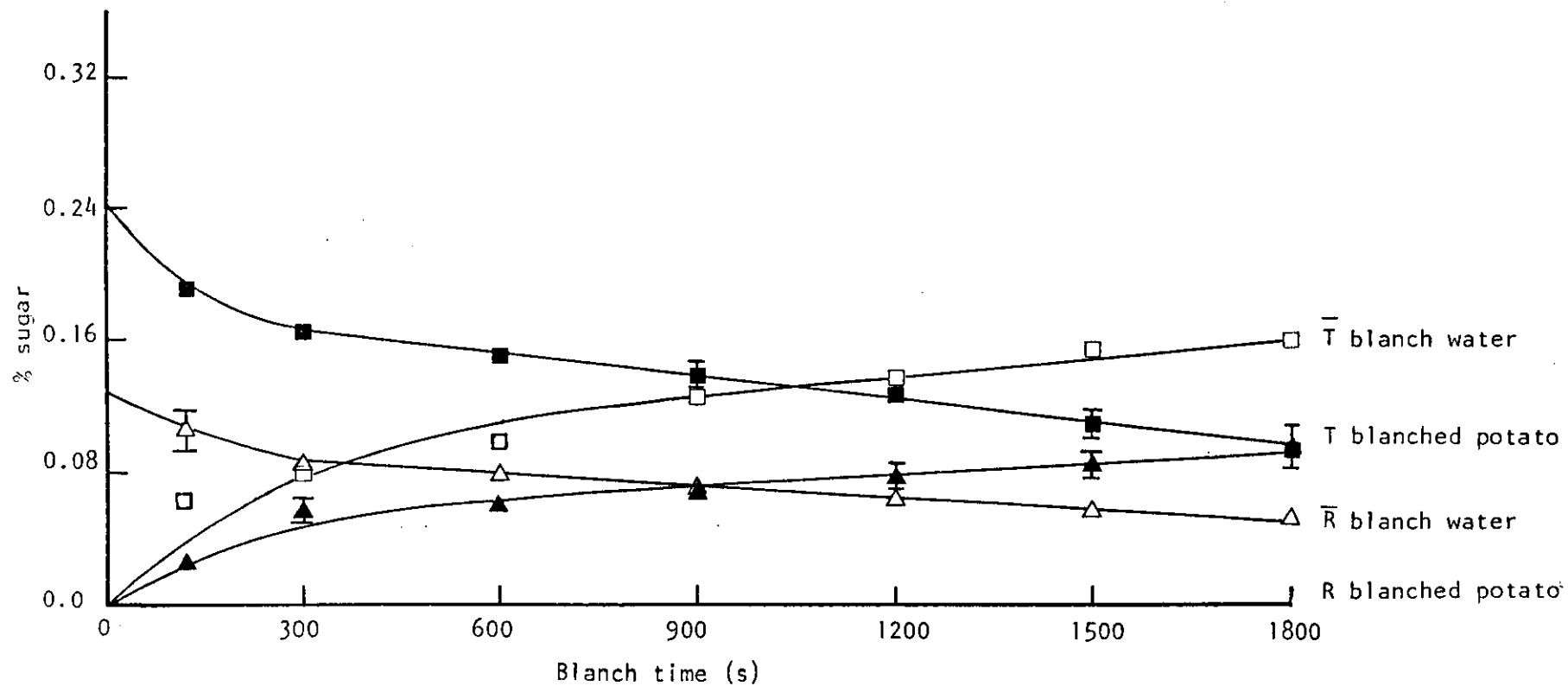
FIGURE 5.46: Percentage of Total (T) and Reducing (R) sugar remaining in Record potato cubes and lost into blanch water ($\overline{T}$, $\overline{R}$) after the given blanch time at 70°C (mean of four replicates)
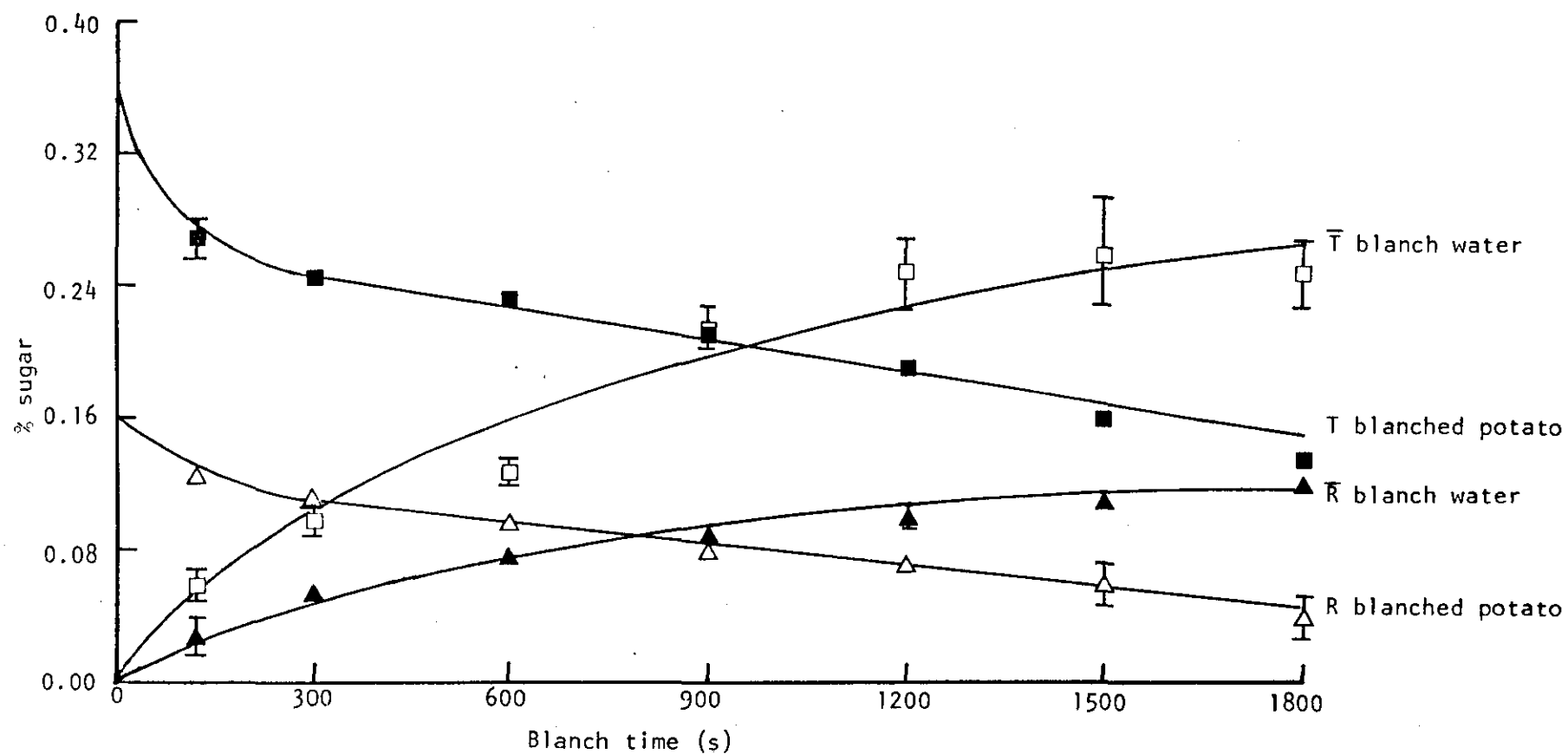
FIGURE 5.47: Percentage of Total (T) and Reducing (R) sugar remaining in Record potato cubes and lost into blanch water ($\overline{T}$, $\overline{R}$) after the given blanch time at $80^\circ C$ (mean of four replicates)
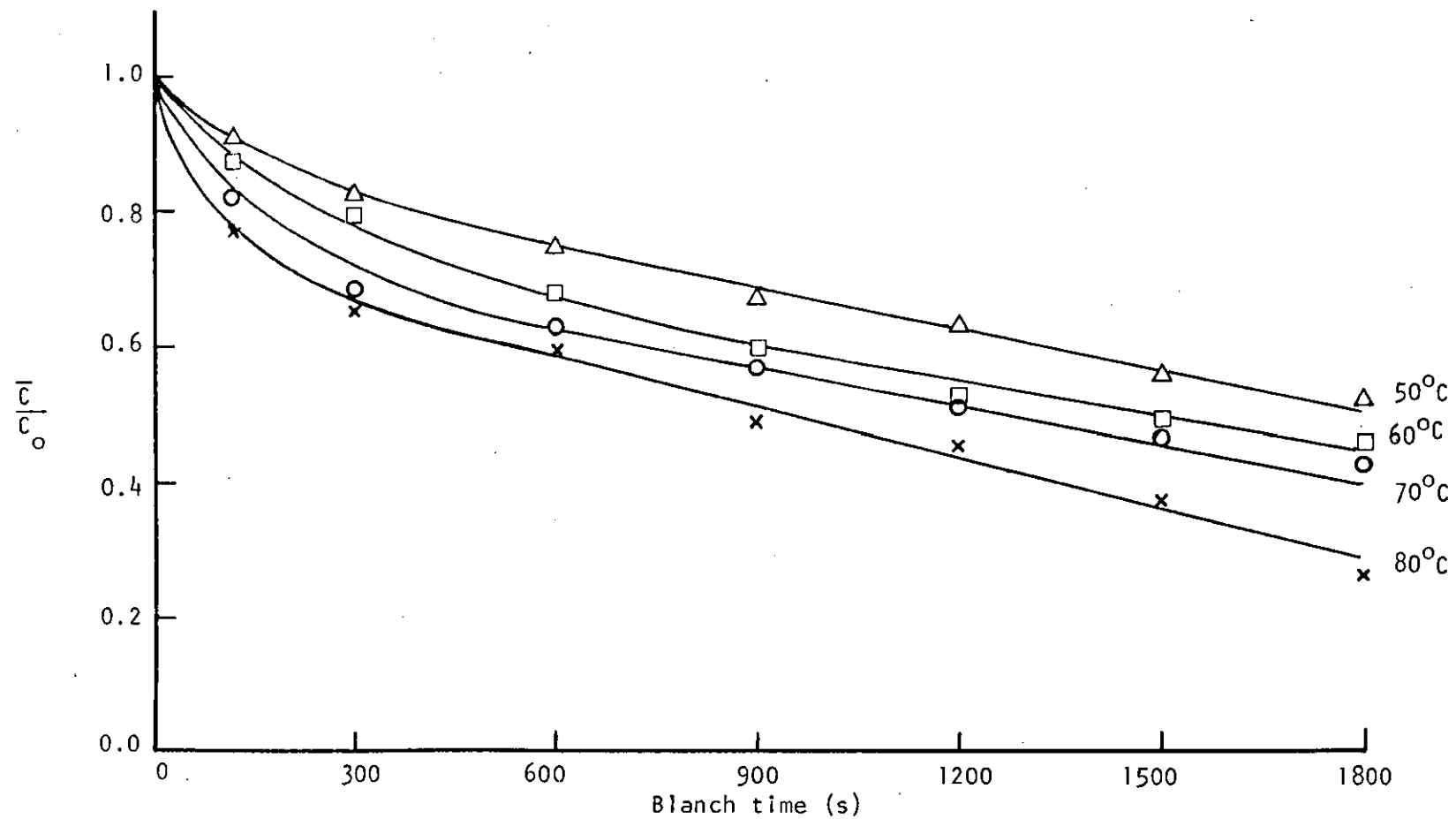
FIGURE 5.48: Reducing sugar remaining (non-dimensionalised) in Record potato cubes after the given blanch time at 50, 60, 70 and 80°C
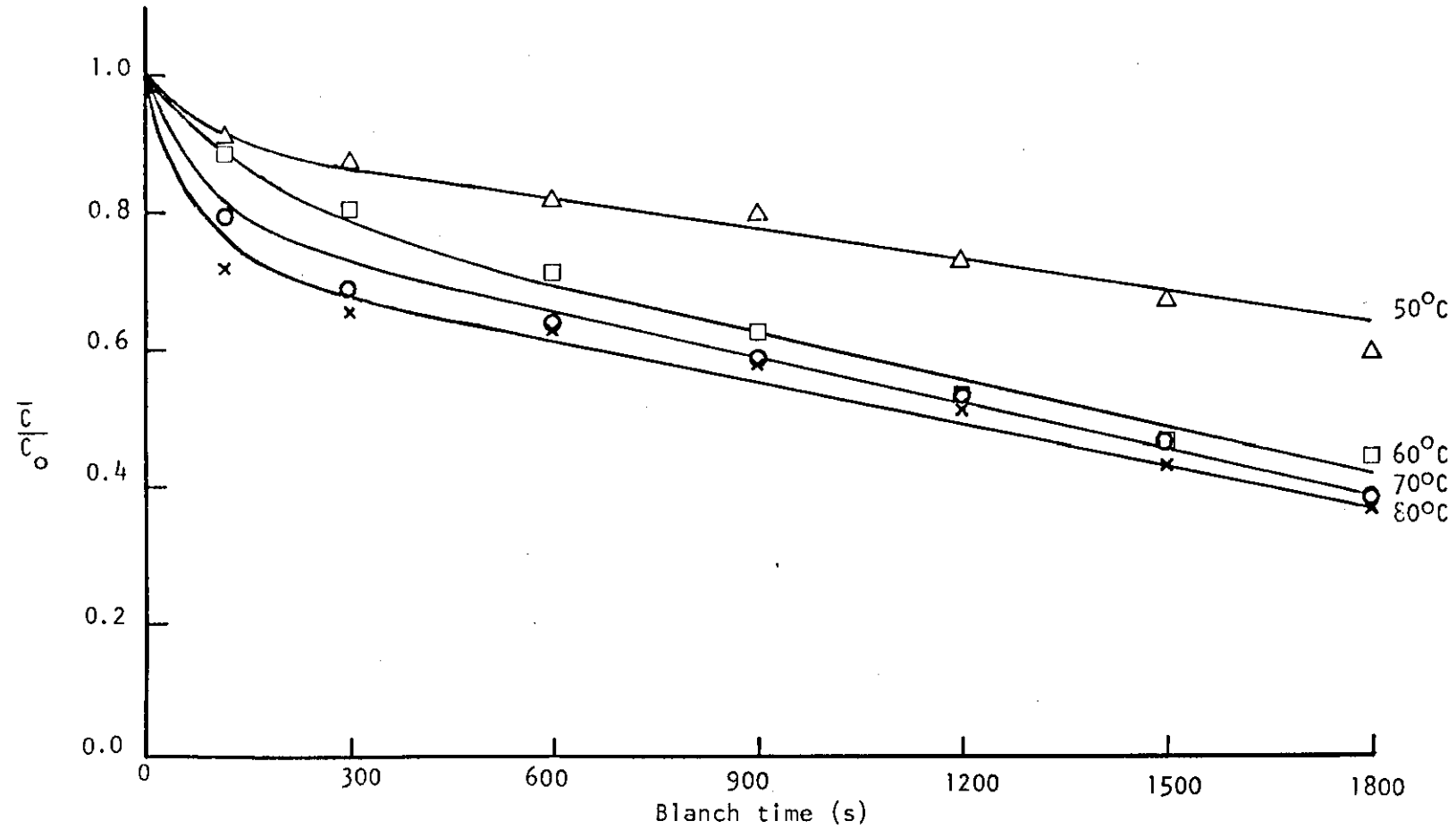
FIGURE 5.49: Total sugar remaining (non-dimensionalised) in Record potato cubes after the given blanch time at 50, 60, 70 and 80°C

TABLE 5.8: Apparent diffusion coefficients (D_a) of sugar of Record
potato cubes when blanched in water under the given
condition (Data from curves in Figures 5.44, 5.45, 5.46
and 5.47)

Sample Type	Diffusing Substance	Conditions	D_a x 10^{10} values (m^2s^{-1}) at the given blanch time (sec)							
			120	300	600	900	1200	1500	1800	Mean 600-1800
Record potato	Reducing sugar	50°C	1.66	2.90	2.80	3.44	3.70	4.42	4.20	3.71
		60°C	5.20	4.30	5.90	6.60	6.90	7.32	7.36	6.82
		70°C	9.20	12.0	9.60	8.90	8.96	8.75	9.40	9.12
		80°C	15.0	15.0	12.0	14.0	14.0	16.3	25.3	16.32
Record potato	Total sugar	50°C	1.63	1.00	1.21	1.25	1.88	2.17	2.67	1.84
		60°C	3.95	4.00	4.50	3.30	6.20	7.50	5.63	5.43
		70°C	11.70	10.30	7.60	7.10	6.90	7.00	9.20	7.56
		80°C	16.00	15.00	9.10	6.90	8.10	9.75	10.8	8.93
Record potato	Sucrose	50°C	1.46	0.066	0.038	0.019	0.479	0.517	1.55	0.521
		60°C	2.9	3.7	4.1	4.9	6.2	9.6	5.4	6.04
		70°C	16.0	13.0	4.5	6.8	6.4	8.67	14.1	8.09
		80°C	8.9	9.5	7.8	5.4	5.8	8.3	7.2	6.90

Standard conditions: Blanch temperature   =   70°C

                            Potato cubes dimension =   0.010m

                            Potato sample to blanch water ratio =   1:5

results for reducing sugar (Table 5.8) shows that the D_a increased with increasing blanch temperature with mean D_a values of 3.71×10^{-10} m^2s^{-1} at $50^{\circ}C$, 6.82×10^{-10} m^2s^{-1} at $60^{\circ}C$, 9.12×10^{-10} m^2s^{-1} at $70^{\circ}C$, and 16.32×10^{-10} m^2s^{-1} at $80^{\circ}C$. The diffusion coefficient values for both total sugars and sucrose (Table 5.8) show the same pattern as the reducing sugar and increase with increasing blanch temperature. The influence of temperature on the diffusion coefficients of reducing and total sugar is shown in Figures 5.50 and 5.51 as a plot of $\ln D_a$ versus $\frac{1}{T}$. The plot shows a linear relationship which is typical of an Arrhenius type temperature dependency and from which the activation energy for diffusion of reducing sugar and total sugar were calculated as 27.6 kJ mol^{-1} for reducing sugar and 31.4 kJ mol^{-1} for total sugar.

5.4.1.2 Effect of the diffusing substance

As expected, the mean D_a values for both total sugar and sucrose (Table 5.8) are lower than the mean D_a values for reducing sugar, as the molecular weight of reducing sugar (glucose and fructose, 180) is lower than that of sucrose (342) and total sugar. For the same reason, total sugar diffused more slowly than sucrose with a mean D_a value of 1.84×10^{-10}, 5.43×10^{-10}, 7.56×10^{-10} and $8.93 \times 10^{-10} m^2s^{-1}$ at 50, 60, 70 and $80^{\circ}C$ respectively. These results indicate that D_a depends on the molecular weight of the diffusing substances and on the blanch temperature. The actual tendency of sugar to diffuse would however be expected to increase as the size of the diffusing substance decreases and temperature of blanching increases and this was shown to be true.

The values of diffusivity of sugars in potatoes are comparable to those reported for other substances. For instance, the diffusion coefficients of sucrose in sugar beets was 7.2×10^{-10} m^2s^{-1} at $75^{\circ}C$ (Bruniche-Olsen, 1962). The diffusion coefficients of sucrose and glucose in water were 5.4×10^{-10} and 6.9×10^{-10} m^2s^{-1} at $25^{\circ}C$ respectively (Schwartzberg and Chau, 1982).
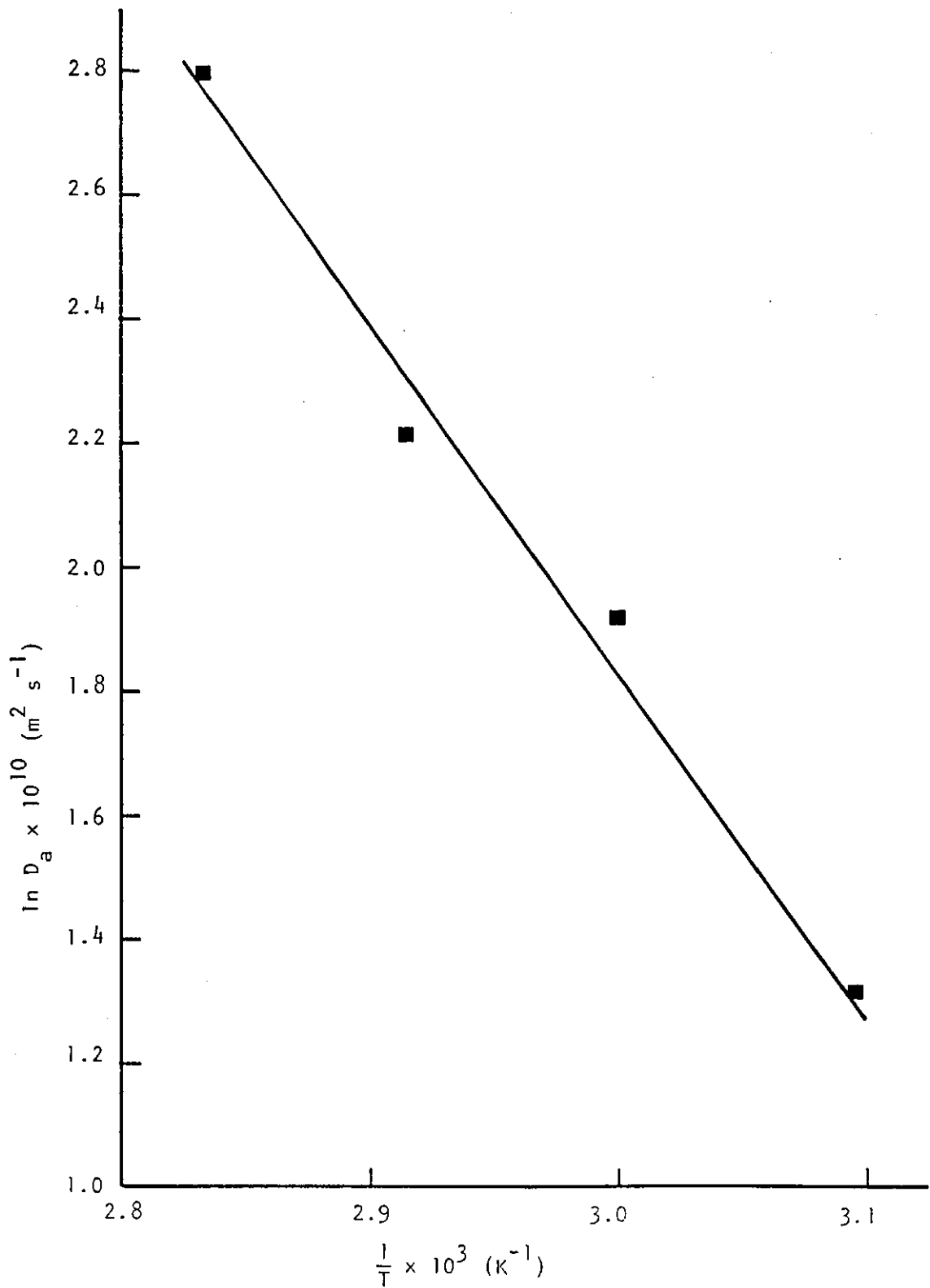
FIGURE 5.50: Graph of ln D_a (mean apparent diffusion coefficients of reducing sugars at 50, 60, 70 and 80°C from Table 5.8) versus the reciprocal of absolute temperature
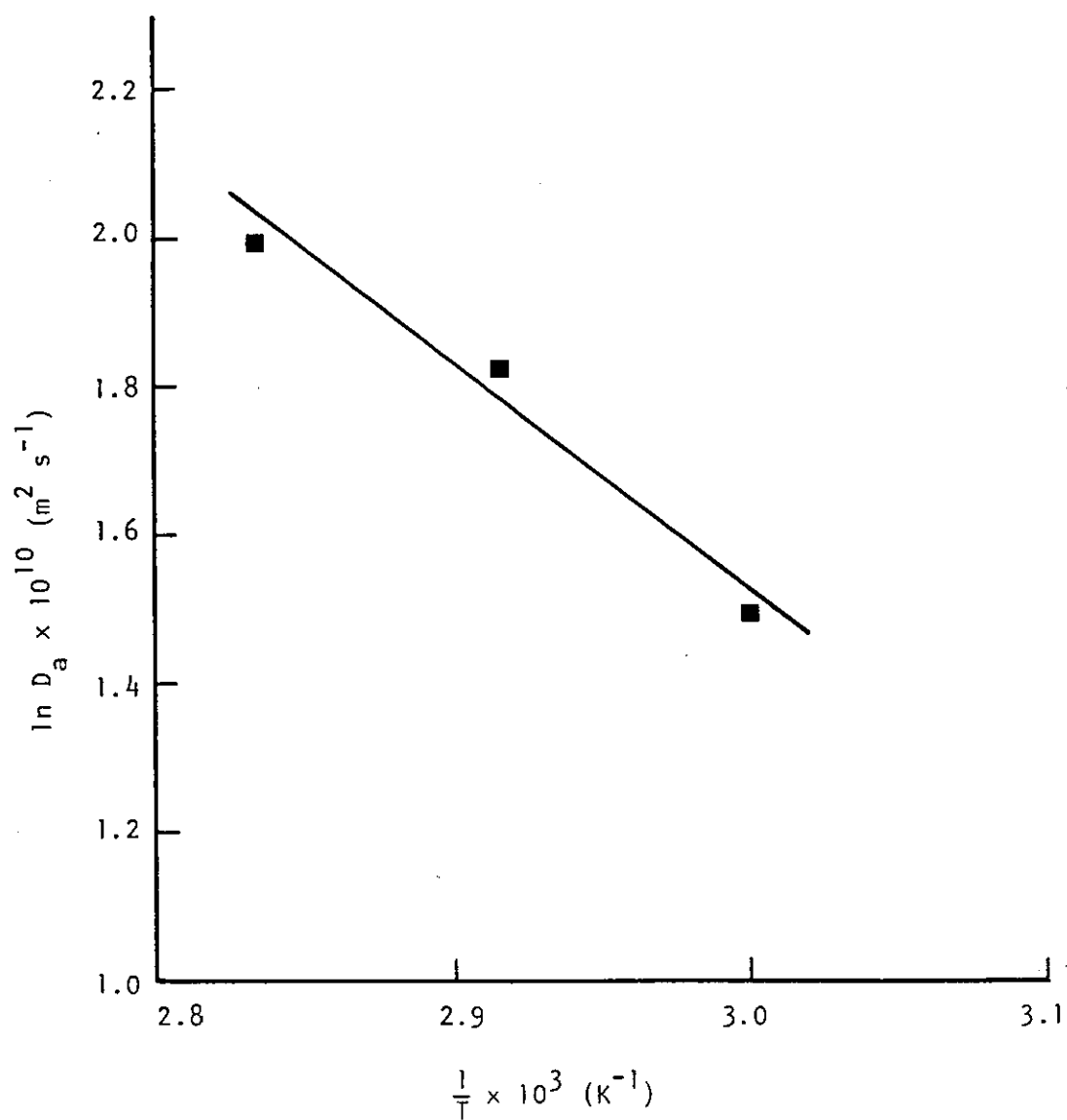
FIGURE 5.51: Graph of In D_a (mean apparent diffusion coefficients of total sugars at 60, 70, and 80°C, from Table 5.8, versus the reciprocal of absolute temperature
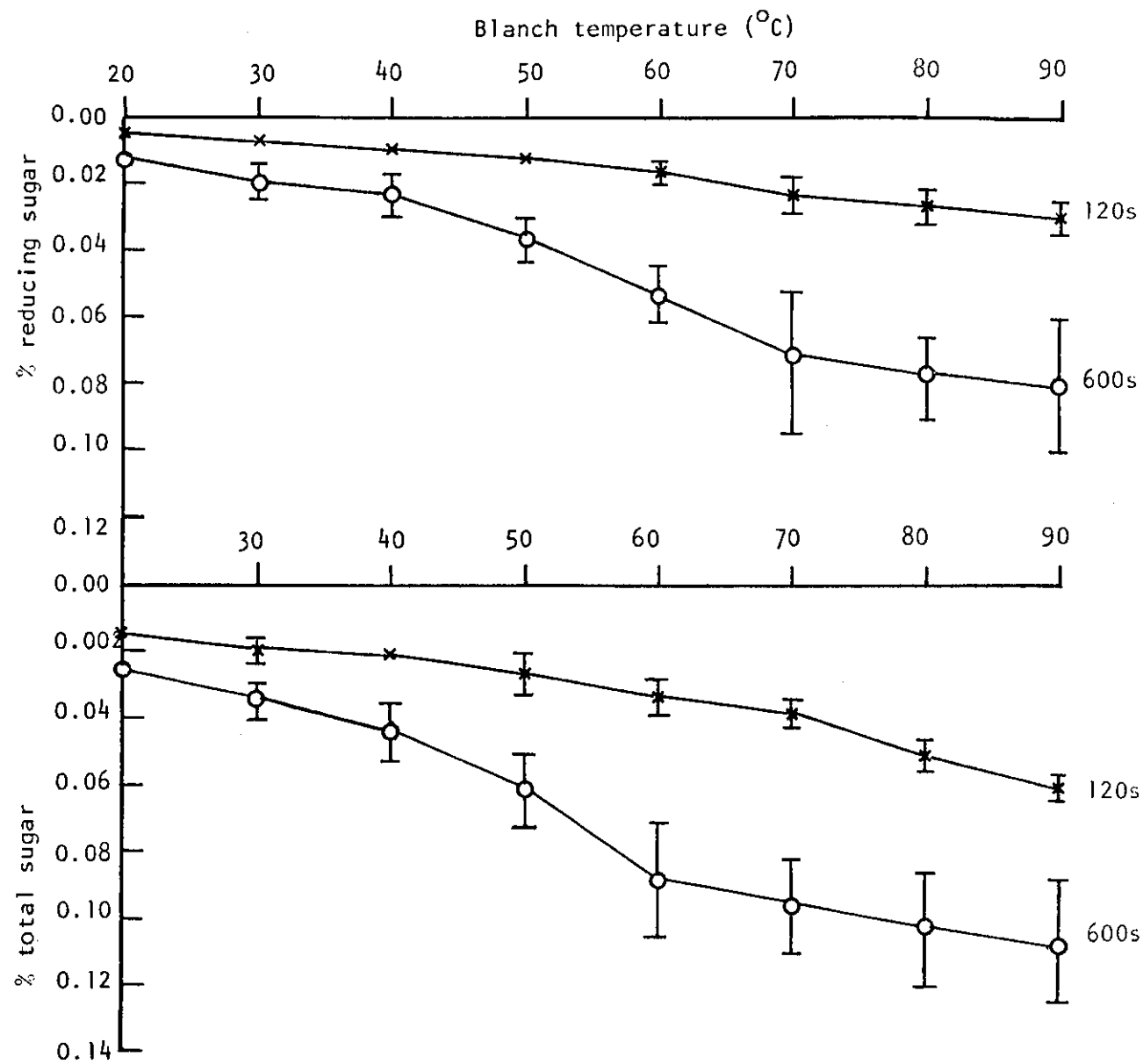
FIGURE 5.52 Percentage total and reducing sugar lost from Record potato cubes into the blanch water after 120 and 600s

5.4.2   Industrial Scale Process

5.4.2.1   Sugar content of potatoes and blanch waters

The results of the sugar analysis are summarised in Tables 5.9 and 5.10.   Table 5.9 shows the percentage of total and reducing sugars in the potato slice during processing, while Table 5.10 shows the percentage of total and reducing sugar in blanch 1 and 2 as well as in the make up water and the overflow of both blanch 1 and 2.

The initial total sugar content was 0.25%.   This was reduced by 12% by blanch 1 and by 32% by the end of spray 2.   The total sugar content of slices ex spray 1 and blanch 2 were nominally the same, but further sampling might have shown a more steady continuation of sugar loss.

The initial reducing sugar content was 0.18% comprising some 72% of the total sugar content.   It is doubtful if there is any significant difference between the composition of slices and whole potatoes.   A reduction of 5.6% reducing sugars was recorded in slices ex blanch 1, and a total reduction of 11.1% after spray 1. These losses would have arisen mainly from the cut surfaces of the slices.   However the reduction in reducing sugar content was more than doubled to 27.8% at the blanch 2 temperature of $74^{\circ}C$, being finally reduced by 38.9% ex spray 2.   The relatively high loss in both total and reducing sugars during blanch 2 and water spray 2 was due to a combination of the increase in permeability as well as the cessation of osmotic properties of the cell membranes as a result of cell membranes disorganization at high temperature.

The total sugar content of the water was low, being 0.010% in blanch 1 and 0.016% in blanch 2.   The associated make up and overflow water contained similar levels to their respective blanch waters.   The higher levels recorded in blanch 2 were as expected. The reducing sugar content was 0.009% in blanch 1 and 0.012% in blanch 2, comprising more than 70% of the total sugars present.

TABLE 5.9: Sugar contents of potato samples at the various sampling points in the process

Potato Sample Point	Type of Sugar	Potato constituents and losses**(%)(FWB)					
		A		B		Average***	Losses
		1	2	3	4		
Ex-store (whole)	T*	0.228	0.267	0.238	0.266	0.25±0.02	-
	R*	0.189	0.198	0.189	0.206	0.20±0.01	-
	S*					0.05	
Ex-slicer	T	0.315	0.246	0.215	0.225	0.25±0.05	-
	R	0.195	0.174	0.194	0.174	0.18±0.01	-
	S					0.07	
Ex-blanch 1	T	0.199	0.245	0.222	0.196	0.22±0.2	12.0
	R	0.174	0.200	0.165	0.156	0.17±0.02	5.6
	S					0.05	
Ex-spray 1	T	0.166	0.193	0.228	0.219	0.20±0.03	20.0
	R	0.142	0.128	0.178	0.198	0.16±0.03	11.1
	S					0.04	
Ex-blanch 2	T	0.177	0.199	0.202	0.211	0.20±0.01	20.0
	R	0.123	0.128	0.141	0.138	0.13±0.01	27.8
	S					0.07	
Ex-spray 2	T	0.159	0.164	0.186	0.180	0.17±0.01	32.0
	R	0.105	0.090	0.122	0.126	0.11±0.02	38.9
	S					0.06	

*   T = total sugar

       R = reducing sugar

       S = sucrose (by difference)

**   Percentage losses based on potato composition ex-slicer

***   Averages to three decimal places were used in D_a values calculation

TABLE 5.10: Sugar content of the blanching waters at the various
sampling points in the process

Water Sample Point	Type of Sugar	Sugar %				Average
		A		B		
		1	2	3	4	
Blanch 1	T*	0.0097	0.010	0.0091	0.011	0.010
	R**	0.0077	0.0090	0.0080	0.011	0.009
	S***					0.001
Overflow 1	T	0.0103	-	0.012	-	0.011
	R	0.0081	-	0.0091	-	0.009
	S					0.002
Make up water 1	T	0.011	-	0.012	-	0.012
	R	0.0101	-	0.0107	-	0.010
	S					0.002
Blanch 2	T	0.018	0.013	0.019	0.014	0.016
	R	0.014	0.014	0.0117	0.0082	0.012
	S					0.004
Overflow 2	T	0.013	-	0.017	-	0.015
	R	0.0103	-	0.011	-	0.011
	S					0.004
Make up water 2	T	0.014	-	0.013	-	0.014
	R	0.012	-	0.013	-	0.013
	S					0.001

*   T = Total sugar

**   R = Reducing sugar

***   S = Sucrose

The pattern of levels was similar to that for total sugars. The proportion of sugars present in the water appeared to be similar to the proportion in which they are present in the potato slices.

5.4.2.2 Apparent diffusion coefficients (D_a) of sugars calculated from industrial data

The diffusion equations previously presented in Section 2.1 were fitted to the experimental data of Tables 5.9 and 5.10 to verify the applicability of diffusion in accounting for sugar removal from potato slices under the factory conditions of washing and blanching. Using these equations, the D_a values for total and reducing sugars were calculated for potato slices ex blanch 1 and ex blanch 2. For blanch 1 the initial mean sugar content was taken as that after slicing, and for blanch 2 the initial mean sugar content was taken as that after spray 1.

It is doubtful if the values for blanch 1 are very useful because the temperature of 29°C is too low to kill cells, and losses would primarily arise from the cut surfaces rather than from within the body of the slice. Laboratory work did not include such low temperatures, but the data collected here may be useful subsequently.

The diffusion coefficients (D_a) for reducing and total sugars from potato slices ex blanch 1 and blanch 2 are listed in Table 5.11. All values of D_a are of an expected order of magnitude. D_a values for reducing sugars were higher than those for total sugars as expected from their molecular weights. The diffusion coefficients of reducing sugars ($2.93 \times 10^{-10} m^2 s^{-1}$) and total sugars ($5.37 \times 10^{-10} m^2 s^{-1}$) in blanch 1 seemed to be higher than expected. Since diffusion was not the only controlling factor in this process, this may have been due to more damage in the surface cells resulting in higher sugar loss. The D_a values for sugars in slices ex blanch 2 are smaller, but of the same order as those obtained in the laboratory scale, $12.8 \times 10^{-10} m^2 s^{-1}$ and $8.08 \times 10^{-10} m^2 s^{-1}$ for reducing and total sugar respectively.

TABLE 5.11: Apparent diffusion coefficients for total and reducing
sugars from potato slices ex blanch 1, and blanch 2.
(Based on mean initial and final sugar contents from
four replicates)

Sample Point	Apparent Diffusion Coefficients $D_a \times 10^{10}$ (m²s⁻¹)	
	Total Sugar	Reducing Sugar
Blanch 1 (29°C)	5.37	2.93
Blanch 2 (74°C)	0.73	6.46
Laboratory test (74°C)	8.08	12.18

The agreement may be regarded as reasonable considering the
very large errors inherent in this industrial study due to such
small and variable samples.

5.4.2.3 Comparison of actual and Predicted losses of sugars

As a further test, the D_a values obtained from the laboratory
work were used to predict the losses of sugars from potato slices
in blanch 2. Table 5.12 presents the actual and predicted losses
of reducing and total sugars from potato slices ex blanch 2. Pre-
dicted values were all smaller than the actual values found due to
the higher laboratory D_a values used for the predictions. The mean
predicted reducing sugar content was 89% of the actual value and the
predicted total sugar content was 84% of the actual value found.

A difference of 10-15% between the controlled laboratory
experimental results and the factory results is to be expected.
Statistical analysis by student-T and F-tests showed that at all
levels the differences were not significant, see Appendix VI.
So it can be concluded that the laboratory D_a values can be used
usefully to predict the losses in practice under different blanching
conditions.

TABLE 5.12: Actual and predicted* losses of sugars from potato
slices ex blanch 2

| Sample No | Sugar Content of Potato Slices % | | | |
| | Reducing Sugar | | Total Sugar | |
	Actual	Predicted	Actual	Predicted
1	0.122	0.107	0.177	0.148
2	0.128	0.091	0.199	0.166
3	0.141	0.128	0.202	0.175
4	0.138	0.144	0.211	0.169
Mean	0.132	0.118	0.197	0.165

* Based on D_a values calculated from laboratory experiments

5.5 Theoretical Correlation for the Optimum Process Conditions on the Industrial Scale

5.5.1 Method for Prediction of Reducing Sugar Contents after Blanch 1, and after Blanch 2

The relation between apparent diffusion coefficients for reducing
sugars and temperature obtained by laboratory experiments is shown
in Figure 5.50. Using this relation it was possible to demonstrate
the theoretical relation between the initial content of reducing
sugars in the potato slices and the final reducing sugar content
after a given set of blanch conditions. (The D_a value at $29^{\circ}C$ was
estimated by extrapolation of the graph in Figure 5.50).

Taking blanch 2 as an example, in practice the blanch time is
kept constant at 27 sec and the temperature is varied according to
the quality of the end product. Using D_a values for reducing sugars
at different temperatures obtained from laboratory scale (see Figure
5.50 for relation between D_a and temperature), and the desired process
conditions (blanch time and thickness) into the following equation,
$\tilde{t} = \dfrac{D_a t}{a^2}$, then by assuming that the blanch medium concentration (C_o)

was zero, (as the reducing sugar and total solubles content of the blanch waters were low, i.e. less than 2%) and solving

$$E = \frac{\overline{C} - C_o}{C_1 - C_o}$$

relationships between the initial (C_1) and final reducing sugar $(\overline{C})$ content can be deduced for different blanch temperatures. For example:

At 50°C	$\overline{C} = 0.8470\ C_1$	(5.1)
60°C	$\overline{C} = 0.7930\ C_1$	(5.2)
70°C	$\overline{C} = 0.7600\ C_1$	(5.3)
80°C	$\overline{C} = 0.6800\ C_1$	(5.4)

By substituting in a range of initial reducing sugar contents (C_1), the corresponding final contents $(\overline{C})$ after blanching, can be calculated and a graph constructed (see Figure 5.53).

A similar graph was prepared for blanch 1 operating at 16 sec holding time for various temperatures (see Figure 5.54) from the following relation:

At 29°C	$\overline{C} = 0.9320\ C_o$	(5.5)
50°C	$\overline{C} = 0.8820\ C_o$	(5.6)
60°C	$\overline{C} = 0.8410\ C_o$	(5.7)
70°C	$\overline{C} = 0.8150\ C_o$	(5.8)

Also by using the same technique but fixing the blanch temperature, the prediction of reducing sugar loss may be made at different blanch times as shown in the example of Figure 5.55 for a temperature of 70°C at 27, 40, 60 and 90 sec residence times in blanch 2 and example of Figure 5.56 for a temperature 29°C at 16, 40, 60 and 90 sec residence time in blanch 1. The related equations used to construct these two graphs were as follow:
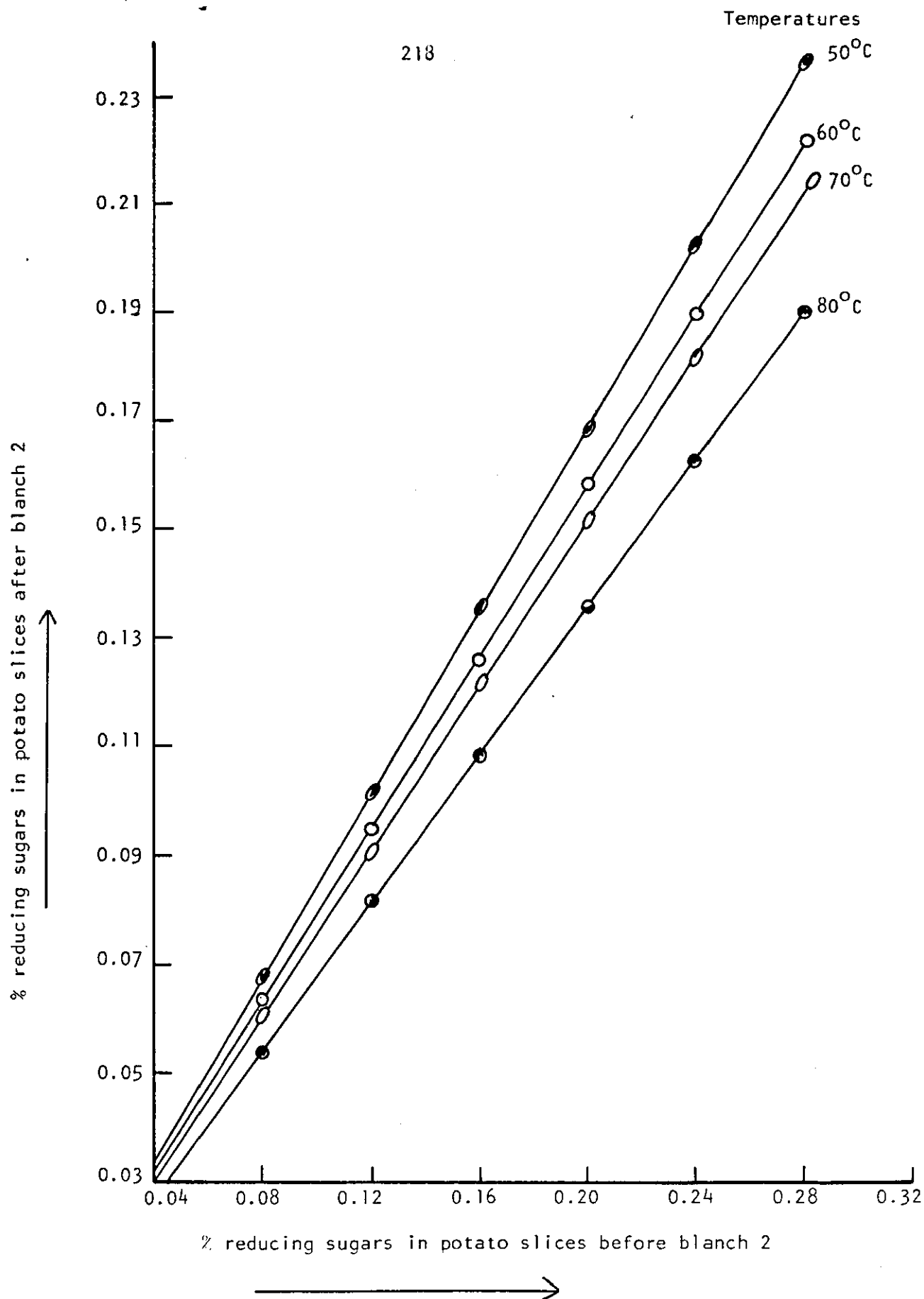
FIGURE 5.53: Predicted relation between percentage reducing sugar content of potato slices before and after blanching (blanch 2) for 27 sec at 50, 60, 70 and 80°C
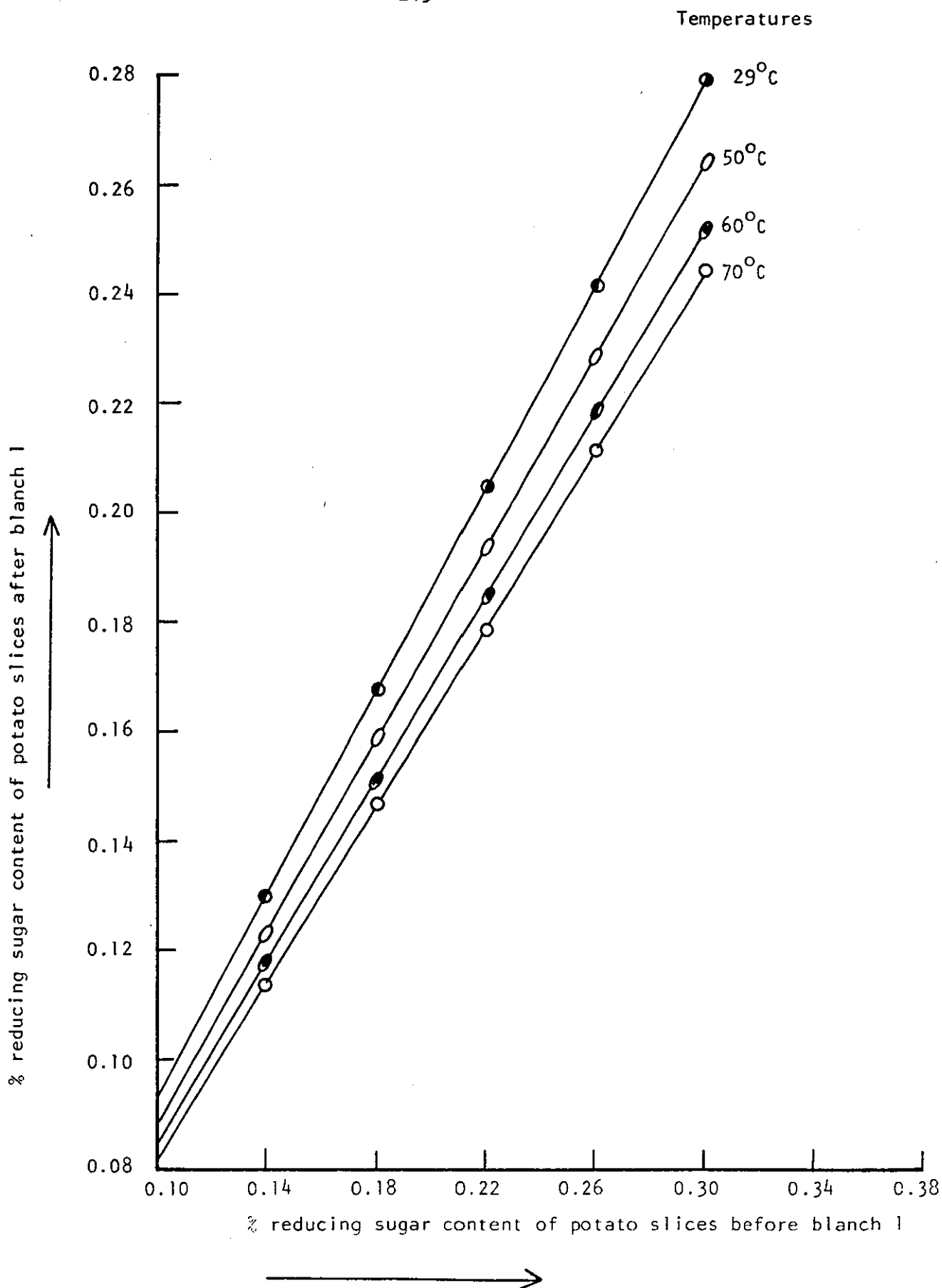
FIGURE5.54: Predicted relation between percentage reducing sugar content of potato slices before and after blanching (blanch 1) for 16 sec at 29, 50, 60 and 70°C
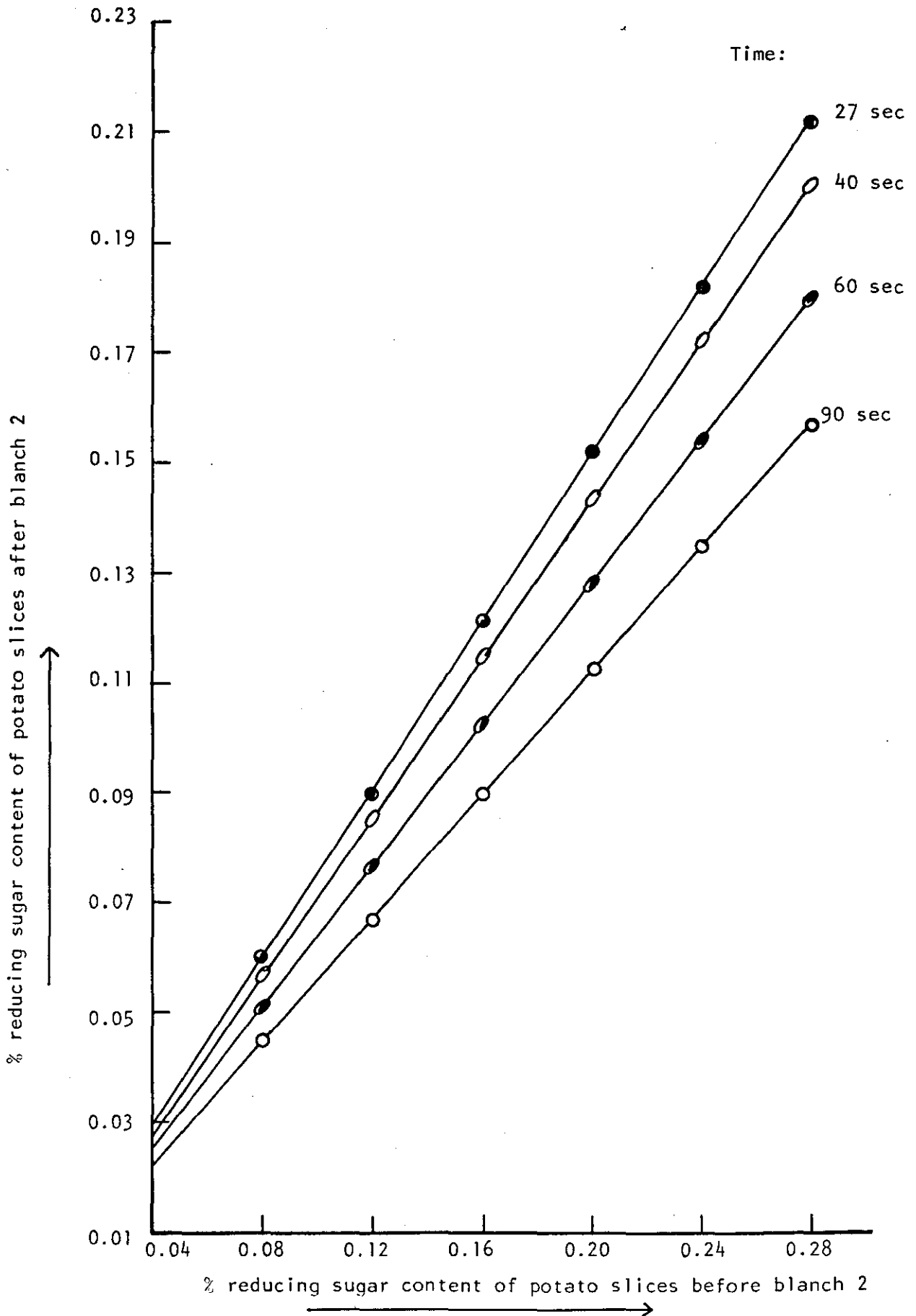
FIGURE 5.55: Predicted relation between percentage reducing sugar content of potato slices before and after blanching (blanch 2) at 70°C for 27, 40, 60 and 90 sec
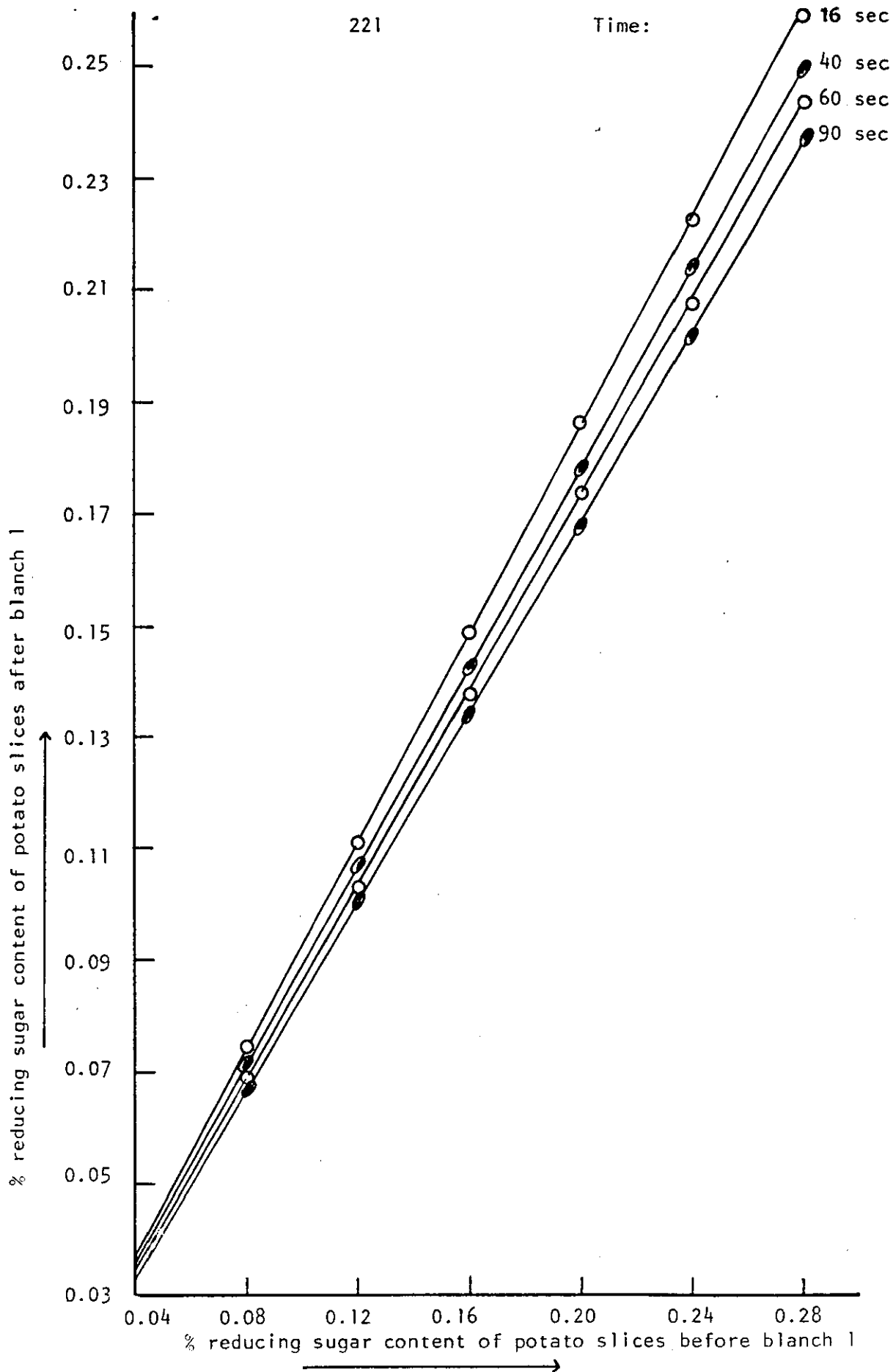
FIGURE 5.56: Predicted relation between percentage reducing sugar content of potato slices before and after blanching (blanch 1) at 29°C for **16**, 40, 60 and 90 sec

Blanch 2 time of 27 sec	$\overline{C} = 0.760\ C_o$	(5.9)
40 sec	$\overline{C} = 0.720\ C_o$	(5.10)
60 sec	$\overline{C} = 0.644\ C_o$	(5.11)
90 sec	$\overline{C} = 0.563\ C_o$	(5.12)

Blanch 1 time of 16 sec	$\overline{C} = 0.9320\ C_o$	(5.13)
40 sec	$\overline{C} = 0.893\ C_o$	(5.14)
60 sec	$\overline{C} = 0.870\ C_o$	(5.15)
90 sec	$\overline{C} = 0.8420\ C_o$	(5.16)

5.5.2 Method for Prediction of Final Reducing Sugar Contents after Overall Blanch Process

The reduction in reducing sugars can also be estimated over the whole process, and the losses produced by the spray operations may be included by introducing correction factors. The losses arising from spraying will vary slightly depending on, for example, spray water temperature and previous blanch temperature. However it was decided to use the mean figures obtained under the factory conditions.

As a result of the slicing operation the level of reducing sugars was decreased by a content of 0.012%. Spray 1 decreased the reducing sugars by a mean content of 0.012% also, and spray 2 by a content of 0.022% making a total decrease in reducing sugar content due to the spray operations of 0.034%.

So where the uncorrected equation for blanch 1 ($29^{\circ}C$ for 16 sec) as before is:

$$\overline{C} = 0.9320\ C_1$$

the corrected equation including the influence of the slicing operation will be:

$$\overline{C} = 0.9320 \ C_1 - 0.012 \qquad\qquad (5.17)$$

where C_1 refers to the initial reducing sugar content of the raw potatoes ex-store.

By solving equation (5.17) with equations 5.1, 5.2, 5.3 and 5.4 and introducing the correction factor 0.034 for the losses due to both spray operations, general equations may be produced which predict the content of reducing sugars after the overall blanch process (i.e. including blanch 1, spray 1, blanch 2 and spray 2). The final reducing sugar content after spray 1 is used as the initial content before blanch 2. So for example after final reducing sugar content would be given by:

$$\overline{C} = 0.7600 \ (0.9320 \ C_1 - 0.012) - 0.034$$

$$\overline{C} = 0.7083 \ C_1 - 0.0249 \qquad\qquad (5.18)$$

The prediction of final reducing sugar content can therefore be made for a wide variety of conditions and Figures 5.57, 5.58 and 5.59 show three examples.

Figure 5.57 shows the relation between the initial and final reducing sugar content after an overall blanch process where blanch 1 conditions are $29^\circ C$ for 16 sec, and blanch 2 is fixed at 27 sec for various temperatures, using the following equations:

Blanch 2 temperatures of $50^\circ C$: $\overline{C} = 0.7894 \ C_1 - 0.0238$ (5.19)

$\qquad\qquad\qquad\qquad 60^\circ C$: $\overline{C} = 0.7391 \ C_1 - 0.0245$ (5.20)

$\qquad\qquad\qquad\qquad 70^\circ C$: $\overline{C} = 0.7083 \ C_1 - 0.0249$ (5.21)

$\qquad\qquad\qquad\qquad 80^\circ C$: $\overline{C} = 0.6338 \ C_1 - 0.0258$ (5.22)
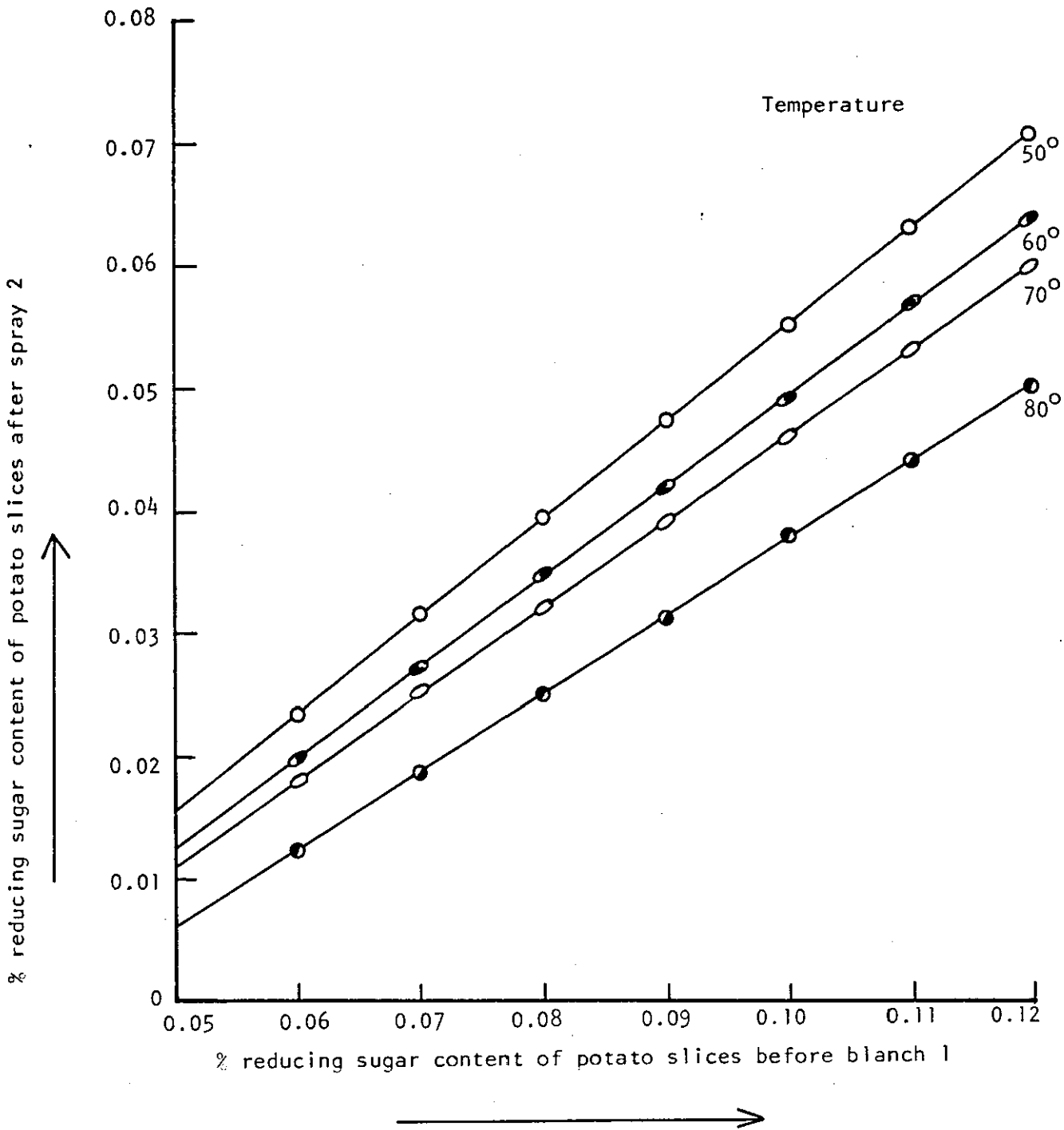
FIGURE 5.57: Predicted relation between percentage reducing sugar content of potato slices before and after overall blanching process (i.e. from blanch 1 to spray 2), using a blanch 1 temperature of 29°C and time of 16 sec and a blanch 2 time of 27 sec at the given temperatures
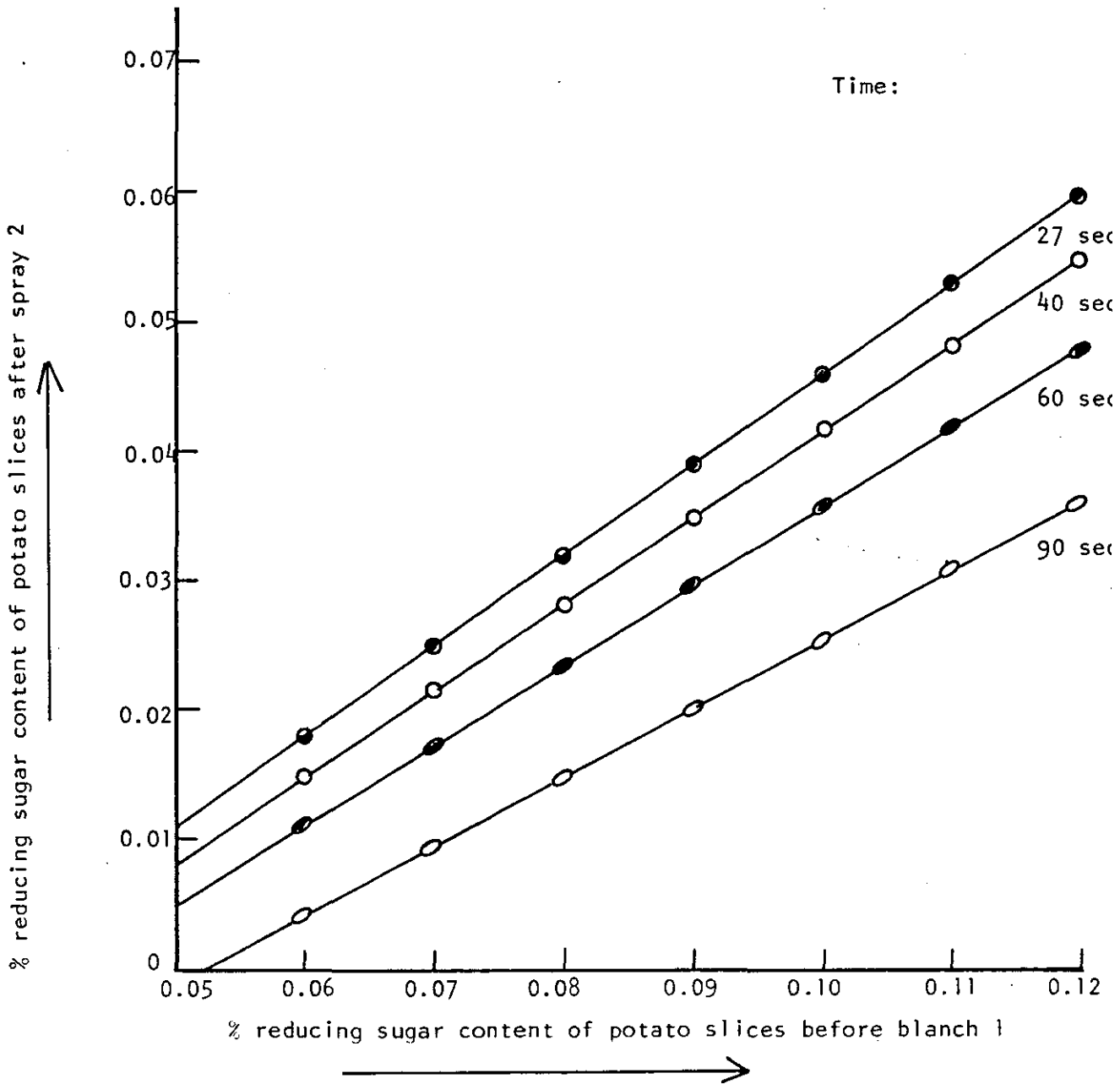
FIGURE 5.58: Predicted relation between percentage reducing sugar content of potato slices before and after the overall blanching process (i.e. from blanch 1 to spray 2), using a blanch 1 temperature of 29°C and time of 16 sec and a blanch 2 temperature of 70°C for the given times
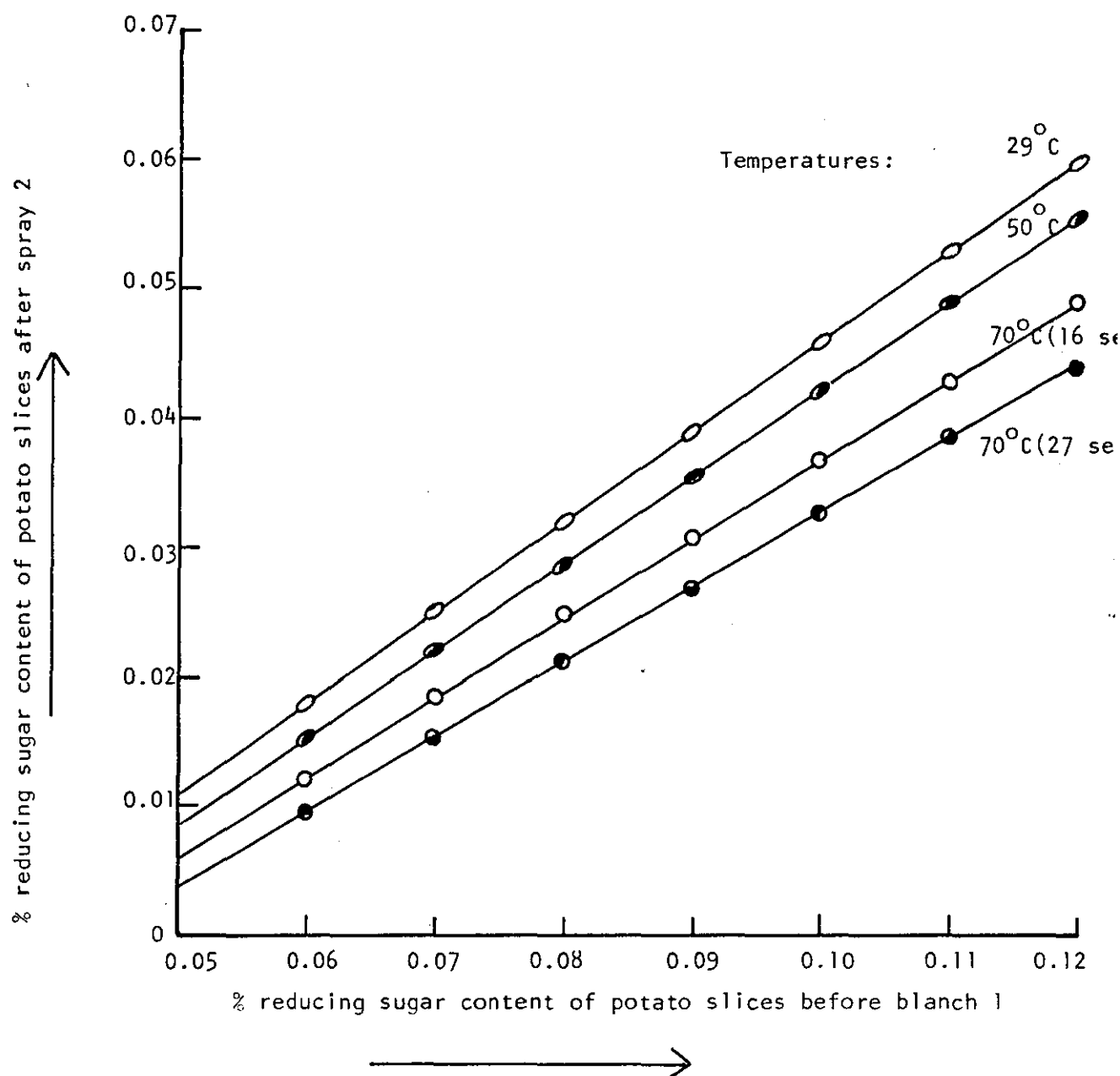
FIGURE 5.59: Predicted relation between percentage reducing sugar content of potato slices before and after the overall blanching process (i.e. from blanch 1 to spray 2) using a blanch 2 temperature of 70°C and time of 27 sec and a blanch 1 time of 16 sec at the given temperatures, and 27 sec at 70°C

Figure 5.58 shows the relation between the initial and final reducing sugar content after an overall blanch process where blanch 1 conditions are $29^{\circ}C$ for 16 sec, and blanch 2 is fixed at $70^{\circ}C$ for various times, using the following equations:

$$\text{Blanch 2 time of 27 sec:} \quad \overline{C} = 0.7083 \; C_1 - 0.0249 \quad (5.23)$$
$$40 \text{ sec:} \quad \overline{C} = 0.6710 \; C_1 - 0.0254 \quad (5.24)$$
$$60 \text{ sec:} \quad \overline{C} = 0.6188 \; C_1 - 0.0260 \quad (5.25)$$
$$90 \text{ sec:} \quad \overline{C} = 0.5247 \; C_1 - 0.0272 \quad (5.26)$$

Figure 5.59 shows the relation between the initial and final reducing sugar content after an overall blanch process where blanch 2 conditions are $70^{\circ}C$ for 27 sec, and blanch 1 is fixed at 16 sec, for various temperatures, and also where blanch 1 conditions are $70^{\circ}C$ for 27 sec, using the following equations:

$$\text{Blanch 1 temperature of } 29^{\circ}C: \quad \overline{C} = 0.7083 \; C_1 - 0.0249 \quad (5.27)$$
$$50^{\circ}C: \quad \overline{C} = 0.6703 \; C_1 - 0.02488 \quad (5.28)$$
$$(16 \text{ sec}) \quad 70^{\circ}C: \quad \overline{C} = 0.6194 \; C_1 - 0.0249 \quad (5.29)$$
$$(27 \text{ sec}) \quad 70^{\circ}C: \quad \overline{C} = 0.5776 \; C_1 - 0.02488 \quad (5.30)$$

Similarly it is possible to construct a graph which will indicate the choice of blanch time or temperature to produce a final reducing sugar content of some maximum desired level (such as 0.10%).

Taking blanch 2 as an example, assuming that the maximum desired percent of reducing sugar required in the potato slices after blanching is 0.10% and the blanch conditions are fixed at 27 sec for various temperatures (50, 60, 70 and $80^{\circ}C$). Using the same method as before, a relationship between the percent of initial reducing sugar in potato slice and blanch temperature was obtained as shown in Figure 5.60. Figure 5.60 also shows the same relation after 60 and 90 sec blanching. In terms of prediction equations,
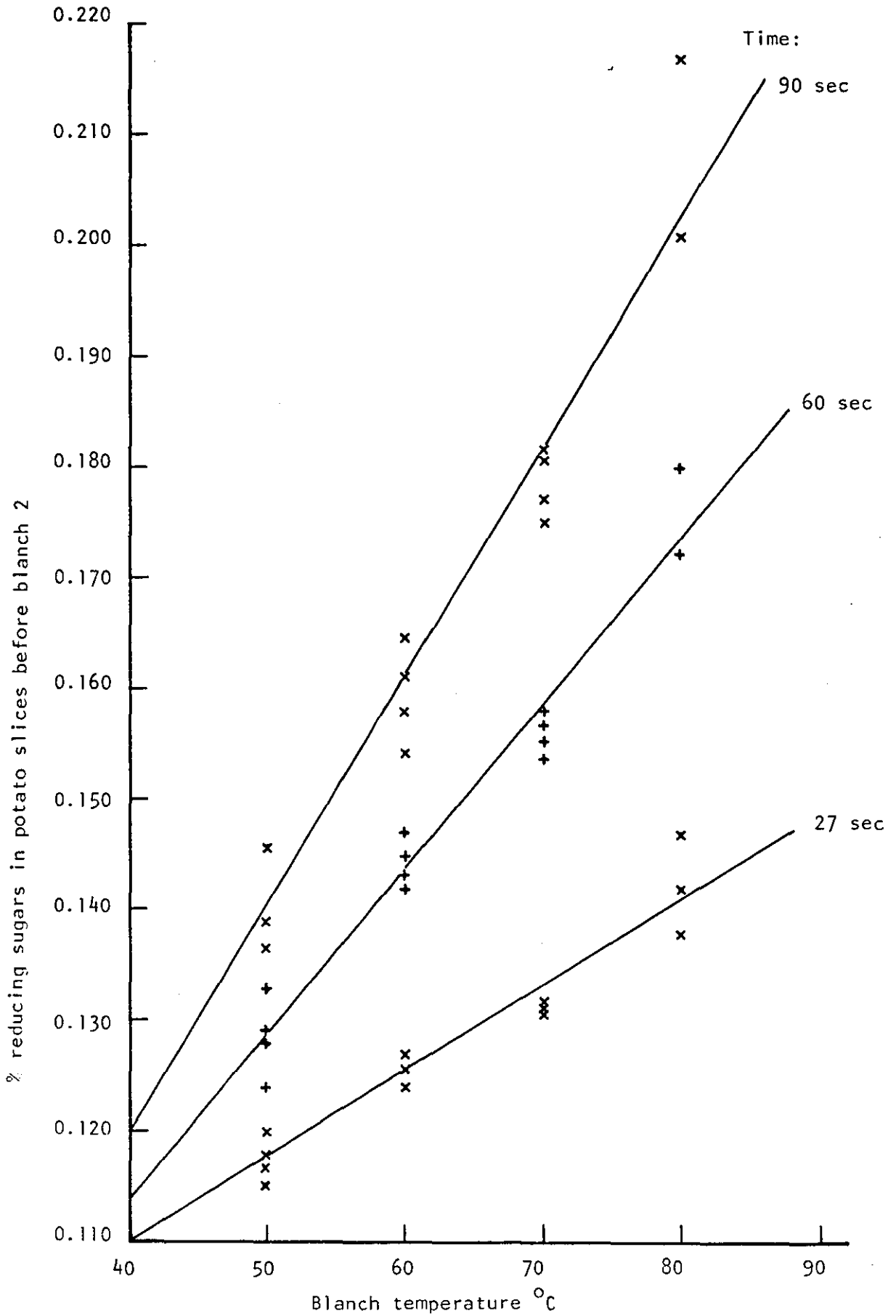
FIGURE 5.60: Predicted relation between blanch temperature and percentage reducing sugar content of potato slices before blanching (blanch 2) for 27, 60 and 90 sec to give 0.1% reducing sugar after blanching

a regression analysis resulted in the following equations:

For a blanch time of 27 sec
$$C_o = 0.00078T + 0.0788 \qquad (5.31)$$

For a blanch time of 60 sec
$$C_o = 0.00151T + 0.0531 \qquad (5.32)$$

For a blanch time of 90 sec
$$C_o = 0.00208T + 0.0368 \qquad (5.33)$$

where C_o is the percent of reducing sugar before blanching and T is blanch temperature in ^{o}C.

By solving equations 5.5 with equations 5.31, 5.32 and 5.33 and introducing the correction factors for sugar loss in slicing and spraying before and after blanching as before, general equations were obtained which give a relation between blanch temperature and reducing sugar for the overall blanch process as follows:

For blanch 2 time of 27 sec
$$[0.00078T = 0.9320 \, C_o - 0.125] \qquad (5.34)$$

For blanch 2 time of 60 sec
$$[0.00151T = 0.9320 \, C_o - 0.0991] \qquad (5.35)$$

For blanch 2 time of 90 sec
$$[0.00208T = 0.9320 \, C_o - 0.0828] \qquad (5.36)$$

where T is the temperature in blanch 2.

5.6   Thermal Diffusion of Potato Tissue

The effects of heating and cooling of foods during processing have extremely important influences upon the quality and characteristics of the final product. Values of the thermal properties such as thermal diffusivity, thermal conductivity and specific heat are required for the prediction of heating and cooling rates and process conditions using suitable mathematical models describing the process. This project was extended to measure some of these properties.

5.6.1   Transient Temperature Distribution

Record potato cylinders, having a diameter of 0.015 to 0.027m, were heated in a constant temperature water bath at temperatures of 30, 40, 50, 60, 70, 80 and 90°C. Figure 5.61 shows the experimental heating curves of 0.015m diameter potato samples in 40, 50, 60, 70, 80 and 90°C water bath. Temperatures were measured at the centre of the sample in all cases. Heating temperatures ranging from 20°C up to 90°C were selected because of the importance of these temperatures to the chemical and physical changes taking place in the potato in this range. The most important physical change to take place during potato processing is the gelatinisation of the starch (see Section 1.3.2).

Figure 5.61 shows that the heat penetration is very high during the first period of heating due to the high temperature gradient between the heating medium and potato. In all cases the centre temperature of the potato cylinder reached 80 to 85% of the heating medium in 180 sec. As heating continued and the temperature gradient between the heating medium and the potato sample became narrow, the rate of heat penetration slowed and became constant as the temperature of potato reached an equilibrium state with the heating medium. Also the rate of heat penetration increased as the temperature of the medium was increased, and in all cases the pattern was the same.

FIGURE 5.61: Experimental time-temperature relationship in the centre of Record potato cylinders during heating in a

In order to study the effect of the cylinder sample diameter on the heating curve and temperature distribution, potato cylinders of 0.015, 0.022 and 0.027m were heated in water at 40 and 70°C. These temperatures of 40 and 70°C were chosen to observe the influence of starch gelatinisation on the temperature distribution. Figure 5.62 shows the experimental heating curves for 0.015, 0.022 and 0.027m diameter potato immersed in 40°C water. Figure 5.63 shows similarly the heating curves for 0.015m and 0.022m diameter potato samples heated in 70°C water. In both cases the centre temperature of the smaller diameter potato reached the equilibrium state faster than the larger diameter potato sample. In heating at 40°C the centre temperature of the 0.015m diameter cylinders reached equilibrium 360 sec faster than the 0.022m cylinders (i.e. 0.015m samples reached equilibrium after 480 sec, while 0.022m cylinders reached equilibrium after 840 sec). At 70°C the centre temperature of 0.015m diameter cylinders reached equilibrium 600 sec faster than the 0.022m diameter samples. The difference in time is due to the different temperature gradients between the heating medium and sample which was 20°C and 50°C respectively. However the trend was the same which indicated that the gelatinisation process had little influence on the time-temperature distribution.

Figure 5.64 shows the centre time-temperature curves for 0.015m diameter potato samples during cooling in water at 20°C. Cooling was studied to see how the physical and chemical changes that had occurred at the higher temperature would influence the time-temperature distribution at the centre of the sample during heat removal over the same temperature range. Potato samples were heated at four different temperatures until they reached the heating medium temperature and then cooled at 20°C. Figures 5.65 and 5.66 show the heating and cooling curves for potato heated in 40, 50, 70 and 80°C and then cooled at 20°C. It was expected that during heating in water at 70°C and above, gelatinisation would occur and thus the shape of the time-temperature distribution curve would be different to that at lower temperatures where gelatinisation did not
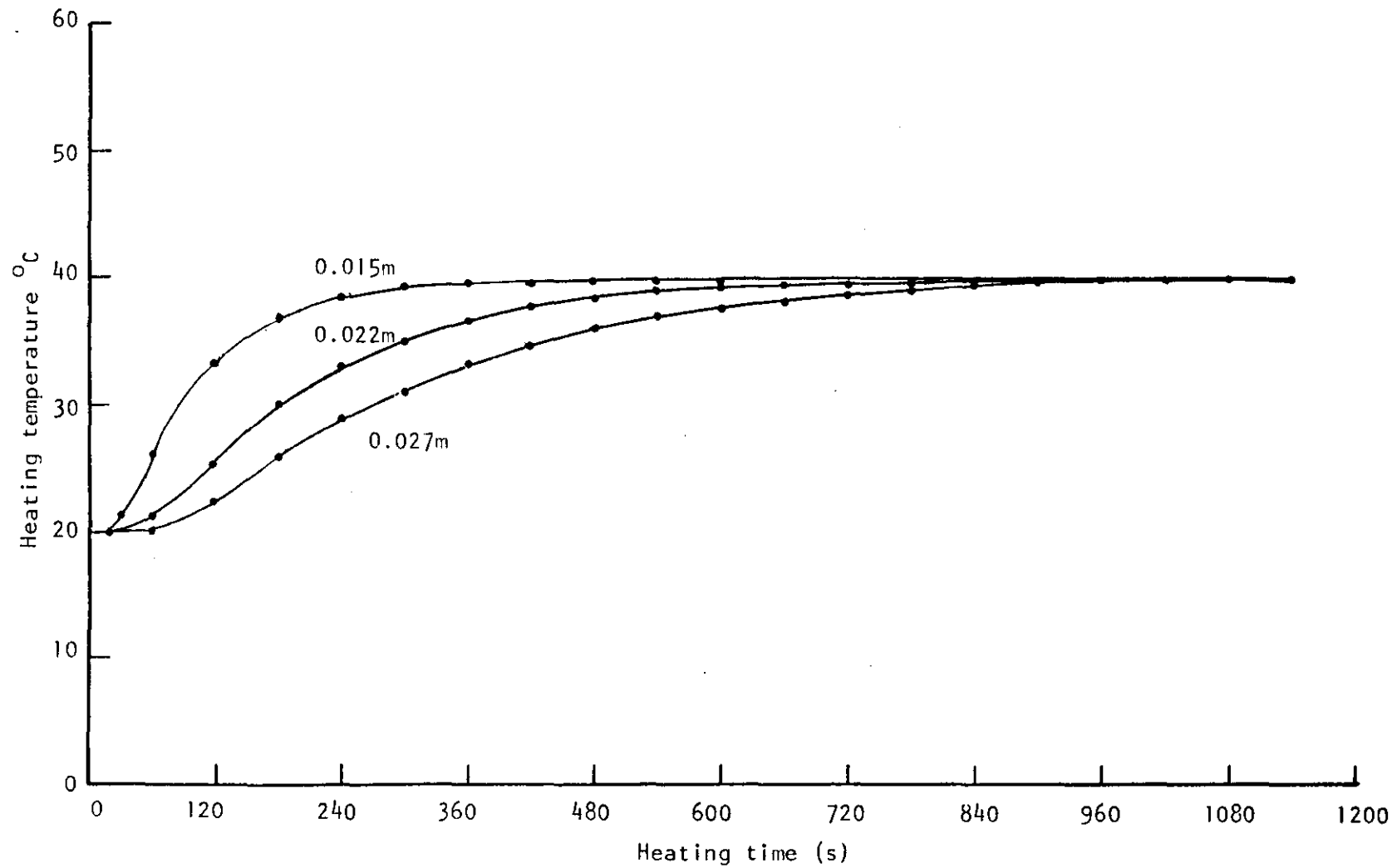
FIGURE 5.62: Experimental time-temperature relationship in the centre of Record potato cylinders having 0.015, 0.022 and 0.027m diameter, during heating in a 40°C water bath (means of three repeats)
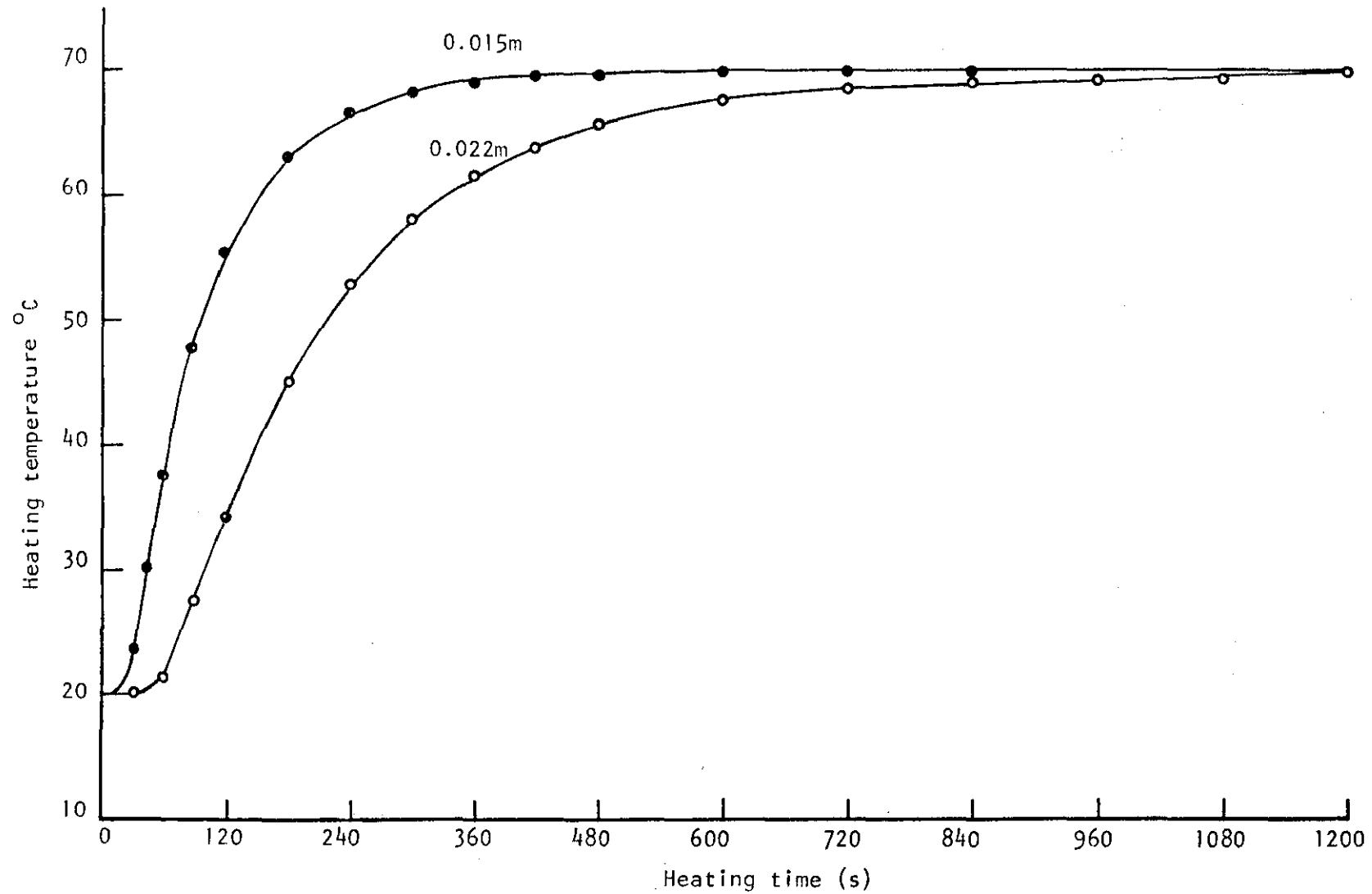
FIGURE 5.63: Experimental time-temperature relationship in the centre of Record potato cylinders having 0.015 and 0.022m diameter during heating in a 70°C water bath (means of three repeats)

FIGURE 5.64: Experimental time-temperature relationship in the centre of Record potato cylinders during cooling
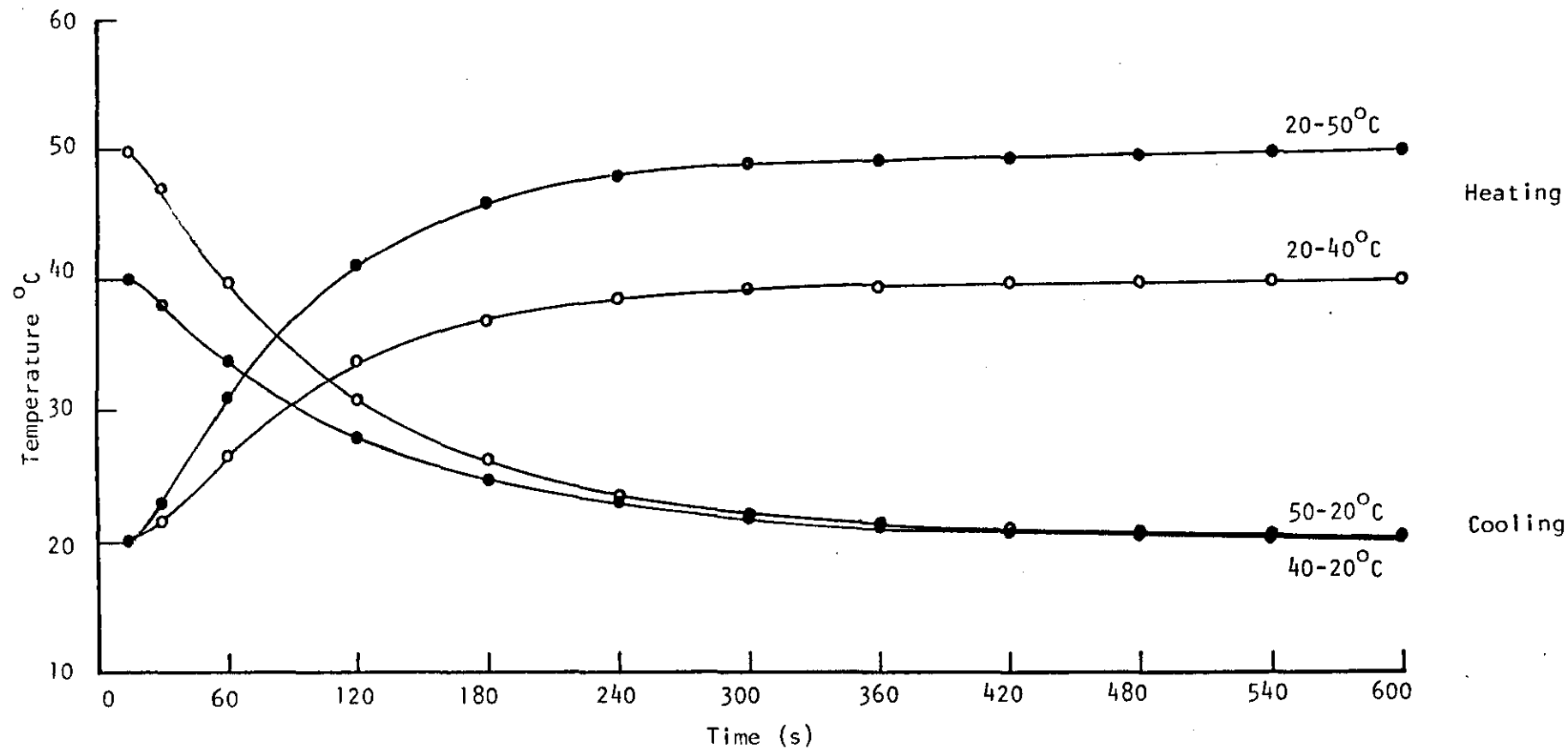
FIGURE 5.65: Experimental time-temperature relationship in the centre of Record potato cylinders during heating at 40 and 50°C in water bath and during cooling at 20°C in water. (Means of three repeats)
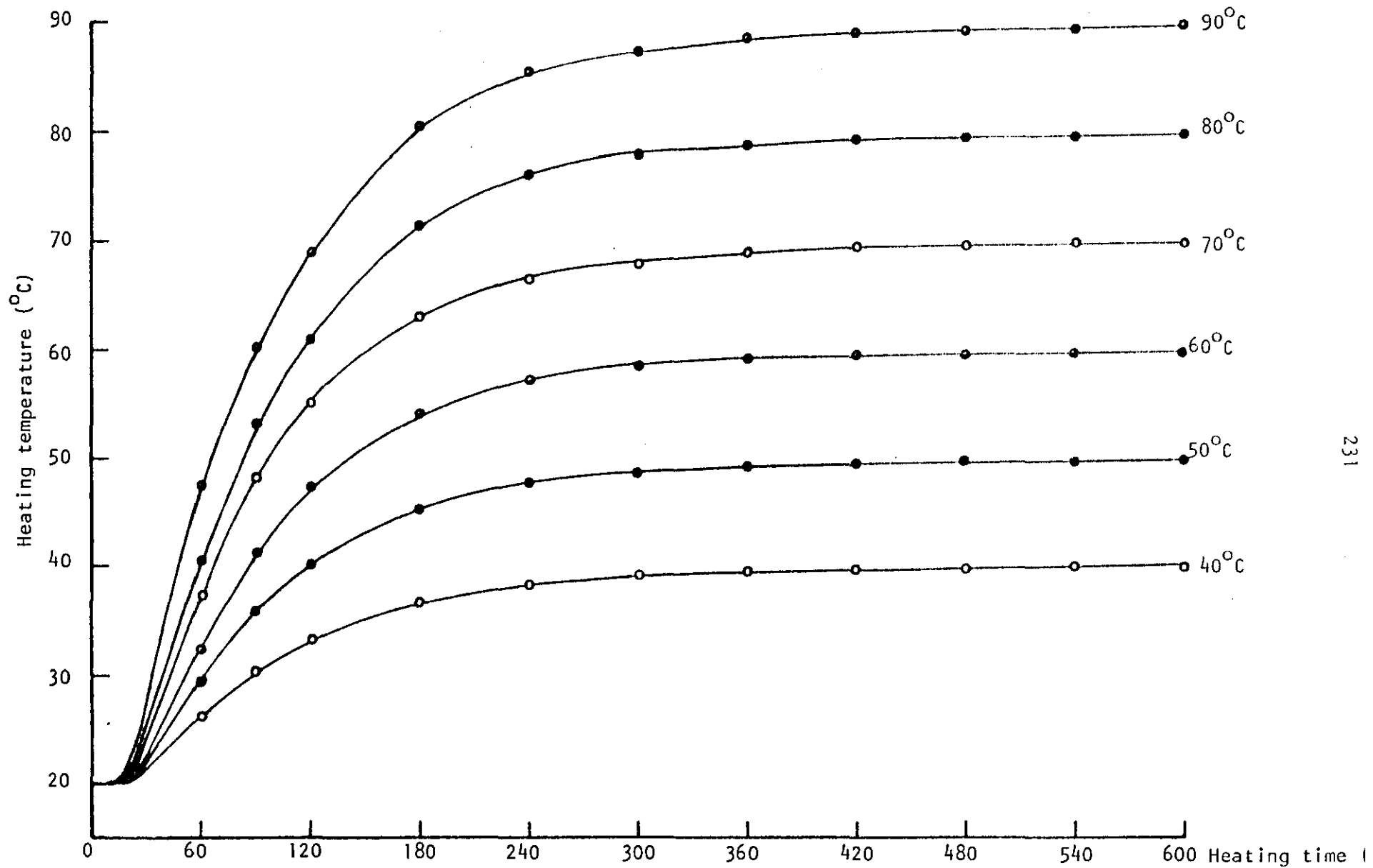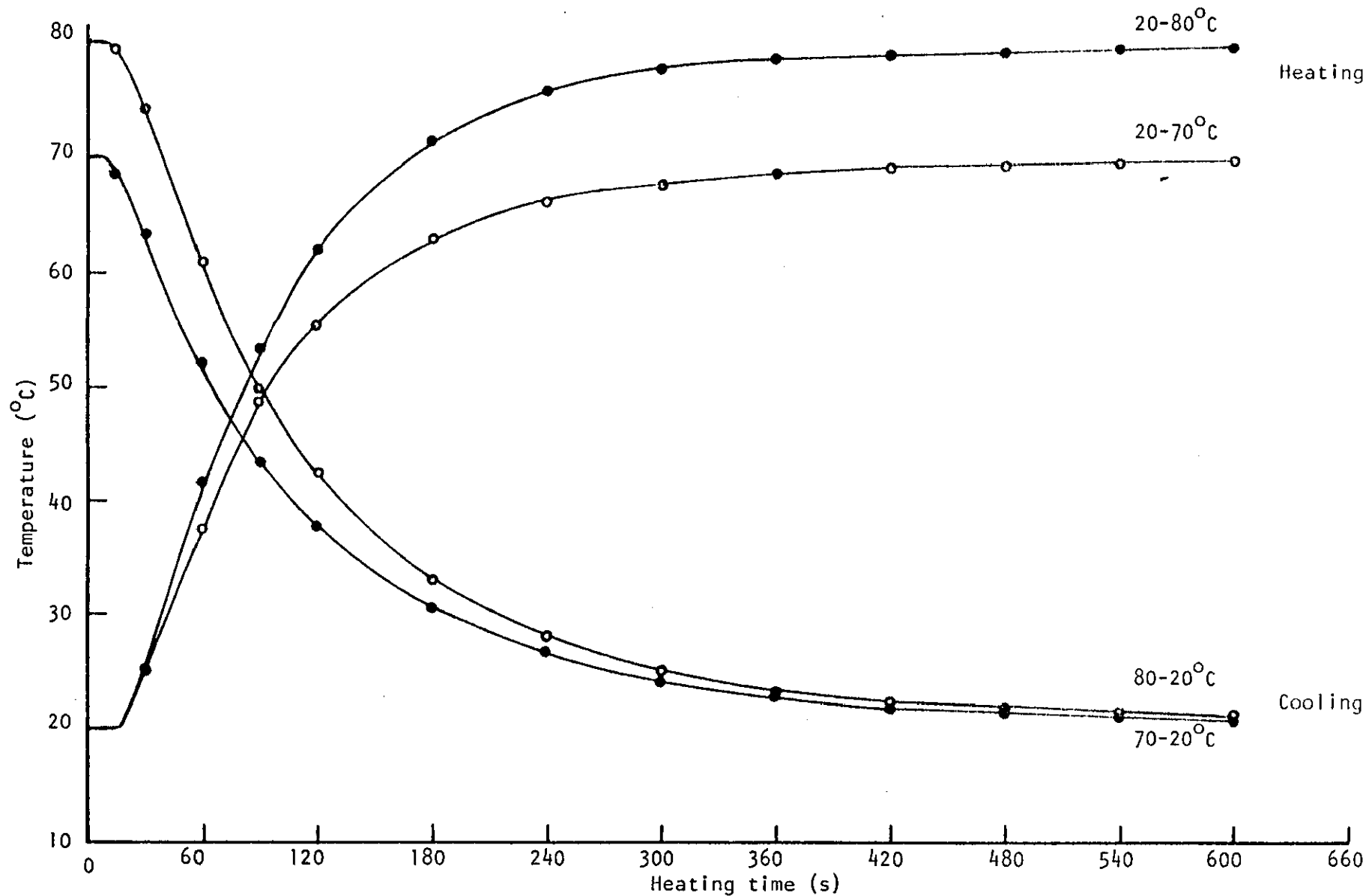
FIGURE 5.66: Experimental time-temperature relationship in the centre of Record potato cylinders during heating at 70 and 80°C in water bath and during cooling at 20°C in water (means of three repeats.)

occur. However the cooling curves (80-20) and (70-20) in Figure 5.64 did not indicate any difference. However thermal diffusivity (α) calculated from these cooling curves gave a significant effect on thermal diffusivity specially after 180 sec cooling where the cooling rate has slowed down, see Section 5.6.2.4.

5.6.2   Thermal Diffusivity

5.6.2.1 Effect of temperature

The experimental data shown in Figure 5.61 were used to calculate the thermal diffusivity of Record potato at different temperatures by the method described earlier. The values of thermal diffusivity are given in Table 5.13 along with the heating time and temperature. The variation of α with temperature during the first 300 sec is shown in Figure 5.67. The thermal diffusivity, α, appeared to increase with increasing temperature. When the temperature of the heating medium rose from 40 to 70°C, the thermal diffusivity, α, increased from an average value of 1.28×10^{-7} m^2s^{-1} at 40°C to an average value of 1.34×10^{-7} m^2s^{-1} at 70°C. At temperatures between 70 and 90°C, the thermal diffusivity decreased slightly. The average values for thermal diffusivity at 80 and 90°C were 1.33×10^{-7} and 1.32×10^{-7} m^2s^{-1} respectively. This indicated that the thermal diffusivity, α, reached a high value between 70 and 80°C before it decreased up to 90°C. The increase in thermal diffusivity around 70°C was probably due to the gelatinisation of potato starch. The decrease in thermal diffusivity after that may have arisen from the weakening and separation of the cell starch as the swelling starch became distended. The thermal diffusivities of potato were of the same order of magnitude as those reported for potato by Matthews and Hall (1968) which ranged between 9.60×10^{-8} to 1.41×10^{-7} m^2s^{-1} in the temperature range 63-73°C. However the magnitudes of thermal diffusivity of potatoes obtained in my investigation are lower than those reported by Rao et al. (1975). The average thermal diffusivity for potato was 1.70×10^{-7} m^2s^{-1}.

TABLE 5.13: Apparent thermal diffusivity (α) of Record potato cylinders when heated in water under the given conditions (data from curves in Figures 5.61, 5.62, 5.63, 5.64 and 5.68).

Data from Fig. No.	Condition	Conditions varied from standard*	$\alpha \times 10^7$ $(m^2 s^{-1})$ at the given blanch time in sec							
			60	120	180	240	300	360	420	480
5.61	heating temperature	Standard	1.36	1.31	1.28	1.24	1.21	1.13	1.18	1.17
		50°C	1.36	1.34	1.31	1.24	1.18	1.16	1.07	1.03
		60°C	1.36	1.34	1.31	1.28	1.28	1.20	1.19	1.10
		70°C	1.41	1.38	1.38	1.29	1.24	1.19	1.18	1.08
		80°C	1.45	1.36	1.31	1.29	1.24	1.20	1.15	1.07
		90°C	1.41	1.38	1.33	1.29	1.22	1.18	1.08	1.02
5.62	diameter	Standard	1.36	1.31	1.30	1.24	1.21	1.13	1.18	1.17
		0.022m(40°C)	1.31	1.33	1.34	1.36	1.35	1.34	1.38	1.31
		0.027m(40°C)	1.37	1.37	1.32	1.36	1.37	1.37	1.39	1.37
5.63		0.015m(70°C)	1.41	1.38	1.38	1.29	1.24	1.19	1.18	1.08
		0.022m(70°C)	1.21	1.36	1.38	1.36	1.35	1.34	1.27	1.22
5.68	agitation	Standard	1.31	1.31	1.31	1.24	1.21	—	—	—
		Without agitation (at 40°C)	1.21	1.24	1.22	1.14	1.00	—	—	—
5.64	cooling	40-20	1.31	1.13	1.05	1.16	0.91	0.85	0.84	0.75
		50-20	1.36	1.27	1.11	1.13	1.06	0.99	1.03	0.98
		70-20	1.40	1.22	1.28	1.05	1.11	0.89	0.84	0.79
		80-20	1.36	1.24	1.11	1.05	0.97	0.91	0.90	0.87

* Standard conditions: heating temperature = 40°C

Potato cylinder diameter = 0.015m
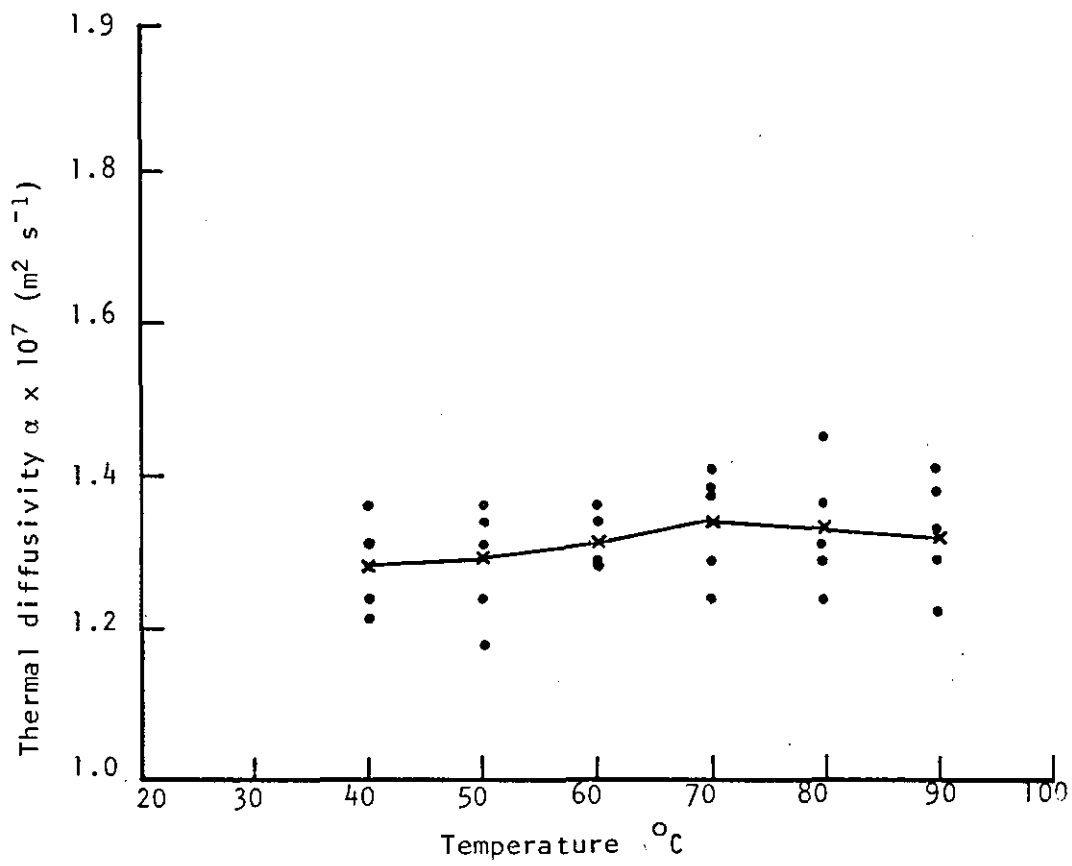
FIGURE 5.67: Effect of temperature on the thermal diffusivity
of Record potato

This could be due to the fact that our potatoes were stored for several months before being used for the measurement, during which compositional and physiological changes may have taken place.

5.6.2.2 Effect of diameter

Table 5.13 shows the thermal diffusivity of potato cylinders of 0.015, 0.022, and 0.027m diameter during heating at 40°C and the thermal diffusivity of 0.015 and 0.022m diameter cylinders at 70°C. The thermal diffusivity values for both cases were calculated from the experimental data shown in Figures 5.62 and 5.63 respectively. From Table 5.13 it is seen that the thermal diffusivity for the three diameters at 40°C were similar, with the exception of the 0.015m diameter sample after 240 sec heating. Table 5.13 shows the same observation with the α values for 0.015 and 0.022m diameter at 70°C. The decrease in thermal diffusivity of the 0.015m sample after 240 sec may be explained by the fact that since the centre temperature of 0.015m sample approached the heating medium temperature faster than 0.022 and 0.027m diameter samples, the temperature gradient between the tissue and medium became small after 240 sec, therefore the heat penetration will decrease and thus the α values will be expected to decrease.

As expected the results revealed that the thermal diffusivity was independent of diameter in the range studied, except for the values calculated after the temperature gradient between the sample and the heating medium has become very small (less than 4°C).

5.6.2.3 Effect of agitation

The most important factor during heating an object in a medium is the rate of heat transfer from the medium to the object. The rate of heating is increased as the heat transfer coefficient, h, increases. This means that the surface resistance approaches zero. This condition
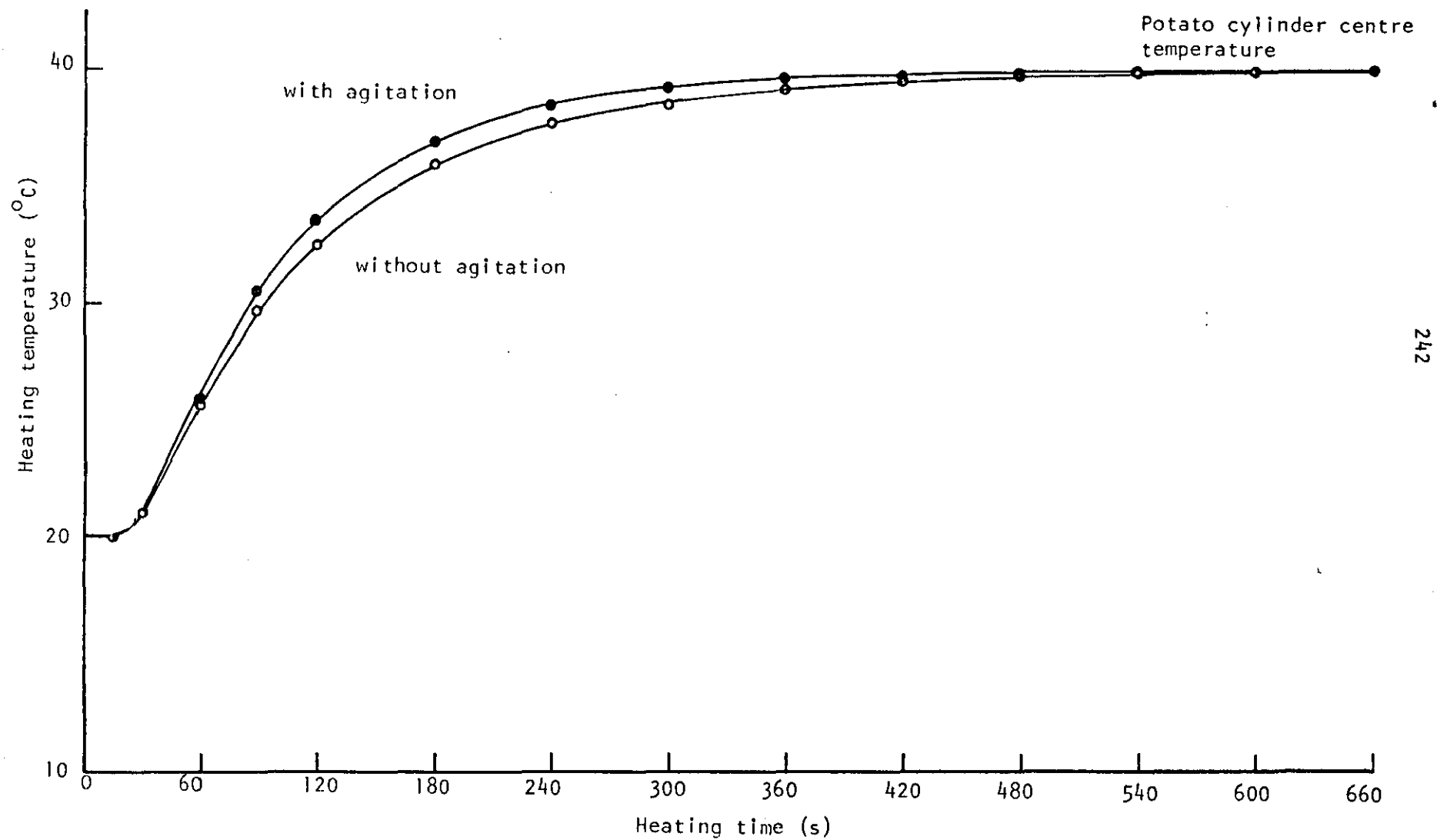
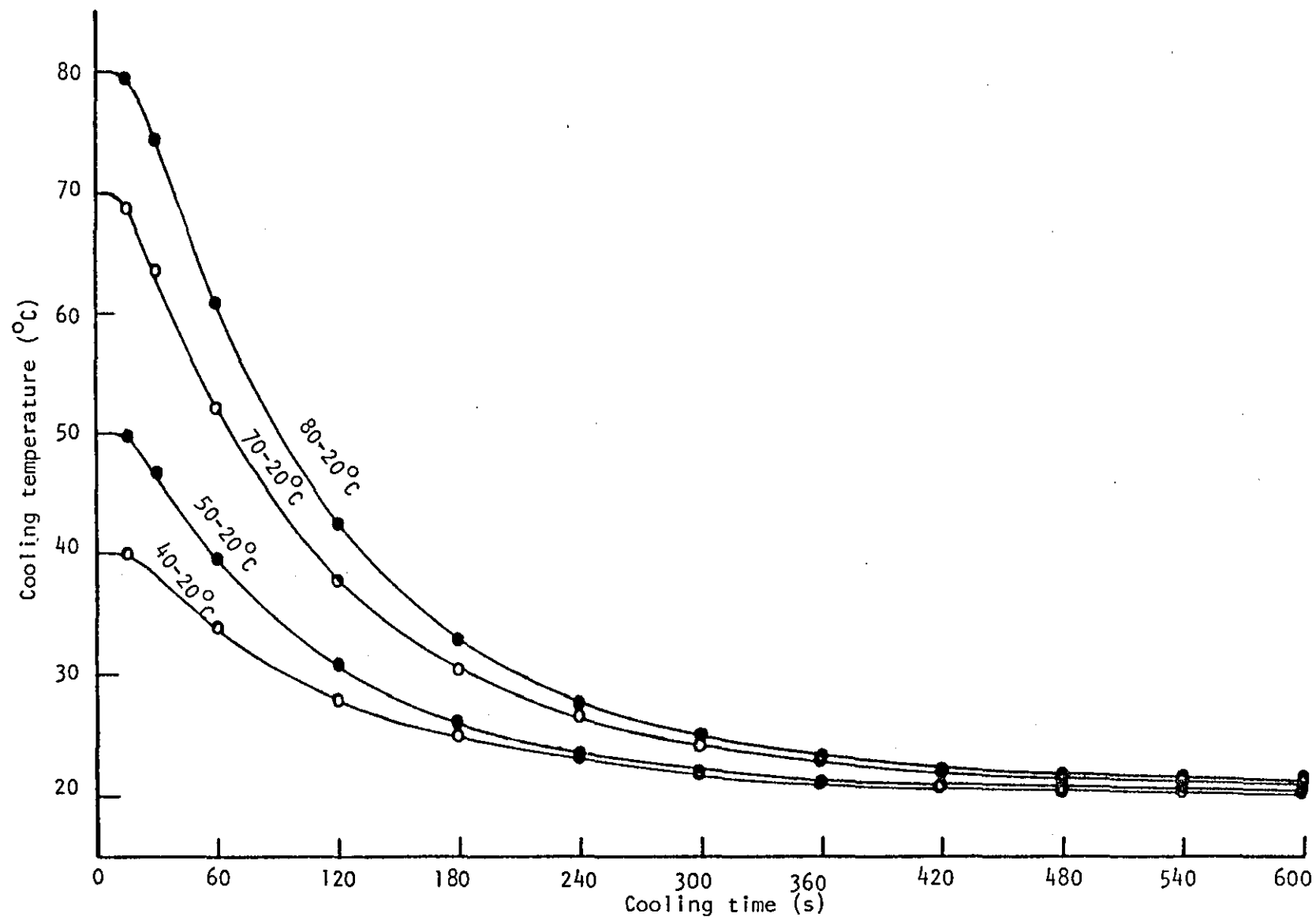FIGURE 5.68: Effect of agitation on the time-temperature relationship in the centre of Record potato cylinders during heating in a 40 ⁰C water bath (means of three repeats)

can be reached by increasing the agitation rate of the heating medium. Figure 5.68 shows the temperature profiles at the centre of 0.015m diameter potato cylinder samples heated at 40°C in a well agitated tank (see materials section) and without agitation. As expected the rate of heat penetration was slightly faster with agitation than without agitation. During heating with agitation, the centre temperature of the sample reached 90% of the heating medium temperature, after 216 sec, while during heating without agitation, 258 sec elapsed.

Table 5.13 shows the thermal diffusivity of potato during heating at 40°C with agitation and without agitation calculated from Figure 5.68. α values calculated from the heating curve without agitation were lower than α values calculated from heating with agitation. This was due as expected to the surface resistance caused by the decreased heat transfer coefficient. In heating without agitation, it was expected that heat transfer coefficient at the surface of the sample is not large and a significant temperature difference between heating medium and sample surface is required to transfer heat to the sample. The heat transfer coefficients for heating without and with agitation were calculated and the values were 507 w/m^{2}K and 1600w/m^{2}K respectively (see Section 4.7).

5.6.2.4 Effect of cooling process

Because the heat transfer characteristics of the potato during immersion heating at high temperatures (above 60°C) differ from those for immersion heating at the lower temperatures (below 60°C), a cooling process was carried out to examine what effect the physical changes produced during heating had on the thermal diffusivity. Table 5.13 shows the thermal diffusivity for potato during the cooling process. The results indicated that there was a considerable effect on the thermal diffusivity at 70 and 80°C, where the gelatinisation takes place. However the α values obtained for potatoes after 60 sec cooling in all cases were the same. The results suggest that the gelatinisation of the starch has a great effect on the heat transfer during heating the potato above 60°C.

5.6.3 Specific Heat

5.6.3.1 Effect of moisture content

Samples of Record potato at four different moisture levels between 72 to 78 percent, wet basis, with four replications at each moisture level were tested to determine their specific heat. Table 5.14 shows the influence of moisture content on the specific heat of potato. As seen from the results, the specific heat of potato varied from a low value of 2.5 kJ/kg^{o}K at 72.3% moisture content to 3.3 kJ/kg^{o}K at 78.8% moisture content. Figure 5.70 shows the relationship between the average value of specific heat and moisture. Regression analysis was applied to all data in Figure 5.70 to determine the effect of moisture content on the specific heat. The regression equation for specific heat in the range 72 to 78% moisture content was:

$$Cp = 0.1303m - 6.8923 \text{ (at } 50^{o}C)$$

Where Cp is the specific heat in kJ/kg^{o}K and m is the water content expressed as percent wet basis.

The values for specific heat obtained in this investigation are in agreement with which has been found by Yamada (1970) who reported values between 2.072 to 3.647 kJ/kg^{o}K for potato in the moisture range of 22% to 83%. Also these values are quite close to the specific heat values reported by Hood (1961), and Frechett and Zahradnik (1968) for other vegetables and fruits.

5.6.3.2 Effect of temperature

Table 5.14 and Figure 5.69 show the influence of temperature on the specific heat of potato. The results show an increase in specific heat values with temperature in the range of 40 to 90oC. using regression analysis , the temperature was found to be linearly

TABLE 5.14: Specific heat of Record potato at different temperatures
and moisture contents

Condi-tions	Condi-tions	Specific Heat kJ/kg°K					Standard Deviation
		1	2	3	4	Mean	
Temperature °C	40	2.8583	2.5397	2.9039	2.6385	2.7351	0.1743
	50	-	3.1878	3.1686	3.1656	3.174	0.0121
	60	3.3206	3.1832	3.4411	3.3389	3.3210	0.106
	70	-	3.3649	3.6153	3.4654	3.4819	0.126
	80	3.9557	3.8987	3.9272	4.040	3.9554	0.061
	90	4.0164	4.0101	-	4.0197	4.0154	0.0049
% Moisture Content	78.8	2.8085	3.3432	3.7559	3.4328	3.3351	0.3933
	76.3	3.3929	3.1878	3.1686	3.1656	3.2287	0.1099
	75.4	2.7264	2.4844	2.9629	2.9889	2.7907	0.2359
	72.3	2.2202	2.4292	2.5322	2.9429	2.5311	0.3039

related to specific heat according to the following regression equation:

$$Cp = 0.02545T + 1.79285 \ (\text{at } 76\% \ m)$$

where Cp in kJ/kgK and T is temperature in °C. According to this
equation the predicted values of specific heat are within ±0.05 of
the actual values.

5.6.4 Thermal Conductivity

5.6.4.1 Effect of moisture content

The data of Table 5.15 shows the thermal conductivity of
potato with its initial moisture content. Examination of the data
in Table 5.15 indicates that the thermal conductivity of potato is
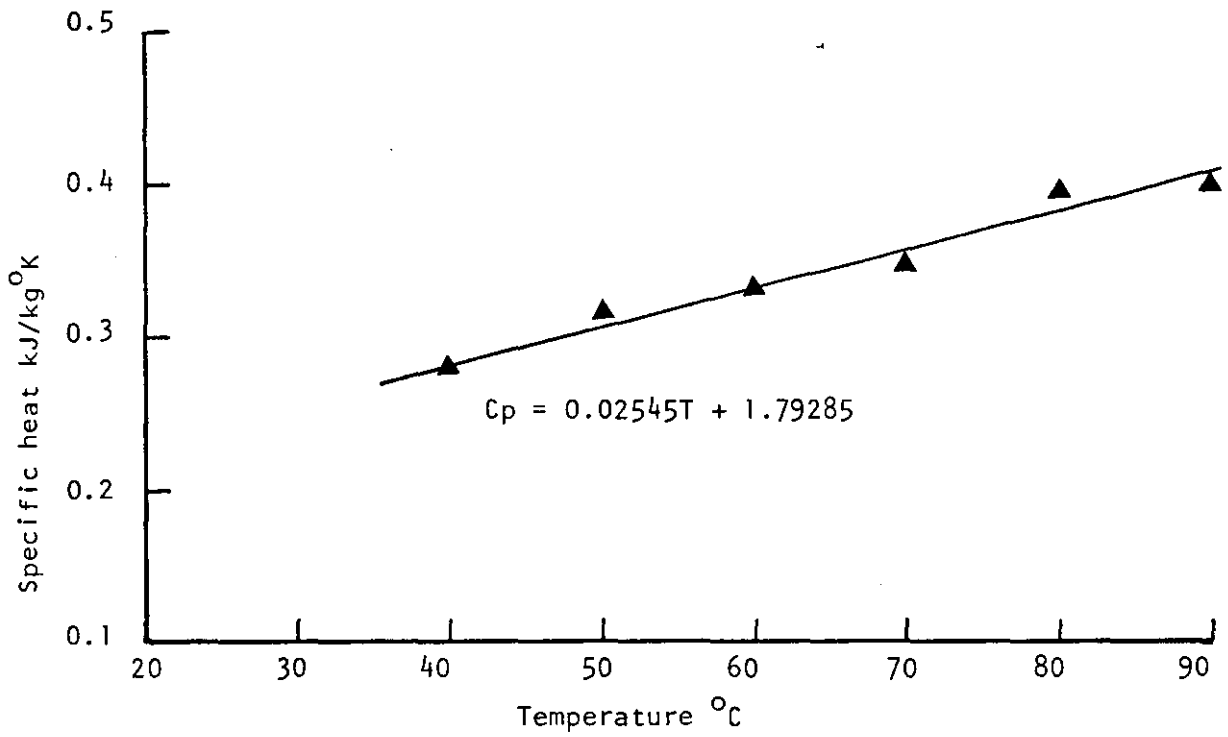
FIGURE 5.69: Relationship between mean specific heat and temperature of Record potato (76.0% moisture)
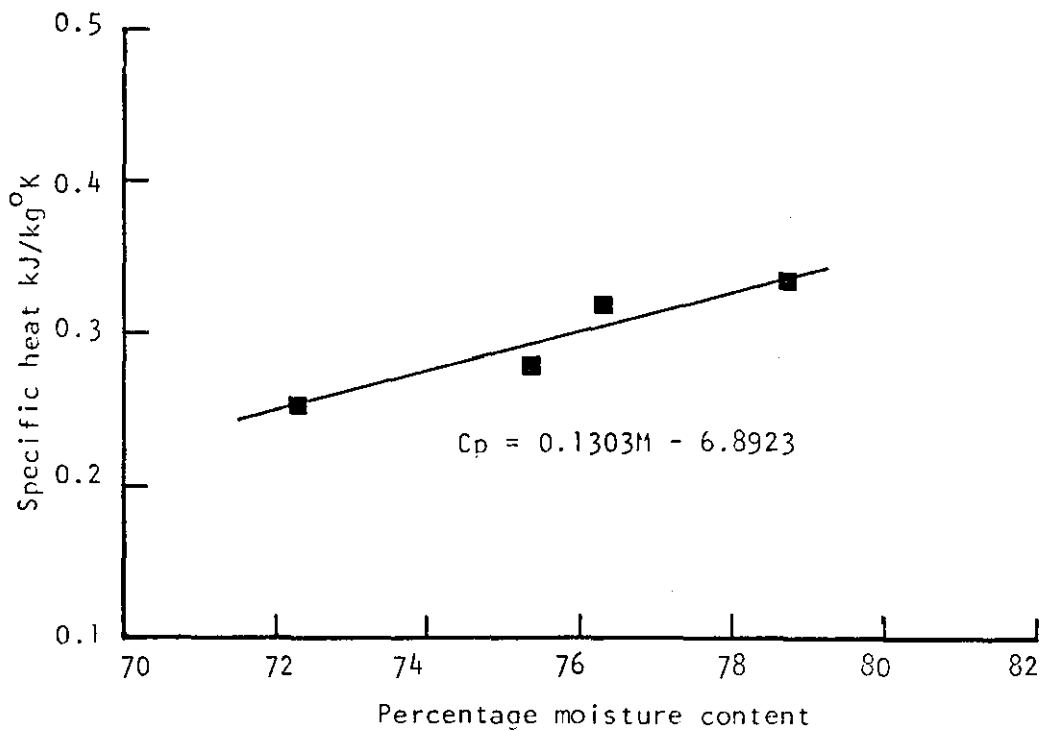
FIGURE 5.70: Relationship between mean specific heat and moisture content of Record potato at $50^{\circ}C$

TABLE 5.15: Thermal conductivity of Record potato at different temperatures and moisture contents

Conditions	Conditions	Thermal Conductivity w/m^{o}K					Standard deviation
		1	2	3	4	Mean	
Temperature ^{o}C	40	0.4284	0.3808	0.4355	0.3957	0.4101	0.0261
	50	0.4879	0.4711	0.4616	0.4538	0.4686	0.0147
	60	0.4627	0.4411	0.4782	0.4640	0.4615	0.0153
	70	-	0.4932	0.5189	0.5038	0.5053	0.0129
	80	0.5651	0.5636	0.5550	0.5580	0.5604	0.0047
	90	0.5574	0.5583	-	0.5556	0.5571	0.0014
% Moisture Content	78.8*	0.4244	0.5055	0.5615	0.5298	0.5053	0.0586
	76.3	0.4879	0.4711	0.4616	0.4538	0.4686	0.0147
	75.4	0.4038	0.3662	0.4439	0.4394	0.4133	0.0362
	72.3	0.3207	0.3418	0.3581	0.4101	0.3577	0.0382

* Percentage wet basis

affected as expected by the moisture content. The magnitude of thermal conductivity values of potato are in good agreement with those reported by Yamada (1970), and Rao et al. (1975). Yamada (1970) reported that values at 76% moisture content ranged from 0.485 w/m°K at 10°C, to 0.556 w/m°K at 75°C. Rao et al. (1975) found the thermal conductivity of white potato varied between 0.533 and 0.571 w/m°K at 82% moisture content.

Figure 5.72 shows a plot of thermal conductivity versus moisture content of potato. The thermal conductivity was found to be linearly dependent on moisture content according to the following regression equation:

$$K_o = 0.0238m - 1.3655 \text{ (at } 50\,^oC \text{)}$$

where m is the moisture content of potato in percent wet basis and K_o is the thermal conductivity in w/m°K.

5.6.4.2 Effect of temperature

The data of Table 5.15 shows that the thermal conductivity of potato is increased as expected by increasing temperature. Since there were very small differences in thermal conductivity at each heating temperature the averages of four replications for thermal conductivity were calculated and used in the statistical analysis. From a plot of thermal conductivity versus temperature (Figure 5.71), the thermal conductivity was found to be linearly dependent on temperature according to the equation:

$$K_o = 0.003012T + 0.29805 \text{ (at } 78 \text{ % m)}$$

where T is the temperature in °C.
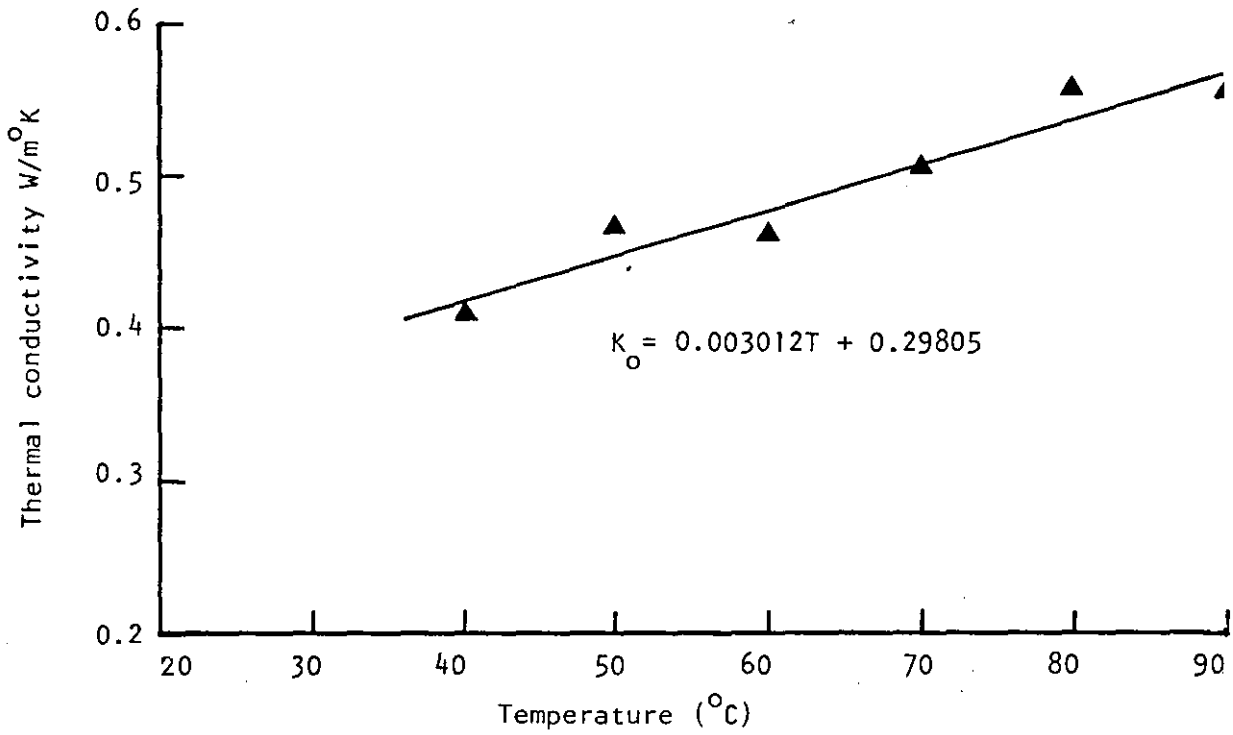
FIGURE 5.71: Relationship between thermal conductivity and
temperature of Record potato (76% moisture content)
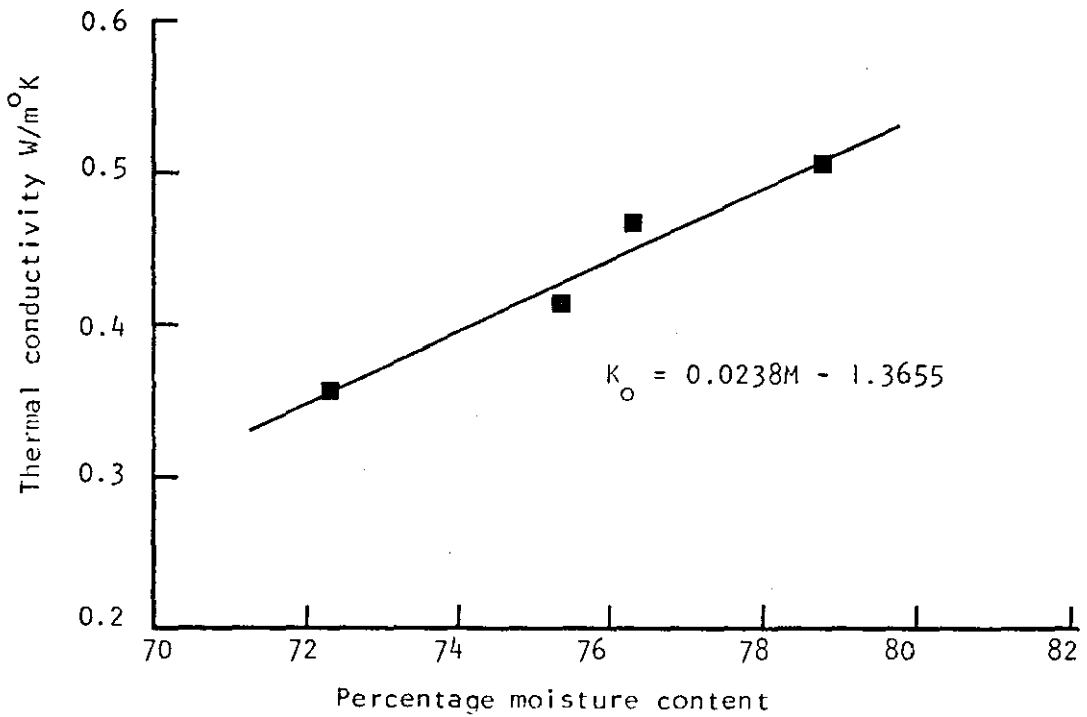
FIGURE 5.72: Relationship between thermal conductivity and
moisture content of Record potato at 50°C

6.   CONCLUSIONS

6. CONCLUSIONS

6.1 Mass Transfer during Blanching

During blanching, solute and sugar levels decreased with time. The rate of this decrease increased with the use of higher blanch temperatures. In most cases, the rate of solute and sugar losses was greater during the first 300-600 sec of blanching than in subsequent seconds which suggested that losses during these first 300 sec were due not simply to diffusion, but also to the expulsion of cell solute as turgor was lost on cell death. In the period 600-1800 sec the solute and sugar losses were found to arise solely by diffusion. In cases of both potato and carrot, the general trend for solute loss remained the same. The gelatinisation of starch in potato tissue had little influence on solute loss during blanching, but did affect water retention within the tissue.

Blanching of carrot tissue in distilled water caused a decrease in the cell solute concentration until equilibrium was reached after about 2 hours. Blanch media with concentrations less than that of the initial value of carrots (e.g. 3% sucrose) gave a similar trend but a small decrease in solute concentration. Blanch media concentrations near the initial tissue sap concentration (9%) resulted in very little change in cell sap concentration because the solution was almost isotonic to the initial cell sap concentration of the carrot. Higher concentrations (15% and 20%) resulted in an increase in cell sap concentration due to the concentration gradient being in favour of the blanching medium. In blanching in water the core behaved very similarly to the cortex.

When blanched in distilled water, cortex tissue of high initial water content showed a weight loss with blanch time compared to a weight gain exhibited by cortex of low initial water content, and the trend for the former was similar to the loss exhibited by the core.

Blanching in 15% sucrose resulted in a much greater water loss due to the high concentration gradient. With blanch time samples fluctuated between weight loss and gain when blanched in 9% sucrose.

Additional solute losses due to post-blanch cooling were minimal from both carrot and potato, due to lower temperature used in this process. However the post-blanch cooling in water resulted in some water uptake which reduced the overall weight loss. From an industrial point of view, this decrease in weight loss may be very important, because of the increase in the product weight. Also it was found that the solute and weight loss increased as sample dimension decreased. The distance that solutes and water moved to reach the surface of the tissue, had a strong influence on the weight loss into the blanch medium, and higher solute loss may be expected from smaller sized samples. The pattern of changes was similar for both carrot and potato, but the amount of weight lost from potato was lower than that lost from carrot, which was largely due to water retention within the potato tissue as a result of starch gelatinisation.

An increase in the initial water content of potato and carrot above its fresh level before blanching, resulted in a higher weight loss than that from fresh samples. Equivalent extra weight loss during blanching was obtained for potato and carrot up to 106%, but in the case of potato, prepared tissue weight of higher than 106% did not give equivalent increases in weight loss after blanching due to water uptake on starch gelatinisation. Similarly, decreasing the initial water content of the fresh samples resulted in less weight loss than the fresh sample. However prepared potato tissue weights of less than 92% gave a greater increase in weight gain than the carrot gave after blanching. These changes in tissue weight are more likely to be influenced by the initial cell volume, cell wall elasticity and the inherent cell turgor pressure.

6.2 Mechanisms of Mass Transfer During Blanching

It is apparent from the literature survey and from the results of this work that the more likely mechanisms for solute and water losses during blanching of vegetable are as follows: when vegetable tissue is blanched in water, protein in the cytoplasmic membranes is denatured, then the cytoplasmic membranes are disorganised and the cells 'die'. The cells now are no longer controlled by an active membrane nor by an osmotic system. At this stage, when turgor is released the cell wall shrinks inwards forcing cell solution (solutes and water) out of the vacuoles into the intercellular spaces and out of the tissue to the blanch medium. The amount of this loss will be governed largely by the initial cell volume, inherent cell turgor pressure and the elasticity of the cell walls. However when starch granules are present inside the cells, as in the potato tissue, they are such large molecules that they cannot pass through the cellulose wall unless the cell walls are ruptured. During blanching in water the starch granules swell, become gelatinized and retain water, and if the blanching process continues, the starch may start to imbibe water from the blanch medium. After the death of the cell, the continued immersion in the blanch medium allows solutes to diffuse out freely and the process will be controlled solely by diffusion.

6.3 Apparent Diffusion Coefficients for Solutes and Sugar

A mass transfer model (i.e. the numerical solution for the unsteady state diffusion equation for diffusion from slabs and cylinders) based upon diffusion as the main rate controlling step, was successfully used to describe and predict the loss of sugar from potato and solutes from carrot tissue during blanching. In general, D_a values were of the same order of magnitude as those reported for diffusive solids loss from other foodstuffs under various conditions. The values were: 3.07×10^{-10} to $7.64 \times 10^{-10} m^2 s^{-1}$ for solute loss from carrot, 4.25×10^{-10} to $7.75 \times 10^{-10} m^2 s^{-1}$ for

solute loss from potato and 3.71×10^{-10} to 16.32×10^{-10} m^{2}s^{-1} for reducing sugar loss from potato. Apparent diffusivities were found in all cases to be dependent on temperature and concentration of the blanch medium, and independent of tissue dimension and blanch time.

For solute loss from carrot, D_a was found to depend on temperature in the range 60-90°C with an E_a of 28.2 kJ mol^{-1}. D_a values were independent of cylinder diameter between 0.005 and 0.007m, during the time when solute loss occurred only by diffusion, the D_a values being 5.04×10^{-10}, 5.00×10^{-10} and 4.83×10^{-10} m^{2}s^{-1} for the 0.005, 0.006 and 0.007m diameter cylinders respectively. For Chantenay carrots, D_a appeared to increase in blanch media concentrations that were higher than the initial carrot cell sap concentration, the D_a being four times larger in 15% sucrose (19.1×10^{-10} m^{2}s^{-1}) than in 3% sucrose solution (5.23×10^{-10} m^{2}s^{-1}) at the same temperature and time. However it was suggested that the results were atypical, as repeated blanch tests with nameless carrots in 15 and 20% sucrose gave D_a values of 6.61×10^{-10} and 9.09×10^{-10} m^{2}s^{-1} respectively.

The mean D_a for losses in 3% sucrose solution was 5.23×10^{-10}m^{2}s^{-1}, which was the same as that in water 5.08×10^{-10}m^{2}s^{-1}. This suggested that solute contents in the blanch water up to 3% do not significantly affect diffusive solids loss under the conditions studied. These D_a values compare well with a reference D_a for 0.38% sucrose in water at 25°C of 5.21×10^{-10} m^{2}s^{-1} (Weast, 1977). For the Nameless carrot core, D_a was found to be 5.30×10^{-10} m^{2}s^{-1}, being slightly less than the Nameless carrot cortex, which had a D_a of 6.40×10^{-10}m^{2}s^{-1}, possibly due to an initially lower cell sap concentration and the small structural differences between the tissues.

The mean D_a values calculated for solute loss from Chantenay carrot cortex cylinders blanched in water at 70°C for two different sets of experiments were 4.13×10^{-10} and 5.08×10^{-10} m^{2}s^{-1}.

The difference between these results would be expected from the variation in initial cell sap concentration shown in Appendix V. Post-blanch cooling was found to have little influence on the D_a value for solute loss from carrot cortex, with the mean D_a values being 0.71×10^{-10} m^{2}s^{-1} higher than the actual value of 4.42×10^{-10} m^{2}s^{-1} for D_a without cooling.

The diffusivity of solute loss in potato blanching was also calculated, and it was found to increase with temperature between 70 and 90°C, following the Arrhenius equation with 41.6 kJ mol^{-1} activation energy. The mean D_a values were 4.25×10^{-10}, 7.75×10^{-10} and 11.5×10^{-10}m^{2}s^{-1} at 70, 80 and 90°C respectively. The mean D_a value for solute loss at 60°C (8.25×10^{-10} m^{2}s^{-1}) was higher than D_a values at 70, 80 and 90°C, suggesting that an enzymic reaction might be initiated at this temperature, causing internal generation of sugar from starch and thus influencing the D_a values.

D_a values were also found to be influenced by dimension, but only during the first 300 sec blanching, thereafter the D_a values were similar with mean D_a values of 4.94×10^{-10}, 4.89×10^{-10} and 5.13×10^{-10} m^{2}s^{-1} for the 0.012, 0.014 and 0.018m cubes respectively. This indicated that the D_a is independent of dimension (as with carrot) during the time when solute loss occurs mainly by diffusion and would be expected. Blanching of potato cubes in a **water** having 1:2.5, 1:5, and 1:20 ratios of sample to water, was found to have no significant effect on the diffusivity of solute loss, with mean D_a values being 7.10×10^{-10}, 6.73×10^{-10} and 6.60×10^{-10} m^{2}s^{-1} for the three ratios respectively. In these three cases, the blanch medium solute concentration was found to be very small (0.001-0.004 g/ml) and was considered to be negligible.

Again the D_a value for solute loss during the post-blanch cooling was very small (0.0425×10^{-10} m^{2}s^{-1}), indicating no

significant solute loss occurring during such process, due to lower temperature. The expulsive losses during the first 300 sec from carrot and potato were reflected in some of the D_a values calculated for 120 and 300 sec blanching, which tended to be lower as might be expected if whole cell solution was being lost during loss of turgor.

The experimental results for the loss of reducing sugar, total sugar and sucrose under laboratory blanching conditions were also interpreted in terms of a diffusive mass transfer model. The apparent diffusion coefficients calculated for sugar loss from potato during blanching showed a quantitative agreement with several previous reports in the literature on similar systems.

The main factors affecting the diffusion coefficients (D_a) of sugars from potato were temperature and diffusing substance. The mean D_a values for reducing sugar loss from potato were increased from 3.71×10^{-10} m^2s^{-1} at 50^oC to 16.32×10^{-10} m^2s^{-1} at 80^oC, demonstrating that the mass transfer of sugar is more rapid at higher temperatures. Diffusion coefficients for sucrose and total sugar showed the same pattern as the reducing sugar and increased with increasing blanch temperature. The activation energies related to reducing and total sugar diffusion in the range of $50-80^oC$ were 27.6 and 31.4 kJ mol^{-1} respectively. D_a values for reducing sugars were higher than those for total sugars and sucrose as expected from their molecular weights. All D_a values for sugar loss from potato were uniformly larger than the associated total solute D_a values, because of the lower molecular weights of the sugars indicating that the soluble protein and soluble starch fractions of the total solutes are influencing the diffusion of total solutes.

Using apparent diffusion coefficients calculated from controlled laboratory experiments, the predicted loss of reducing sugars in factory scale blanching process was 89% of the observed loss. Predicted total sugar loss was 84% of the observed value. It was concluded that the laboratory data could be usefully used to predict real losses

under a variety of blanching conditions. The agreement of the D_a
values obtained may be regarded as reasonable considering the
very large errors inherent in this industrial study, because it
was only possible to take a very small number of samples on one
occasion.

6.4 Significance of D_a Value Determination

The formal numerical solutions for unsteady state diffusion
mass transfer were recalculated in the relevant small cell solute
concentration and were given in tabular form for the shapes of slab
of infinite extent, sphere and cylinder of infinite length. In
design, if the D_a value is known, then $\frac{D_a t}{a^2}$ can be evaluated and
$E = \frac{\bar{C} - C_o}{C_1 - C_o}$ may be found from the graphs constructed from the above
tables, results will allow the prediction of mean solute concentra-
tion, and hence the overall loss incurred after a given blanch or
wash treatment in the temperature range 60-90°C. Due to the
inherent variability of plant material this will give only an
approximate value of $(\bar{C})$.

6.5 Thermal Diffusion

The thermal diffusivity (α) of Record potato was calculated
from the experimental time-temperature curves, using the method of
unsteady state heat conduction in cylinders. At 40°C α was
1.28×10^{-7} m^{2}s^{-1}. It increased with temperature gradually to
reach a maximum mean value of 1.34×10^{-7} m^{2}s^{-1} at 70°C. Above
70°C, α decreased, reaching a mean value of 1.32×10^{-7} m^{2}s^{-1} at 90°C.

It is suggested that the increase in α at about 70°C was due
to the gelatinization of potato starch, and the decrease in α
between 70 and 90°C is probably due to the weakening and separation
of the cells as the swelling starch distends the cells.

As expected the thermal diffusivity, was independent of sample diameter between 0.015 and 0.027m, except when the temperature gradient between sample and the heating medium had become less than 4°C. α values calculated from the heating curve without agitation (1.22×10^{-7} m^2s^{-1}) were 0.09×10^{-7} m^2s^{-1} lower than α values calculated from heating with agitation (1.31×10^{-7} m^2s^{-1}). This was due as expected to the smaller heat transfer coefficient of 507 W/m^2 $^\circ$K compared with 1600W/m^2 $^\circ$K during heating with agitation.

Calorimetry and the thermal diffusing method were successfully used for the simultaneous determination of specific heat (Cp) and thermal conductivity (K_o) of Record potato. The temperature and moisture content were correlated with specific heat and thermal conductivity. As expected, specific heat and thermal conductivity increased with moisture contents (m) and were linearly proportional to moisture, as given by the following regression equations:

$$Cp = 0.1303m - 6.8923$$

$$K_o = 0.0238m - 1.3655$$

At 76% moisture content, the specific heat of potato ranged from 2.7351 kJ/kg$^\circ$K at 40°C to 4.0154 kJ/kg$^\circ$K at 90°C, while thermal conductivity ranged from 0.4101 W/m$^\circ$K to 0.5571 W/m$^\circ$K at 40-90°C. In terms of prediction equations, a least squares regression analysis for temperature (T) resulted in the following equations:

$$Cp = 0.02545T + 1.79285$$

$$K_o = 0.003012T + 0.29805$$

Results of this study indicate that the heat transfer process involved in water blanching of potato is quite rapid relative to the mass transfer process involved.

7. SUGGESTIONS FOR FURTHER WORK

7. SUGGESTIONS FOR FURTHER WORK

1. The diffusion model used for predicting diffusivity requires
   further testing to determine if it is applicable to other
   sizes of potato and carrot tissue, particularly whole carrot
   and whole potato, and to other types of vegetables.

2. More research is required in order to determine if the diffu-
   sion model for leaching can be used to correlate and predict
   the losses of other water-soluble constituents, such as vita-
   mins, minerals and amino acids, from potato and carrot in hot
   water blanching.

3. The experimental conditions could be extended by altering the
   agitation rate, to take into account different surface resis-
   tances.

4. The transient temperature distribution in carrot tissue of
   different sizes under various heating conditions could be deter-
   mined and the thermal diffusivity calculated from the experi-
   mental data.

5. A more detailed study of the relation between the starch content
   and gelatinisation process in potato tissues and the losses of
   solutes during water blanching could be carried out.

APPENDICES

APPENDICES

APPENDIX I: Computer programme equating $\tilde{t}$ $[= \frac{D_{at}}{a^2}]$ for various values of E $[= \frac{C - C_o}{C_1 - C_o}]$ for slab of infinite extent, sphere and cylinder of infinite length

```
100 OPEN 1,4,1
200 OPEN 2,4,2
250 CMD 1
300 PRINT"     .","  SLAB","  SPHERE","CYLINDER"
400 PRINT"DT/X2","  E  ","    E  ","   E  "
450 PRINT#2,"9.999","9.9999","9.9999","9.9999"
470 FOR A=.002 TO .008 STEP .002
475 GOTO 600
500 FOR A=.01 TO .61 STEP .01
600 D=0
700 FOR N=1 TO 21 STEP 2
800 B=EXP((-A*(3.14159/2)↑2)*N↑2)
900 C=B/N↑2
1000 D=D+C
1100 NEXT N
1200 E=8*D/(3.14159↑2)
1300 X1$=STR$(.001*INT(A*1000))
1400 X2$=STR$(.0001*INT(E*10000))
1500 D=0
1600 FOR N=1 TO 10 STEP 1
1700 B=EXP((-A*(3.14159↑2)*N↑2))
1800 C=B/N↑2
1900 D=D+C
2000 NEXT N
2100 E=6*D/(3.14159↑2)
2200 X3$=STR$(.001*INT(A*1000))
2300 X4$=STR$(.0001*INT(E*10000))
2350 E=0
2400 FOR I=1 TO 10
2500 READ Z(I)
2600 Z(I)=Z(I)*Z(I)
2900 E=E+EXP(-A*(Z(I)))/(Z(I))
2910 NEXT I
3000 E=E*4
3200 X5$=STR$(.001*INT(A*1000))
3300 X6$=STR$(.0001*INT(E*10000))
3525 PRINT#1,A,X2$,X4$,X6$
3550 RESTORE
4600 NEXT A
4900 DATA 2.4048,5.5201,8.654,11.792
4910 DATA 14.931
5000 DATA 18.071,21.212,24.352,27.493
5010 DATA 30.635
5015 IF A<0.6 GOTO 500
5500 PRINT#4
6000 CLOSE 4
6010 STOP
READY.
```

APPENDIX II: Thickness Measurement of Record Potato slices

Sample Position	Crisp Thickness (m)													Average	Average
	1	2	3	4	5	6	7	8	9	10	11	12	13		
A	0.0012	0.0015	0.0015	0.0014	0.0015	0.0014	0.0015	0.0015	0.0014	0.0014	0.0016	0.0015	0.0015	0.0015	
B	0.0014	0.0014	0.0015	0.0015	0.0015	0.0012	0.0014	0.0014	0.0015	0.0017	0.0015	0.0013	0.0015	0.0014	0.00147
C	0.0015	0.0015	0.0014	0.0015	0.0015	0.0014	0.0015	0.0014	0.0014	0.0016	0.0015	0.0013	0.0014	0.0015	

APPENDIX III

BLANK RUN WITHOUT POTATO FOR DETERMINATION OF K_f (CORRECTION FACTOR) IN SPECIFIC HEAT MEASUREMENT

Time (mins)	Temperature (^oC)	Correction factor k_f (^oC)	Temperature (^oC)	Correction factor k_f (^oC)
0	51.6	0.0	80.1	0.0
5	51.5	0.1	80.0	0.1
10	51.4	0.2	79.9	0.2
15	51.3	0.3	79.8	0.3
20	51.3	0.3	79.7	0.4
25	51.2	0.4	79.6	0.5
30	51.2	0.4	79.6	0.5
35	51.1	0.5	79.6	0.5
40	51.0	0.6	79.5	0.6
50	50.9	0.7	79.3	0.8
60	50.8	0.8	79.3	0.8

APPENDIX IV

SPECIFIC HEAT OF WATER

(After Perry and Chilton, 1973)

Temperature (°C)	Specific Heat of water Cal/g. °C	Specific Heat of water kg/kg °K
20	-	-
30	0.99866	4.18119
40	0.99869	4.18132
50	0.99919	4.18341
60	1.00007	4.18709
70	1.00131	4.19228
80	1.00294	4.19911
90	1.00502	4.20782

APPENDIX V

CELL SAP CONCENTRATION (PERCENTAGE REFRACTOMETRIC SOLIDS, AS SUCROSE) OF CHANTENAY CARROT CORTEX CYLINDERS CUT FROM EIGHT DIFFERENT CARROTS

Cylinders cut from the given carrot, at the same radius	Cell sap concentration (as % sucrose w/w) in cylinders of carrot cortex cut from the given carrot							
	A	B	C	D	E	F	G	H
1	7.8	9.6	10.1	10.1	8.5	9.0	9.2	8.3
2	7.9	10.1	10.4	10.1	8.4	9.0	9.5	8.0
3	8.3	10.2	-	10.2	8.3	9.1	-	8.0
4	7.8	10.1	-	-	-	9.6	-	8.0
5	-	10.1	-	-	-	-	-	-
Means	8.0	10.0	10.2	10.1	8.4	9.2	9.4	8.1

APPENDIX VI

STATISTICAL ANALYSIS FOR THE EXPERIMENTAL AND THEORETICAL
VALUES OF $(\overline{C})$ IN INDUSTRIAL SCALE BLANCHING

1. Statistical analysis for actual and predicted values of reducing su

THIS PROGRAM REQUIRES TWO SETS OF DATA. THE FIRST OF SIZE N ,AN
SIZE M ,TO BE ENTERED IN DATA STATEMENTSSTARTING FROM LINE 500.

N= 4 M= 4

FIRST SAMPLE OF SIZE 4
 .122   .128   .141   .138
SECOND SAMPLE OF SIZE 4
 .107   .091   .128   .144

SAMPLE	MEAN	STD. DEV.	VARIANCE
1	.1323	7.6E-03	1E-04
2	.1175	.0202	4E-04

F-VALUE= 6.98174095
POP'N VARIANCE= 3E-04   STD. DEV.= .0176

STUDENT-T = .5

   * Not significant at all levels.

2. Statistical analysis for actual and predicted values of total sugar

THIS PROGRAM REQUIRES TWO SETS OF DATA, THE FIRST OF SIZE N ,AN
SIZE M ,TO BE ENTERED IN DATA STATEMENTSSTARTING FROM LINE 500.

N= 4 M= 4

FIRST SAMPLE OF SIZE 4
 .177   .199   .202   .211
SECOND SAMPLE OF SIZE 4
 .148   .166   .175   .169

SAMPLE	MEAN	STD. DEV.	VARIANCE
1	.1973	.0125	2E-04
2	.1645	.0101	1E-04

F-VALUE= 1.54259251
POP'N VARIANCE= 2E-04   STD. DEV.= .0131

STUDENT-T = .5
   * Not significant at all levels.

APPENDIX VII

DIFFUSION COEFFICIENTS (D_a) CALCULATION

The following calculation shows how to calculate the D_a for diffusing out of total sugar from potato cubes having 0.01m dimension during blanching at $70^{\circ}C$ for 1800 sec, see Figure 5.46 and theory section (2.1) for the experimental results and for the meaning of the symbols.

Blanch time = 1800s

Weight of potato sample = 10.50g

Weight of moisture in potato sample (W) = 8.13g

Initial percentage of total sugar (S_1) = 0.240%

Final percentage of total sugar in potato ($\overline{S}$) = 0.092%

Percentage of total sugar lost from potato sample
to blanch water after 1800s (S_o) = 0.161%

Weight of blanch medium (W_w) = 50g

The fraction of total sugar remaining in the potato (E) was calculated from the following equation:

$$E = \frac{\overline{C} - C_o}{C_1 - C_o}$$

where: $\overline{C}$ = total sugar concentration (weight of sugar (M_t) divided by weight of moisture) in potato cubes at time t

C_1 = total sugar concentration of unblanched potato cubes (weight of sugar at time t = 0 (M_o) divided by weight of moisture

C_o = total sugar concentration of blanch water (weight of total sugar in blanch water at time t (M_w) divided by weight of the blanch water)

In this case the percent total sugar content (S) of the total weight of potato sample was actually measured, rather than the concentration of sugar in the cell solution. So in order to calculate values of E, the values of initial (S_1) and final $(\overline{S})$ sugar content were first converted to concentration of sugar solution as follow:

$$C_1 = \frac{M_o}{W} = S_1 \times \frac{\text{Sample weight of potato}}{\text{Potato moisture content} \times 100}$$

$$= 0.240 \times \frac{10.50}{8.13 \times 100} = 0.00309$$

$$\overline{C} = \frac{M_t}{W} = \overline{S} \times \frac{\text{Sample weight of potato}}{\text{Potato moisture content} \times 100}$$

$$= 0.092 \times \frac{10.50}{8.13 \times 100} = 0.00119$$

$$C_o = \frac{M_w}{W_w} = 0.161 \times \frac{10.50}{50 \times 100} = 0.0003381$$

As the total sugar concentration in blanch water may vary from say C_{ol} initially to C_{ot} at the end of the blanch time, a mean concentration was estimated from:

$$C_o = \frac{C_{ol} + C_{ot}}{2}$$

$$C_o = \frac{0.0003381}{2} = 0.00017$$

$$\therefore \quad E = \frac{0.00119 - 0.00017}{0.00309 - 0.00017} = \frac{0.00102}{0.00292}$$

$$E = 0.349315$$

In order to get E for diffusion from two parallel faces (i.e. diffusion from slab)

$$E = \sqrt[3]{0.349315}$$

$$E = 0.7043$$

From the E value, the corresponding value of $\tilde{t} = \dfrac{D_{at}}{a^2}$ was obtained from the relevant chart (see Figures 2.1, 2.2 and 2.3)

$$\therefore \quad \tilde{t} = \frac{D_{at}}{a^2} = 0.066$$

Knowing t (blanch time) and a (half thickness of the slab) the apparent diffusion coefficient was then calculated.

$$D_a = \frac{0.066 \times (0.005)^2}{60 \times 30} = 9.2 \times 10^{-10} \ m^2 s^{-1}$$

APPENDIX VIII

PHOTOGRAPHIC REPRESENTATION OF VARIOUS OPERATIONS AND SAMPLING

POINTS IN POTATO CRISPS PRODUCTION (COMMERCIAL SCALE)

(See Figure 4.2)

FIGURE 1: Potato emerging from dry cleaning operation

FIGURE 2: Potato emerging from the peeler
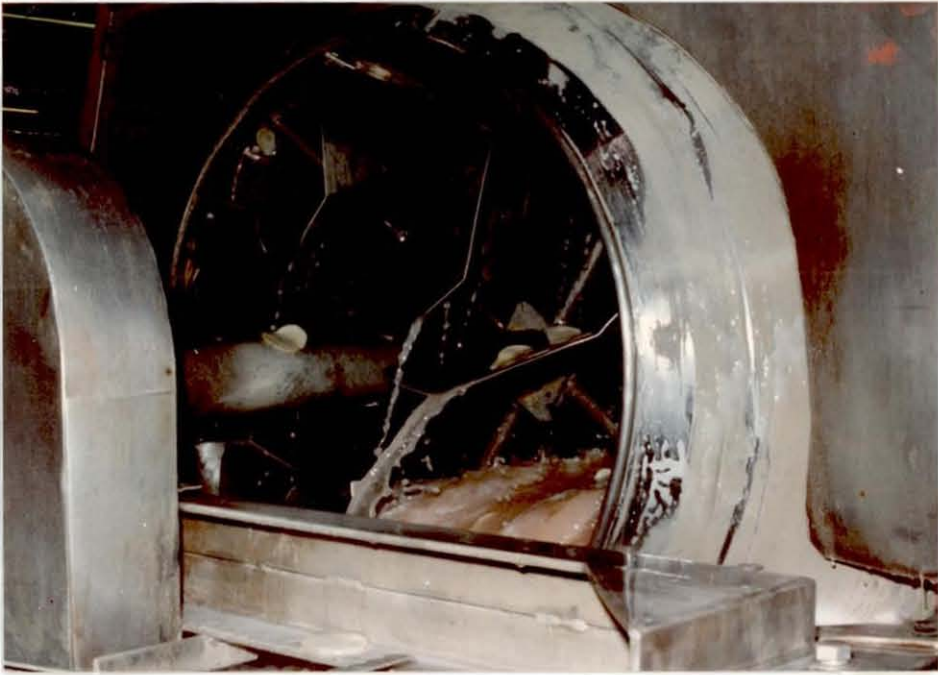
FIGURE 3: Potato slices in Blanch 1

FIGURE 4: Potato slices emerging from Blanch 1

FIGURE 5: Potato slices passing through Spray 1

FIGURE 6: Potato slices emerging from Blanch 2

FIGURE 7: Potato slices passing through Spray 2

FIGURE 8: Potato crisp emerging from the fryer

APPENDIX IX

% Dry matter contents of different samples of Home Guard, Maris Bard and Record potato varieties

Sample	Dry matter content %		
	Home Guard	Maris Bard	Record
1	16.6	18.6	26.4
2	16.3	19.7	26.6
3	16.3	19.9	25.8
4	17.9	18.6	22.5
5	17.3	18.8	24.9
6	16.7	20.1	23.6
7	18.6	18.1	24.5
8	15.2	20.2	26.3
9	17.0	-	24.4
10	16.6	-	-
Mean	16.9	19.3	25.0

% Alcohol insoluble solids of Record, Home Guard and Maris Bard potatoes

Sample	Alcohol insoluble solids		
	Home Guard	Maris Bard	Record
1	10.7	15.2	13.0
2	11.4	17.4	14.5
3	-	16.0	16.0
Mean	11.1	16.2	14.5

APPENDIX X

MEASUREMENT OF DENSITY OF RECORD POTATOES

1. Method:

Potato cylinders 2.2 cm in diameter and 6.0 cm in length were accurately prepared for measurement of specific heat (see page 245, Table 5.14). At equilibrium the samples were removed from the dewar flask, placed in a covered petri dish and weighed. Density was calculated from the ratio of mass divided by the computed volume.

2. Results:

The sample numbers shown in the table correspond to those in Table 5.14 (page 245).

Density (ρ) of Record potato at different temperatures and moisture contents used in the calculation of thermal conductivity (k_0)

Condi-tions	Condi-tions	Density (ρ) g/cm^3				
		1	2	3	4	Mean
Temperature (°C)	*30	1.0755	1.0887	1.0965	1.1049	1.0900
	40	1.1281	1.1268	-	1.1275	1.1275
	50	1.1062	1.1369	1.1207	1.1027	1.1166
	60	1.1237	1.1176	1.1207	-	1.1207
	70	1.0935	1.1189	1.0957	1.1097	1.1045
	80	1.1163	1.1294	1.1040	1.0790	1.1072
	90	1.1014	1.1049	1.1079	1.0969	1.1028
% Moisture content	78.8*	1.1623	1.1632	1.1500	1.1873	1.1657
	75.4**	1.1394	1.1337	1.1524	1.1308	1.2320
	72.3**	1.111	1.0822	1.0879	1.0720	1.0883

* Diameter:2.2 cm and length 6.0 cm
** Diameter:2.1 cm and length 6.0 cm

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