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ENERGY-EFFICIENT COOKING SYSTEMS, FOOD-PREPARATION FACILITIES, AND HUMAN DIETS.

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ABSTRACT

This thesis aims at identifying the opportunities for saving energy, which are available to those working within the final link of the UK food system (i.e. at, or in relation to, the points of consumption). Substantial prospective savings exist, because relatively little attention has, as yet, been given to energy-thrift in food-preparation facilities. Within the food-service industry, cooking systems are characterised by high thermal capacities, excessive external surface temperatures and poorly-designed control systems. Catering staff, who use such appliances, are rarely trained to use energy wisely when preparing foods, and kitchens (and their associated dining facilities) tend to be designed without sufficient regard to energy-thrift. Similar problems prevail in domestic kitchens, but to a lesser extent because the cooks there usually pay (or contribute towards) the fuel bills. However, manufacturers still provide household appliances, which are unnecessarily energy-profligate. Furthermore most people have insufficient knowledge of the nutritional suitabilities and the primary-energy costs of their diets. Thus a major educational need exists, which must be satisfied if industrialised food systems are to become more energy efficient. This thesis attempts to make a contribution to this requirement, by analysing cooking systems, food-preparation facilities, kitchen operatives, and human diets from an energy-thrift perspective. Long-term savings (i.e. those achieved as a result of implementing the recommendations within a 15-year period) of approximately £10^9 p.a. (at 1987 prices) are predicted, although this could be increased substantially if Britons adopt more energy-efficient, yet nutritionally-balanced, diets.

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'All fuels must be managed prudently to ensure that food, the fuel of life, is available to nourish all humans.'

Pierotti et al, 1977

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CHAPTER ONE

DESIGNS AND THERMAL PERFORMANCES OF COOKING APPLIANCES AND THEIR ANCILLARIES

SUMMARY

Cooking appliances are notoriously wasteful of energy. The present survey and investigations outline the history and behaviours of the main forms of cooking equipment available and indicate the energy efficiencies of the various designs. Improvements regarding equipment design, cooking techniques and consumer education are suggested from an energy-thrift perspective.

GLOSSARY AND ABBREVIATIONS

ASCR	Asymmetrical silicon-controlled rectifier.
Bain-Marie	A device for maintaining the contents of a vessel for long periods at approximately 100°C.
BGC	British Gas Corporation.
CBTS	A 15 cm diameter, 1·27 cm thick, *cylindrical brass test sample*, with polished surfaces, which was used (with its flat faces horizontal) in several measurements of oven performance. A thermojunction was embedded at the centre of mass of this block to provide an indication of its temperature.
Cooking	Heating raw food to a prescribed temperature, and in a few cases maintaining it at this temperature, in order to bring about physical and chemical changes which make the food more palatable and digestible.

Cooking efficiency	The quantity of heat entering the food specimen, during the period in which it is being cooked, divided by the overall amount of heat supplied during the same period.
CSCR	Capacitor-start capacitor-run (single-phase induction motor).
Dielectric constant of a material	The ratio of the capacitance of a capacitor, at a specified alternating-current frequency, with the material as the dielectric between the plates to that of the same capacitor with the dielectric replaced by a high vacuum.
End-use efficiency	The efficiency at the point of use: this does not take into account the delivery or transmission losses for the energy supply to the point of use.
GHz	Gigahertz = 10^9 cycles/s.
GJ	Gigajoule = 10^9 J $\approx$ 278 kWh.
Glass ceramic	A material consisting of more than 15 constituents, the principal ones being SiO_2, Al_2O_3 and Li_2O_3. After mixing at high temperatures, a glass crystalline structure is formed upon cooling. Its transmissivity at a particular wavelength is dependent upon the mixture composition.
Griddle plate	A nominally-flat cooking surface, which is used chiefly for grilling and 'dry' frying purposes.
kHz	Kilohertz = 10^3 cycles/s.
LDC	A nation that is much less developed than the UK.
Loss factor	An indication of the amount of energy a material absorbs when subjected to microwave radiation. This is the product of the material's dielectric constant and loss tangent.
Loss tangent	The tangent of the phase angle between the electromagnetic field in the material being heated (i.e. the food) and the applied field. This gives an indication of the average 'friction' effect provided by each polarised component within the food.
Microwave	Electromagnetic waves in the frequency band 0·3-300 GHz.
MJ	Megajoule = 10^6 J.
Pay-back period	The capital cost of the new system divided by

	the annual financial savings resulting from its application.
PJ	Petajoule = 10^{15} J.
Pre-heat time	The period required to reach a specified oven temperature without food in the oven.
'Radiant' ring	A commercial, but partly misleading, description of a flat spiral-element hob-heater. In practice, an appreciable part of the heat is transferred from the ring to the pan via conduction through the solid–solid contacts between them.
RCA	Radio Corporation of America.
VLED	Visible-light emitting diode.

FOOD AND COOKING TRENDS

Food is fundamental to life– man cannot exist without it. Consequently those engineers associated with its production and preparation have been (and always will be) in demand.

In prehistoric times, food was eaten in its raw state. However, by about *5000 BC*, relatively advanced humans had devised methods for preserving meat by cooking, cultivating edible plant life and producing wine and beer. Approximately two thousand years later, in Babylon, rich Sumerians commonly dined off fish, meat or poultry (roasted or boiled) supplemented by barley cakes, vegetables, fruit and beer.[1] Around *2000 BC*, in India, a major step forward in cooking techniques occurred: the traditional method of cooking dough on heated stones was superseded by the use of baking ovens. These were built, of stones or bricks, alongside open hearths and were heated by ashes from the fireplace. When the oven was sufficiently hot, its door was opened and the ashes raked out quickly. The lumps of dough were then put rapidly into the oven, its door closed, and the dough baked while the oven gradually cooled, so producing loaves of bread. The heat remaining within the oven served to dry herbs and firewood, which could be used for subsequent cooking purposes.

The *early Roman* kitchen was small and simple. It was positioned centrally in the house and smoke was permitted to exit from the vicinity via a roof-hole, which was also fitted with a means of collecting rainwater for subsequent use in cooking. As the Roman Empire grew and prospered, richer households relegated the kitchen to a less conspicuous location at the rear of the building. Usually this room contained a raised hearth, which was used mainly for grilling purposes. Also at least one clay oven per house was fitted to facilitate baking operations. Portable ovens were employed for baking small quantities of food (relatively efficiently) and sometimes were positioned in the dining room for keeping food warm. The kitchen was generously staffed by slaves: they included bakers, pastry-cooks, general cooks, stokers, storekeepers and cleaners. Consequently, Roman cuisine was varied and generally attained a high culinary standard.[2]

Unfortunately, the departure of the Roman garrisons from Britain, in the *fifth century AD*, led to a deterioration in cooking techniques. For several centuries thereafter, British cooking was performed mainly outdoors over, or in front of, an open (wood or peat fuelled) fire: most foods being cooked slowly in cauldrons or by enclosing them in the skin of an animal.

It was not until the *medieval era* that cooking regained the esteem that it had received during the Roman Occupation (approximately 1000 years earlier). The hearth was now again built indoors, the fire burned on a flat stone-slab set in the centre of the room, and a slatted louvre was built into the roof to facilitate smoke and cooking fumes escaping from the indoor environment. Usually many people were catered for simultaneously by the huge single-storey kitchens of medieval castles and abbeys. For example, a monastic kitchen (having a floor area of approximately 190 m^2) at Canterbury was equipped with several large ovens for baking, and huge fireplaces each of which was often used for roasting an entire ox.[2] On a smaller scale, the lord of the manor provided food and shelter for his serfs and retainers in rural areas, and in towns master craftsmen were responsible for similar services for their apprentices and journeymen.[3]

During the *sixteenth and seventeenth centuries*, money became more widely used for payments as it slowly replaced the traditional practice of bartering, although the provision of food as a payment for services rendered was still fundamental to the British way of life. In large Tudor kitchens, the fireplace had an associated chimney, which together formed part of a main structural wall of the building. This permitted smoke and cooking odours to be removed more effectively from the kitchen, but frequently caused the wall to reach an excessively high temperature so resulting in structural damage to the building. To overcome this an ornamental cast-iron radiation reflector was often fitted to the wall at the rear of the fire.[2] Heat losses through the wall were thereby reduced and therefore some increases in cooking efficiency were achieved.

By the *late 1700s*, the rapidly increasing population of Britain led to a rise in the demand for food. As a result of the simultaneous Industrial Revolution, major sociological changes occurred, affecting working and domestic environments, food consumption and health. Usually men, women and children worked long hours in the new industries and generally were badly treated and poorly fed—the staple diet of the working class consisted of potatoes, bread, butter and tea.[3] Domestically, most foods were still cooked on open fires which in the UK were now fuelled by coal instead of wood, partly because of the substantial deforestation that had ensued during previous centuries. Various pots and kettles were hung from adjustable hooks in the chimney, while meat was roasted on a spit in front of the fire. However, the development in the UK, during the *early 1780s*, of the cast-iron, coal-fired, kitchen range—consisting of a central fire, with an abutting oven above which 'hot-plates' were positioned for simmering and boiling purposes—permitted increases in cooking efficiencies to be achieved by those who could afford such an appliance.[4]

An eminent scientist of this period, Sir Benjamin Thompson, proposed further developments of the iron range in order to replace completely the *late-eighteenth century* kitchen fireplace, which he claimed was inefficient and extravagantly wasteful of fuel. His solution was to enclose the fire within a stove, and design the latter to achieve a higher rate of heat transfer from the fire to the food.[1] His stove was built of brick and had a flat top, into which covered pans were sunk and held in position by circular iron rings. Beneath each pan was a separate fire and a draught control to permit the cooking temperature to be regulated relatively accurately. An insulated roasting oven was heated by a separate fire, and a boiler was fitted to provide hot water for the kitchen. Unfortunately these energy-saving ideas incorporated successfully in Thompson's solid-fuel fired kitchen range were generally ignored in the UK for more than a century, i.e. until the relatively versatile, well-insulated and efficient Aga cooker was marketed in 1929.[2]

Gas cookers evolved during the *nineteenth century*, although initially they were expensive to buy and were often considered to be dangerous. In 1851, a single large gas cooker called the 'Phidomageireion' was able to roast, bake, stew, steam, fry and grill economically for groups of up to 70 people at one sitting.[2] Domestic models were introduced and became competitive during the late 1800s because: (i) they could be hired as well as purchased, and (ii) a prepayment slot-machine system was introduced for the purchase of the necessary amount of gas. The gas oven's chief advantage was that it could be employed during the summer without creating an uncomfortably hot kitchen atmosphere, unlike that associated with the solid-fuel fired kitchen range. Its competitiveness was further enhanced when, in 1923, it became the first mass-produced thermostatically controlled oven.

The idea of an electric stove was first conceived in Britain in 1885, but was then dismissed because it was alleged that 'the absence of a true flame renders it unsuitable'. Man had always been used to seeing the characteristic flames associated with fossil-fuel burning appliances. However, 8 years later, Crompton and Co. of Chelmsford marketed the first electric cooker. Its rate of acceptance domestically was impeded because: (i) most people already possessed a gas or solid-fuel fired cooker; (ii) the elements were unreliable and slow to heat up; and (iii) few homes at that time were wired for electricity. Also an electric cooker could attain a temperature high enough to burn human skin without the warning presence of a flame. Thus it was received with much scepticism.[2] Nevertheless, the technical problems were overcome, and by the *1930s* the electric cooker began to compete effectively with other types of cooking equipment. Since then, relatively clean, low thermal inertia, free-standing and built-in gas and electric cookers have almost replaced solid-fuel fired cookers in the UK.[5]

In the *Third World*, wood is still the commonest cooking fuel. However, harnessing solar energy (concentrated by means of cheap aluminium foil reflectors) for cooking at up to 250°C, has been undertaken successfully for more than 30 years:[6,7] the baking of bread being accomplished regularly in Nigeria by this method.[8] In India, a solar oven, developed by Malhotra and Ramana Rao,[9] has a claimed efficiency of 41 % indicating that solar energy (which is both plentiful and 'free') can be harnessed efficiently for basic cooking purposes. Therefore, the use of similar equipment in both underdeveloped and developed countries benefiting from relatively high annual insolations, could achieve significant energy savings. However, such initiatives are inhibited because these appliances: (i) can only be used in the daytime; (ii) usually permit merely slow-cooking operations; and (iii) are unreliable (i.e. they are ineffective during inclement weather).

During the final years of the *twentieth century* significant alterations in

(i) the ways in which food will be prepared (and the equipment for accomplishing this) and (ii) the forms in which it will be eaten, are likely. For example, research attention is being devoted to the evolvement of new varieties of vegetables that will not need to be cooked. More pre-cooked, pre-packed and frozen convenience foods are being introduced thereby facilitating the rapid preparation of meals when required.[10,11] Consequently, the rate of energy consumption in the food-processing industry will *increase*, whilst simultaneously the domestic energy demand for cooking will *decrease* (see Table 1). However, changes are being inhibited by man's inherent reluctance to alter his diet, cooking techniques and eating habits because of his financial income, traditions, culture and religion.

Comprehensive energy analyses of the processes involved in the production, preparation and cooking of *all* foods are needed (e.g. see Fig. 1). These should be considered with the 'health values' of the end-products as eaten. Although it is the accepted logic to use energy effectively in order to produce and cook foods, much waste and

TABLE 1
Predicted Trends for Cooking in Post-1975 UK Domestic Dwellings (adapted from ref. 5)

	Year				
	1975	*1990*	*2000*	*2010*	*2020*
Amount of *cooking* carried out domestically in relation to 1975 levels (%)	100	94	90	86	80
Fuel consumption per typical domestic cooker in relation to 1975 value (%)	100	75	55	50	50
Percentage of domestic premises in which there are gas cookers	56	55	50	40	40
Percentage of domestic premises in which there are electric cookers	41	45	50	60	60
Total delivered quantity of energy for domestic cooking purposes in relation to 1975 consumption levels (%)	100	93	63	53	48

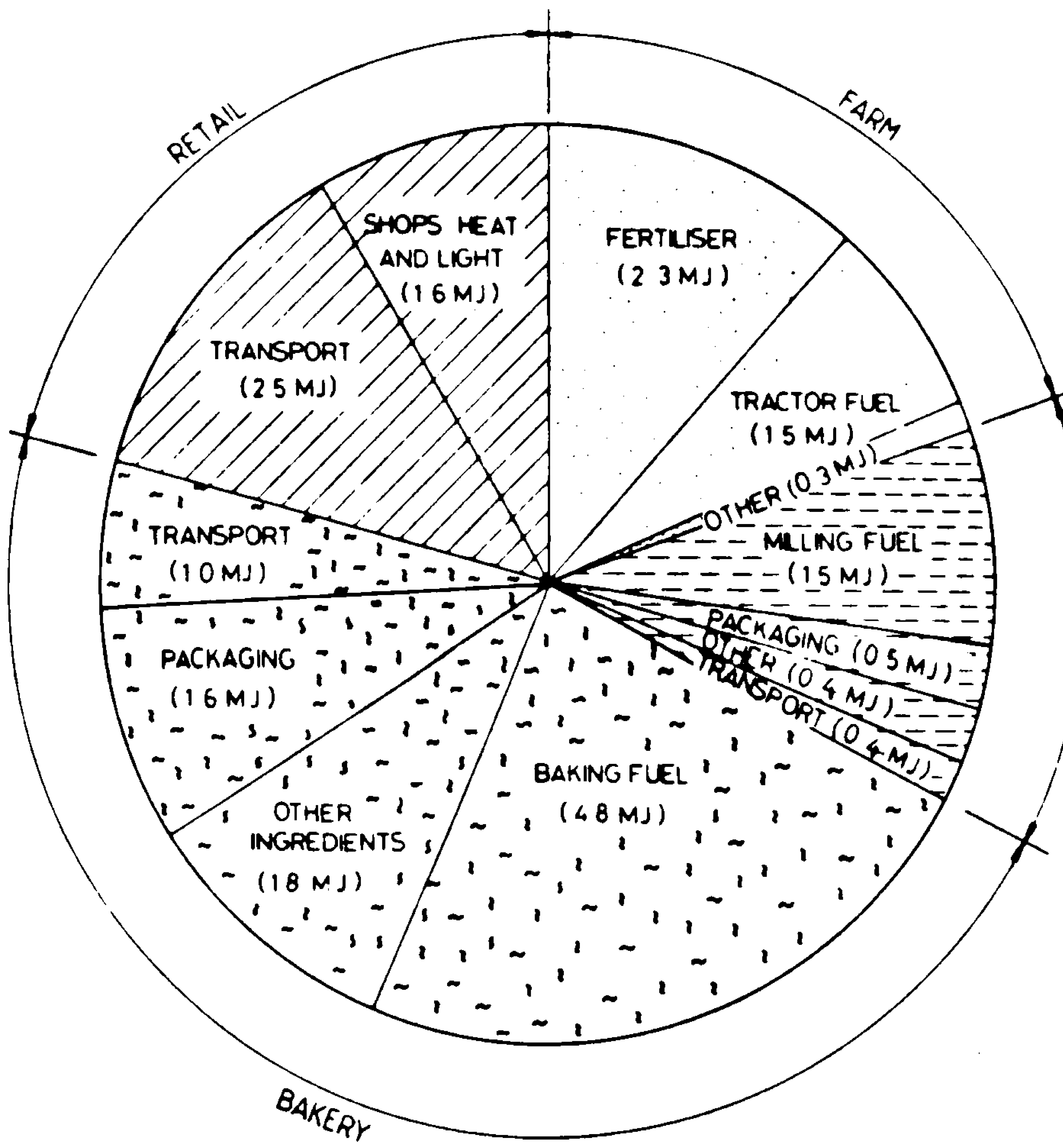

Fig. 1. The primary energy inputs required to produce one standard loaf of white bread (after ref. 12). The total primary energy consumption per loaf of bread ≃ 20 MJ.

misconception prevails. Fortunately all food is derived from the photosynthesis of vegetation (i.e. the conversion of carbon dioxide and water into carbohydrate) which is driven by 'free' solar energy. Because man is an omnivore, the most effective way for him to reduce energy expenditures on food, is to eat as low down the food chain as is feasible (i.e. to consume plant-life rather than meat)—see Tables 2, 3 and 4. However, as most people prefer to eat at least a little meat, the rearing and consumption of chickens, geese and goats in preference to beef cattle, sheep and pigs should be encouraged.

The amount of energy available in photosynthetic products is approximately $3{\cdot}1 \times 10^{21}$ J (i.e. only 0·1 % of the annual solar radiation intercepted by the Earth's surface, but approximately 10 times and 200 times greater than the world's present consumptions of energy and food,

TABLE 2
Conversion of Protein by Livestock
(after ref. 13)

Protein food produced	*Average mass (in kg) of protein feed which when processed by the respective animal produces 1 kg of protein suitable for human consumption*
Beef	21·4
Pork	8·3
Poultry	5·5
Milk	4·4
Eggs	4·3

respectively). However, the amount of energy stored in plants can be increased by good agricultural techniques (e.g. sugar cane will achieve a conversion efficiency of up to 3% if grown under optimal conditions). Therefore, plant matter should be viewed as both a source of food and hydrocarbon fuels.[18-20] Hodam and Lew[21] reported that, theoretically, if 210×10^6 people living in the USA each adopted a balanced diet which had a daily energy content of about 12·6 MJ, then approximately 147×10^6 hectares of that nation's total agricultural land (166×10^6 hectares) could be made available for energy farming. This alone could

TABLE 3
Estimated Annual Primary Energy Consumptions by UK Food Manufacturing Industries
(adapted from ref. 14)

Food manufacturing industry	*Primary energy used annually in stated industry (PJ)*
Sugar	30·6
Beer	25·9
Spirits	22·5
Dairy	15·0
Bread	11·4
Fats	10·1
Sweets	9·7
Meat	9·4
Vegetables	8·6
Biscuits	4·5
Margarine	2·1
Tobacco	1·9
Cider/wine	1·3

TABLE 4

The Ranking of Some Common Foods According to Their Primary Energy Ratios
(i.e. the primary energy required to produce the food divided by the nutritional energy gained by eating it)[12,15–17]

Raw food	*Percentage of energy contained in the stated nutrient of the food*			*Primary energy required to produce 1 kg of the stated food divided by that required to produce 1 kg of potatoes*	*Approximate amount of energy obtained by eating 1 kg of the stated food (MJ)*	*Primary energy required to produce 1 MJ of the stated food divided by that required to produce 1 MJ potatoes*
	Fat	*Carbohydrate*	*Protein*			
Potatoes	1	88	11	1·0	4	1·0
White bread	5	81	14	6·9	10	2·8
Refined sugar	0	100	0	11·6	16	2·9
Cheddar cheese	73	3	24	19·4	17	4·6
Milk	52	29	19	5·6	3	7·5
Eggs	61	0	39	13·0	6	8·7
Beef steak	69	0	31	31·3	11	11·4
Bacon	94	0	6	51·3	17	12·0

The table assumes that 1 calorie = 4·19 joules; the specific energy of fat ≃ 38 MJ/kg and the specific energy of carbohydrate ≃ 17 MJ/kg. (If protein is used as a fuel, its specific energy approximates to that of carbohydrate.) A typical adult male requires about 7 MJ to stay alive but up to 14 MJ if he is very active. However, in order to maintain good health (i.e. to satisfy minimum energy, protein, fat, carbohydrate, mineral, vitamin, roughage, water and salt needs) it is important to eat a balanced diet, but from an energy-thrift viewpoint, high consumptions of foods—found towards the bottom of a more comprehensive list than that shown above—should be discouraged. Preferably, when compiling such a list, an attempt should be made to include an allowance for the energy expended during any cooking operation which is commonly employed prior to the food being eaten—it is not accounted for in this table.

contribute in the order of $1{\cdot}2 \times 10^{19}$ J towards the world's annual primary energy requirement. Thus, in a worse fossil-fuel scarcity situation than exists at present, it may become necessary to cultivate plants and algae for just two purposes:

(i) to provide a good source of nutrients for direct human consumption; and
(ii) to convert solar energy rapidly into vegetation, which can then be processed efficiently into high-grade energy stores (e.g. ethanol, vegetable oil or methane).

In other words, a future global energy policy may be based on the premise 'if it can be grown, then ensure that it is either eaten or converted into a fuel'. This is being followed to an increasing degree in LDCs but unfortunately in some nations too many farmers are practising 'energy farming'. Consequently food production has decreased and so people find it increasingly difficult to satisfy their nutritional requirements. Because crops cultivated for their fuel values will tend to be grown in the Third World due to economic, climatic, agricultural and labour considerations, this situation may occur to an even greater extent in future, especially if developed nations decide to increase their usage of biomass fuels. Indeed, Brown[22] warns that, due to the depletion of fossil fuel reserves, 'the prices of oil may soon set the price of food'. Thus in times when energy prices are likely to increase more rapidly than food prices, it is imperative that only 'integrated biomass farms' (i.e. those that contribute towards international food *and* energy requirements simultaneously) are developed.

In the UK today, to *maintain* good health, one should not eat excessive amounts of inessential fats and preferably adhere to an optimal salt, least sugar, high fibre diet. Consumption of fruits, vegetables, poultry and fish should be increased whilst consumption of foods containing considerable proportions of saturated fat (e.g. meat), alcohol (e.g. whisky) or sugar (e.g. jam) should be reduced. These recommendations are gradually being accepted, but unfortunately the average British diet does not conform to such medical advice (e.g. see Table 5). Vast quantities of energy are still used to produce foods of little or no health benefit to man. For example, the average Briton consumes too much sugar! While this remains an ingrained eating habit, much high-grade energy is used not only to refine the sugar itself—see Table 3—but also to develop and manufacture harmless sugar substitutes to satisfy man's acquired 'sweet tooth'.

TABLE 5
The Distinctive Features of the Average British Diet in 1985[23]

Consumption of nutrients		
Adequate	*Inadequate*	*Excessive*
Protein	Starch	Saturated fat
Iodine	Fibre	Chlorine
Pantothenic acid	Polyunsaturated fat	Phosphorus
Vitamin A	Folic acid	Sodium
Vitamin B_1	Vitamin B_6	
Vitamin B_2	Vitamin D	
Nicotinic acid	Vitamin E	
Vitamin B_{12}	Iron	
Vitamin C	Magnesium	
Vitamin K	Potassium	
	Chromium	
	Copper	
	Selenium	
	Zinc	

The energy expended (in terms of research, medication and hospitalisation) to treat and cure diseases related to malnutrition, e.g. obesity in Western societies and protein deficiency in LDCs, is much greater than that needed to keep mankind healthy. Furthermore, because fossil-fuel reserves are being depleted by the rapidly increasing world population, it is advisable to use available agricultural land to produce foods of greater benefit to man's health. However, the environmental effects of employing energy-expensive synthetic fertilisers and insecticides in order to boost agricultural production must be assessed carefully. Although modern agricultural methods have produced higher crop yields per hectare recently, this trend follows the law of diminishing returns—e.g. between 1949 and 1968, agricultural production in the UK increased by 35% whilst the use of nitrogen fertilisers grew by 800%.[13]

Similarly, the overall primary energy ratio for food production has also increased rapidly—e.g. in 1900 this ratio was approximately unity, but by 1970 it had risen by nearly 800%.[24]

Thus it is important to monitor and adjust the production of food in order to prolong the life of fossil-fuel reserves as well as to ensure the health and longevity of man. In attempting to achieve these aims consideration should be given to 'energy/health' data similar to those shown in Table 4. Food prices should then be adjusted to discourage consumers from buying relatively unhealthy, low energy-content foods which are expensive (in energy terms) to produce. Initially, this could be done solely on an energy basis, e.g. if the unit energy price of potatoes was held constant, the prices of bacon, sugar, bread and Cheddar cheese would need to be increased by approximately 800%, 500%, 300% and 50%, respectively. Some re-adjustment would then be necessary according to the desirability (from the medical viewpoint) of maintaining present consumptions of each food, e.g. the price of sugar would probably be further increased to reduce the national intake to a level which is more advisable in health terms. Although not easily implemented, such a food policy would ensure that foods were sold at prices which reflect their relative energy ratios and nutritional values. This would achieve substantial energy savings and reduce consumptions of foods which are presently too popular for good health. Even if only minor measures were taken on this basis, e.g. introducing or increasing VAT for foods which are eaten to an undesirable degree, energy would then be used to produce relatively more wholesome foods at the expense of many presently-eaten energy-expensive ones. Finally, it is important to remember that most of the world's population is undernourished and eat to survive rather than live to eat. Therefore the production of expensive, attractively-packaged, convenience foods by highly energy-intensive and wasteful food-processing industries in developed nations, can only be perceived as an immoral use of energy by the majority of the Earth's population.

ENERGY USE FOR COOKING

Over 40% of the UK's national primary energy expenditure, which amounts to nearly 10^{19} J per annum, is employed for services in buildings (see Table 6). Of that used in a typical centrally-heated house, cooking accounts for about 8% (see Table 7). It has been estimated that the direct annual primary energy input into the preparation and cooking of food in both the domestic and commercial sectors was about 449 PJ in 1974-75 (see Table 8): the domestic sector accounting for approximately 280 PJ of this. These amounts have increased during the last decade because:

(i) a significant rise in the domestic and commercial use of freezers and dishwashers has occurred;

TABLE 6
Annual Primary Energy Consumptions in the UK during 1980
(adapted from ref. 25)

Sector	*Annual primary energy consumption (PJ)*	*Percentage of total*
Industrial processes	3 280	32·8
Domestic buildings	2 970	29·8
Transport	1 810	18·1
Industrial buildings	600	6·0
Offices	310	3·1
Shops and stores	240	2·4
Educational buildings	180	1·8
Hotels and catering premises	180	1·8
Hospitals	170	1·7
Others	250	2·5
Total	9 990	100·0

TABLE 7
Comparison Between the Various Energy-Consuming Activities in a Typical Centrally Heated UK Home[26,27]
(Such dwellings constituted, in 1980, only about one-third of the total housing stock. In non-centrally heated homes, the distribution is slightly different because less energy is employed for space heating purposes, and a greater proportion (about 10%) is devoted to cooking.)

Application	*Percentage of total annual energy demand*
Space heating	71
Water heating	18
Cooking	8
TV, lighting, etc.	3
Total	100

(ii) the overall annual energy expenditure in the domestic sector has risen;[29]

(iii) there have not been substantial improvements in the energy efficiency of commonly-employed cooking appliances and processes.

If due allowances for the indirect energy inputs (see Fig. 2) are made, it is alleged that more than twice as much energy is expended by the consumer in storing and cooking food as that which is gained nutritionally by eating it.[28]

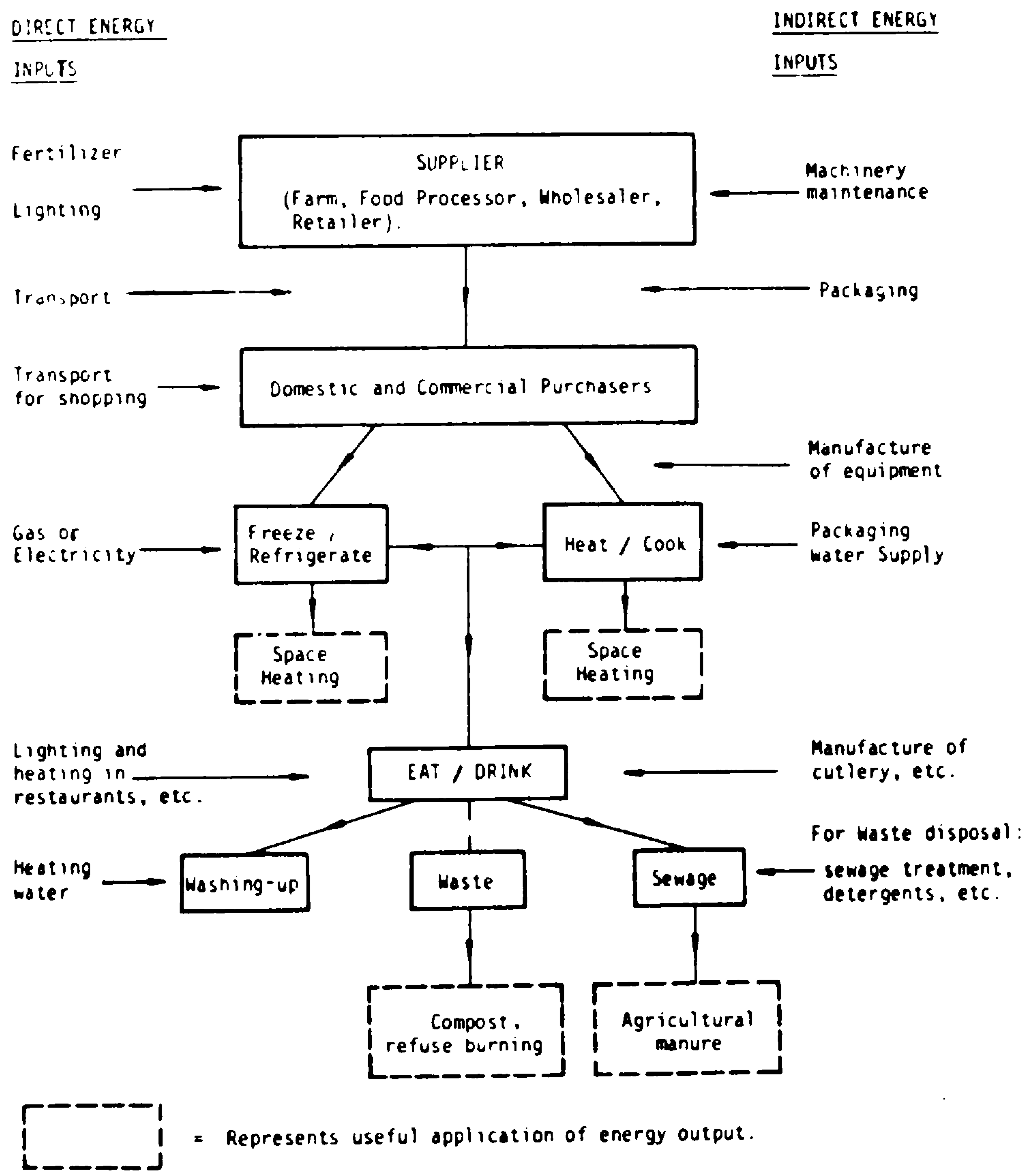

Fig. 2. Summary of the principal direct and indirect energy inputs involved in the domestic and commercial preparation and storage of food (after ref. 28).

TABLE 8
Direct Primary Energy Inputs, During the Financial Year 1974-75, for the Preparation and Cooking of Food and Associated Activities in the UK
(adapted from ref. 28)

Energy application	*Amount (PJ)*	*Percentage of total*
Domestic { electric cookers	108	24
Domestic { gas cooking	87	19
Commercial { electric cooking	12	3
Commercial { gas cooking	43	10
Domestic kettles	46	10
Electric refrigeration	67	15
Freezers	32	7
Domestic dishwashers	4	1
Transport involved in shopping for food	50	11
Total	449	100

FUEL CONSUMPTIONS OF COOKERS

The cooker is one of the least energy efficient and most expensive to 'run' of all domestic appliances (see Tables 9 and 10). Unfortunately, the British cooking-equipment industry tends to be traditional, and therefore improvements concerned with reducing energy consumption have not been implemented rapidly if at all. Furthermore, because the unit prices of fuels prior to November 1973 were so low, the energy effectiveness of cooking attracted little attention. Developments in cooker design have been concerned mainly with reducing cooking periods, making the appliances easier to use and clean, improving their appearances and raising the aesthetic quality of the cooked food.

In the commercial sector, the attributes usually required of cooking systems, in decreasing order of precedence, are: reliability, labour saving, speed of operation, ready availability of spare parts and competent servicing staff, safety, low running costs (i.e. high energy efficiency) and low capital cost.[35] Although the energy effectiveness of equipment influences many purchasing decisions, much apathy still exists due to the relative cheapness of the principal cooking fuel (i.e. natural gas) compared with electricity: commercial unit-electricity prices are more than five times greater than commercial unit-gas prices.

TABLE 9
Annual End-Use *Electricity* Consumptions of Some Typical Appliances in a Representative House in the UK
(adapted from ref. 30)

Electrical domestic appliance	*Annual energy consumption (GJ)*	*Annual expenditure (£)*[a]
Immersion heater	14·5	201·9
Cooker	4·9	67·8
Freezer	3·3	45·7
Dishwasher	2·6	36·5
Washing machine (twin-tub)	1·7	23·4
Refrigerator	1·7	22·8
Colour TV	0·8	10·8

[a] Assumes a unit-electricity charge of 5 pence/kWh

TABLE 10
Typical Efficiencies for Natural-Gas or Electric Cooking Activities[11,31-34]

Operations using the appliance listed below	*End-use efficiency of the considered operation (%)*	*Overall national efficiency of the operation (%)*
Electric hob-heater	41–88	14·0–24·4[b]
Gas hob-burner	41–48	37·7–44·2[c]
Electric oven (not fan-assisted)	8–24	2·2–7·0[b]
Electric oven (fan-assisted)	~33	~9·2[b]
Gas oven (not fan-assisted)	7–9	6·4–8·3[c]
Microwave oven	35–42	9·8–11·8[b]
Electric fryer	~17	~4·7[b]
Electric griddle	~14	~4·0[b]

Where possible, ranges of values are stated in this table because of the considerable variations in appliance and utensil designs, and management effectiveness of cooks. If the equipment is under-utilised, the efficiency of the particular cooking operation may be less than the appropriate value shown in the table.

[a] The differences between the end-use and overall national efficiencies arise because in the latter, production and delivery energy costs of the fuel are considered. The overall national efficiency for a certain electrical appliance may vary, regardless of the cooking techniques practised, due to the fluctuating nature of the domestic voltage supply.

[b] Assumes a generation plus supply efficiency of 28%.

[c] Assumes a production plus supply efficiency of 92%.

At present there are about 11 million domestic gas cookers and 8 million domestic electric cookers in use in the UK. The annual primary energy consumptions for each gas and electric cooker are, on average, 9 GJ and 23 GJ, respectively.[36] In general, the annual primary energy consumptions of domestic appliances, which are used for storing and preparing foods, are far higher than those required annually for their manufacture. Thus pertinent energy savings can soon be achieved by improving the designs of cooking equipment. For cooker efficiencies to be doubled by the year 2010, as urged by Leach,[5] it is now desirable to apply energy-thrift measures to cooking processes, because:

(1) The Earth's fossil-fuel reserves are being depleted rapidly.
(2) The real (i.e. after due allowance is made for inflation) unit prices of commercially available power supplies in the UK are likely to rise for at least the next 25 years.
(3) Although the UK's primary energy consumption fell overall by 11% between 1973 and 1982, the nation's domestic energy consumption *rose* by 4% during that same period.[29]
(4) Low-energy dwellings are slowly replacing older buildings as a result of the relatively recent unit fuel price rises. Thus, the ratio of the energy used for cooking per year to the total amount consumed in the domestic sector annually is growing.
(5) Successive UK governments, the education system and the domestic appliance industry have not given a high priority to reducing domestic-cooking energy consumption.
(6) Consumer knowledge concerning energy-efficient cooking skills and cooking equipment, and the long-term effects of continuing thermal pollution, is both inadequate and insufficient. (If man continues to pollute his environment by liberating excessive amounts of waste heat, the Earth's ecosystem could eventually become unbalanced. This may lead, as a result of ignorance, to climatic changes, which may be difficult to rectify. One contribution towards reducing the probability of this problem occurring could be made by the inveterate British catering industry, which for too long has exhibited a disappointing attitude concerning the effective use of energy for food preparation.)

COOKING OPERATIONS

For most cooking processes, it is the *temperature* (and the duration at that temperature) which should be controlled, because the temperature usually has more influence upon the effectiveness of the process than the heat-supply rate. Some processes require cooking to occur at a set temperature, for a prescribed period, in order to ensure that appropriate chemical changes ensue (e.g. as-picked red-kidney beans should be immersed in boiling water for more than 10 min—otherwise they can be poisonous). Admittedly the attained temperature can be achieved by adjusting the rate of energy input appropriately, but this is normally accomplished more economically by incorporating the optimal economic level of thermal insulation into the cooking assembly. If the process can be accomplished as well at room temperature as at a higher temperature, then no thermal insulation or heating would be necessary. (For an analogous reason, the recent widespread introduction of 'cold-water' detergents for washing clothes has occurred.) There are other advantages, besides requiring less energy for preparation, of using certain foods in their raw state, e.g. vitamin degradation due to heating is avoided.

Conventional free-standing cookers permit three different types of process to be undertaken:

(1) *Heating via the hob* (85–225°C)—this usually involves warming liquids, or cooking foods in heated or boiling liquids.
(2) *'Low temperature' (< 150°C) oven processes*, in which the food is cooked slowly, usually to achieve a uniform consistency.
(3) *'High temperature' (150–300°C) toasting, baking, searing, roasting or grilling*, whereby, for example, the surface of a slice of bread is 'browned' quickly, before too much moisture is lost from its interior, thereby producing an acceptable piece of toast.

When subjected to such cooking operations characteristic changes in the food are observed. These include changes in colour, volume, mass, nutrient-content, water-content, aroma, tenderness and flavour. The correct combination of these is needed to give the desired end-product, and ideally this should be achieved in the most energy-efficient manner possible.

ELECTRICALLY HEATED HOBS

'Radiant' rings

Before the advent of the radiant ring (see Fig. 3), it was common practice to employ the less efficient, solid hot-plate, which also served as a grill.

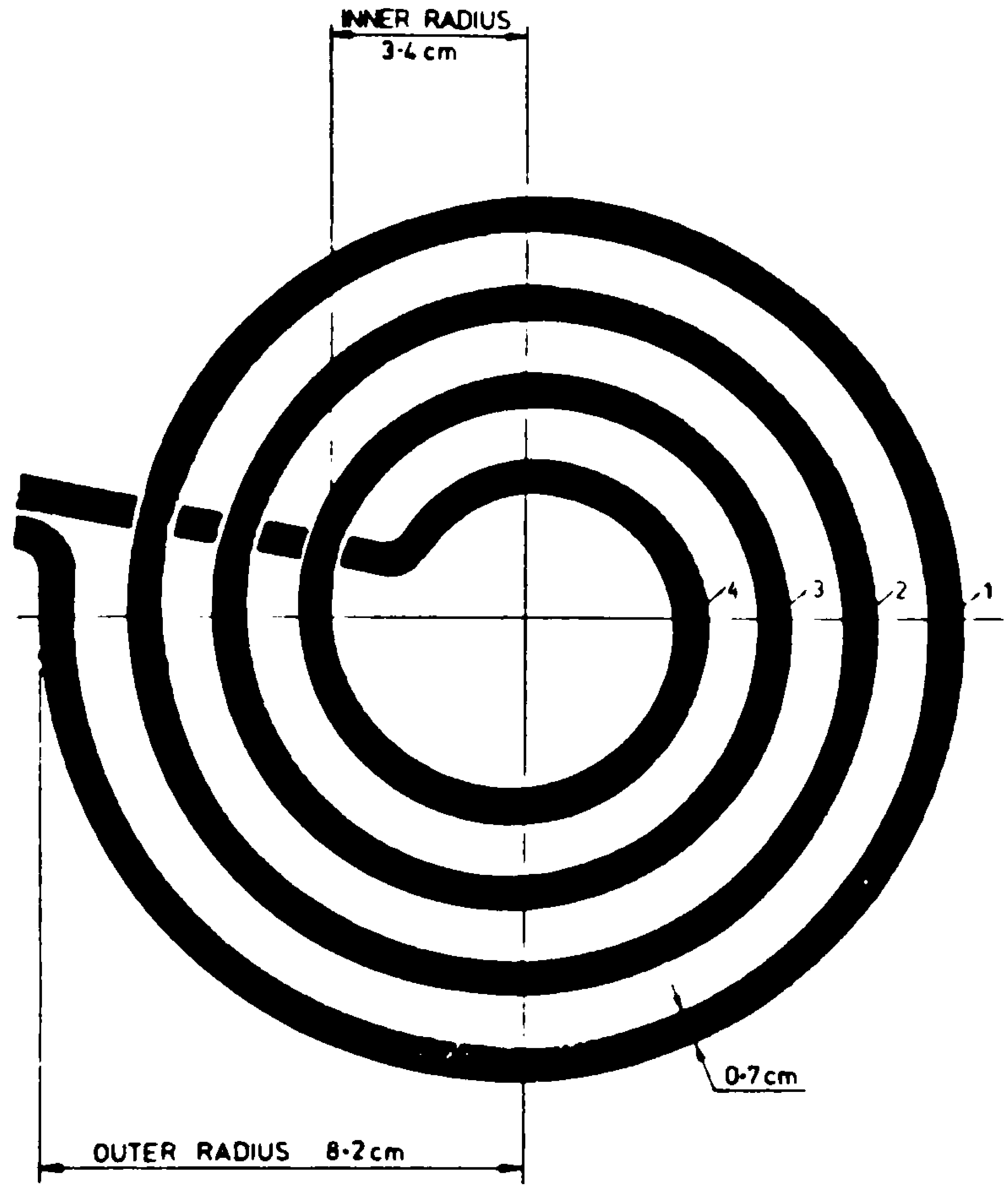

Fig. 3. Representation of a 'circular' radiant ring, indicating the coil numbering designation referred to in the subsequent text.

Nowadays, the widely used dual-circuit radiant ring permits either its central zone or the complete spiral to be energised. As such, it is capable of more precise temperature control and, being of smaller mass, heats up more rapidly than the comparable size hot-plate. The normal control mechanism (called a 'Simmerstat'), consists of a bi-metallic strip, with a heating coil wrapped around it. If the control knob is turned to a selected 'on' position, both heating elements (i.e. the hob heater as well as the coil around the bi-metallic strip) increase in temperature, so that the strip tends to bend and, in so doing, may break a contact in the electric-power circuit. The larger the angle through which the control knob is turned, the more the bi-metallic strip has to bend in order to break the contact, and consequently the higher its temperature has to become before the circuit is broken.

With a saucepan resting on the hob heater, the speed of the temperature response is slower than with no thermal load imposed. In order to achieve more rapid responses (comparable with those obtained using gas burners), an electronic control for radiant rings has been designed by the Electricity Council:[37] this results in an initial slight 'overshoot', so that the required temperature is attained more quickly—see Fig. 4.

Efficiency

There are two main reasons why the efficiencies of 'radiant' rings are not higher:

(i) Heat losses occur directly from the radiant ring to the ambient environment.
(ii) The low ratio of the true-to-nominal contact areas between the upper face of the radiant ring and the base of the imposed saucepan constricts much of the heat transfer to be conducted via the solid/solid asperity bridges between the surfaces. The ensuing pressed contact resistance can be reduced by:
    (a) making the radiant ring more flexible in order to conform better with the surface topography of the pan's base; and
    (b) increasing the contact's mechanical loading; i.e. increasing the weight of the pan.

Experimental observations

Systematic tests have been performed with various duralumin saucepans, each containing an identical volume of the same liquid, heated by either the inner portion of a dual-circuit radiant ring or the full ring. It was concluded that the diameter of the pan's base should be slightly (~ 3 cm) larger than the peripheral diameter of the used part of the radiant ring in order to maximise the heating effectiveness. This is corroborated by the independent findings presented in Table 11. (Similar tests carried out by the BGC—using pans with diameters between 19 cm and 31·5 cm—found that the efficiency of the typical gas-hob burner varied by up to 13% according to the size of the pan placed on it.[38])

The cooking efficiency of heating achieved via a radiant ring was also improved significantly by the presence of a circular, close-fitting, highly

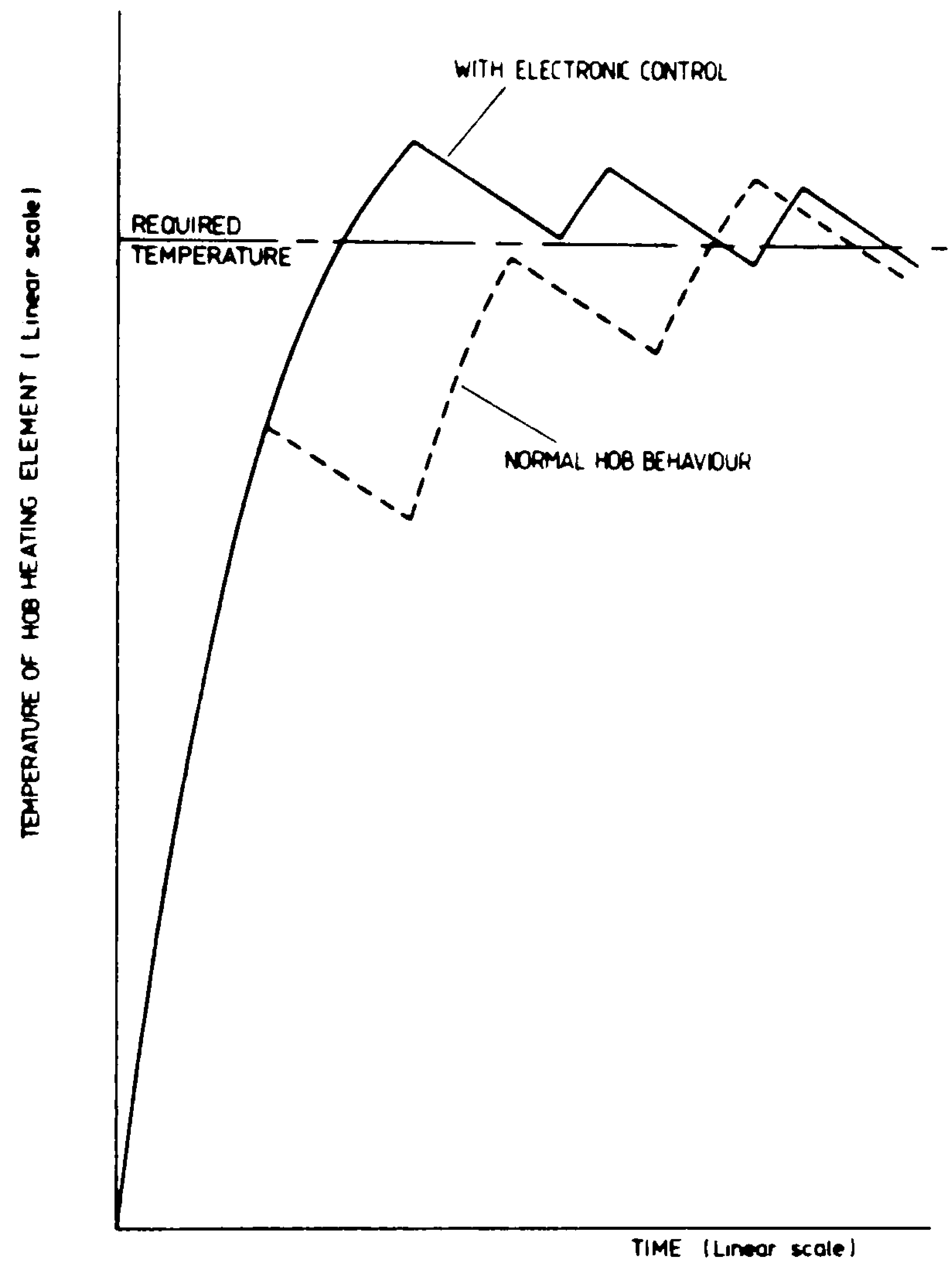

Fig. 4. The temperature versus time response of a hob-heating element controlled by either (i) an electronic system, or (ii) a conventional thermostatic system. Both 'schematic' graphs are for the hob with a large thermal load imposed.

reflective dished, drip-tray (see Fig. 5 and Table 12) beneath the heating element (see Table 13).

The temperature distribution along the surface of the radiant ring was also measured under 'no thermal load' conditions with the heating element on full power, both with and without the close-fitting dished reflector directly under the element—see Table 14. The average temperature of coil number 1—i.e. the outer-most coil of the spiral (see Fig. 3)—actually *decreased* as a result of the presence of the close-fitting, dished reflector. This was because, without the reflector present, a slight

TABLE 11
Energy Savings Achieved by a Better Choice of the Size of the Pan Base Relative to that of the Used Part of the Radiant Ring
(The diameters of the 'half' and 'full' rings were respectively 10·0 and 16·4 cm)

Substance being heated to a required temperature	*Used saucepan diameter (in cm)*		*Energy saved by using Method II instead of Method I (as a percentage of that used in Method I)*
	I *Not recommended practice (using a full ring except where stated)*	*II* *Preferred procedure using a half-ring*	
Milk	17·8[a]	17·8[a]	10
	15·0[b]	17·8[b]	16
	12·7[b]	12·7[b]	50
Vegetable soup	15·0[b]	15·0[b]	6
	15·0[b]	12·5[b]	34
	15·0 (using a half-ring)[b]	12·5[b]	38

[a] From ref. 28.
[b] From ref. 32.

amount of reflection from the drip tray ensued towards this peripheral coil, but with the reflector in position, much of this radiation was reflected by design towards the inner zones of the ring. Coils 2, 3 and 4 of the ring, all increased in temperature as a result of introducing the reflector. Such increases lead unfortunately to shorter lives for existing electric elements if the same power dissipation is maintained. Therefore such heating elements need to be down-rated (i.e. their maximum power dissipations reduced) in practice due to the presence of the reflectors.

TABLE 12
Dimensions of the Tested Combined Circular Reflector Radiant Ring System Shown in Fig. 5

Type of reflector	*Configuration dimensions (cm)*		
	A	*B*	*C*
Flat	21	2·5	0
Dished	18	5·0	3·5
Closer-fitting, dished	18	3·75	3·5

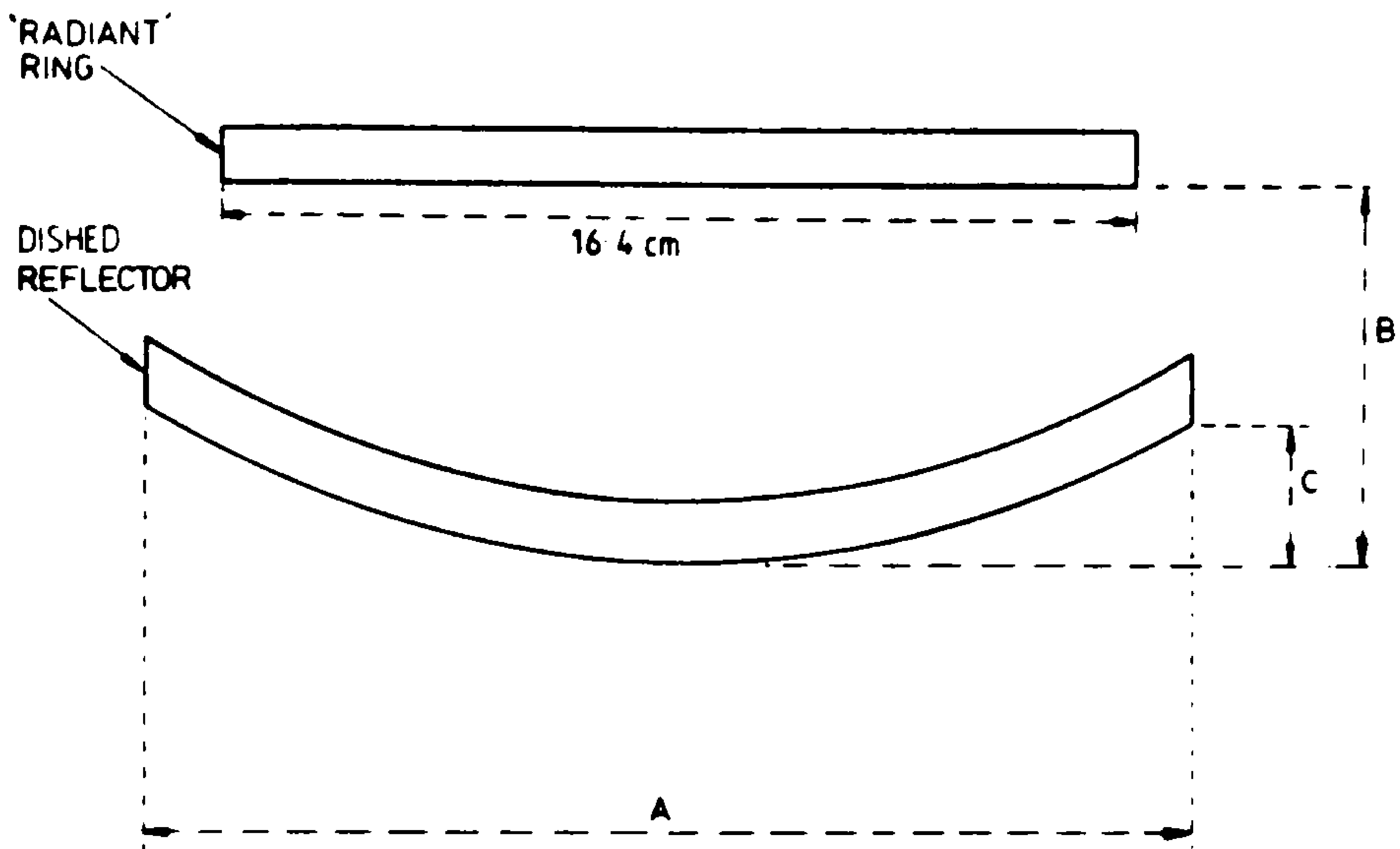

Fig. 5. Schematic sectional drawing showing the parameters describing the geometry of a radiant ring and its associated circular reflector: for the dimensions of the systems used experimentally see Table 12.

Dished close-fitting reflectors are cheap, easily-manufactured and typically lead to hob operations being up to 20% faster. Therefore radiant rings fitted with such reflectors are likely to be more energy effective. Reflectors were once incorporated, but have been removed subsequently from most designs because manufacturers allege that (i) their surfaces rapidly become less reflective as a result of soiling, and (ii) due to the necessary down-rating of the rings, the average cook becomes dissatisfied with the resulting slower heating performances. However, if reflectors became reasonably resistant to soiling and easily cleaned it is likely that more manufacturers would consider reintroducing reflectors into their designs, maybe as a technological 'break-through' in an energy-thrift sales campaign.

Economiser rings

These were developed (in the mid-1970s) to consume about 10% less energy, without a reduction in heating performance. The major difference between this ring and the more usual 'radiant' ring is that the cross-sectional area of the coiled heating element has been reduced, thereby lowering its thermal inertia. Also a different cross-sectional shape and fewer coils than the usual radiant ring, have been employed. Thus the total surface area has been reduced yet a larger nominal area (as seen by the pan's base) of the ring faces upwards and so decreases in the rates of

TABLE 13

Reductions in the Necessary Heating-up Periods Achieved by the Use of a Circular Reflector Beneath a 16·4 cm Diameter Radiant Ring

(Results for deliberately wasteful pan/heater combinations, which are nevertheless commonly employed, are presented to indicate what can be achieved by the use of a reflector)

Duralumin pan containing the water used without the lid in place	*Type of reflector fitted*	*Average time taken for 1·25 litres of distilled water* to reach the stated required temperature:*		*Reduction (%) in time taken divided by the period using the same radiant ring without a reflector present, at temperature:*	
		80°C	*90°C*	*80°C*	*90°C*
Small pan	None	5·35	6·34	—	—
(ground base,	Flat	5·11	6·04	4·4	4·8
13·5 cm nominal	Dished	4·57	5·37	14·5	15·3
diameter)	Close-fitting dished	4·45	5·15	16·9	18·8
Large pan	None	4·44	5·36	—	—
(ground base,	Flat	4·24	5·10	4·5	4·9
16 cm nominal	Dished	3·79	4·47	14·6	16·6
diameter)	Close-fitting dished	3·61	4·31	18·7	19·6

* Initially at ~15°C.

radiation loss are achieved. Furthermore, the change in cross-sectional shape has permitted the ring to deform more easily, thereby increasing the number of contact spots between it and the nominally conforming base of the pan. This reduces the constrictional resistance.

The speed of response of this economiser ring can be enhanced still further by increasing the power dissipation per unit length of the electrically conductive core of the heating element, the nearer one proceeds towards the centre of the spiral. This results in higher efficiency operations of a single ring even when used with a wide range of pan sizes.

Rapid-heating electric hot-plates

When initially energising these low thermal inertia plates, the heating element within each plate is controlled so that it dissipates more power

TABLE 14
Steady-State Average Temperatures of the Coils of a 16·4 cm Diameter Radiant Ring, with No Imposed Thermal Load (i.e. No Saucepan Resting on the Ring)

Designation number for the coil of the radiant ring (see Fig 3)	*Maximum temperature (in °C) of the coil with:*		*Temperature change (in °C) as a result of using the close-fitting dished reflector beneath the ring relative to the temperature for the same coil, but without a reflector present*
	No reflector present	*A dished, close-fitting reflector (as specified in Fig. 5 and Table 12) beneath the ring*	
1	638	620	−18
2	664	760	+96
3	648	760	+112
4	630	727	+97

than while in its quasi-steady state at high temperatures. Such hot-plates thus compete more favourably with the faster heating responses of gas hobs. Also, recently developed hot-plate hobs are considerably easier to clean than radiant ring or gas hobs.

Automatic hot-plates

These have been introduced recently, alongside rapid-heating and ordinary hot-plates, in order to provide the cook with the diversity of hob-heating capabilities that are required for more efficient and easier cooking operations. The centre of the automatic hot-plate incorporates a temperature-sensing probe, which comes into contact with the flat base of any pan placed on it. The temperature of the pan thus controls the power supply to the heating elements so that simmering may be achieved automatically. With hot-plates, no drip trays are required, and therefore it is possible to have a thinner hob, which permits slightly more space to be available for the grill compartment or the main oven of a standard-size cooker.

It is estimated that as much as 90% of the energy consumption of conventional domestic electric cookers is incurred in undertaking hob operations.[30] For an electric cooker, fitted with four radiant rings, usually a maximum supply of about 6·5 kW is provided compared with a maximum input of about 2·5 kW to the oven. Therefore improvements in the design of electric hob-heaters could lead to significant energy savings. For example, by designing a hob-heater in which each element is a small spring-loaded stud as in Fig. 6, the true contact area between the pan and its conforming heat source could be relatively high. This should reduce the thermal contact resistance between the pan and the hob-heater and thereby increase its cooking efficiency. (Erickson[31] alleged that an improvement of 10% in the energy efficiency of an electric hob could be achieved if the aforementioned thermal contact resistance could be halved.) Furthermore, this electric 'stud-hob' could be controlled such that only pan-supporting studs become energised during the cooking operation. This would ensure that:

(a) immediately the pan is lifted off the hob, the power to the heating elements is switched off automatically; and
(b) only the hob area in contact with the base of the pan is heated: this will reduce energy wastage when small or medium size pans are used.

If, despite its disadvantages (e.g. high production costs and a reduction in hob-top cleanability), manufacturers were to develop such a stud-hob, it is recommended that a matching set of saucepans be made available to the cook. The outermost circle of energised studs and the superimposed pan should mate together so that the diameter of the pan's base exceeds the active heat source diameter by about 3 cm (see Fig. 6). By permitting only rotational and vertical movements of the pan, while it is being used for cooking on the hob, the pan will be better located from a heat transfer viewpoint. The combined attributes of this type of stud-hob, with fitting pans, should lead to substantial energy savings.

A large amount of energy is wasted by a conventional electric hob immediately after it is used because of the relatively large heat capacities of the elements and their associated neighbouring equipment. Also, the heat remaining in the element may be a potential high-temperature hazard for several minutes after the power has been switched off, and serves no purpose other than to heat the kitchen environment (which may or may not be required). Some of this residual heat may be inhibited from being lost so rapidly (and therefore used in subsequent hob operations) by fitting lightweight, tightly-fitting, highly insulating, low thermal-mass 'hob-caps' to cover each hob-heater. These caps should be placed precisely on the hob-heaters immediately the power is switched off (see

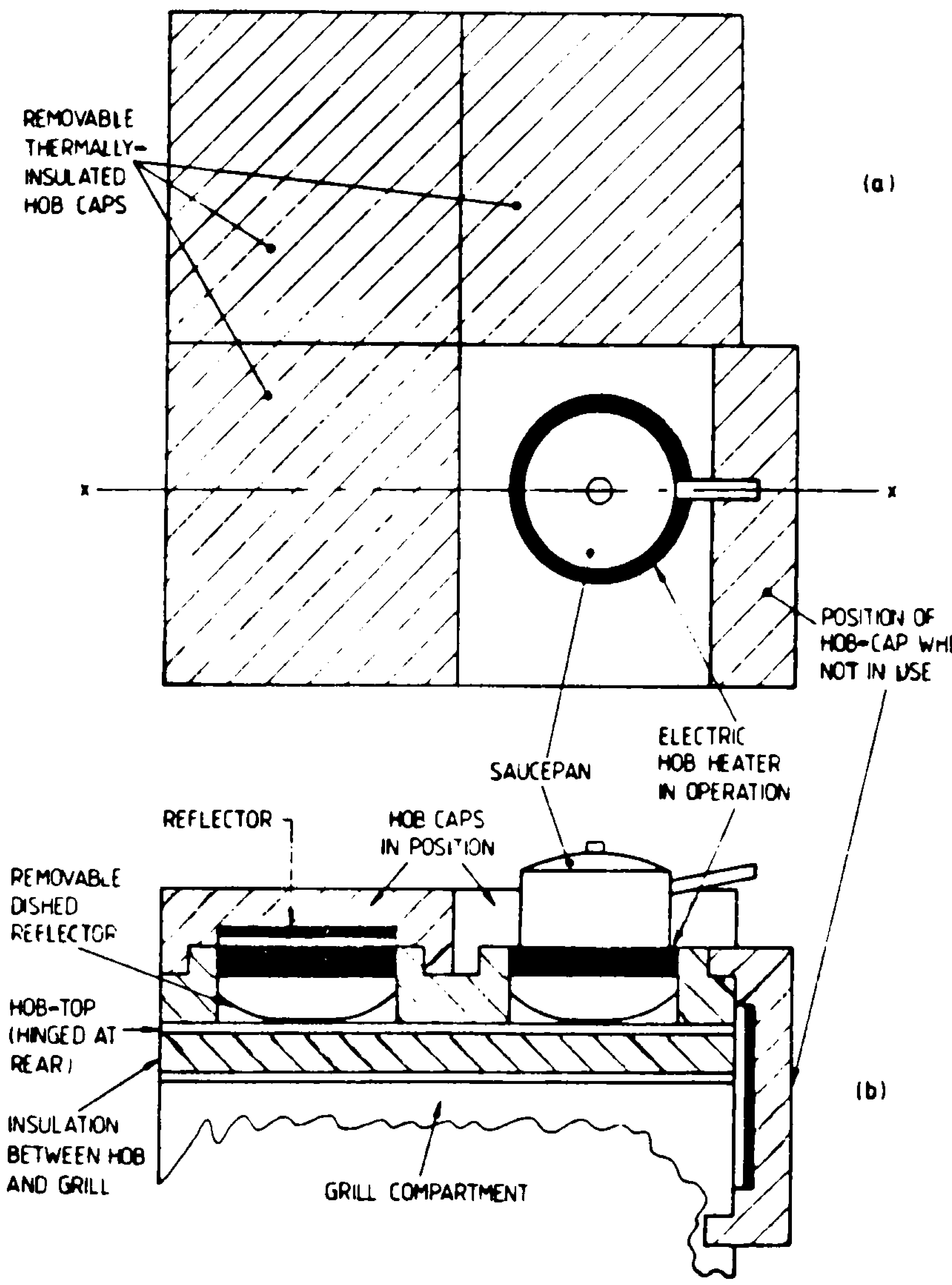

Fig. 7. Hob caps for an electric hob: (a) horizontal plan view; (b) vertical section view along section x-x of (a).

Fig. 7). If the hob is used frequently each day (e.g. as in a kitchen of a large industrial or commercial enterprise), some reduction in energy consumption will then be achieved economically. To aid domestic saleability, these hob-caps should be manufactured with a decorative appearance, thereby improving the visual appeal of say a conventional hob fitted with radiant-rings.

Somewhat similar modifications could be made to the design of portable electric hobs. These usually consist of one or two radiant rings, which besides being used for boiling fluids also act as grills. Unfortunately, they tend to be uninsulated and thus wasteful of energy, especially when grilling. Therefore, thermally insulated radiation-reflectors (similar to hob-caps) should be developed. These could fit above the rings when grilling, and below them when performing hob operations, in order to improve the energy efficiencies of such appliances.

GAS-HEATED HOBS

Fluid boiling can usually be achieved in shorter periods and is more easily controlled with gas-stimulated hobs than with electric hobs. Of the gas used for cooking by a typical British family, 46% is burnt on gas hobs, with the oven and grill consuming 40% and 14%, respectively.[36] The Consumers' Association[39] reported that domestic gas hobs typically cost only about one-third as much to 'run' as electric ones. By replacing gas-hob pilot lights with automatic ignition systems reductions in gas consumptions of up to 30% can be achieved.[40] Also, thermostatically controlled gas hobs are available. These achieve energy savings by adjusting the energy supply automatically to ensure that the food in the pan does not exceed the temperature required as pre-set by the cook.[41,42] Tests show that further energy savings (as indicated below in parentheses) can be achieved[36,43] by:

(a) fitting flame-failure valves, which automatically shut off the gas supply if it is accidentally switched on but no ignition ensues;
(b) fitting pan-sensing devices, designed to prevent unattended burners wasting gas ($\leq$25%);
(c) developing 'sequential' burners, which can cycle on-and-off, at frequencies controlled by the cook, in order to achieve very low heat outputs for simmering purposes ($\leq$25%);
(d) optimising the burner to pan-support separation to achieve the maximum rate of heating ($\leq$6%);
(e) re-designing the hob in order to limit flame-impingement on the pan support ($\leq$5%);
(f) optimising the burner aeration ($\leq$25%); and
(g) having all the elliptical ports in each gas ring angled so that the ensuant flames are directed helically inwards and slightly upwards, rather than outwards from the ring or vertically upwards as is current practice ($\sim$20%).

Catering establishments rely mainly on gas for cooking purposes, but consume about 6·5 times the energy per meal served than the domestic cook achieves.[28] Studies of catering premises by Lawson[11] indicated that the energy consumed for food storage, preparation, cooking, service, dishwashing and building services varied between 7 MJ/meal and 65 MJ/meal according to the type of establishment (see Table 15). This variation arises partly because many caterers have to keep food warm and equipment running for long periods of time. Also it is alleged that some kitchen staff are in the habit of keeping equipment running *even when not in use*. Furthermore, caterers usually employ durable flat-top gas hobs, which consist of one or more sheets of grey cast-iron fitted above the burners. These are uninsulated, have high thermal masses (e.g. they normally take 4–7 min to reach surface temperatures of only 300 °C) and

TABLE 15

Typical Average Total Energy Costs for Various UK Commercial Catering Premises (The analysis excludes consideration of cold snacks and beverages[11])

Catering establishment	*Average energy cost per meal served (pence)*
Snack bar	4
Coffee shop	7
Steakhouse	18
Traditional English restaurant	19
High-class restaurant	27
Hotel restaurant	36

Assumptions:
commercial electricity cost = 1·472 pence/MJ
commercial fuel-gas cost = 0·278 pence/MJ.

their temperatures are difficult to control. If, for example, spheroidal-graphite sheets are fitted instead of cast-iron ones,[44] the cooking efficiency of this type of gas hob can be increased slightly.

It is therefore apparent that catering kitchens in particular, would benefit from an energy-thrift campaign involving the implementation of some of the aforementioned improvements. Unfortunately, by implementing points (d) and (e), the cleanability and visual appeal of the hobs may suffer, and so their introduction may not be favoured by the domestic cook. Nevertheless, the widespread adoption of these modifications would lead to a substantial reduction in the nation's gas consumption.

GLASS-CERAMIC HOBS

Both gas and electrically-powered glass-ceramic domestic hobs are available commercially. Although these have higher capital costs than conventional hob-heaters, their advantages are as follows.

Look tidy.
Easy to clean.
Act as work surfaces, when not being used for cooking purposes.

The gas-stimulated variety consists of either: conventional burners hidden beneath a large ceramic plate[45] or individual ceramic discs fitted over each of the burners. The former type is more attractive, but tends to spread the heat over the entire cooking area and thus is inefficient when cooking with only one or two pans. However, 'ceramic-disc' gas hobs still require further development if their performances and fuel consumptions are to compare favourably with conventional gas hobs.[36]

The electrical types fall into three main categories, employing:

(i) resistive heating elements, resting in an insulating block;
(ii) radiation filaments backed by an insulated reflector; or
(iii) induction coils (these will be discussed in the next section).

Option (i) heats by conduction and is less responsive and less efficient (by 10-20%) than a conventional radiant-ring hob.[37] Thus it is not a worthwhile investment from an energy-thrift viewpoint. Indeed Consdorf and Behrens[46] reported that increases in cooking efficiencies of between 8 and 15% can be achieved by *eliminating* this type of glass-ceramic hob-heater.

Option (ii), the 'light hob'—which heats the pan by short-wave infra-red radiation, provided by long-life (~ 10 years), tungsten-halogen, light filaments—is alleged to be 80% efficient and as responsive as a gas hob.[33] From a safety viewpoint its advantage over all other electric hob-heaters is that the brightness of the heat source can be seen to vary throughout the heating range. However, the capital cost of this domestic system is very high at present: Thorn's 'Haloheat' unit, with four hob-heaters, costs approximately £615.[33] The Consumers' Association[39] found that this type of hob-heater required approximately the same amount of energy, for the cooking tests carried out, as conventional ceramic hobs (option (i)). Thus there seems to be little incentive for domestic cooks to use 'light hobs'.

Induction hobs

These may well become the most widely employed type of ceramic hob-heater, especially in the commercial sector. For example, an induction hob has been fitted to a hospital kitchen, which provides nearly 1200 meals per day. It reduced the average daily electricity consumption from 1100 kWh to 650 kWh during winter months. Consequently, the annual savings and pay-back period were estimated to be approximately £2500 and two years, respectively.[47]

The development of fast switching ASCRs has also encouraged the domestic application of high-frequency induction heating.[48] According to Singer *et al.*,[28] induction hobs are approximately 50% cheaper to 'run' than conventional electric hobs. Meals prepared from nine different menus, by Le Lycée Hôtelier de Strasbourg, using induction cooking appliances achieved an average energy saving of 59% when compared with the traditional employment of conventional electric equipment for the same purposes (e.g. see Table 16). Thus their use, in both commercial and domestic kitchens, should achieve substantial energy savings nationally.

Operating principle of induction hobs

A high frequency (20–30 kHz) generator supplies alternating current to a coil. If a pan made of a ferromagnetic material is introduced into the electromagnetic field of this coil, then eddy currents are induced in the pan: their dissipation leads to an increase in the pan's temperature. The rate of heating, so produced, depends upon the magnetic permeability and electrical conductivity of the pan's material, as well as upon its geometry and location relative to the induction coil(s). Studies have been carried out in the USA to determine the optimal pan-base composite construction, i.e. one which enhances the rate of heat transfer to the food (see Appendix I).

Normally the cooking utensil rests on that part of a ceramic plate, which is just above the induction coil (as in Fig. 8). However, a more energy-efficient configuration would be with the coil around the lower sides and base of the pan, i.e. the cylindrical or truncated conical pan fitting into a matching recess, whose insulated walls contain the induction coil. The pan could then be optimally located consistently. It would also be more secure, and therefore the probability of it sliding off the ceramic plate or spilling its contents, possibly onto a young child, would be reduced.

TABLE 16

Electrical Energy Consumed When Preparing Various Meals Using an Induction-Cooking Appliance or a Traditional Electric Stove[49]

Food on the menu	*Number of helpings*	*Energy consumption (kWh)*		*Energy saving achieved by using the induction stove instead of the traditional stove (%)*
		Traditional stove	*Induction stove*	
Spaghetti Neapolitan style (with tomato sauce) Chicken casserole (with onions, bacon, croutons)	10	25·8	5·5	79
Mushrooms Greek style (in olive oil white wine dressing) Braised steaks with chestnut and onion sauce	10	13·0	3·0	77
Braised chicken casserole with Riz pilaff (boiled and sauted seasoned rice) Cream Puffs	20	10·0	3·0	70
Clear soup with diced mixed vegetables Braised chicken casserole with boiled rice	10	8·0	3·0	63
Tomato salad with tuna, anchovies, olives, etc Stewed chicken in white sauce with fresh cream and boiled sauted rice	20	15·5	7·0	55
Spanish omelette with tomatoes, peppers, etc. Fried breadcrumbed veal escalope with anchovies, olives, capers	10	6·0	3·0	50
Dumplings in white sauce with Gruyere	20	6·0	3·5	42
Split-pea and sorrel soup Fried pork chop with gherkin sauce	10	11·0	7·5	32
Split-pea soup with croutons Veal stew in clear white sauce with plain boiled rice	20	9·0	6·5	28

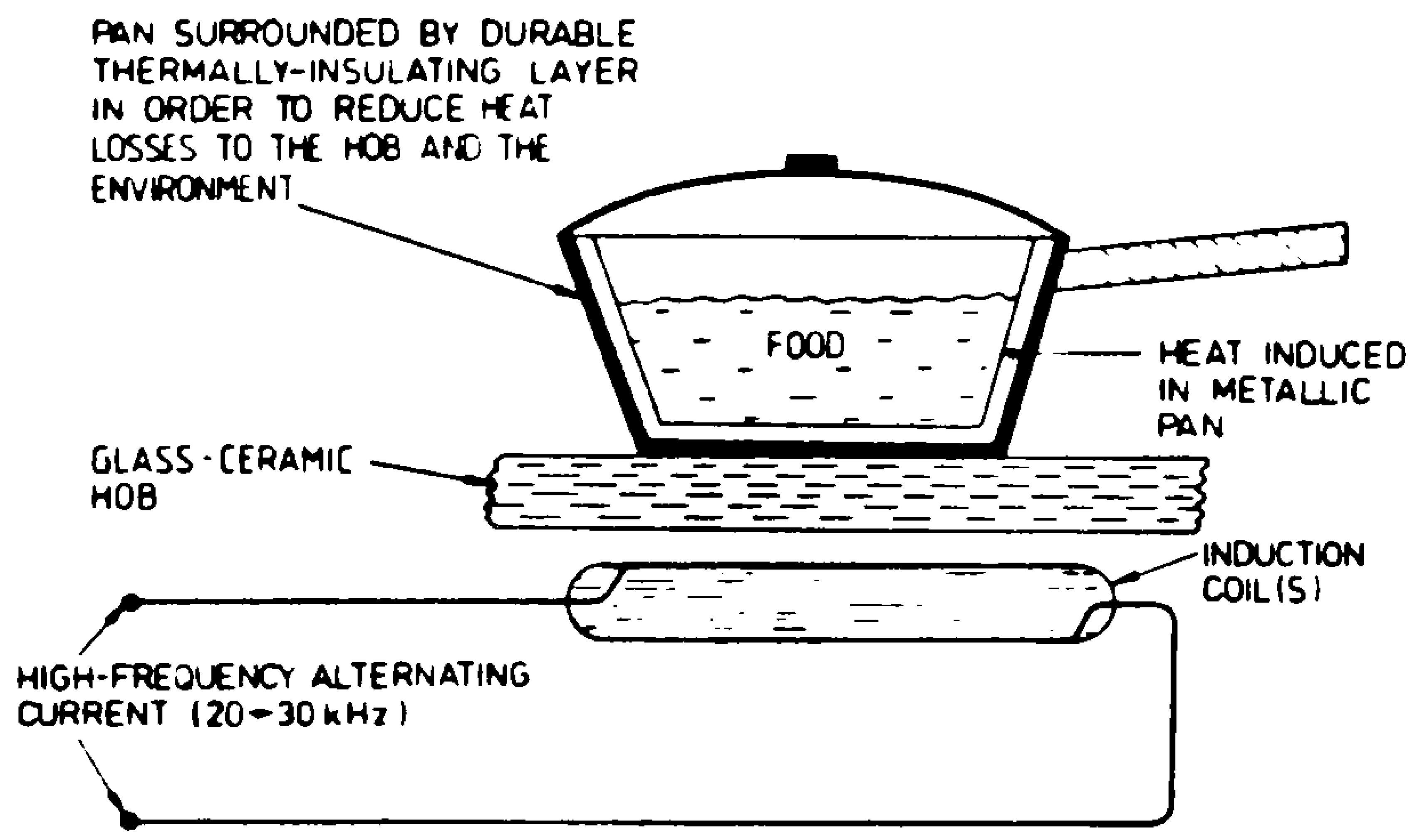

Fig. 8. A simplified schematic section of an induction hob in operation.

However, the hob would then be slightly more difficult to clean, and so *possibly* less marketable.

Attributes of induction hobs

Ceramic induction-hob heating systems possess the following *advantages*:

(a) High rates of heat release are achievable. The temperature response is very rapid because the heat is generated *directly within the pan*, which is the hottest component in the whole assembly. Consequently the heating-up period is very short—on average the time taken to boil 1 litre of water with an induction hob is about 56% of that taken by a radiant ring of the same power rating.[50]

(b) RCA reports 70% as the lowest efficiency for their induction hobs. Such high efficiencies are due mainly to: (i) the low switching losses of the ASCRs; (ii) the relatively small radiative and convective heat losses; and (iii) the almost negligible thermal inertia of such heating systems.

(c) The rapid response of the heater and the absence of a flame or red-hot surface when the pan is removed, ensures that an induction hob is both relatively safe and clean to use. The possibilities of scorching cookware, igniting spilled grease or baking on spills are reduced considerably.

(d) The induction system lends itself to precise electronic control. Induction hobs should include the following features:

   (i) An automatic reduction in power, to a stand-by dissipation rate of less than 10 W, occurs as soon as the pan is removed from the cooking surface.[50] By good design, the local presence of small metallic objects (e.g. cutlery) will not lead to the heater being energised.[48]

(ii) Safe-temperature indicators, which become illuminated whenever the cooking surface is above its 'safe-touch' temperature.[51,52] This is a necessity with each type of ceramic hob, although the induction version is relatively less dangerous because the ceramic plate is heated only by the presence of the higher temperature pan. Nevertheless, surface temperatures of about 200 °C may be encountered when deep-fat frying.[53] The resulting heat loss could be reduced by insulating the pan (see Fig. 8) and making the true contact area between it and the ceramic hob less.[54]

(iii) An accurate control of the heating rate is employed. The hob can reach and maintain a pre-selected cooking temperature without needing regular adjustment by the cook. Furthermore, comparatively low pan-warming temperatures can be held constant and thus efficient food warming—compared with the conventional practice of using the oven, small oven or grill—can be achieved.

However, induction-hob heating equipment has three main *disadvantages*:

(a) The pans used for cooking must be made from a high magnetic permeability material, e.g. cast iron or steel. Glass, aluminium, copper and porcelain vessels cannot be heated directly by this means, although they may be warmed (relatively inefficiently) by being placed on, for instance, a steel plate, which itself rests on the ceramic surface.

(b) The long-term exposure of cooks to even relatively low frequency electromagnetic radiation may be harmful. However, common misinterpretations have resulted from the oversimplistic extrapolations (of conclusions concerning the deleterious effects) from observations on fish or quadrupeds, to humans.[55,56] The ultrasonic frequency at which induction heating is usually achieved is too high to be detectable by human hearing but may irritate certain domestic animals if they are in close proximity to the hob.

(c) They tend, at present, to be at least three times as expensive as comparable resistive-type ceramic hobs.

ELECTRICALLY HEATED OVENS

Construction of a conventional electric oven

The thermal insulation of an electric oven frequently takes the form of a glass-fibre blanket, sometimes with a backing of aluminium foil, that encloses completely the oven cavity: the main structure of the oven being of pressed steel (see Fig. 9). The top of the oven usually has a removable steel panel, which acts as an easily cleanable ceiling as well as an additional radiation reflector. The horizontal heating elements are normally contained within the vertical gaps between the hanging pressed-steel vertical leaves and the side walls. A plate should be positioned above each element to deflect the heated air, through horizontal slots, into the

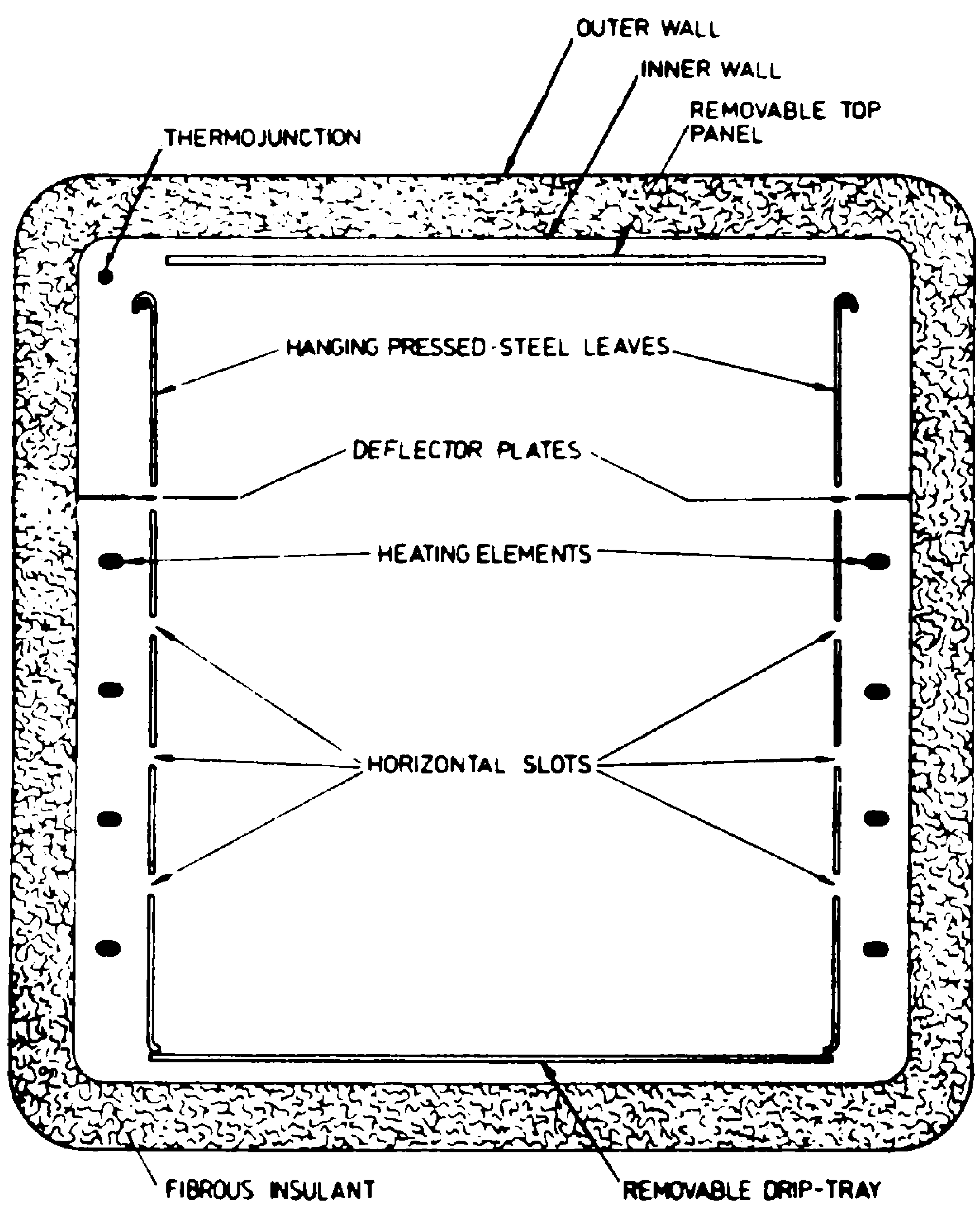

Fig. 9. Schematic vertical cross-sectional front-view of a typical electric oven.

oven compartment, though unfortunately quite often only one deflector per side wall is fitted (as shown in Fig. 9).

The conventional oven door is usually made from pressed steel, although it often contains a glass window, or is accompanied by an inner glass door (see Fig. 10). The main door has a peripheral seal of either a heat-resisting cloth or a flexible plastic hollow tube attached to it, and sometimes the inner wall of the outer door is shaped to fit partially into the aperture recess (see Fig. 10). The resulting closer fit of the door to the oven walls, roof and floor tends to protect the seal from exposure to excessively high temperatures and also inhibits heat flows out of the oven.

The conventional oven door is supported by two vertical hinges, and, when closed, fastens with a spring-loaded catch in which an extension tongue of the door is pushed into the side walls until it catches with its mate. Therefore each of the two hinges and the door catch, is a prospective low thermal resistance bridge, i.e. a possible thermal short. During the next century, metal components will be replaced increasingly by ceramic ones.

Heat transfers within conventional electric ovens

These occur mainly by convection through the enclosed air and partly by radiation. The electric elements at the sides of the oven heat the air, which rises along the adjacent walls, resulting in vortex patterns of the form

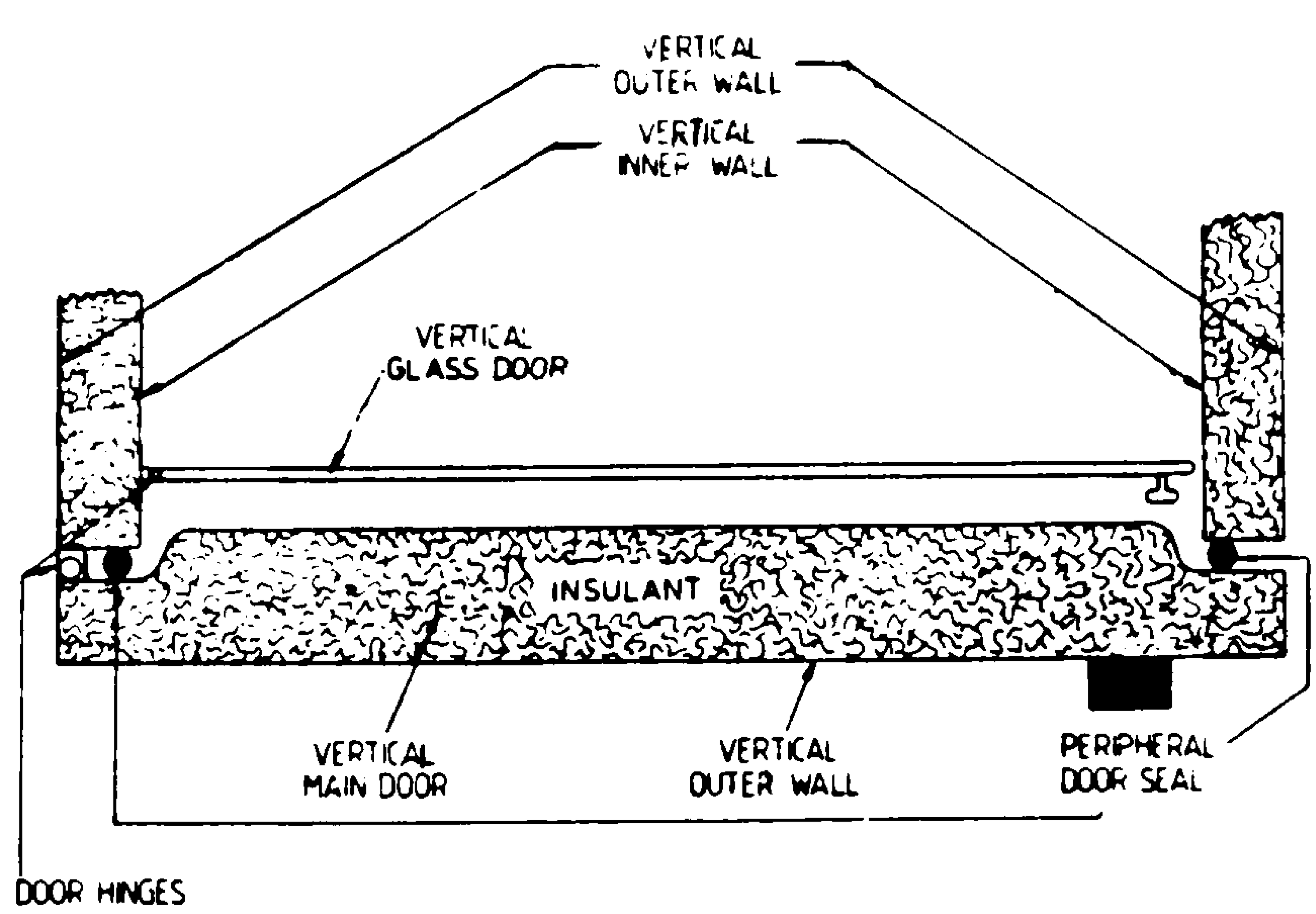

Fig. 10. Schematic cross-sectional plan view showing the vertical doors and the door seal of a typical electric oven

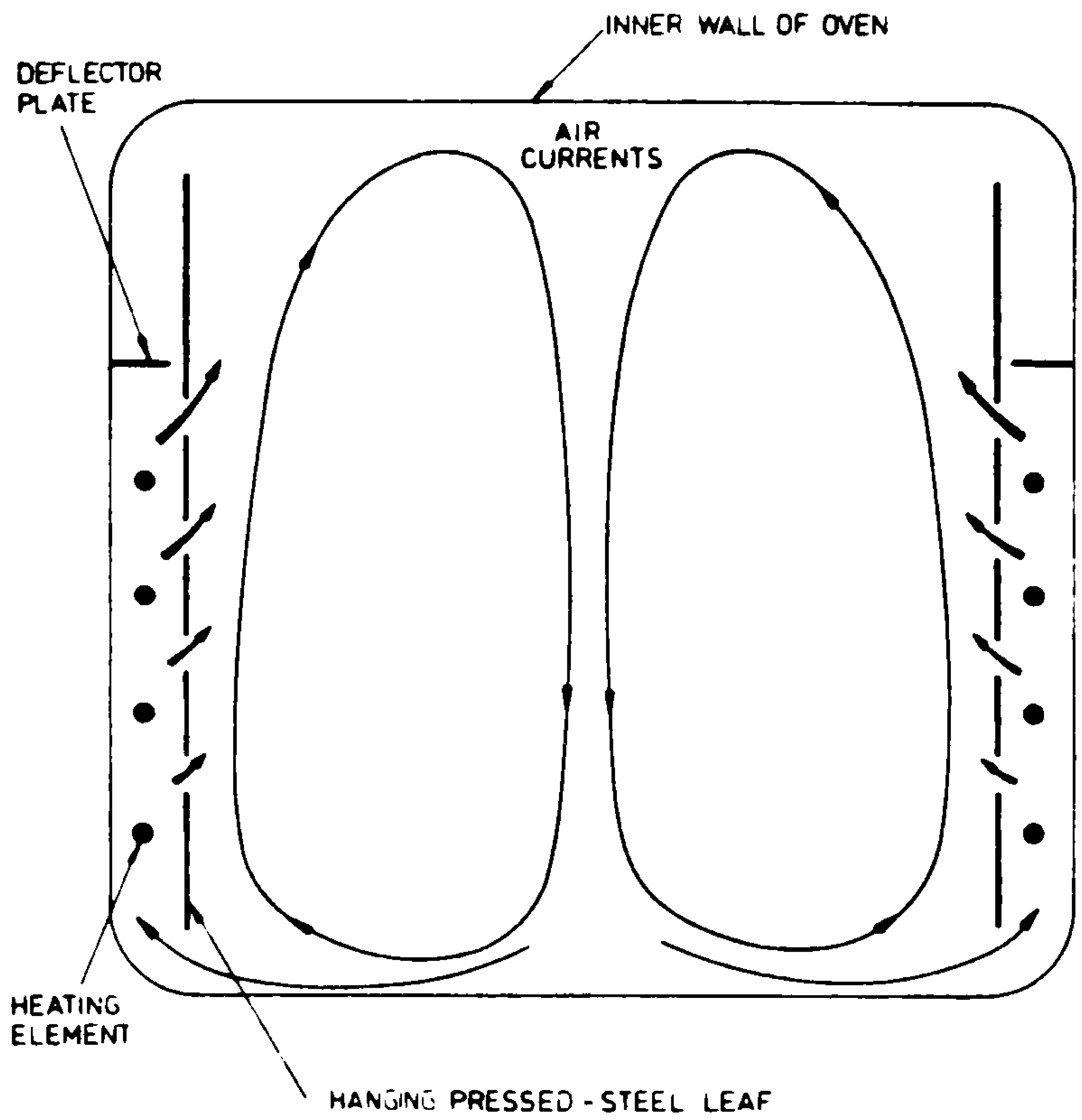

Fig. 11. Vertical sectional view of the air currents in a typical empty electric oven, as viewed from its front.

shown schematically and over-simplistically in Fig. 11 for an empty oven. As the air falls, it warms the food, and when it reaches the lower regions of the oven, it is drawn, by buoyancy forces, over the heating elements once again. Unfortunately, with this heating-element configuration, the heated air tends initially to come into contact with the relatively cold oven roof, and thus is cooled *before* impinging upon the food to be cooked. Therefore, improving the air-flow patterns within the oven could, simply yet appreciably, increase the rates of heat transfer to the contained food. (Thus it is logical that several types of fan-assisted ovens have been manufactured for both domestic and commercial cooking purposes.)

Radiation accounts for about 40% of the total heat transfer to the contained food,[57] but it can represent a more significant fraction if the heating is permitted for only short periods. One series of tests in the present investigation was undertaken with a commercially available domestic cooker (see Fig. 12), using a cylindrical brass block (of 15 cm diameter and 1·27 cm thickness), centrally placed in the oven, as the thermal load. It was found, after 40 min with the oven switched on, that the centre of

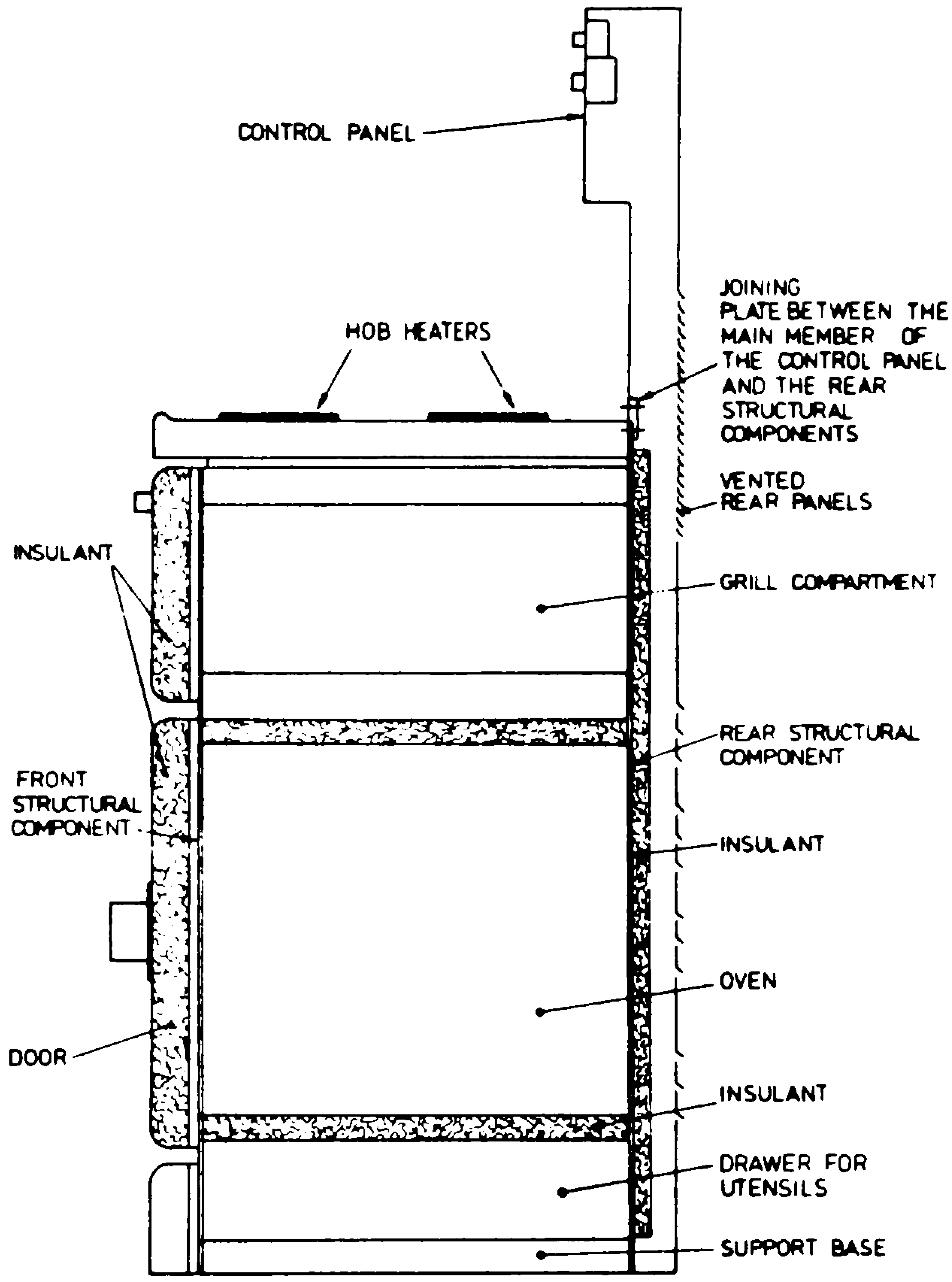

Fig. 12. Cross-sectional side view of a Tricity Marquis free-standing electric cooker showing its main structural and heating components.

mass of the block was about 35 °C lower in temperature if its surface was polished (i.e. of low emissivity) than if its surface was painted matt black (see Fig. 13).

The change in the wet-bulb temperature of the air contained in an oven (which regulates the rate of evaporation of moisture away from the surface of the food and thus controls the length of the necessary cooking period) while roasting a sample of beef is shown in Fig. 14. When moisture was deliberately admitted into the enclosed atmosphere of the tested oven, so that it had a relative humidity in excess of 80 %, the temperature of the

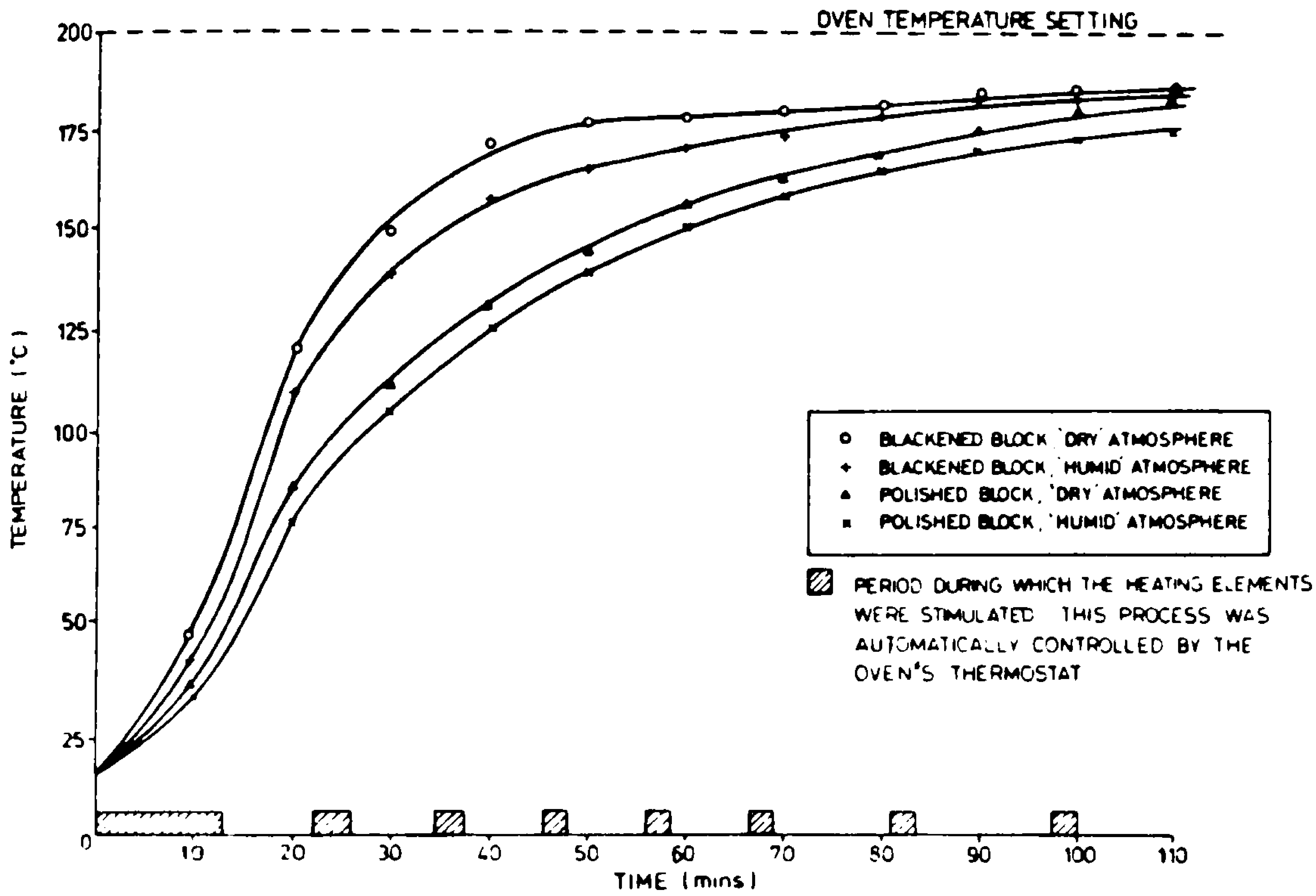

Fig. 13. The temperature response of a thermojunction embedded at the centre of the CBTS, with a polished or blackened surface, which was placed centrally (in a dry or a humid atmosphere) in the oven, at an oven temperature setting of 200°C.

centre of the block (hereafter referred to as the CBTS) was significantly lower than if moisture had not been present (see Fig. 13). These phenomena indicate that radiative heat transfer is important when cooking with a conventional electric oven.

The contribution by solid conduction from the heating elements to the overall rate of heat transfer in such a cooking process was small because it took place primarily along the demountable shelves and was further inhibited by contact resistances. (The shelves each consisted of a rigid arrangement of nine 3·5 mm diameter, parallel steel rods which spanned the oven compartment.)

Influence of thermostats

One sequence of experiments, with the CBTS as the thermal load in the Tricity Marquis oven, indicated as expected, that the heating rate rose the higher the setting of the oven's thermostat (see Fig. 15). The rate of

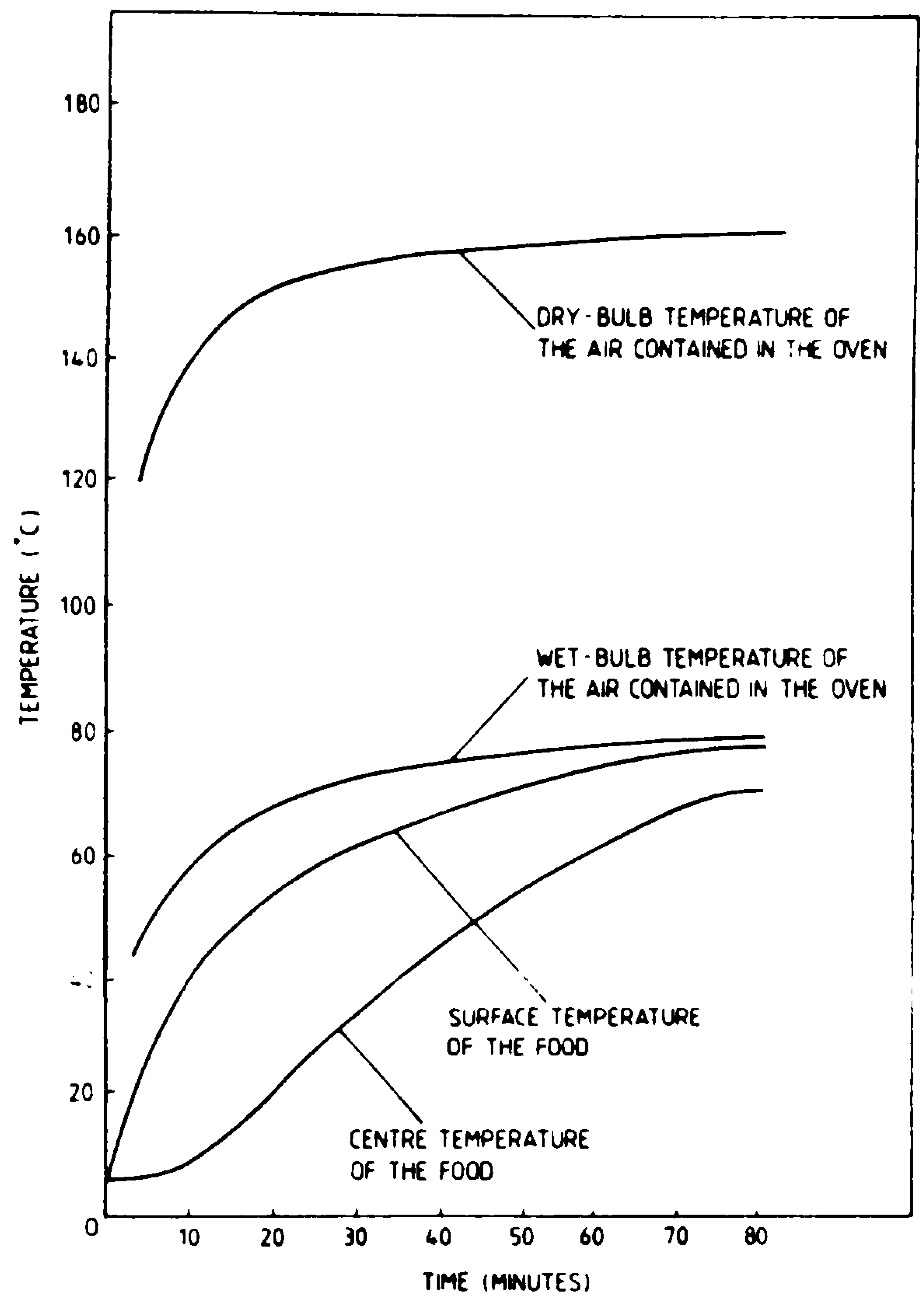

Fig. 14. Temperature response in beef and air during oven roasting.[58]

temperature increase of the CBTS was approximately proportional to the difference between its rates of heat gain and loss, which respectively decreased and increased with its temperature. Therefore, the oven's heating process became less effective the higher the CBTS temperature. Also the total heat loss was smaller, the shorter the heating period. From such considerations, it might be inferred that the maximum thermostatic setting should always be employed initially. However, this would have to be changed subsequently to the required cooking temperature, and so would involve the cook in monitoring and controlling the heating process more frequently. Alternatively, in order to shorten pre-heat periods, a control system could be employed to ensure that the maximum voltage is

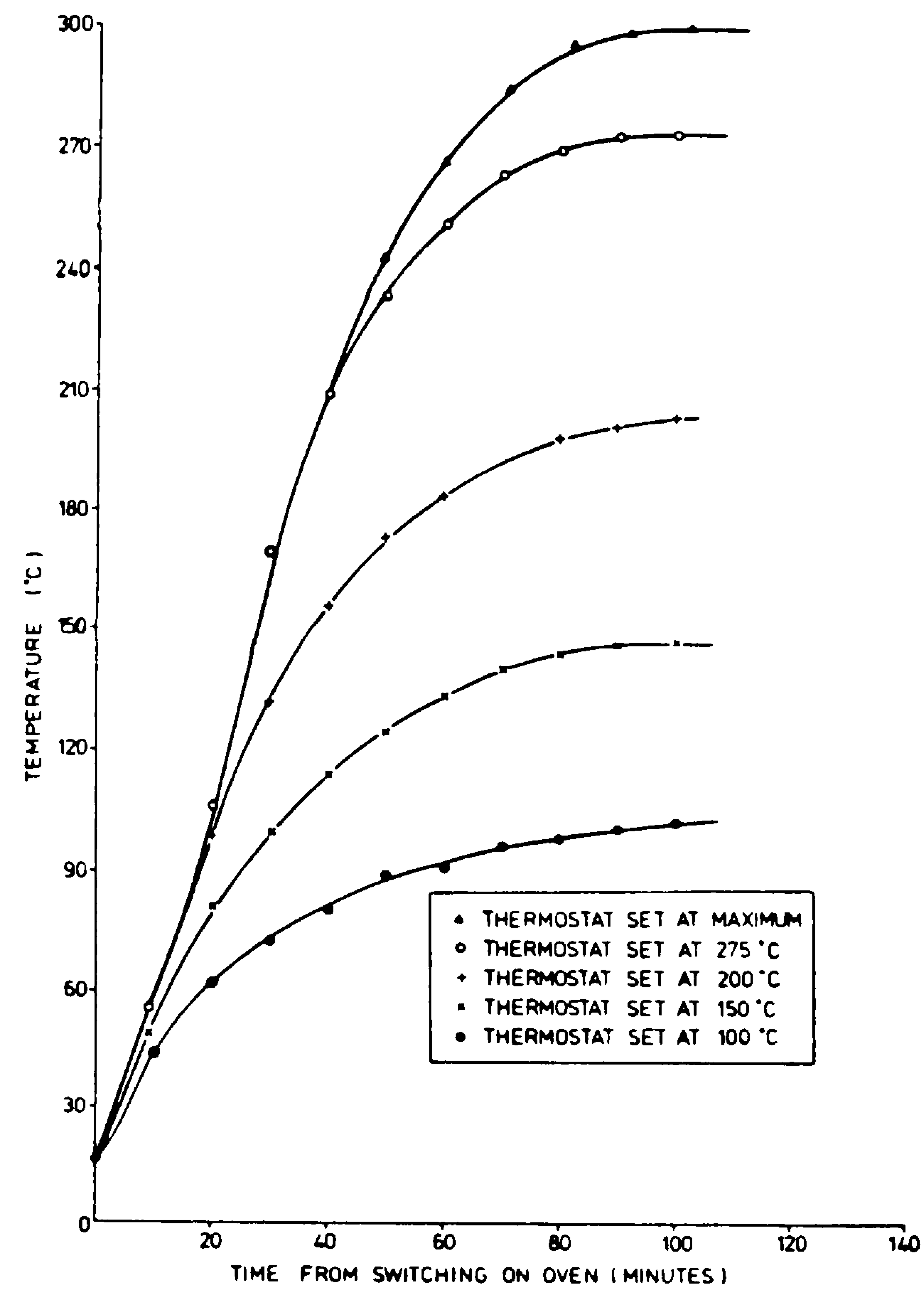

Fig. 15. The temperature response of the centre of the CBTS placed centrally in the oven for various thermostat settings.

applied to the heating elements immediately after the oven is switched on, regardless of the thermostatic setting. Once the required oven temperature has been attained, the heating elements should be controlled by the thermostat, i.e. in the conventional manner.

The heat transfer behaviour of typical foods would be quantitatively quite different from that shown in Fig. 15 for the CBTS under similar applied conditions. This is because brass conducts heat faster that foods, which also tend to have higher surface roughnesses (and hence greater heat absorptivities and emissivities) than the CBTS.

To try to simulate the presence of more than one body being cooked simultaneously, a horizontal flat (22 × 21·5 × 6·5 cm) steel plate was placed 3 cm symmetrically above the CBTS (which again acted as the thermal load under consideration). This plate did not extend completely across the oven compartment. Figure 16 shows the temperature response of the CBTS under these conditions, and indicates that significant thermal stratification occurs in the conventionally-heated oven. A drop in heating performance of the oven occurs solely as a result of introducing the steel plate, but a greater fraction of the supplied energy is usefully employed to heat the contained bodies (i.e. the CBTS plus the steel plate). Therefore, as expected, a more efficient use of energy is achieved if the oven is well

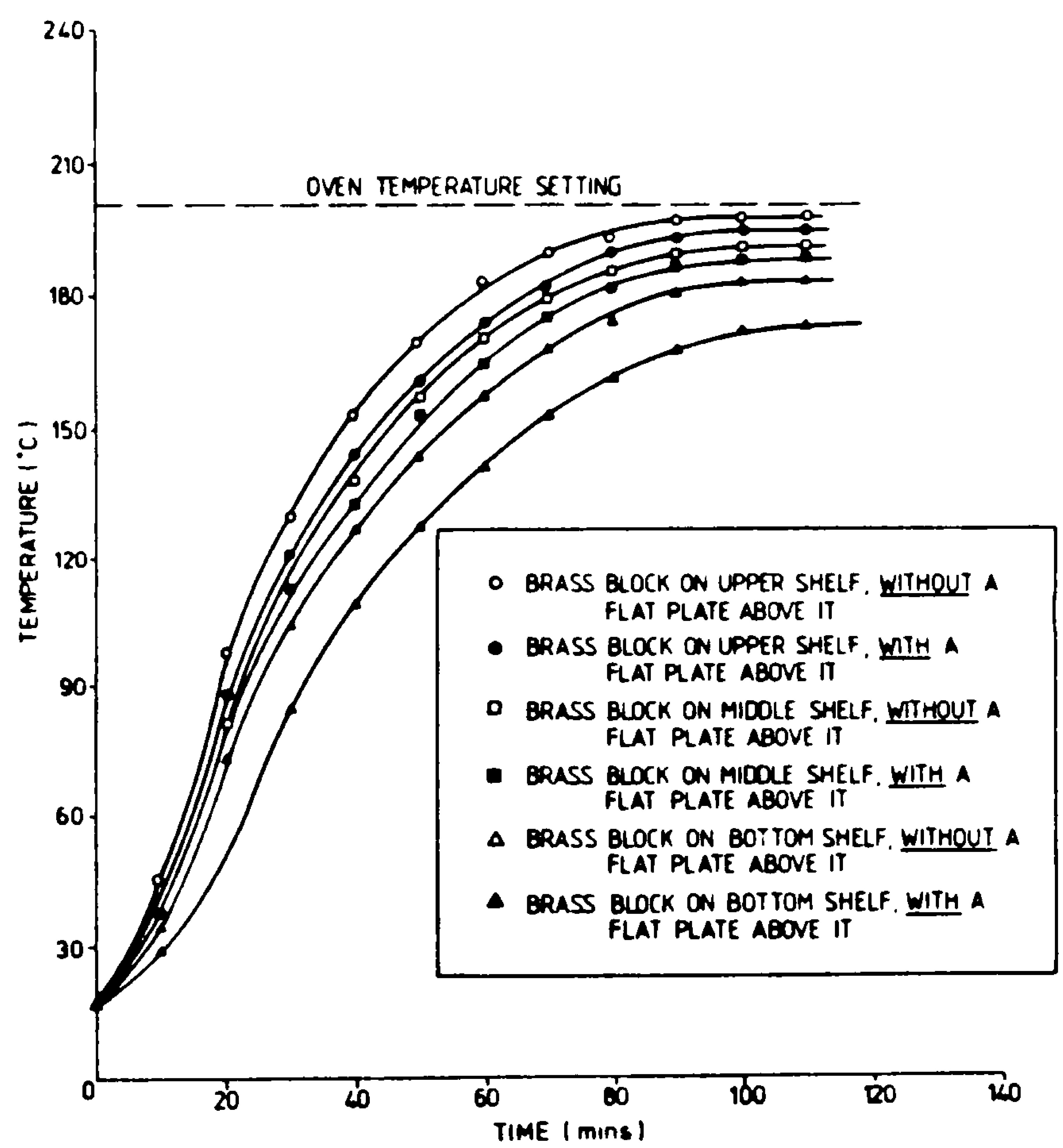

Fig. 16. The temperature responses of the centre of the CBTS which had been placed in various positions in the oven, with and without a flat steel plate 3 cm symmetrically *above* it.

filled. However, using this cooking technique results in an increase in the time required for the complete cooking of each individual item.

The temperature responses of the CBTS placed successively in central positions in seven typical ovens, built during the period 1948 to 1978, were recorded. In general, the more modern the cooker, the lower was the thermal inertia of its oven and so the faster was the temperature response of the CBTS (e.g. see Fig. 17). This trend, whereby manufacturers

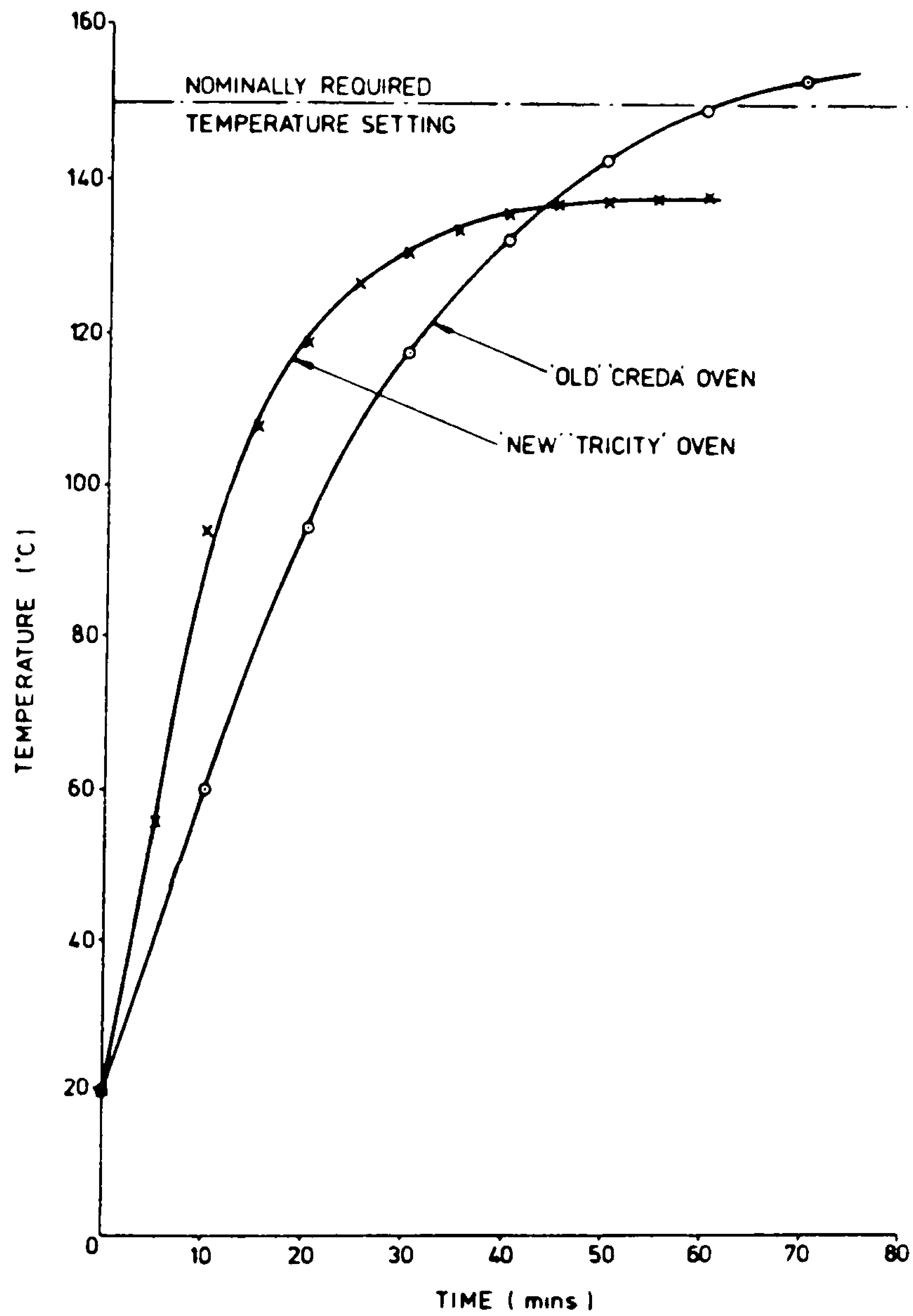

Fig. 17. The temperature response of the centre of the CBTS placed centrally in typically 'old' and 'new' ovens.

increased the performance of their ovens, was established well before the rapid escalation of fossil-fuel unit prices, which started in November 1973.

Thermal 'shorts' and their elimination

For the tested oven, the external surface temperatures, when the oven was in operation, were relatively high around the regions of the door catch and hinges, indicating that significant amounts of thermal bridging occurred via them (see Figs 18-21 and Plates 1-4).

The door seal for the tested oven (and for six others considered) was partially ineffective when the oven was heated due to the differential expansion of the door's inner leaf, relative to its outer leaf, thereby causing the door to distort (see Fig. 22). The resulting convective losses from the oven compartment could be eliminated by making it mandatory to fit, for all ovens, a spring-loaded inner door (see Fig. 23), such as that incorporated in some 'self-cleaning' ovens. In addition, or alternatively, the use of a triple-engagement system is recommended, whereby the oven door handle controls not only the catch, but also the simultaneous movements of two vertical shafts which slot into recesses at the top and bottom of the oven casing when the door is shut. The design should ensure that the whole mechanism, including the catch and bolts and the parts of the casing into which they engage, is always at temperatures near those of the external casing in order to avoid severe thermal bridging.

The thermal resistances of oven door *hinges*, which are normally made from steel, should be increased. This could be accomplished by making the whole or part of the offending hinges from a low thermal conductivity, high-alumina ceramic, which would be strong enough to withstand the high stresses incurred. Alternatively, each hinge could be a stack of thin metal (or ceramic) hard washers: these would permit rotational movements, but have large thermal contact resistances even under high compressive loads. A suitable stack, would be of 'witches hat' shaped washers (see Fig. 24) punched out of 56 μm thick hardened, stainless-steel sheet.[59] The attachment points for fixing the hinges should be on the *outside* surfaces of the oven casing and door, thereby avoiding thermal bridging.

Relatively high temperatures of the external surfaces often occur near the oven compartment's lamp if it is located in a gap in the oven wall. This

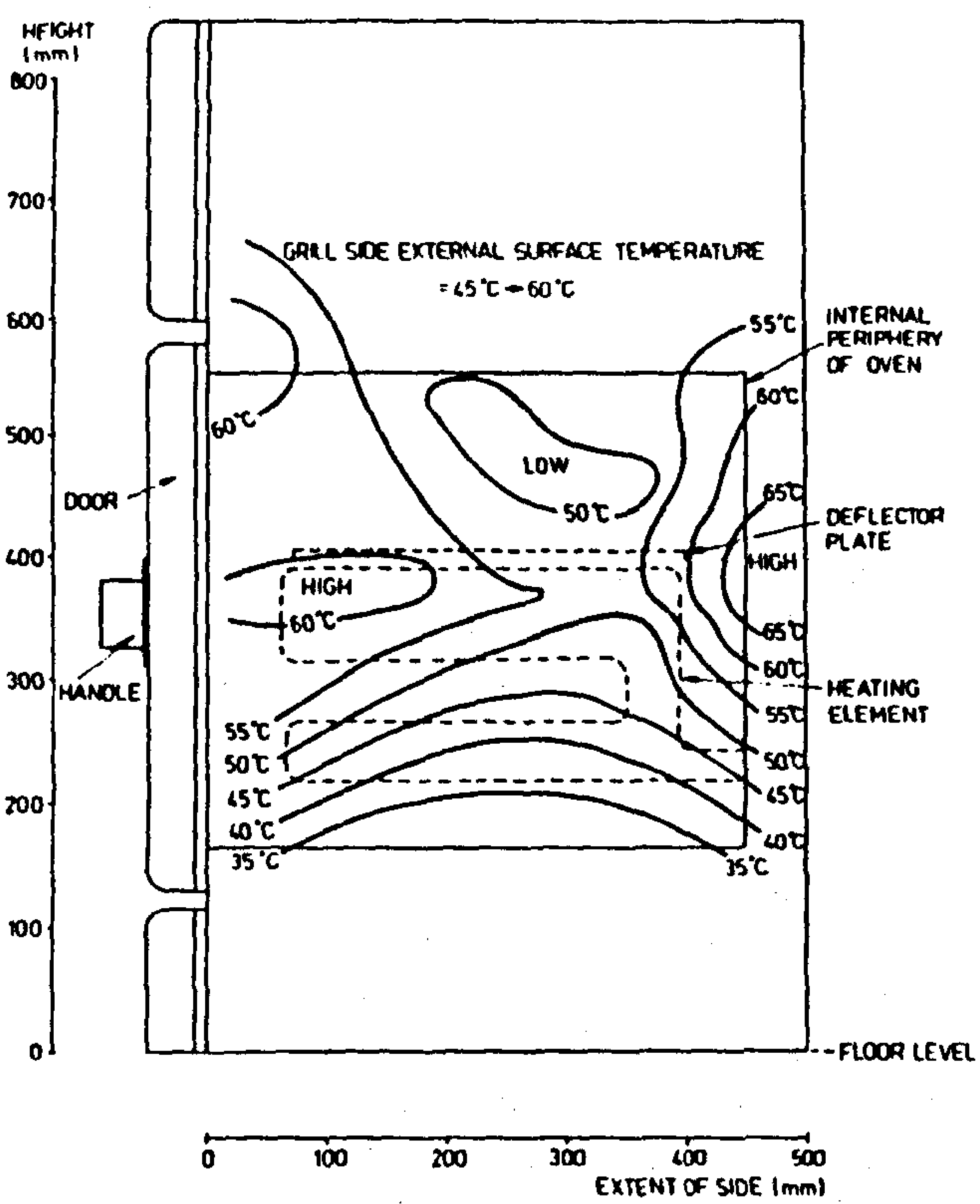

Fig. 18. Isothermal contour map of the *external* surface of the side of the cooker nearer the oven door handle for an oven temperature setting of 200°C and an average ambient temperature of 18°C. The temperature distributions were measured with moveable thermojunctions.

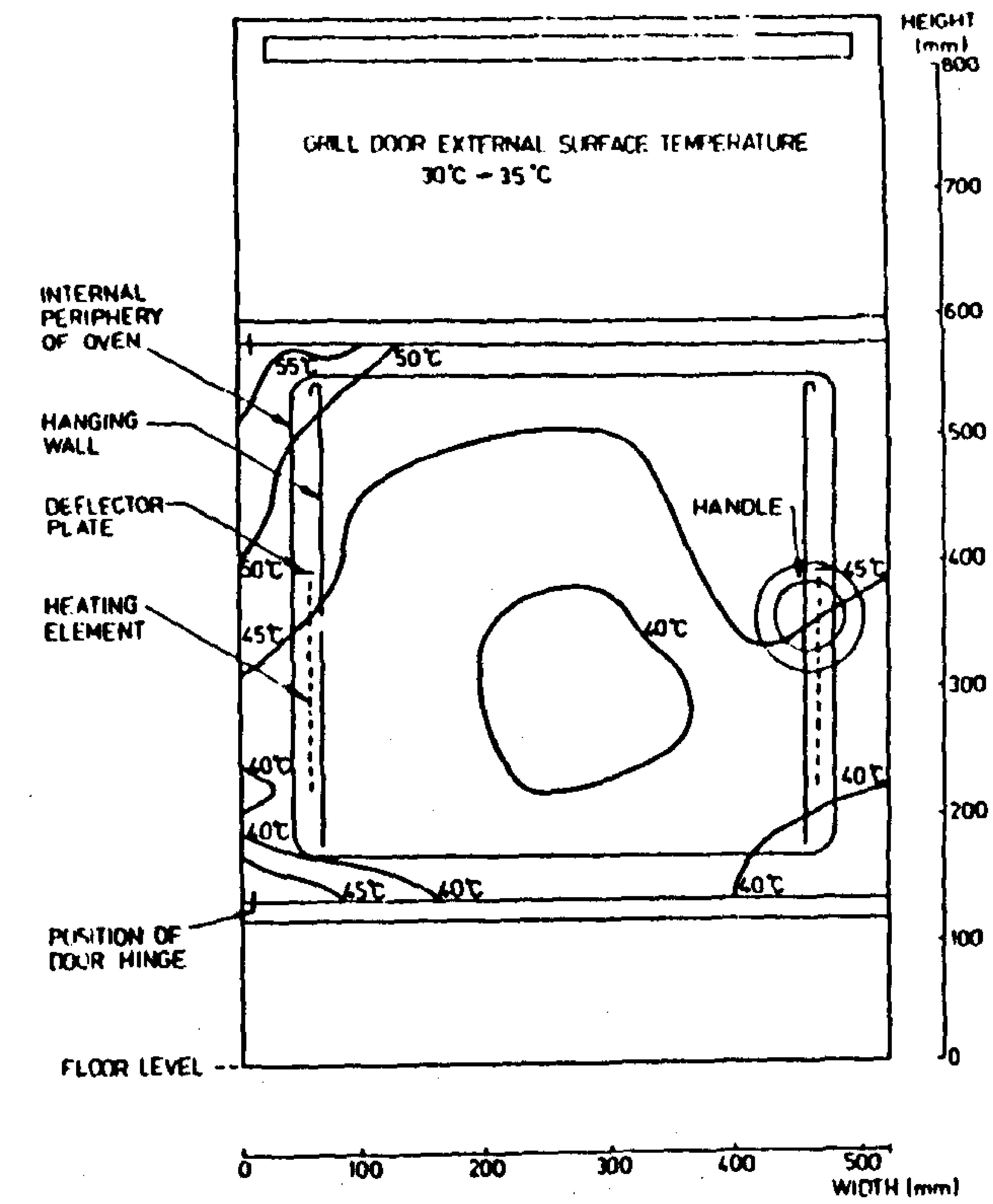

Fig. 19. Isothermal contour map of the *external* surface of the cooker front, corresponding to the temperature conditions applying in Fig. 18.

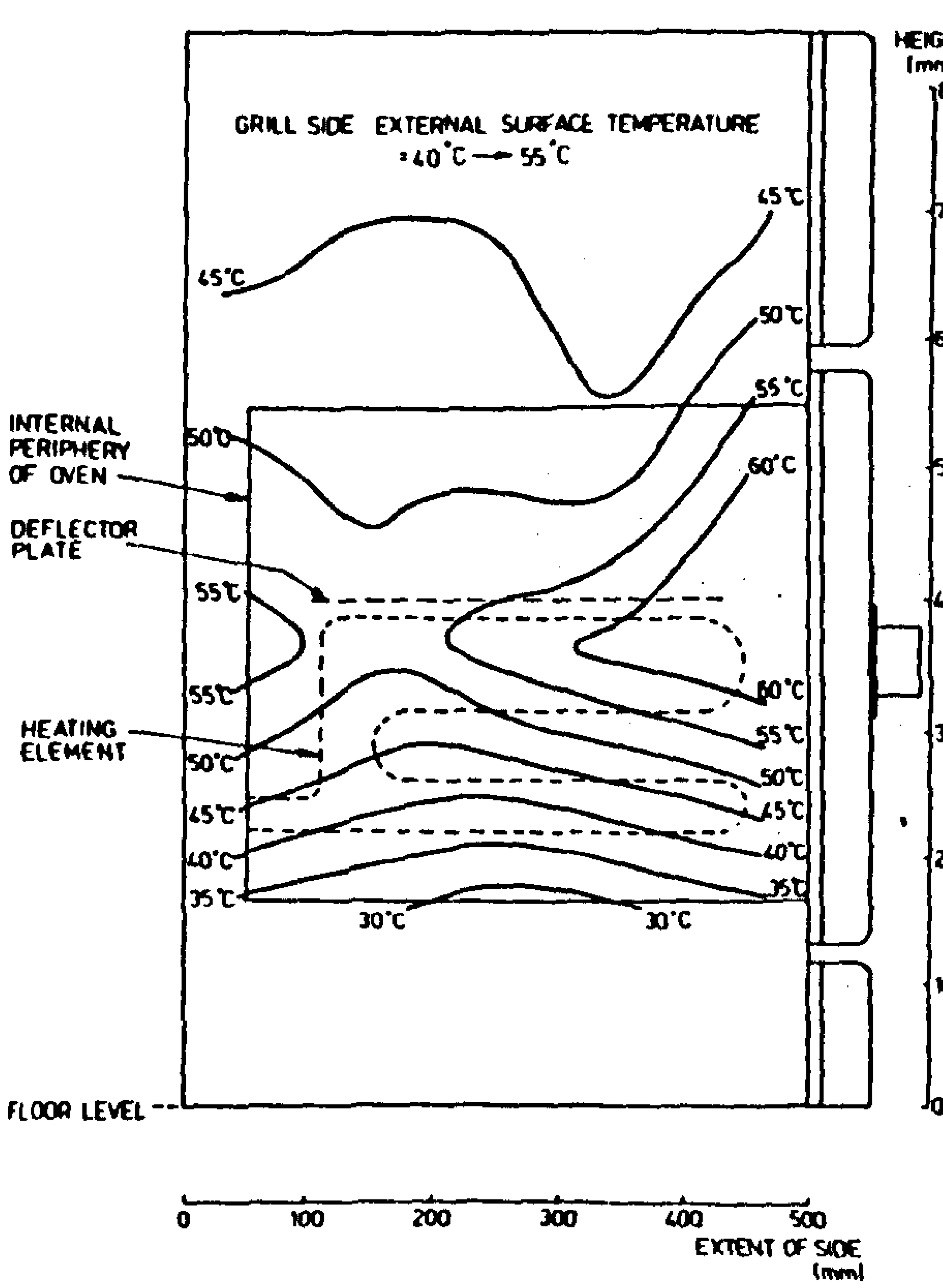

Fig. 20. Isothermal contour map of the *external* surface of the side of the cooker nearer the oven door hinges, corresponding to the temperature conditions applying in Fig. 18.

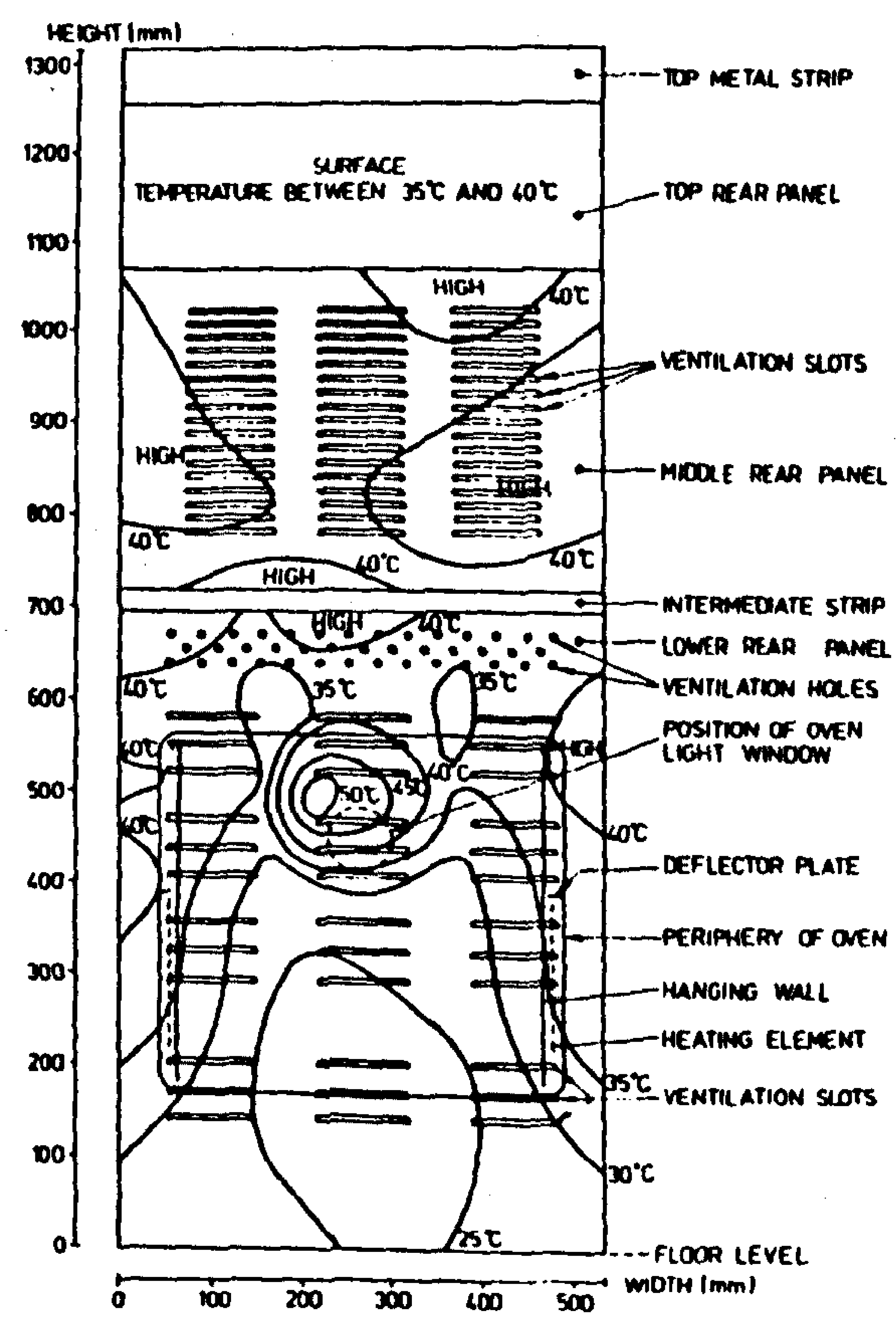

Fig. 21. Isothermal contour map of the *external* surface of the rear of the cooker, corresponding to the temperature conditions applying in Fig. 18.

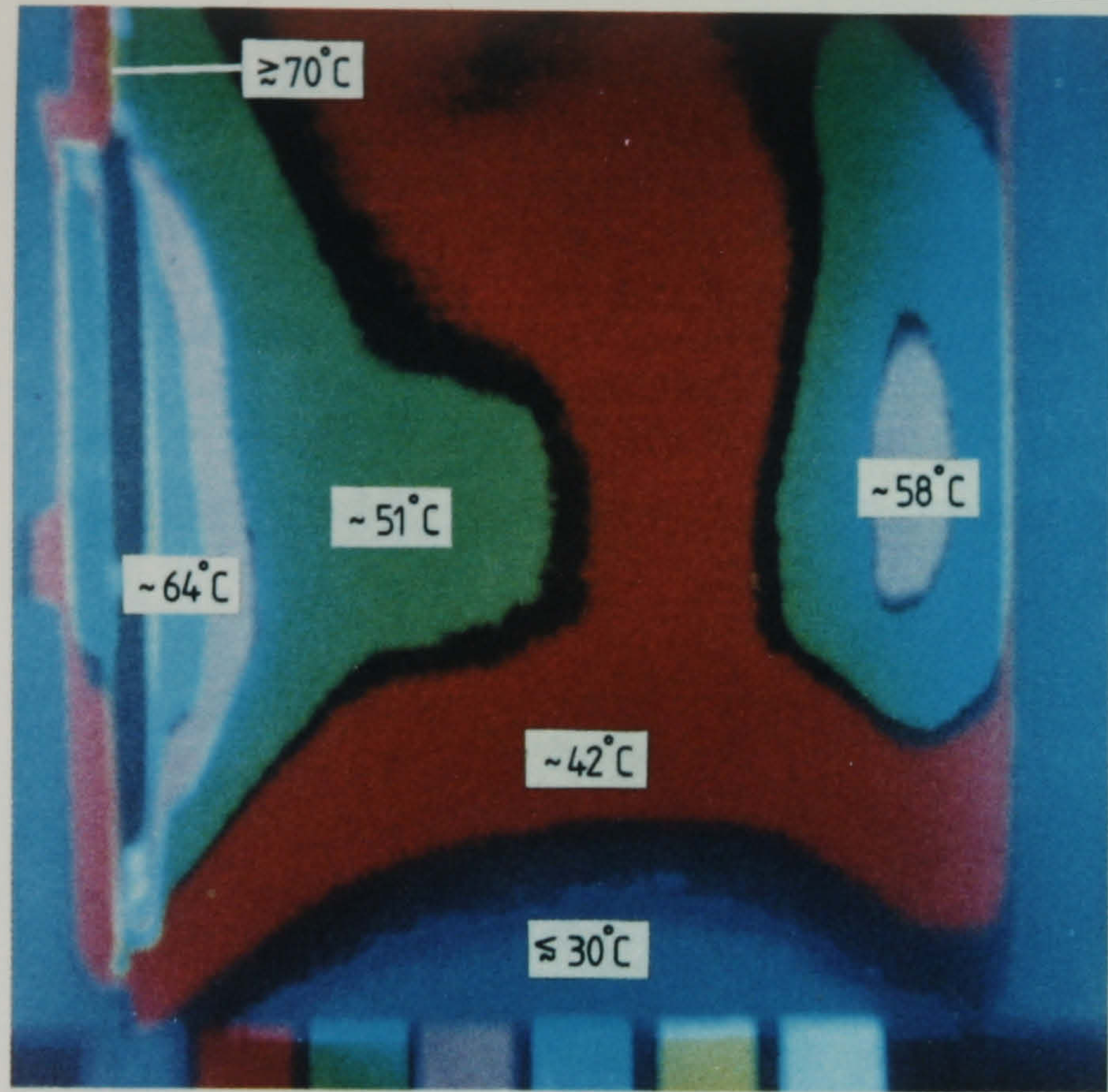

Plate 1. Infra-red colour photograph of the *side* of the cooker nearer the oven door handle, with an oven temperature setting of 200 °C and an average ambient temperature of 18 °C. The colour coding in this instance was arranged to give: dark blue (≤ 30 °C), red (~ 42 °C), green (~ 51 °C), purple (~ 58 °C), turquoise (~ 64 °C) and yellow (≥ 70 °C). The apparent high temperature zone immediately adjacent to the door/cooker-sidewall interface was due to a highly reflective vertical strip at the left-hand extremity of the cooker's sidewall (see Fig. 18).

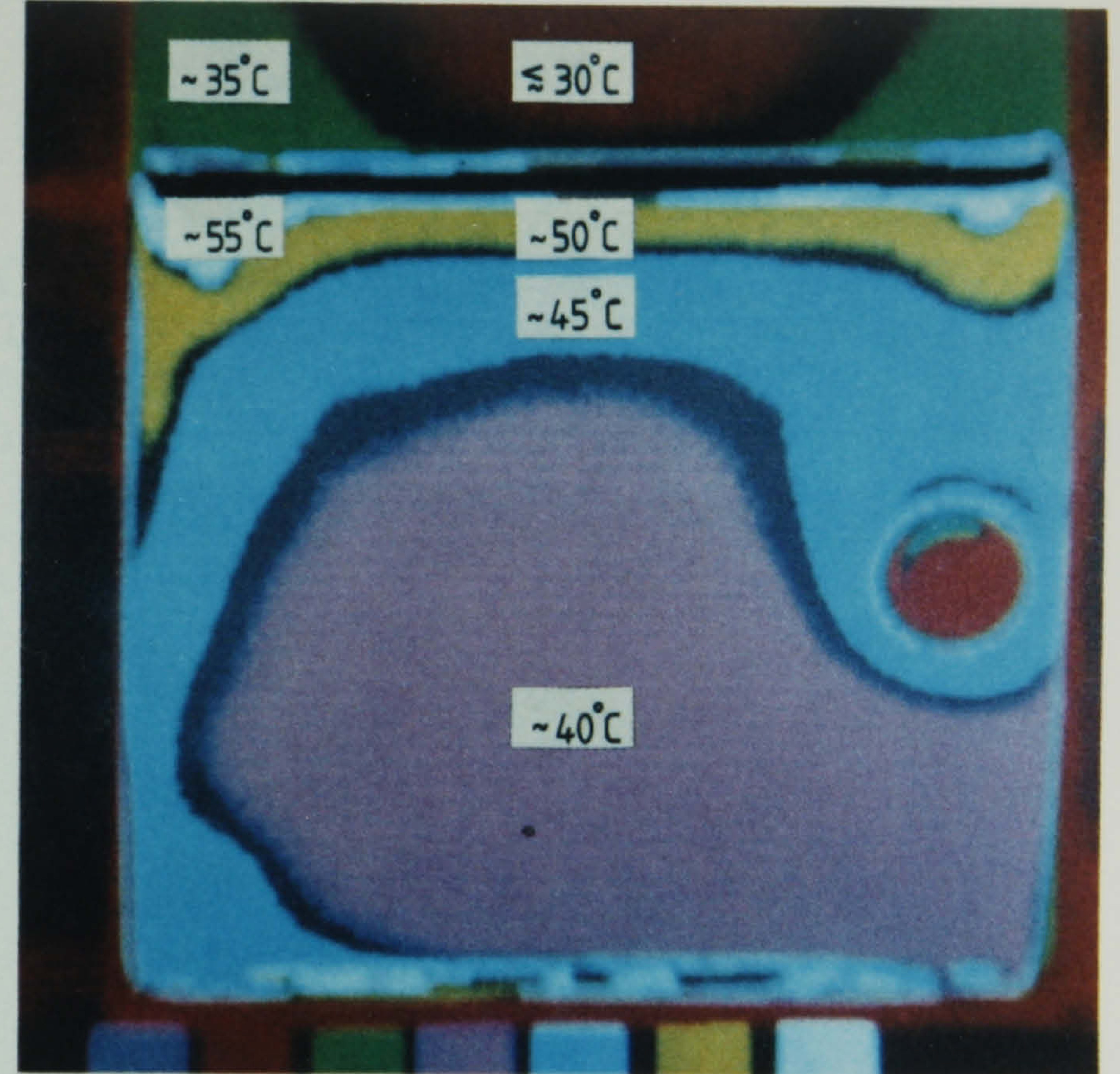

Plate 2. Infra-red colour photograph of the cooker *front*, corresponding to the temperature conditions applying in Plate 1. The colour coding in this instance was as follows: red (≤ 30 °C), green (~ 35 °C), purple (~ 40 °C), turquoise (~ 45 °C), yellow (~ 50 °C) and light blue (≥ 55 °C). No interpretation of the colour of the door handle is given because the material from which the handle is made has a different emissivity to that of the door (see Fig. 19).

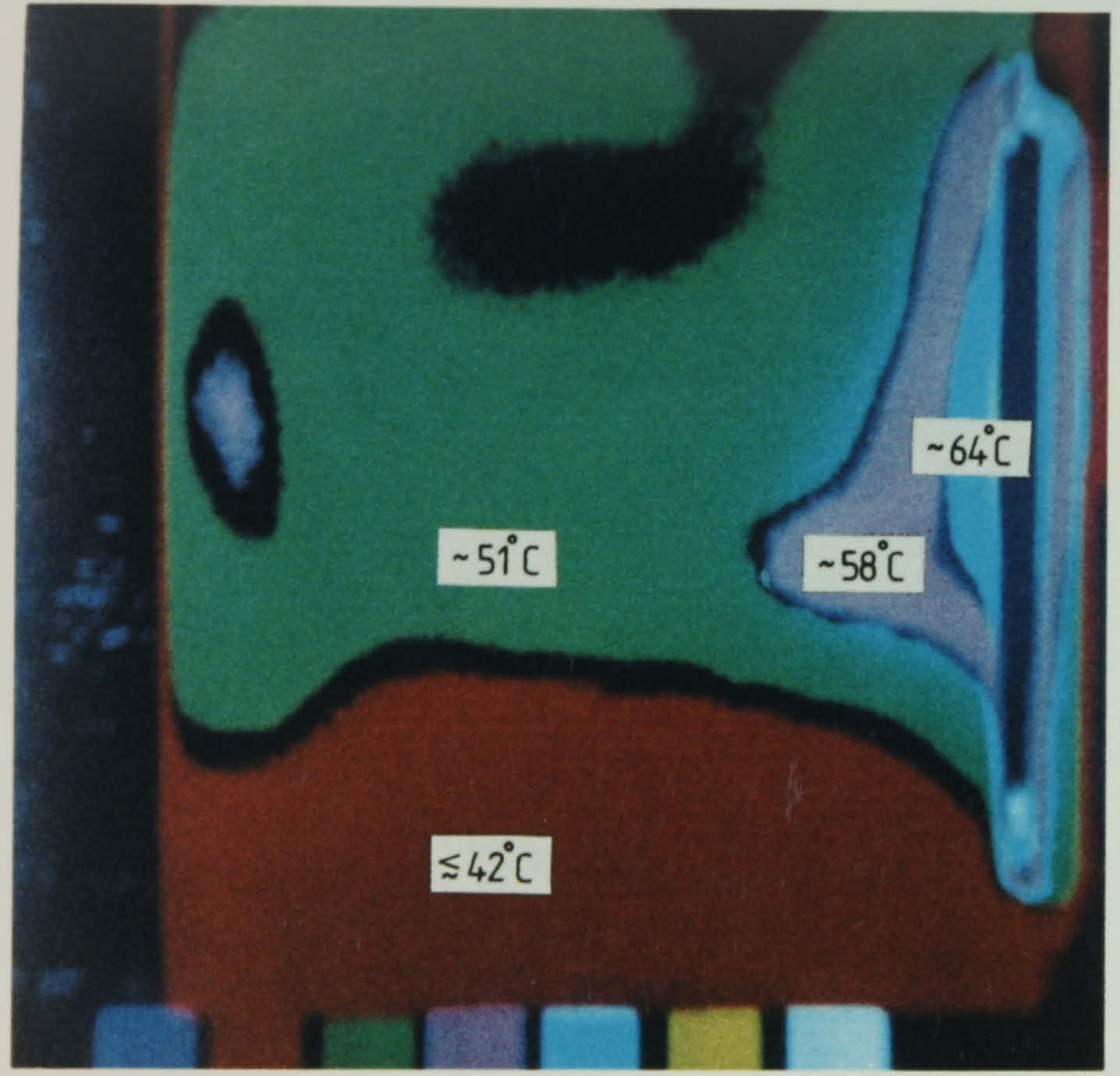

Plate 3. Infra-red colour photograph of the *side* of the cooker nearer the oven door hinges, corresponding to the temperature conditions applying in Plate 1. The colour coding in this instance was chosen to give: red (≤42 °C), green (~51 °C), purple (~58 °C), turquoise (~64 °C) and yellow (≥70 °C). The apparent high temperature zone immediately adjacent to the door/cooker-sidewall interface was due to a highly reflective vertical strip at the right-hand extremity of the cooker's sidewall (see Fig. 20).

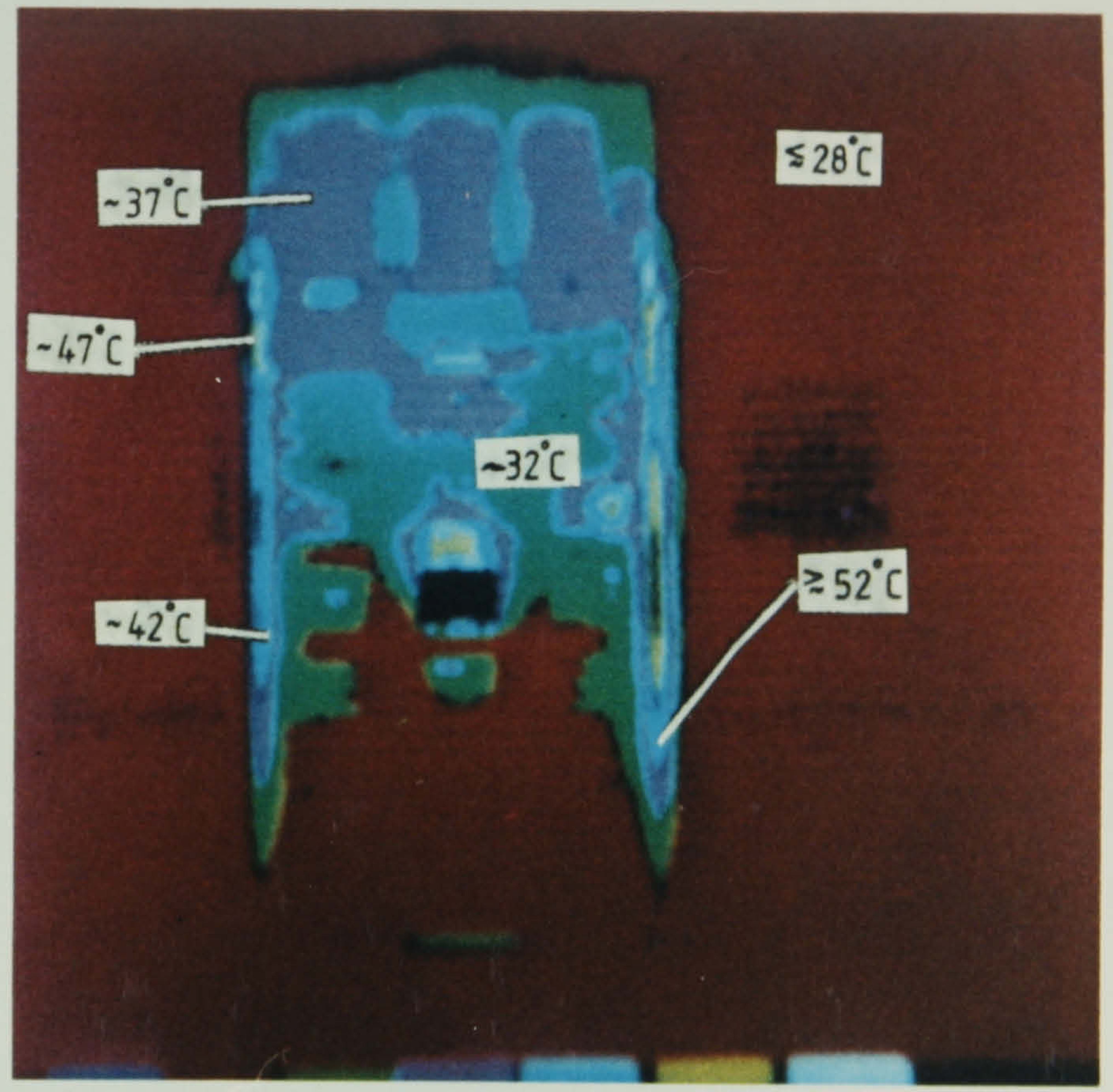

Plate 4. Infra-red colour photograph of the *rear* of the cooker, corresponding to the temperature conditions applying in Plate 1. The colour coding in this instance was chosen to range from: red (≤28 °C), green (~32 °C), purple (~37 °C), turquoise (~42 °C), yellow (~47 °C) to light blue (≥52 °C)—see Fig. 21.

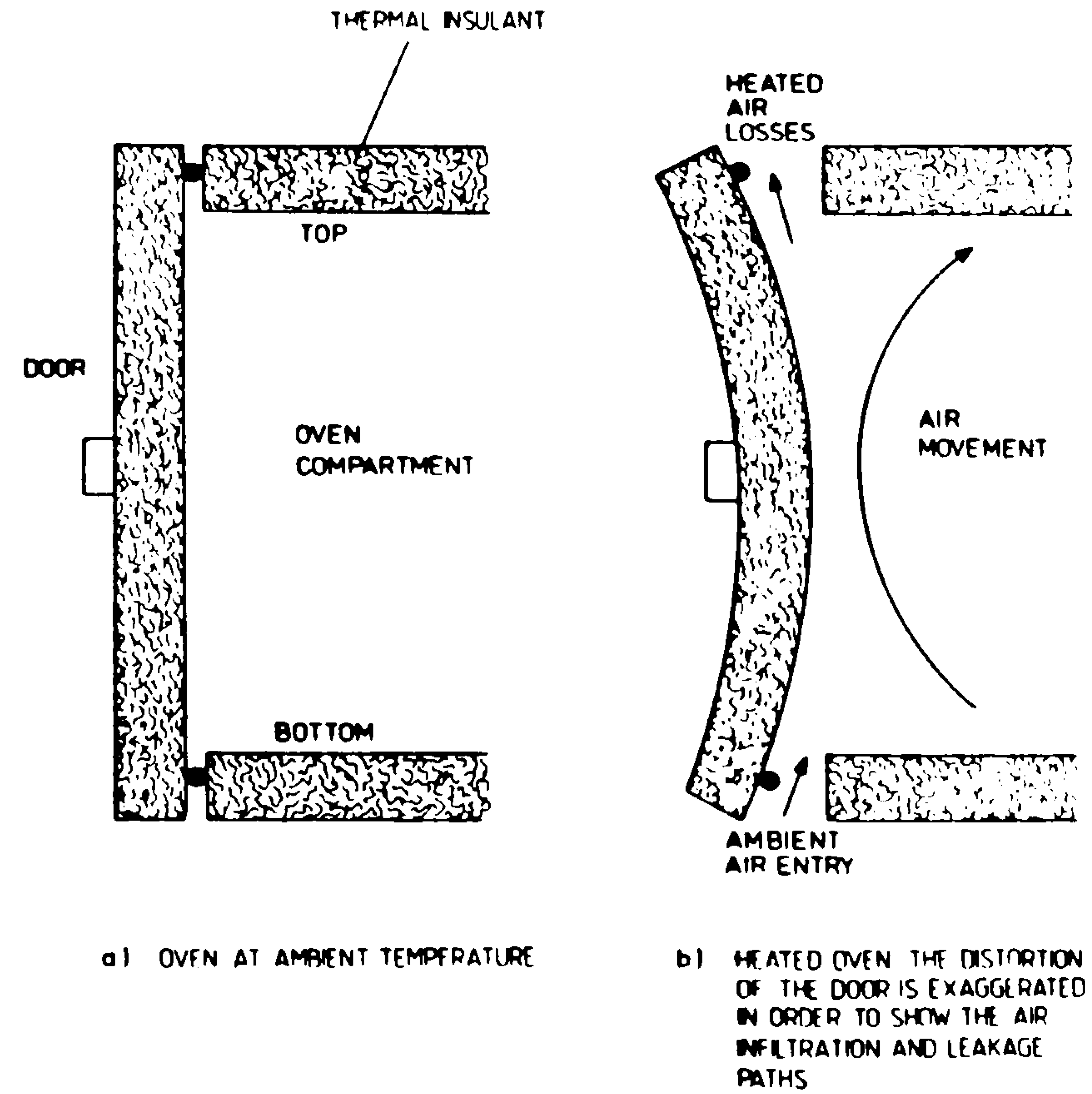

Fig. 22. Exaggerated vertical cross-sectional view of the distortion of the oven door due to the temperature distribution that it experiences when the oven is in operation.

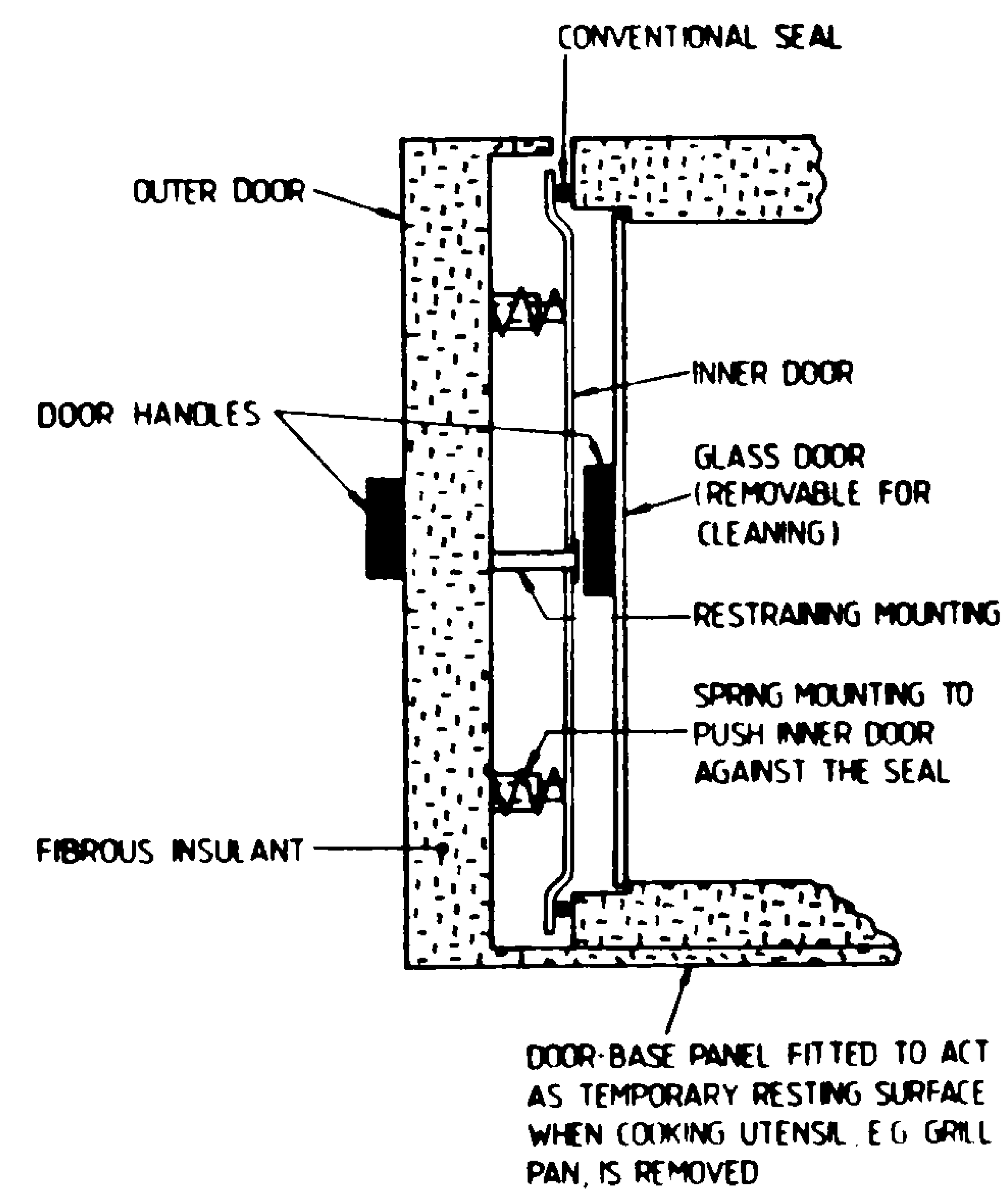

Fig. 23. Schematic vertical section, side view of an oven showing a spring-loaded door, which permits the inspection of the state of readiness of cooked food without incurring large convective losses.

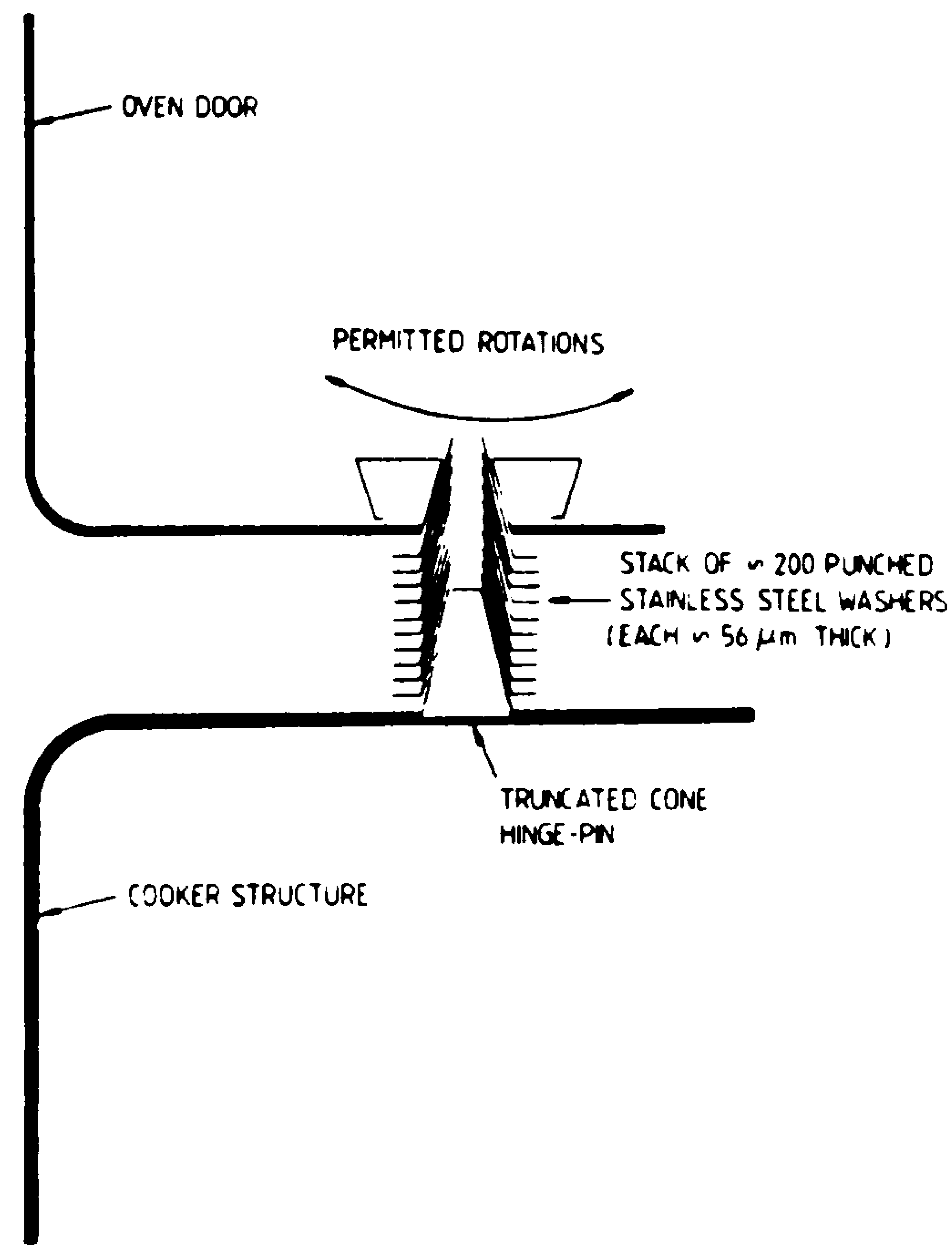

Fig. 24. Front view of the use of a stack of truncated cone-shaped washers as a high thermal resistance, mechanically-strong (in compression), pivot.

space would otherwise be filled with insulant. Using double or triple-glazing for the compartment window in front of the lamp would reduce the rates of heat loss, but for energy thrift it would be better to have no lamp (as in the case of many gas ovens), or one which could withstand the high temperatures to which it would be exposed if positioned within the oven compartment, e.g. an infra-red lamp.[60] However, the latter increases the capital cost of the cooker and thus an illumination system using more traditional technology, similar to the one shown in Fig. 25, *may* be more attractive, both in terms of energy thrift and economics. A narrow insulant-backed reflector is fitted along the rear of the oven compartment's floor: when the oven door is opened, the reflector is turned into its operating position (as shown) by means of a high thermal resistance mechanism linked to the door. The lamp (which is situated on the cold side of the oven compartment's insulation) is then energised. Consequently, light is reflected onto the back of the oven compartment to

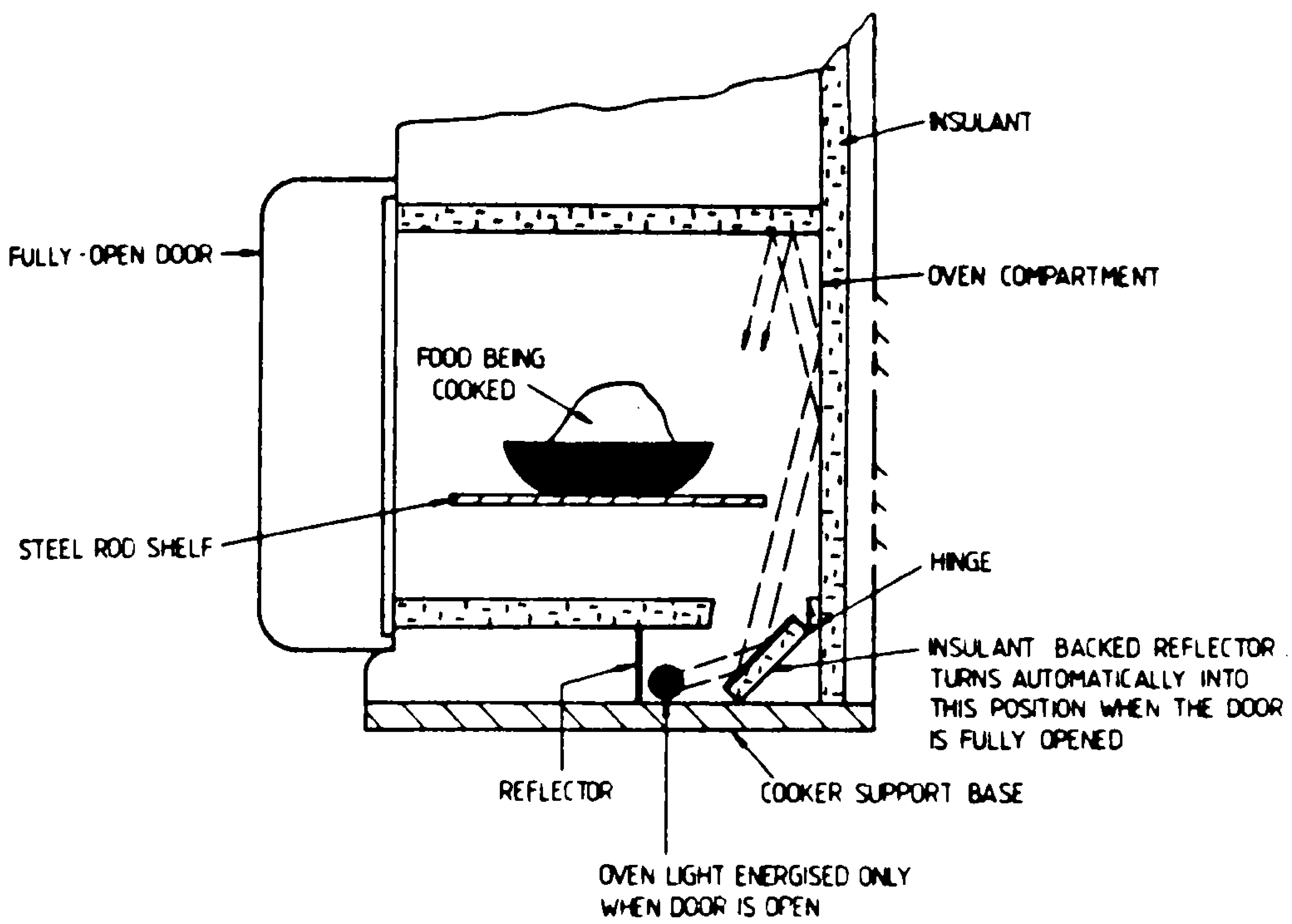

Fig. 25. A proposed oven-illumination system designed to reduce heat losses which usually occur via a conventional oven lamp.

enable the cook to view the food contained therein. However, when in normal operation, i.e. when the door is closed, the insulant-backed reflector forms part of the floor of the oven and the lamp is not energised: this ensures that heat losses which occur with conventional oven illumination systems do not ensue.

FAN-ASSISTED OVENS

These are generally claimed to use less energy than conventional ovens because: first, cooking times (including pre-heat periods) can be reduced, and secondly, lower than conventionally adopted temperatures (usually by 10°C–40°C) are adequate for cooking to occur owing to better temperature distributions and higher rates of heat transfer within the fan-assisted ovens. The principle of operation consists of accelerating the flow of hot air over the food, in order to reduce the thickness of its insulating-fluid boundary layer: this increases the convective heat transfer coefficient and thus increases the rate of heat transfer.

Belling and Company Ltd[32] showed that the temperature response of a sample being cooked with their fan-assisted electric oven (type 430X) was faster than the response for the same sample in a conventional, but otherwise similar, oven (type 430T) for the same power expenditure (see Fig. 26). In practice, energy savings can be achieved (see Table 17), but the performances and 'running' costs of fan-assisted ovens available to the domestic consumer vary considerably (e.g. see Table 18). Other studies undertaken by Thorn Domestic Appliances Ltd[33] also indicated that fan-assisted ovens were more economical in operation than conventional ovens because a more uniform temperature distribution was achieved, and the time taken for the cooking operation was reduced by approximately 15%. Further tests concerning a Neff 'Circotherm' fan-assisted oven showed that despite its many attributes, the contained food tended to cook more rapidly on one side.[32] However, there was a basic design difference between these two electric ovens: the Neff Circotherm drew air in from the oven, heated it and then exhausted it rapidly into

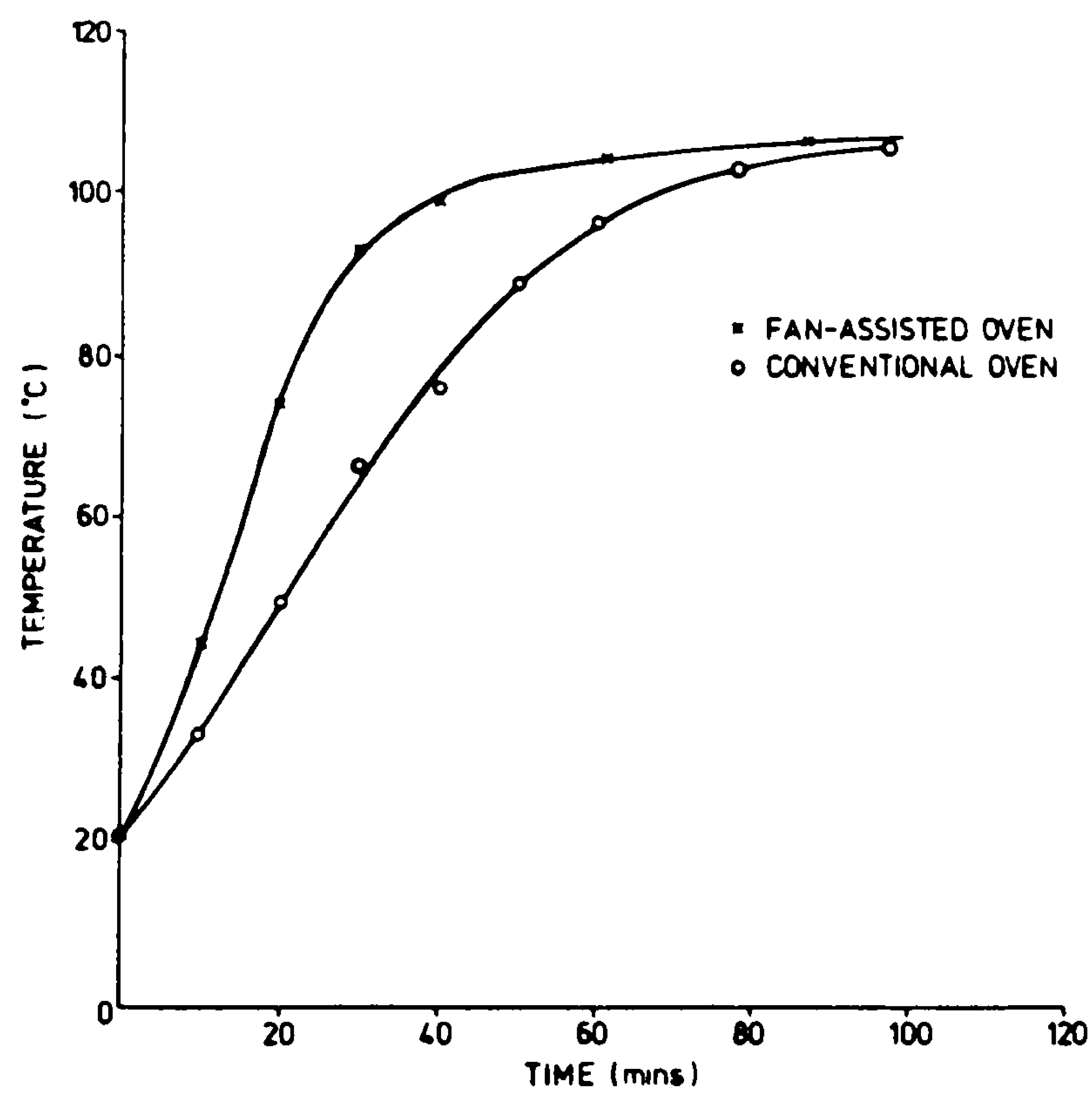

Fig. 26. The temperature responses for a fan-assisted oven and a comparable size conventional oven, at the same rate of power expenditure (from present measurements and data made available by Belling & Co. Ltd[32]). The thermostat was set at 104 °C.

TABLE 17
Comparison of Energy Consumptions in Order to Cook the Specified Items with Either a Conventional Electric Oven (Belling 430T) or a Fan-Assisted Electric Oven (Belling 430X) (adapted from ref. 32)

Food	*Energy used by fan-assisted oven (MJ)*	*Energy used by conventional oven (MJ)*	*Percentage of energy saved by cooking food with the fan-assisted oven*
Four trays of 12 small cakes conforming to BS 3999[61]	3·2	3·4	6
Two-pint beef casserole	8·0	10·4	23
Roast beef, potatoes, Yorkshire pudding and apple pie conforming to BS 3999[61]	8·1	11·0	26
Dundee cake (in a 0·3 m diameter tin)	8·0	11·4	30

the oven compartment via ducts positioned in the oven's rear panel; whereas the Belling oven enclosed the heating elements and the fan merely stirred the air contained within the oven. Most British forced-convection ovens use a helical heating element in close proximity to the fan. Thus some extra cooking space at the sides of the oven compartment is provided, relative to that available in a standard buoyancy-driven convection British oven.

The fan-assisted oven is particularly suitable for commercial use because of three reasons:

(i) It can reduce cooking times, e.g. an 8·2 kg turkey was cooked thoroughly in 2·5 h with a gas-fired forced-convection oven compared with 6·5 h for a standard gas oven of similar capacity.[63]

(ii) The fan-assisted oven can be used effectively for batch baking. The cook can set the thermostat and then fill the oven with food suitable for cooking at the chosen temperature, knowing that each food container will be at an almost identical temperature regardless of its position within the oven. This promotes energy-efficient techniques and a consistently cooked end-product.

TABLE 18
Comparison of Running Costs for Three Similar Fan-Assisted Electric Ovens[62]

Domestic cooker	*Capital cost (£)*[a]	*Fan-assisted oven capacity ($10^{-2} m^3$)*	*Hourly cost (pence) of maintaining oven at 200°C*[a]	*Description of cooker*
Electra Fantasia (EF90C)	315	6·1	3·8	Free-standing hob, grill and oven, four radiant rings (two dual-circuit). Dual circuit grill
Belling Format (600X)	540	6·6	4·0	Free-standing hob, grill, main oven and second oven. Four resistive-type ceramic hobs (one dual-circuit, and one thermostatically controlled). Dual-circuit grill. (Grill cannot be used if second oven is in operation.)
Husqvarna (QC600M)	400	5·9	5·1	Free-standing hob, grill and oven. Four gas burners. Grill fitted inside oven; both cannot be used simultaneously

[a] September 1983 prices—electricity charged at £0·051/kWh.

(iii) The effective cooking capacity of the oven can be increased, relative to a conventional oven of similar volume. Due to the improved temperature distribution, a closer spacing of the shelves is permitted and it is unnecessary to move food around in the oven during cooking. Furthermore, food can remain close to the sidewalls without becoming partially burnt.

Domestic cooks often argue that point (ii) is not necessarily beneficial for their preferred type of cooking. A vertical temperature gradient (which exists in conventional ovens) is frequently desirable because dishes requiring different temperatures can then be cooked together in the same oven. Consequently, in practice, fan-assisted ovens may limit the amount of cooking carried out simultaneously and thus meal preparation, in the extreme, becomes a sequential process rather than an 'in-parallel' process. This would increase cooking-energy consumptions. Therefore it is desirable to provide the cook with the facility to decide which type of oven cooking he/she requires. By making the use of the fan optional, the cook can choose either forced or buoyancy-driven convection depending on the type and variety of foods being prepared.[64-66] Furthermore, frozen food can be defrosted in the oven by air at *ambient temperatures* using the fan only, prior to the cooking operation.[63] The use of such an oven for this purpose, incurs a lower energy-wastage penalty than the process of defrosting frozen food in a heated conventional (buoyancy-driven or forced convection) oven, and provides a more rapid alternative technique to the energy-conscious method of thawing deep-frozen food in a refrigerator.

The use of the domestic 'cook-freeze' system has increased recently due to the *time saving* and *batch baking* attributes of fan-assisted ovens. For example, during the weekend the domestic cook can prepare, cook (preferably together or in quick succession), cool and then deep-freeze foods for several meals, which can then be defrosted, re-heated and consumed as required during the following week. In 1976, Singer *et al.*[28] suggested that the electrical energy saving achieved by this type of procedure was between 50% and 75% of the energy consumed by more traditional practices. It is estimated that today, with the use of a fan-assisted or microwave oven for initial cooking and a microwave oven for re-heating, the potential savings are even greater.

Forced-convection cooking becomes less effective in reducing the cooking periods required as the size of the food item increases.[67] Cooking times for frozen chicken noodle casseroles (0·28 kg each) and 20 cm diameter cakes, cooked in an 0·059 m^3 fan-assisted gas oven, were approximately 50% less than those achieved when cooking with a gas oven of 0·123 m^3 volume. However, those for 5·5 kg roast turkeys were only 24% less than conventional cooking times. Nevertheless, the comparative energy savings were approximately 36% and 54% respectively, indicating that fuel savings tend to increase with food size. Furthermore, it is generally claimed that the cooking operation in a fan-assisted oven is cleaner especially for roasting meats, because the fat is then less likely to splutter. Another attribute is that the circulating hot air rapidly enveloped the meat joint being cooked, thereby sealing in the meat juices: this is alleged to improve the flavour of the end-product.

However, the fan can increase convective losses: therefore when the oven door is opened, the blower should be switched off automatically.

Further developments may include the fitting of a multi-speed blower, which can provide the cook with the facility to vary the rate of forced-air circulation within the oven according to (i) the cooking method and (ii) the dimensions and type of food item being cooked. Also, by controlling the blower, so that its fan-speed increases automatically as the temperatures of the heating elements decrease (i.e. when they are not being stimulated), a more nearly constant rate of heat transfer from the elements to the air inside the oven (and from that air to the food being cooked) should be achieved.

GAS-HEATED OVENS

There are two main types of gas oven used in cookers. British-made domestic gas ovens tend to be *internally* heated by a burner at the rear of the oven compartment's floor, whereas most continental gas ovens are *externally* heated by a burner beneath the oven compartment's floor. The internally-heated variety usually consumes 20–30% less gas than its externally-heated counterpart to achieve the same end-product.[36] However, Enga[44] reported that the cross-sectional areas of the flues of all gas ovens could be reduced by up to 75%, thereby achieving savings in fuel consumptions of 10–20% when under steady-state conditions.

Ovens used for commercial cooking are generally externally heated—the burners usually operating with 200–300% excess air to achieve a high rate of heat transfer to the food.[31] Consequently, the cooking efficiency of this type of gas oven is lower than that of the internally-heated variety. To improve the energy effectiveness, an electric fan can be fitted into the oven compartment. The air contained therein is heated indirectly through a heat exchanger while the combustion gases are vented to the external environment. However, the efficiency of this 'indirectly-fired' fan-assisted gas oven can be raised considerably if the combustion gases are allowed to mix completely with the air circulating around the food, by fitting the fan in the combustion chamber adjacent to the oven compartment.[68]

Such 'directly-fired' fan-assisted gas ovens (see Fig. 27) were developed originally by the American Gas Association[67] firstly, to increase the oven's cooking speed (which had been recently challenged by the microwave oven in the USA), and secondly, to reduce oven heat losses to

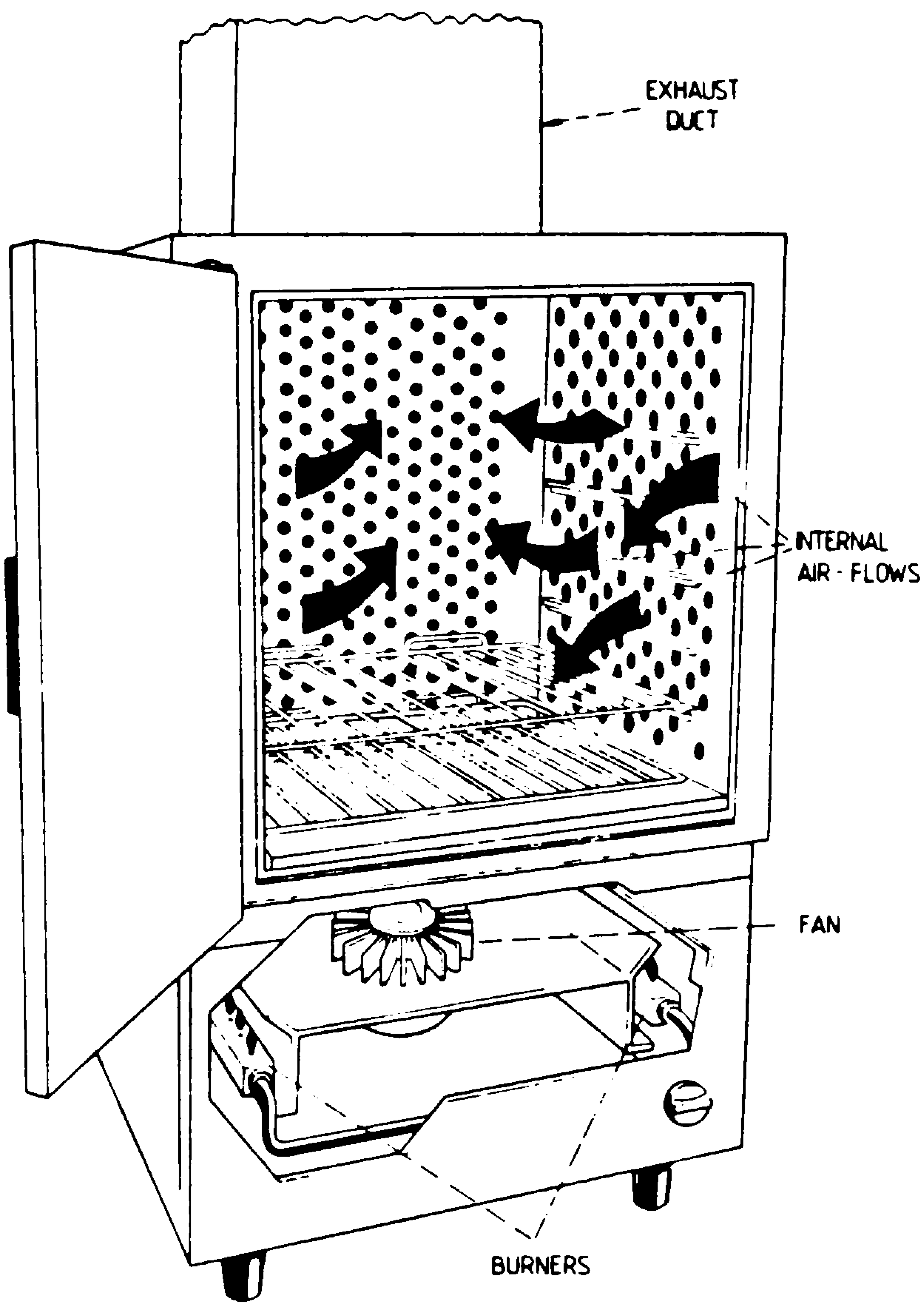

Fig. 27. A directly-fired fan-assisted gas oven (after ref. 63). The exhaust duct should include a heat exchanger to permit the exhausting air to heat the combustion air being supplied to the oven.

the kitchen. Tests indicated that this type of fan-assisted oven shortened cooking times by between 20% and 50%, and reduced overall heat losses to the kitchen by up to 50% when compared with externally-heated, conventional, gas ovens. It was also alleged[31] that such ovens can operate satisfactorily with only 75% excess air and thereby achieve a reduction in flue losses of about 50% and an overall increase in efficiency of about 40% compared with conventionally-heated gas ovens. In the UK, ovens based on the same principle are claimed to save 20%, 32% and 40% of the energies used on average for cooking frozen food, for cooking non-frozen food and for pre-heating the oven before cooking, respectively, when compared with indirect-fired fan-assisted gas ovens.[68]

However, although fan-assisted gas ovens are used in catering establishments throughout the world,[69] they are not readily available on the UK domestic market because:

(a) the vertical temperature gradient within the oven is removed;
(b) the additional design complications increase manufacturing costs and therefore reduce saleability in a market where comparable electric cookers are already cheaper; and
(c) the proper operation of the oven is dependent on the fan and thus satisfactory cooking cannot be achieved during a mains-electricity failure.

To overcome limitations (a) and (c), a 'dual-purpose' gas oven has been developed by the BGC—see Fig. 28. Tests carried out with this type of oven, having a capacity of approximately 0·05 m^3, yielded results similar to those obtained with a conventional gas oven when the fan was not used; but with forced convection, it cooked many foods at almost double the speed and for lower energy expenditures.[63] For example, the time taken

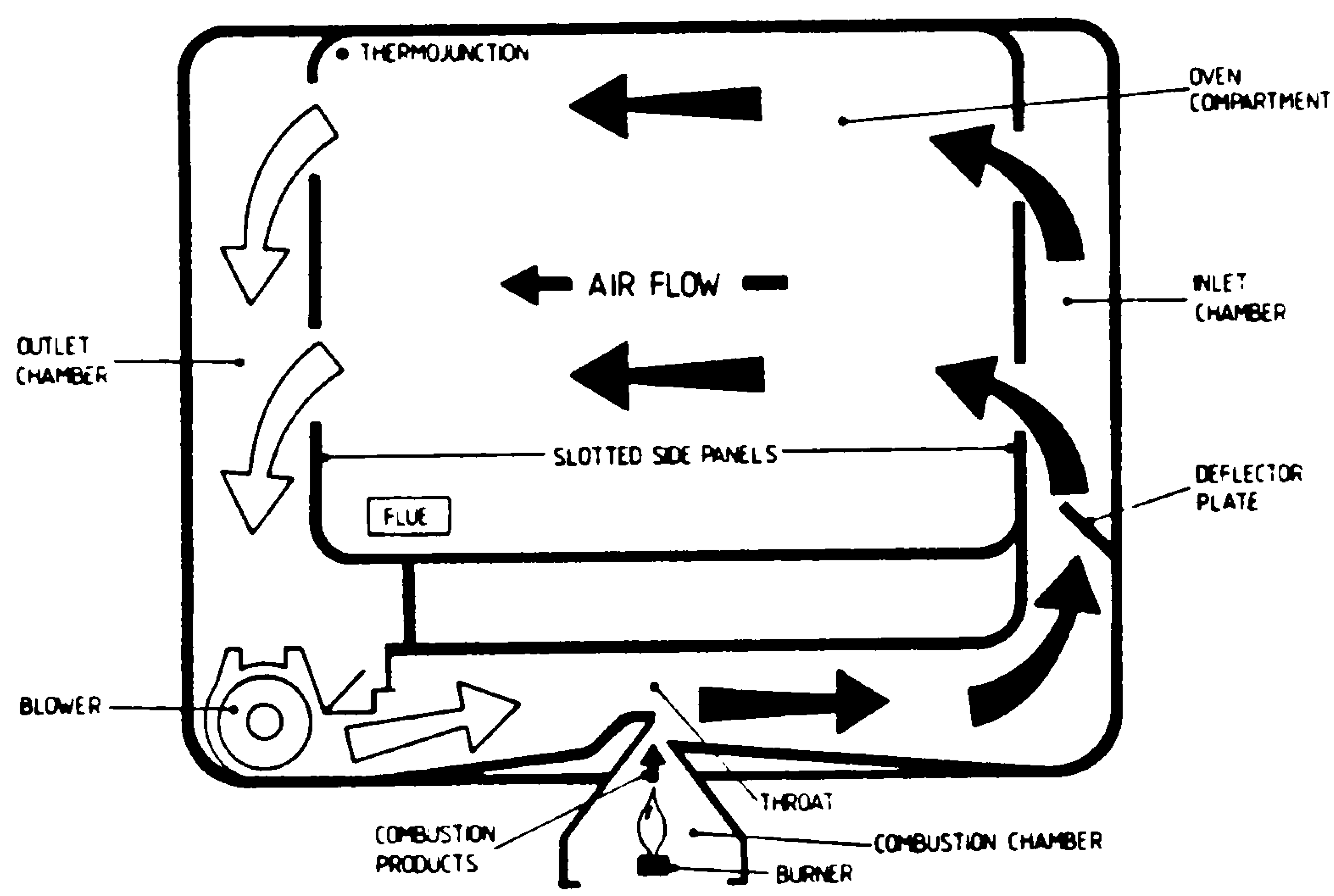

Fig. 28. Schematic representation of a 'dual purpose' gas oven which provides a choice of forced or natural convection cooking as required (after ref. 63).

to cook a 'full dinner' was reduced from 120 min to 77 min. These results corroborated those obtained for comparison purposes with a fan-assisted electric oven and were achieved at temperatures approximately 20°C lower than in conventional ovens.

However, the prospective energy savings of a fan-assisted gas oven are considerably greater than those of a fan-assisted electric oven, and thus the use of the former would probably reduce significantly domestic cooking-energy expenditures.[31,70] Indeed Flood and Enga[36] predict that the introduction of forced-convection gas ovens into UK domestic dwellings, as replacements for conventional domestic gas ovens, would save ~7·2 PJ (i.e. approximately 8 % of the gas used annually by domestic cookers). In the meantime, efforts are being made to find a cost-effective compromise between the attributes of forced-convection gas cooking and conventional gas cooking. For example the TI New World 'System-One Gyroflo' (a built-in gas cooker) is claimed to have a more uniform temperature distribution and is able to cook 25% more food than a comparable size conventional gas oven, due to the improved air flow patterns within its oven compartment.[71]

Differences in performances between gas and electric ovens

The *end-use* efficiencies of standard domestic gas ovens are inherently lower than comparably sized electric ones because the gas appliance needs to be ventilated continually in order to achieve adequate and safe combustion of the fuel. However, the *overall* energy effectiveness of gas cookers is in general superior to that of electric cookers (see Table 10) because of the low national electricity supply efficiency (≃28%). In 1975 it was estimated, somewhat pessimistically, that a complete conversion from electric to gas cooking in the UK would save 50 PJ per annum (i.e. about 0·5%) of the nation's primary energy supply.[26]

Some electric cookers tested by the Consumers' Association cost, on average, between three and four times as much to 'run' as comparable gas ones, although the latter were 10–20 % more expensive to purchase in the first instance.[72] Therefore replacing a conventional domestic electric cooker with a traditional gas cooker should, on average, achieve long-term financial savings, provided that the home is already fitted with a gas-fired space heating/hot water system (otherwise the restrictive nature of the 'standing-charge' energy pricing policy for fuel-gas inhibits such fuel substitutions). Nevertheless, considerably more energy (and hence money) can be saved by practising energy-efficient cooking techniques (see later), than by replacing a domestic electric cooker with an equivalent gas one.

An important difference for the housewife is that electric ovens are alleged to remain cleaner during cooking than their gas counterparts. Because the humidity of the air within a gas oven is much higher, its use is preferred by many cooks, even though this increases the probability of condensation occurring within the kitchen. Dunning[57] suggested that a means of controlling the humidity within an oven during cooking operations would generally improve the quality of the end-product. For example, high humidity in an oven while roasting a meat joint will cause the salts and juices to drip off into the cooking utensil. Thus many cooks may find a low-humidity (i.e. electric oven) atmosphere preferable when roasting meats, because salts and extractives are then more likely to remain on the meat, thereby improving its flavour. However, in the catering sector, the primary intentions may be to minimise weight loss (which occurs via evaporation and fluid dripping off the meat), and to reduce energy expenditures. Bengtsson *et al.*[58] reported that (i) 'drip' losses were only significant when the temperature of the meat was above 65 °C, and (ii) evaporative losses could be reduced by raising the relative humidity of the air within the oven. Therefore the 'slow cooking' of meat in a gas oven may be preferred by caterers, who wish to obtain the greatest number of servings for given inputs of energy and uncooked food.

THE GRILL COMPARTMENT/SMALL OVEN

For successful grilling, radiant heating is required during a relatively short period in order to brown the surface of the food without incurring excessive moisture loss from its interior. Unfortunately only a small fraction of the heat emitted from a typical gas-fired or electric grill is absorbed and retained by the food—the remainder being lost to the appliance and its surroundings.

Reliable data are scarce concerning the performances of these cooker systems. This is partly because judgements of effectiveness are subjective (e.g. different individuals have various preferences for rare, medium or well-done steaks). The assessment difficulty is compounded because foods of differing absorptivities require different levels of grilling. Nevertheless the typical gas grill of a domestic cooker is claimed to be the least efficient appliance when compared with fan-assisted ovens, conventional ovens, griddle plates or various hob heaters.[73] Griddle plates were found to use 8% less energy than grills for similar tasks, and thus cookers fitted with these are to be preferred. The (now) common fitment of a grill into the roof of a built-in electric oven will, it is estimated, further reduce grill efficiency whilst removing the facility of, for example, grilling and baking simultaneously. However, high-level grills may afford some increase in cooking efficiency because the food can be viewed without the need to remove the pan from the grill.

In tests carried out by Thorn Domestic Appliances Ltd,[33] it was shown that the small ovens in general had rates of heat loss about twice those from the main ovens. The small oven normally incorporates a grill heating element, additional heating elements at its sides, and sometimes a heating element near its base. Recently-manufactured small ovens usually have temperature controls rather than, as formerly, merely on–off switches, so that these small ovens can be used to cook in a precisely predefined manner as well as just to keep foods warm.

The better domestic electric cookers have fast-response dual-circuit grills, which permit some reductions in energy consumption to be achieved especially when cooking only small quantities. However, fan-assisted 'hot-air' grills, which have been incorporated in electric cookers recently, may supersede conventional electric grills.[64,65,74,75] Advantages claimed by the consumer as a result of adopting this system include more uniform grilling of the food (which need not be turned over during the operation) and an energy saving, compared with conventional electric grilling. A reduction in energy expenditures can be achieved mainly because the small-oven door can be closed when the grill is in use: this also helps to inhibit the escape of cooking odours from the grill to the kitchen environment.

Most electric grill compartments (and some main ovens) have 'drop-down' doors, hinged at their bases. When open, such small-oven doors hinder access to the main ovens and provide enticing and convenient load-bearing surfaces. The consistent misuse of these doors in this manner causes the hinge mechanisms to deteriorate quickly, thus resulting in the doors' seals becoming less effective when the ovens are in use. This is sometimes rectified by fitting a sturdy catch or spring-loaded mechanism to pull each door firmly shut. However, to achieve a reduction in energy consumption, especially when using the grill, a similar door to that recommended for the main oven (see Fig. 23) could be fitted to the small oven. Both the inner and outer doors should be shut when the small oven is being used for cooking, but only the inner glass door need be shut completely when grilling, thereby providing easy viewing yet some inhibition of convective losses. Clearly for this modification to be successful practically, the typical grill pan and its handle would have to be re-designed to allow the glass door to shut.

Improvements in the effectiveness of gas grills have resulted from the development of a higher temperature 'surface combustion' grill by the BGC.[34] This uses a metal gauze, instead of a conventional grill fret, to radiate heat onto the underlying food and is claimed to operate with an efficiency of up to 48 %[44] whilst providing a more uniform grilling at any setting. Another recent step forward for the conventional gas grill is the introduction of a 'duplex' burner control, which permits the use of only approximately 50 % of the grill burner when preparing small quantities. If fitted to all UK domestic gas cookers, duplex grill burners will, it is estimated, save 1·7 PJ per annum nationally.[36]

From an energy conservation perspective, employing a toaster, sandwich-toaster or an infra-red grill is preferable to using a conventional grill. A typical toaster consumes only about 20 % of the energy dissipated by an electric grill to toast two slices of bread.[28] Alternatively, more versatile rapid-response infra-red grills, some of which are fan-assisted, can be used to reduce the rates of energy expenditure, by between 10 and 75 % according to the food being cooked, compared with employing traditional electric grills. Indeed, high efficiency short-wave infra-red heaters can be used to cook food both rapidly and uniformly. In future, these may be employed to a greater extent because even though their capital costs will be slightly greater, their lower operational costs will be more appealing to the consumer.

THE SELF-CLEANING OVEN

The *pyrolytic* type of self-cleaning oven functions by raising, for a period of approximately 2 h (but not whilst cooking), the oven temperature to around 500 °C, thereby burning-off any splashed deposits. Later when cool, the resulting debris on the floor of the oven, can be removed using a damp cloth. To achieve the necessary high surface temperature, additional heating elements are needed at strategic positions around the oven and these are used *only* for this self-cleaning operation. To ensure that the *outside* surface temperatures during the cleaning process will always be less than 95 °C—which appears excessive, but nevertheless complies with British Standard 3456,[76] a greater thickness of insulant is required for this type of oven. This, it is claimed,[31] increases the overall efficiency of the oven by 1–4 % over a typical sequence of cooking operations, including due allowance being made for the energy expended for self-cleaning. However, during the self-cleaning process, the high temperature difference between the inner and outer leaves of the oven door may cause it to warp (see Fig. 22). A design, such as the one illustrated in Fig. 23 could be used to reduce this possible thermal distortion, thereby inhibiting air leakages and so contributing to energy thrift.

The use of high-grade energy to clean the inside surfaces of an oven compartment by this type of self-cleaning process is very wasteful, especially when good traditional cleaning techniques are available and slight modifications to the design of the conventional oven will simplify the cleaning process. By manually cleaning the oven at regular intervals, the amount of soiling will be kept small: provided that it is cleaned shortly after use, the cleaning operation will be considerably easier because fat deposits will then be relatively soft. However, this practice is irksome with free standing cookers, partly because of the low position of the oven compartment. Even with the raised, 'eye-level', built-in ovens, cleaning is somewhat awkward. Therefore it is suggested that a removable three-piece oven liner (see Fig. 29) should be fitted to future appliances. This could be removed easily and cleaned in the conventional manner. Furthermore it could be manufactured with a low emissivity surface which would help reflect radiation back towards the centre of the oven, thereby improving the overall cooking effectiveness. However, when cleaned, this component must not be scoured, because such action would raise its emissivity and reduce its reflectivity. Nevertheless, the ease of cleaning, relative to that achievable with conventional ovens, may encourage the cook to clean such an oven more frequently and more carefully. Consequently, its application as an energy-saving alternative to the pyrolytic self-cleaning oven is recommended.

The *catalytic* type of self-cleaning oven has its inside leaves coated with a matt-finish enamel, which, due to the inclusion of special oxides, tends to keep the internal surfaces clean during cooking. If the amount of soiling becomes excessive, the oven temperature may be increased to approximately 300 °C for up to 2 h. After subsequent cooling to near

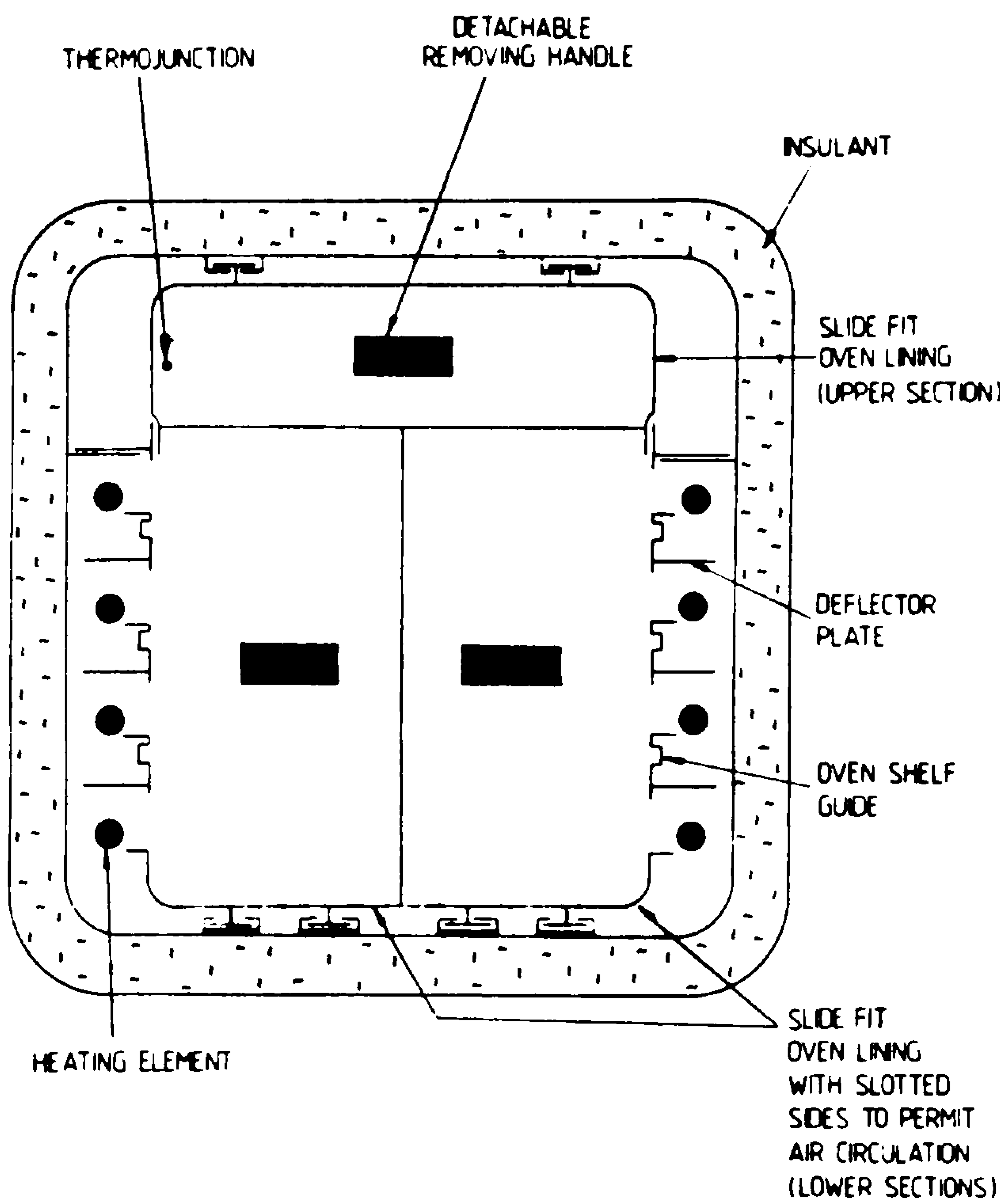

Fig. 29. A sectional vertical front view of a conventional electric oven fitted with an internal oven lining which can be easily removed, for cleaning purposes, in three pieces

room temperature, the cleaning process merely involves wiping (but never scouring) these linings. The use of this more popular variety of self-cleaning oven is preferred, because its self-cleaning process is less energy wasteful than that for the pyrolytic type.

IMPROVING THE EFFICIENCIES OF CONVENTIONAL OVENS

The internal configuration of an oven should be designed such that, per watt expended, a high rate of heat gain by the food being cooked is achieved. Then, the economically-justifiable thickness of a low thermal mass insulant should be determined and applied, ensuring that no low

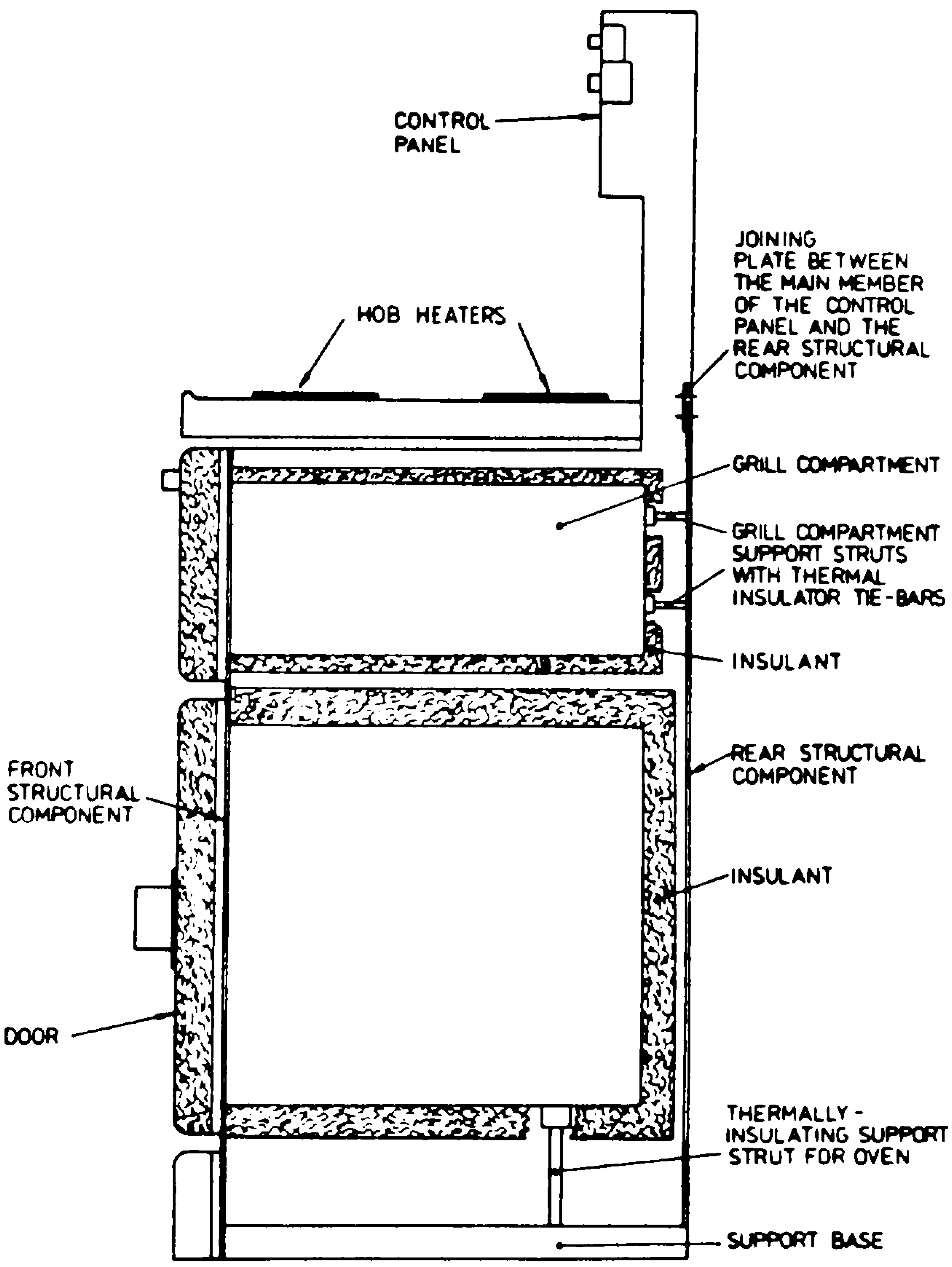

Fig. 30. Cross-sectional side view of an improved free-standing cooker, showing the rear structural component which is more thermally isolated from the oven than is conventional practice. A multi-layer, structurally-strong insulator (not shown) inhibits thermal bridging across the front structure of the cooker, thereby reducing heat transfers between the grill compartment and the oven.

resistance thermal bridges occur between the inside of the oven and its external surfaces (see Fig. 30). The latter was attempted by Philips[77] in their built-in 'Deluxe Single' electric oven: the oven cavity is suspended within, but clear of, the framework which supports it in the kitchen unit, thereby inhibiting conductive losses.

The external shape of the oven should be such as to result in only a relatively low rate of heat loss, e.g. protruberances which may act like heat exchanger fins should be eliminated from the design. Theoretically, the ratio of the oven's surface area to its volume should be minimised in order to minimise heat losses from the oven for a given energy input. However, in practice, an optimum will exist which takes into account oven cooking techniques and the size of the average food item cooked. Further to this, it is important to ensure that the thermal inertia of the oven (especially of its internal components) is as small as is feasible, because the typical oven will be used only intermittently. Efficient door-seals should also be fitted to reduce convective losses, e.g. Erickson[31] reported that the flow of hot air from a standard US domestic electric oven, when in normal operation (i.e. with its door closed), could be reduced from about 0·125 m^3/min to less than 0·06 m^3/min by using a better designed door-seal. In practice, the optimal design for an oven will be a compromise which satisfies these interdependent criteria.

From an energy-thrift viewpoint, in order to transfer heat by *buoyancy-driven convection* to the food being cooked in an electric oven, the heating elements should be arranged so that the most favourable flow pattern is achieved within the oven compartment. The heated air should impinge on the food to be cooked before being deflected by the relatively cold oven roof. Thus the elements should be positioned near the floor of the oven compartment (see Figs 31 and 32). Preliminary experiments (including smoke visualisation tests) indicate that an improved temperature distribution and rate of heating can thereby be achieved (e.g. see Plate 5). Further improvements in oven efficiency can be accomplished by increasing the surface area of the heating elements.[31] The judicious positioning of thermal-insulant backed area-heaters—as suggested by Newborough and Probert[78] for heated seating—or etched foil elements[79] could offer more versatile, uniform and responsive heating, and occupy less space inside the oven cavity. If the voltages applied to these elements were adjusted continuously according to the temperature difference between the food being cooked and the air surrounding it, oven cooking operations could be regulated more accurately than those carried out with conventional systems, which employ traditional heating elements controlled by bimetallic strips. Because the oven would be heated continuously it would: (i) have a less erratic transient temperature distribution than that created by the sporadically stimulated, high temperature (~650 °C), high thermal mass heating elements of a conventional oven; (ii) subsequent to the oven door being opened and closed, regain thermal stability relatively quickly; and (iii) demand a

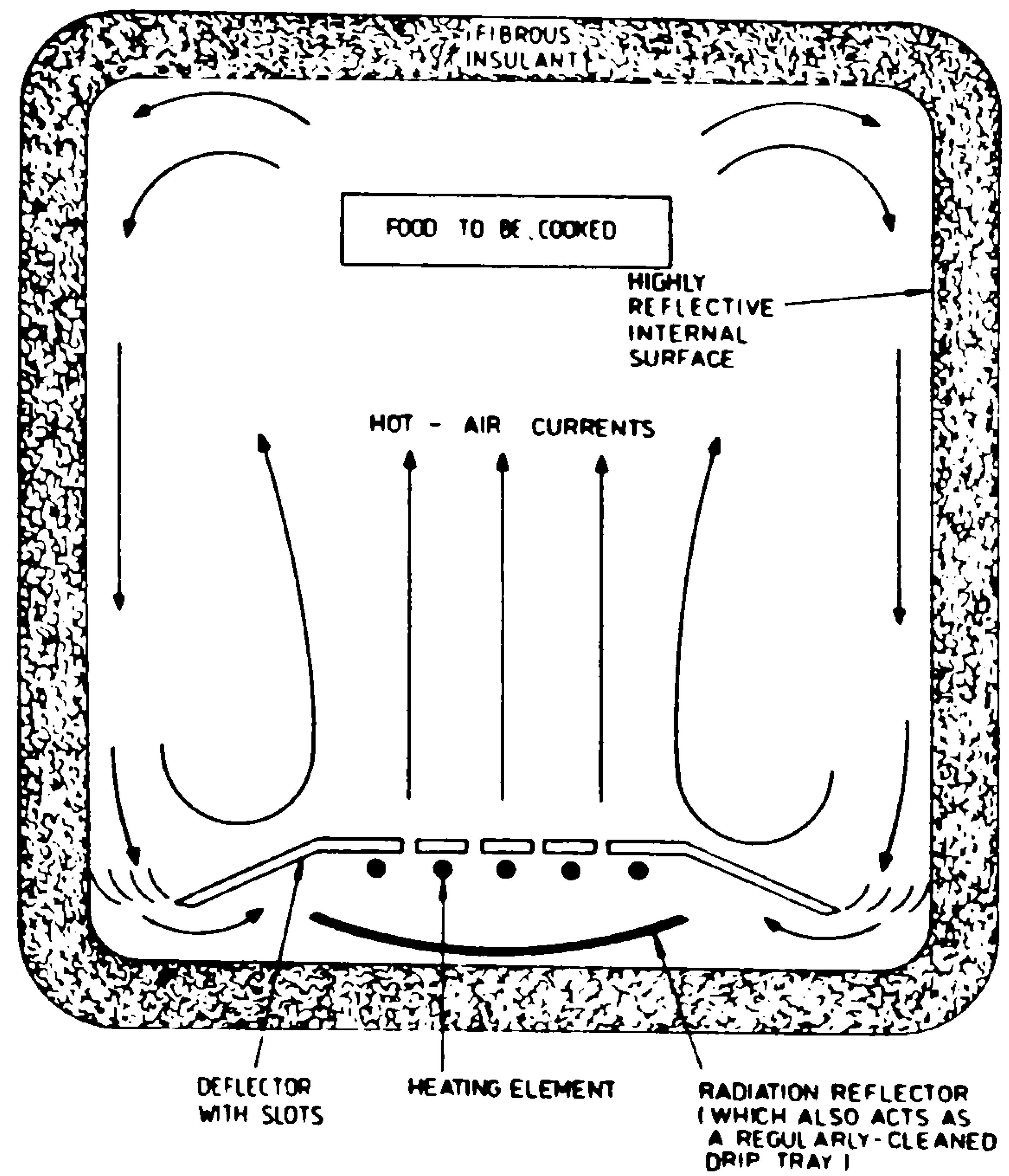

Fig. 31. Schematic vertical section of a proposed oven heating system. (The scale of the heater unit is somewhat exaggerated compared with that of the oven.)

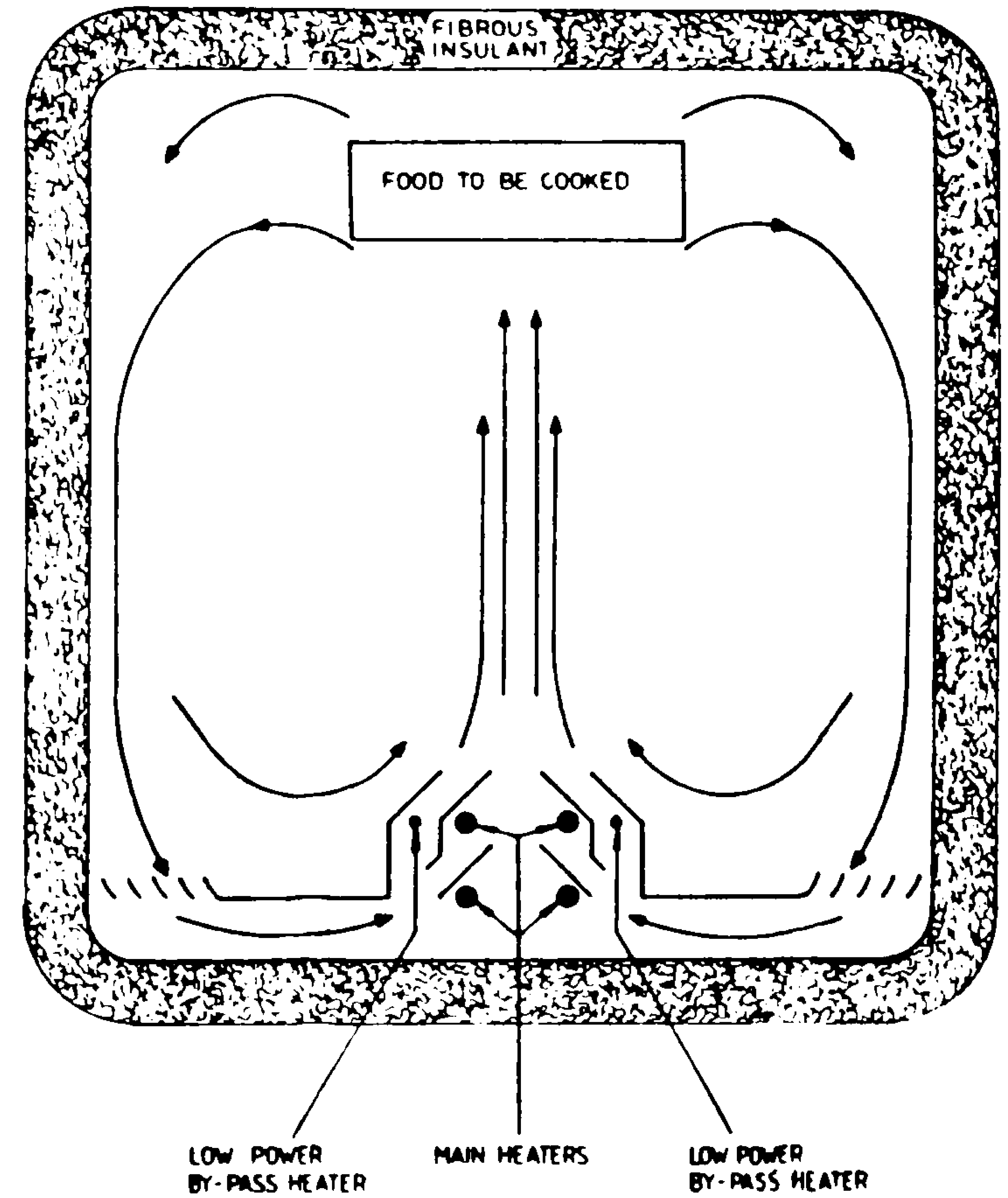

Fig. 32. Schematic version of an alternative proposed oven heating system. (The scale of the heater unit is again exaggerated compared with that for the oven.) The by-pass system increases the 'throw' of the natural convection air jet issuing upwards from the heaters, without requiring any extra power expenditure.

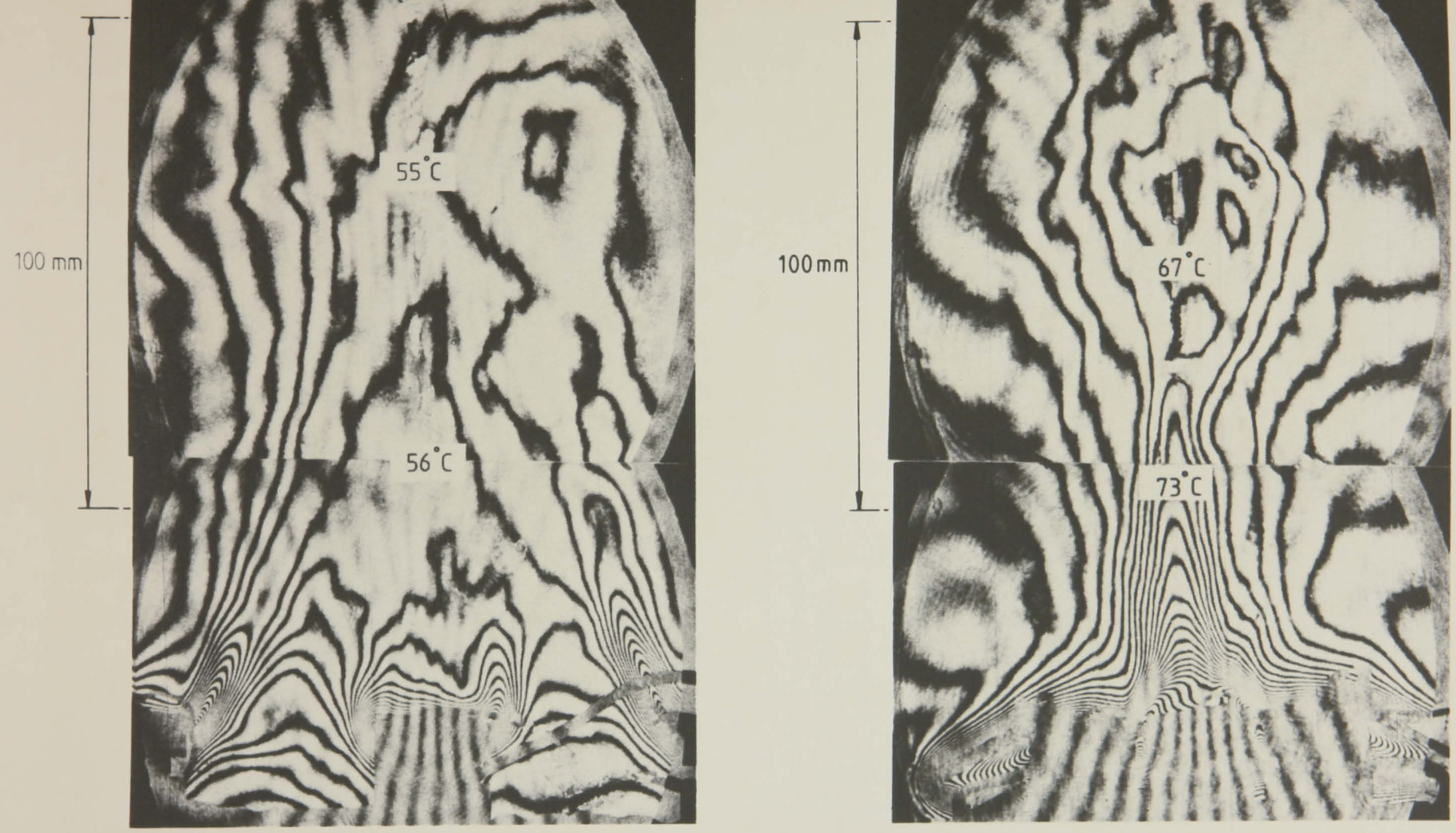

Plate 5. Typical steady-state interferograms for a base-heated experimental oven of the form shown in Fig. 3. The continuous power input was 107·2 W in each case. The slots in the deflector plate positioned above the electric elements were, in case (a) 45 mm wide, and in case (b) 3 mm wide. The latter arrangement is preferable because the air temperatures (as indicated), achieved near the centre of the oven for the given continuous power input, are greater. (Optimisation of this heater design is still needed.)

lower instantaneous electrical power input. If such a design caused the vertical temperature gradient (see Plate 5) to be too great or the undersides of food items to be overcooked, additional heaters could be placed on the roof of the oven compartment to radiate downwards (i.e. in a similar fashion to the heating systems employed in continental electric ovens). This would not necessarily cause the surfaces of food items to be over-cooked, as can occur when conventional heating elements are employed, because the maximum attainable surface temperatures of such area-heaters are normally less than 300°C. Indeed, Dunning[57] indicated that the method of heat transfer to the food is less important than the temperature it attains. This suggests that improvements in an oven's energy efficiency (and possibly the quality of the cooked food that it produces), may be achievable if the ratio of convected to radiative heat transfers within it can be varied.

If additional thicknesses of a low thermal-mass insulant were introduced as the lining of a cooker (of fixed external dimensions) in order to increase its oven's efficiency, a decrease of the oven compartment's volume would result and so the system would appear to be at a commercial disadvantage when competing against conventional cookers. Even so, it has been shown[80] that by reducing each of the interior dimensions of a standard oven compartment by 5cm, and if the same amount of insulant and the same door seals as in a self-cleaning oven are employed, an increase in cooking efficiency of about 15% can be achieved. Alternatively, or in addition, substituting Microtherm (see Appendix 2) for the conventional glass-fibre insulating blanket will increase the oven's efficiency or permit an increased compartment capacity to be achieved for the same outside dimensions of the cooker. Unfortunately, many manufacturers may be opposed to such modifications even though the incurred increase in the cost of insulant represents such a small fraction of the total cost of the cooker. (The cost of Microtherm is approximately four times the cost of an equivalent *volume* of glass-fibre insulant matt.) However, as suggested by Norgard,[81] such oven insulation could serve to partially bear the weight of the oven and so reduce the need for some of the relatively high heat-conducting metal supports. Further to this, manufacturers should be encouraged to (i) decrease the emissivities of the internal surfaces of oven compartments, and (ii) reduce the thermal masses of oven shelves.

Recent domestic oven developments have included the introduction of fully or partially-glazed doors to improve the oven's appearance, and to provide a means for the cook to visually check the food that is being cooked in the oven without having to open the door. Unfortunately this has conflicting virtues from an energy viewpoint. An oven door, fitted with a small sealed triple or double-glazed window—having an optimal air space between vertical panes ($\sim$16 mm width for the temperature differences encountered in most oven cooking operations) and a perforated radiation reflector fitted on the inside of the inner pane—which is surrounded by ample thermal insulant, will contribute towards increased energy efficiency, mainly because of the low frequency with which the door will be opened due to the improved viewing capability. Nevertheless a glazed window will usually lead to the door's thermal resistance being reduced because, when the oven is in use, the rate of radiative heat loss from the oven will increase. Therefore there will be an optimal area of the door which should be glazed,[31] but because energy-thrift in cooking is still in its infancy in the UK, design specifications for this optimum do not as yet exist. The use of commercially available, domestic convection ovens with fully glazed doors is not recommended. Furthermore, the 'air-wipe' feature fitted to many double-glazed doors (especially those belonging to self-cleaning ovens of foreign origin), where room air is allowed to pass between the inner and outer panes (in order to reduce the outside surface temperature of the latter), is very energy-wasteful.

The best arrangement for general cooking purposes is probably a tightly-fitting, well thermally-insulated door with an equally well fitting internal-glass door (see Fig. 23). Occasional visual inspection can be accomplished by opening the oven door whilst keeping the glass door firmly closed. Opening both doors should only occur for the introduction, removal or testing of the food. In this way, the high radiative losses from a standard glazed door, and the large convective losses resulting from the relatively more frequent opening of a conventional oven with a single door, will be reduced. Alternatively a highly reflective insulating blind, which can be pulled down from the top of the oven could be fitted to reduce convective losses. Dishes which need least heating should be placed on the lowest shelf (i.e. in what subsequently becomes the lowest temperature zone) of the conventional oven, and when the food is cooked, the dishes should be removed by lifting the blind up only the necessary amount. However, further energy savings could be achieved by fitting some means of remotely testing (e.g. for its temperature) the food being cooked (i.e. providing this facility without necessitating the opening of the oven door). This would reduce the number of times the door needs to be opened and may therefore be particularly effective in catering premises, where many similar dishes are cooked simultaneously.

When considering raising the efficiency achievable with a cooker (or any energy-consuming appliance), it must be realised that for the purchaser there will be an optimal choice, often corresponding to the minimum overall cost. A measure of this cost can be obtained simply as the sum of the present initial capital cost of the installation and the operating and maintenance costs over the expected lifetime of the cooker. The financial 'best-buy' choice of design will not usually achieve maximum technological efficiency for that specified financial expenditure. However, with the rise in the unit costs of fuels leading to an increase in the summed operating cost, this optimal choice will move closer to the maximum efficiency design (see Fig. 33).

Other design improvements

Erickson[31] developed energy-efficiency targets for cookers on behalf of the USA Federal Energy Administration. Measurements were carried out on four electric cookers, three gas cookers and one microwave oven. Mathematical models, to describe the thermal behaviours of a typical oven and hob unit, were constructed using electrical analogues for the heat-transfer processes. Subsequently economically-justifiable improvements to reduce these losses were deduced (see Table 19). However, the conclusions are not all relevant to the British scene, because for example the tests were conducted for ovens with some heating elements near their bases whereas, primarily for safety reasons, the typical British electric oven has evolved with horizontal heating elements only along its vertical sidewalls. Generally though, it would appear that US ovens tend to be more energy efficient than UK ovens.[82]

Further research is being carried out to develop a 'bi-radiant' electric oven which it is alleged will reduce energy consumption by over 60%.[30] This has a highly reflective internal surface, which directs radiation onto the contained food from the heating elements positioned at the top and bottom of the oven compartment. Because of its efficiency, it will enable the elements, which are independently controlled, to function at lower temperatures than those fitted in a typical conventional oven. However, the inside of the oven must be very carefully cleaned to ensure that the high cooking efficiencies are maintained. The average cook may feel that

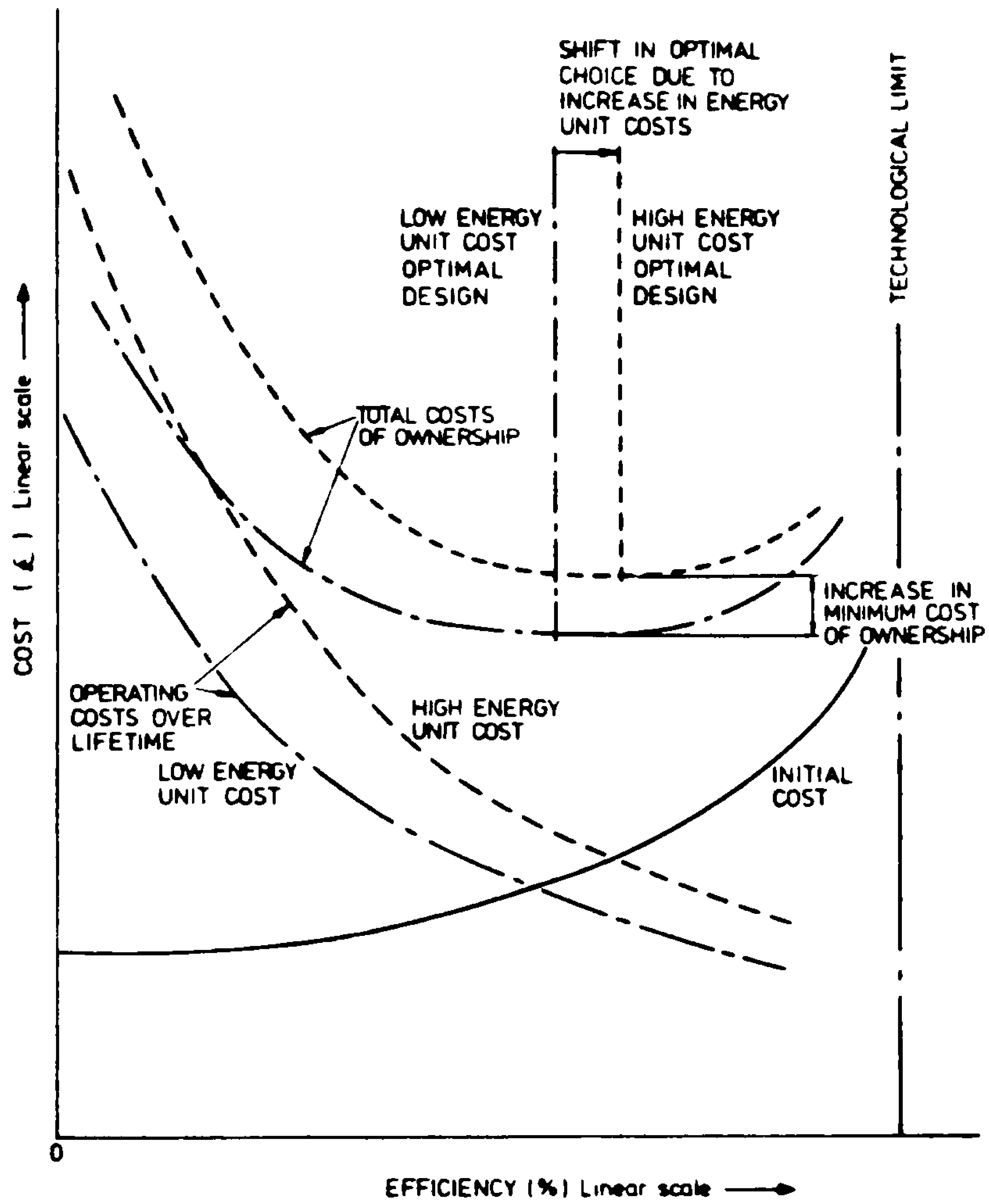

Fig. 33. The total cost, i.e. of purchase and operational charges over the lifetime (≃ 15 years), of a typical domestic cooker. A more detailed analysis would involve a net present value estimation of future fuel charges, due allowance being made for the inflation of unit energy costs. However, these factors tend to lead to opposite trends and so to some extent compensate for one another. The simple approach adopted above (assuming present energy charges without a discounted cash flow analysis) is usually a sufficiently good approximation.

similar improvements in efficiency could be achieved simply by fitting an aluminium foil liner around the inside of the oven compartment. Unfortunately this may adversely alter the temperature distribution within the oven (i.e. create hot-spots), reduce the life of the elements and cause the thermostat to function incorrectly. Nevertheless, the feasibility of implementing this type of inexpensive retrofitting should be thoroughly investigated, the aim being that the cook should be able consistently to reduce his/her oven-cooking energy expenditures. Also

TABLE 19

Savings Achievable as a Result of Implementing Some Economically Justifiable Modifications to USA Cookers[31]

Suggested improvements	*Feasible primary energy saving per cooker per year (GJ) using:*				
	Gas appliance[a]		*Electric appliance*[b]		
	Oven	*Hob*	*Oven*		*Hob*
			Standard	*Self-clean*	
Increase thermal insulation of oven	—	—	0·32	—	—
Improve seals for oven door	—	—	0·44	—	—
Reduce thermal mass of oven	0·10	—	0·35	0·33	—
Change electric element configuration in oven	—	—	0·18	0·17	—
Reduce thermal resistance of the contact between the pan and heating element	—	—	—	—	0·43
Use pans with low emissivity cylindrical walls	—	—	—	—	0·14
Introduce automatic ignition	1·61	3·01	—	—	—
Reduce burner input	—	0·13	—	—	—
Total	1·71	3·14	1·29	0·50	0·57

[a] Assumes a production plus supply efficiency of 92%.
[b] Assumes a generation plus supply efficiency of 28%.

oven cleaning should then become more convenient (e.g. if the foil can simply be discarded when dirty).

MICROWAVE OVENS

These permit rapid heating to be achieved at high efficiencies. At present in the UK, standard domestic microwave ovens are available at capital costs approximately equal to those of free-standing domestic cookers, but they do not offer the same versatility and thus are rarely installed as replacements for their more traditional counterparts. The growth in public acceptance of microwave ovens in the UK has been suggested to be similar to that of refrigerators in the 1960s and freezers in the 1970s (see Fig. 34).

The employment of microwave heating techniques is increasing more rapidly in the commercial sector, e.g. in 1983, 66% of 400 caterers surveyed used microwave ovens.[35] However, the widespread adoption of this device is impeded by the typical cook's inherent reluctance to adopt non-traditional cooking techniques, and largely depends upon:

(a) the ability of food manufacturers to tailor their prepared foods to the oven's capabilities;
(b) the abilities of chefs and creative cooks, to develop food dishes particularly suited to microwave cooking, and to adjust the recipes of already popular foods so that a high standard of microwave cuisine can be achieved by the typical domestic user; and
(c) the provision of adequate information and advice, to enable typical domestic consumers to use their microwave appliances for other cooking purposes besides defrosting frozen foods and re-heating pre-cooked foods.

The cooking process

The ease with which electromagnetic microwaves (at $2{\cdot}45 \pm 0{\cdot}05$ GHz, the permitted international radio frequency band) penetrate a material depends upon their frequency, the material's temperature and dielectric constant, and the loss tangent.[10] Because of the high-frequency distortions of the material's molecular bonds in the presence of microwaves, heat is generated within the material (i.e. the food). The rate of heating is large for foods with a high loss factor at 2·45 GHz, e.g. water.

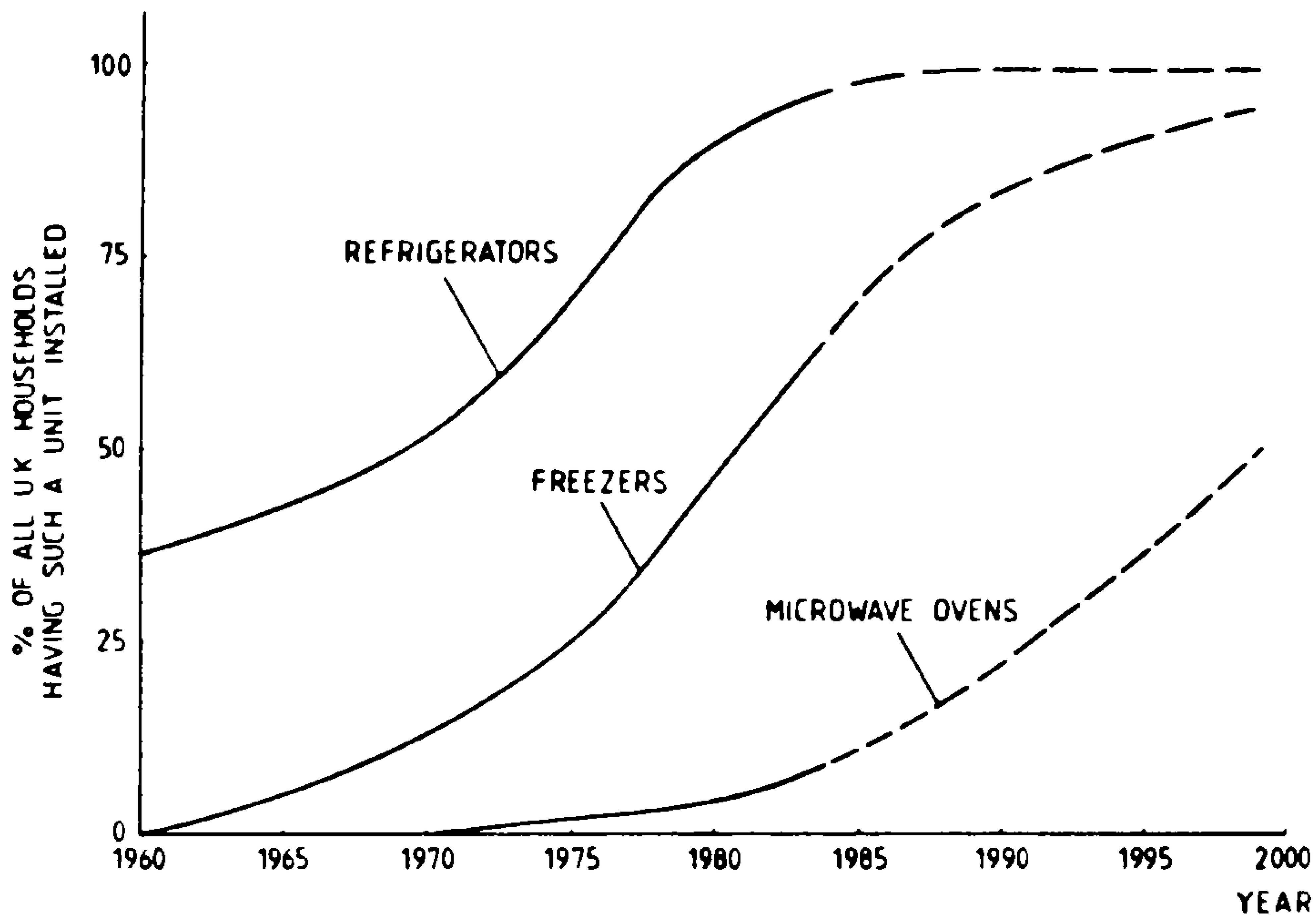

Fig. 34. Trends in consumer acceptance of the microwave ovens in relation to those for domestic refrigerators and freezers (after ref. 83).

Thus because water molecules are usually almost evenly distributed throughout foods, relatively uniform heating can be achieved (e.g. see Fig. 35), provided that the distribution of the microwaves within the oven is also reasonably uniform. To ensure that this occurs in practice, turntables are usually fitted, and these rotate during the cooking operation. However, it is alleged[87] that although microwave oven turntables often avoid hot and cold 'spots' in the food they sometimes create hot and cold 'rings'. Therefore some manufacturers offer alternatives to the conventional microwave oven turntable, e.g. Philips[77] claim that their 'rotating-antenna', fitted beneath the oven compartment's floor, is a better way of achieving an even distribution of heating: this device also improves the oven's cleanability.

More expensive, yet superior, 'microwave-convection' ovens have been developed to provide *convection* cooking, as well as microwave heating, and thus traditional results can be achieved, but usually in much shorter periods.[66,88,89] For example, meat or poultry can be partially cooked by convection to seal in the juices and brown the food, and then the oven can be switched to microwave heating to speed up the cooking process. Generally, browning and crisping of the surface of the food cooked in a microwave oven can be achieved by means of standard electric heating

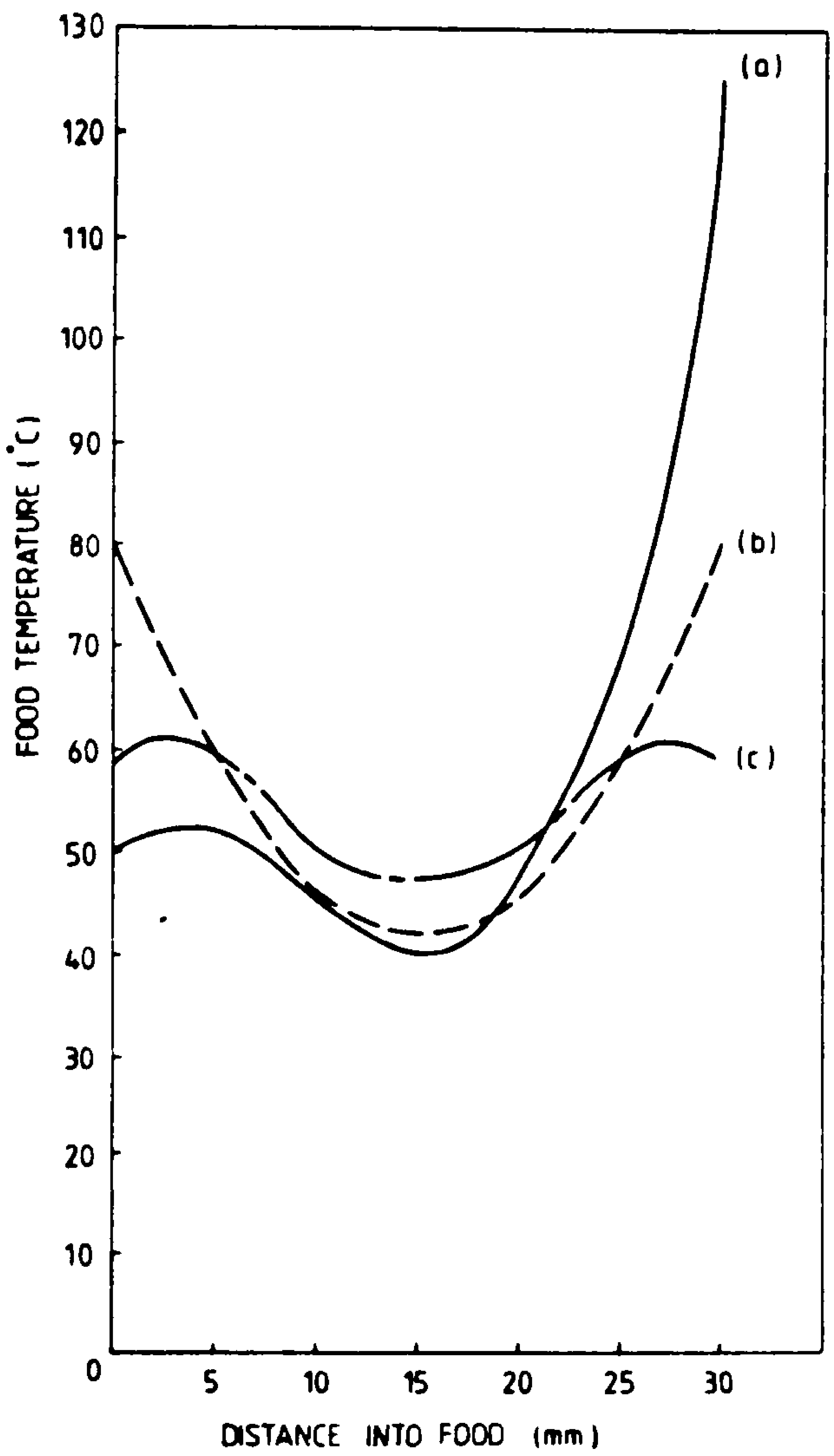

Fig. 35. Temperature distributions through a 3 cm thick piece of meat, when cooked to an average temperature of approximately 55 °C by: (a) single-sided frying for 12 min; (b) oven heating for 17 min; or (c) microwave heating for 5 min.[84-86]

elements or infra-red lamps fitted inside the oven compartment. However, common types of domestic microwave oven are not fitted with these facilities and therefore the food, when cooked, is often less appealing aesthetically. Provided that the food is not overcooked this does not detract from its nutritional value,[90] but as most cooks would agree, items such as cakes, steaks and sausages often look less appetising with respect to our traditional expectations. Some degree of browning can be achieved by using a 'browning dish', which has a surface coating that absorbs microwaves and then re-radiates heat to the surface of the food, but this reduces the energy efficiency of the cooking operation and thus prolongs the overall cooking period.

It has been alleged that the cooking of vegetables in a microwave oven sometimes takes longer than by conventional techniques.[91] However, using an appropriate procedure will usually lead to a reduction in the time required, e.g. most frozen vegetables can be cooked in suitable plastic bags: little or no extra water needing to be added. Admittedly one of the chief drawbacks of microwave cooking is that foods of different consistencies (e.g. vegetables and meat) cannot be satisfactorily cooked together, because the rate of heating in each is different. Consequently, complete meal preparation using a microwave oven can become much more complicated and so less advantageous than the cooking of just a single type of food. Heating times and energy consumptions for cooking some common foods are shown in Table 20 together with commensurate traditional electric heating practice values for comparison.

Although manufacturers generally issue 'microwave cookbooks' with their appliances, the power outputs of such ovens need to be standardised in order to encourage the authors of cooking literature to compose advice and recipes that are applicable to all time-controlled domestic microwave ovens of a specified power rating. This will help cooks to achieve consistent results with the least energy expenditure. However, as many owners will testify, food cooked in a conventional microwave oven can have a different taste to that cooked with conventional equipment (partly because less moisture is retained in the food when heated by microwave radiation). Indeed in many ways, microwave cooking has its own set of rules, and the development of new procedures is important if consistent cooking of highly-palatable foods is to be achieved. Cooking for 5–10 min too long or too little in a conventional oven does not usually spoil the food, but in a microwave oven even a few seconds of overcooking can sometimes ruin a meal. Therefore, it may well be argued that regardless of the time, energy or convenience benefits, some consumers will be disinclined to employ the appliance. To overcome this, the use of conventional gas or electric cookers, fitted with *standard-size oven compartments* (of about 0·06 m^3 capacity) offering (buoyancy-driven or forced) *convection and microwave heating*, similar to those more widely employed in the USA, Japan and West Germany, is recommended. For example, the Bosch 'Multi-Micro' which provides microwave, conventional and fan-assisted heating is alleged to reduce cooking periods by approximately 50% and energy consumptions by about 30%.[66]

TABLE 20

Approximate Energy Consumptions and Time Requirements for Standard Domestic Microwave Cooking in Relation to Conventional Practice for Some Typical Dishes (after refs 88, 92 and 93)

Food, and its amount	*Percentage of output power required*	*Microwave cooking period (min)*[a]	*Conventional oven-cooking period (min)*	*Microwave process/conventional technique*	
				For cooking duration	*For energy consumption*
Macaroni cheese (to serve four)	100	36	30	1·2	2·1
Instant coffee (four cups)	100	8	2·5[b]	3·2	1·5
Whole roast chicken (3 kg)	100	42	140	0·64	1·0
	70	48			
Four baked apples	100	11	50	0·22	0·4
Fruit pie (to serve five)	100	7	35	0·2	0·4

[a] 'Cooked' in a 600 W output microwave oven operating with an assumed efficiency of 42%. No allowance has been made for an additional standing time which is often required to achieve a uniform temperature distribution within the food after removal from the microwave oven. The food's surface temperature tends to increase during this period. This can result in overcooking, reduced tenderness and losses of nutrients and moisture; thus due allowances should be made if high-quality results are to be achieved.[84]

[b] 'Cooked' with a 3 kW electric kettle.

Rapid re-heating of pre-cooked foods can be achieved by microwave ovens. Similarly microwave heating can be used for the quick and thorough defrosting of deep frozen items, but at a high energy-wastage penalty. Defrosting occurs more quickly in the presence of pulsing microwaves, the optimal pulse rate being around once every 15 s.[91] However, the defrosting, re-heating and cooking of food with microwave energy is best achieved if the appropriate operation is controlled according to the temperature of the food contained within the oven, rather than solely on a time basis.[66,74,89,94] For example, Hitachi's microprocessor-controlled 'Autosensor MR6300' oven attempts to achieve this, firstly by memorising the temperature of the air surrounding the food item when it is placed in the oven, and secondly by monitoring continuously this temperature throughout the cooking operation. When the air reaches the pre-programmed temperature, the power is switched off automatically. This method provides a good indication of the temperature of the food because the food tends to heat the air (rather than the other way around). Improved cooking results are claimed because the guesswork necessary to judge the period needed to cook a food item of a certain size, shape, initial temperature and density in a conventional time-controlled microwave oven is eliminated.[89] Such ovens can maintain foods at a chosen temperature far more accurately than conventional ovens, and therefore if foods must be kept warm after cooking, temperature-controlled microwave ovens provide one of the most efficient means for achieving this.

Controls and safety

Domestic microwave ovens require only a 13 A supply because they operate in the 400–1300 W range. The resulting temperatures of surfaces that a user may come into contact with are far lower than those appertaining to conventional cookers, and thus microwave ovens are less likely to cause fires or to lead to accidents in which human skin suffers a burn. Nevertheless, microwaves at 2·45 GHz are a health hazard. In practice, many design safety factors are built into the ovens, so that there is little real danger, e.g. the oven can be energised only when its door is closed. However, food particles may become trapped in the door seal, and so lead to the release of dangerous amounts of radiation.[91] Therefore all such residual food particles should be removed carefully. Another fail-safe device, which serves to switch off the power, in the event of electric arcing (e.g. with a metal utensil in close proximity to the oven's internal lining) is usually incorporated.

There is ambiguity in the literature regarding the safe level of exposure to microwaves, with Eastern European nations enforcing far stricter limits than the UK. Little is known about the long-term effects of low-intensity microwave radiation on human beings. However, according to Harlen[95] if there is only a limited depth of penetration of this microwave radiation, it should be reasonable to regard the absorption of microwave energy by the body as little more than a thermal load. Nevertheless there have been various alleged hazardous effects of long-term exposures, causing for example eye cataracts.[96] The best advice is to be aware that microwave ovens are a potential source of danger, but provided the manufacturers' instructions are adhered to, such ovens will probably have *no* harmful effects upon typical domestic users. The recommendations usually include:

(1) Keep the oven clean, especially the door seal.
(2) Treat the door and its locking mechanism with care.
(3) Do not stare directly, for extended periods, through the oven window.
(4) Do not operate the oven when either it is empty, an object is caught in the door, its door is not completely closed, or when either the door, seal, hinge or latch is damaged.
(5) Do not put metallic or melamine formaldehyde equipment inside the oven.

Microwave leakage detectors have been developed so that users can check their own appliances, but such detectors are not claimed to be particularly accurate.[87,97] Thus it is advisable for the owner/user of a microwave oven to have his appliance serviced regularly by a competent engineer.

Efficiency

The end-use efficiency of microwave cooking is high—provided that the food container employed is virtually transparent to this type of electromagnetic radiation (see Appendix 3)—because the heat is generated *within* the food being cooked (e.g. see Fig. 36). Published data for the performances of microwave ovens exhibit considerable scatter, partly because in the various experiments the degrees of fullness of the ovens differed, and the comparative cooking technique practised using

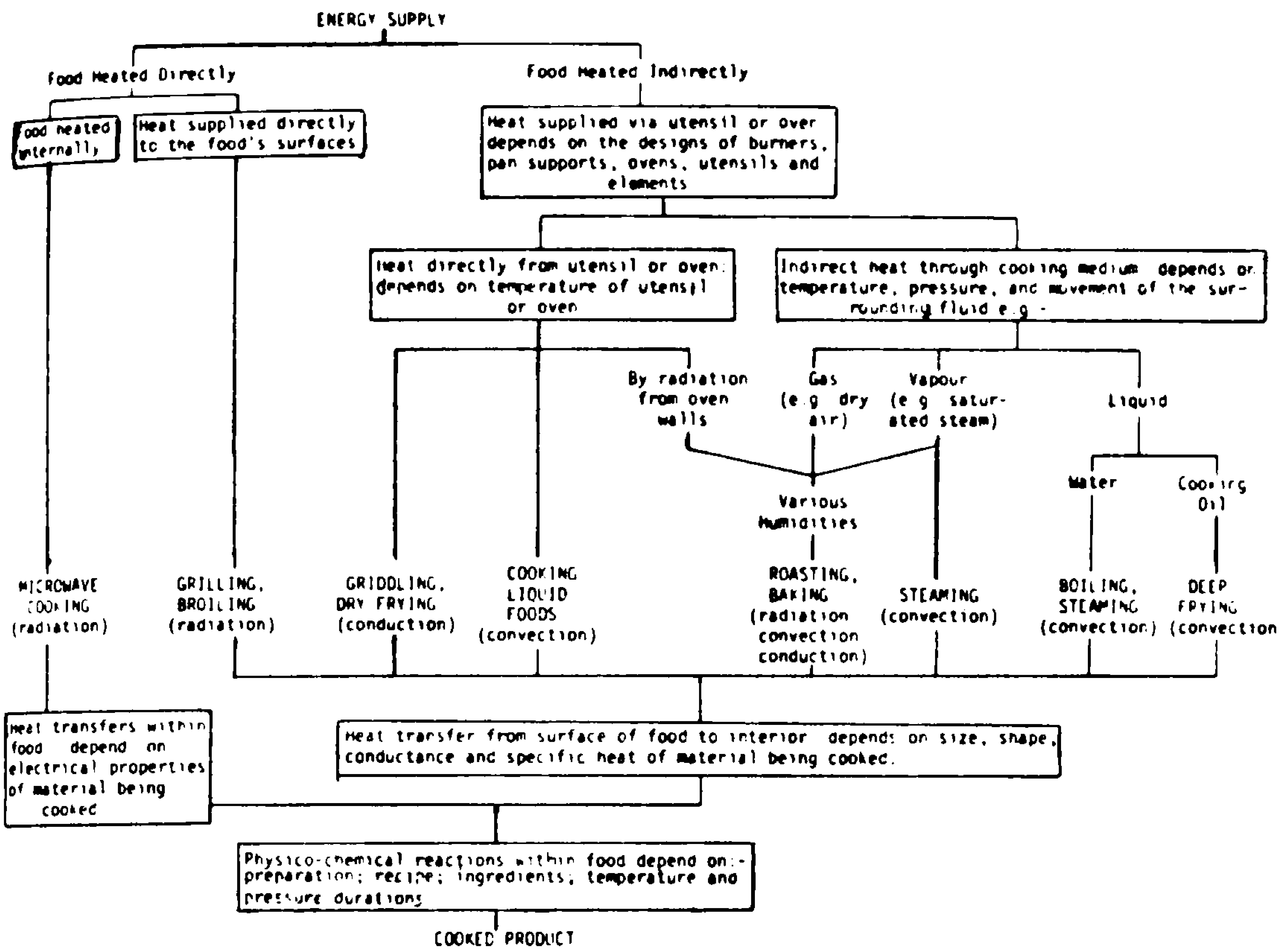

Fig. 36. The mechanisms of heat transfers to food by popular cooking methods (after ref. 57).

more traditional equipment varied, e.g. conventional ovens were pre-heated in some cases. Singer *et al.*[28] concluded that standard microwave ovens are up to 75% more efficient than conventional electric ovens. Consdorf and Behrens[46] suggested that, on average 5% less energy is needed with microwave ovens to cook a typical combination of commonly-consumed foods for a meal, than with conventional electric ovens. Other tests (see Table 21) indicate that much greater savings are achievable. Woodson[99] alleged that if a family used a conventional microwave oven for satisfying half of their cooking requirements then the device would 'pay-back' in about 14 years, whereas if it was used for the vast majority of their cooking operations a pay-back period of 5–6 years could be achieved. Nowadays, due to their increased popularity conventional microwave ovens are sold at slightly lower capital costs (in real terms) and so more favourable pay-back periods *may* be achievable by typical domestic users. Conversely the employment of microwave cooking appliances in catering establishments should be far more attractive from a financial viewpoint.

TABLE 21

Energy Savings Achieved by Using a Microwave Oven Rather than a Conventional Electric Cooker (Using Both the Hob and the Oven) when Preparing 27 Items of Food from a Menu Suitable for Microwave Cooking[98]

Appliance used for cooking operation	*End-use energy supplied to an electric cooker on an annual basis (GJ)*	*End-use energy supplied to a microwave oven on an annual basis (GJ)*	*Savings (%)*
Hob	0·76	0·60	21
Oven	0·89	0·22	75
Total	1·65	0·82	50

Comprehensive studies were carried out by McConnell[100] who also compared the energy expenditures for domestic cooking using a typical microwave oven and a free-standing electric cooker. Food dishes were selected randomly from all sections of a microwave cookbook and a conventional cookbook: it was found that less energy was consumed for 79 % of the food items when cooked in the microwave oven. Consdorf and Behrens[46] concluded that an *overall* energy saving of about 15 % of present cooking expenditures could be achieved by using microwave ovens, provided that cooks realised which foods could be cooked more efficiently via microwave radiation. However, more traditional results may be achieved for similarly reduced energy expenditures by using microwave-convection ovens. For example, Bosch[66] claim that their 'Gourmet' oven can be used to save up to 87 % and 81 % in electricity costs and cooking periods respectively, when cooking by a microwave heating method or a combined microwave/convection heating technique instead of solely by a convection heating method. Due to their versatility and energy-saving capabilities the use of this type of microwave oven is recommended.

Because many foods only occupy a small part of the available volume of the microwave oven, an effective increase in cooking efficiency often can be attained by fitting a suitable shelf to the oven compartment, as in the 'Micromat' oven for instance.[75] Approximately twice the quantity of food can then be heated simultaneously. Further to this, some energy can be saved if a low-power VLED, instead of the viewing light, indicates that the oven is in operation. The viewing light should have a manual over-ride control so that it is only energised when the oven door is open, or when the cook wishes to view the food, but it should be switched off automatically when the door is shut properly.

MICROPROCESSOR-CONTROLLED COOKERS

These may involve conventional or microwave ovens, and gas or electric hobs, incorporating a microprocessor capable of retaining and employing when required, information concerning process temperatures and cooking-period durations for several items. (This type of programmable controller is now commonplace in microwave ovens and clothes-washing machines.) Its memory permits a combination of heating sequences at different power dissipations to be accomplished. The conventional-oven controller can be set (up to 24 h in advance) so that the thermojunction in the oven achieves a specified working temperature at a certain time. Then the cook does not have to worry about resetting the oven, even if different temperatures are needed at various stages during a single cooking sequence. This leads to the production of consistently well-prepared food, once the optimal cooking sequence has been determined.

High cost is the main deterrent to the widespread adoption of microprocessor-controlled cookers. For example, the Cannon 'Combination',[42] which can be controlled automatically to cook food by convection and/or microwave methods, costs nearly £1300, i.e. about four times that of a traditional but smaller capacity electric cooker. However, in the catering sector—where cooking is a major time consumer—the benefits of controlling accurately both oven and hob operations (preferably using induction heating) are much more attractive, especially where a large number of similar dishes are prepared on a regular basis. Indeed, the future employment of computer systems in the catering industry will facilitate much tighter management and thereby substantially improve operational efficiency.

BUILT-IN SPLIT-LEVEL COOKERS

At present, in the UK, there is a growing trend towards the installation of built-in appliances in order to:

(i) improve the appearances of domestic kitchens, and
(ii) simplify the processes of meal preparation and kitchen cleaning.

Matching built-in appliances (including ovens, hobs, grills, refrigerators, freezers, dish-washers, washing machines and tumble dryers) are available and represent the most significant change in domestic kitchen equipment design since free-standing electric and gas appliances were first introduced more than 50 years ago. Stringer[101] estimated somewhat optimistically, that by 1985 built-in ovens would account for 39 % of the British domestic cooker market. Nevertheless, it is timely for the domestic-appliance industry to regard such a trend as a stimulus for improving the designs and efficiencies of its cooking equipment.

The installation of the oven, at a relatively high position, permits the cook to use it without stooping and offers appliance designers the possibility of applying additional thermal insulation, especially above and below the oven compartment, without reducing the available cooking space. If the oven is fitted at eye level, and the door is only partly glazed, the energy consumption for a given cooking operation can be reduced, because the oven door will probably not be opened as frequently or for so long during cooking. Extra insulation can also be applied beneath the hob-top. Therefore savings in operating costs can be achieved by using such split-level systems. However, this advantage for the domestic consumer is usually outweighed by the additional expense incurred when purchasing the necessary kitchen units. The capital cost of a built-in oven and its kitchen unit is approximately the same as the cost of an entire free-standing cooker.[102] Thus there is a disincentive to purchase and use a typical split-level domestic cooker compared with a comparable size free-standing one (assuming each has a similar useful-life expectancy). Nevertheless, if a split-level built-in cooker is preferred, the installation of a 'dual-fuel' system (i.e. one stimulated by both gas combustion and electricity) should be considered. Many cooks would achieve energy savings by using a gas hob and a fan-assisted electric (main and small) oven combination. They would also appreciate the superior features of this system, i.e. the controllability and speed of cooking with a gas hob, and the speed, cleanliness and consistency of using a fan-assisted oven. However, at present, this combined installation is not recommended by either the BGC or the Electricity Board in the UK.

PORTABLE OVENS

These devices have the following advantages for the typical domestic cook:

(1) relatively low capital costs;
(2) adequately sized for most domestic oven cooking operations;
(3) easily moved and cleaned, because they operate from a 13 A domestic electricity supply.

When first introduced approximately 30 years ago portable ovens were not readily accepted by consumers, partly because domestic kitchens were not as well designed then as they are today. However, the recent increase in the employment of table-top cooking appliances (e.g. toasters and microwave ovens) and split-level cookers in 'fitted' domestic kitchens, indicates that a more favourable market may now exist for portable electric ovens. Because of their smaller capacities, energy savings are achievable if these ovens are employed instead of standard-size electric ovens.

At present, portable convection ovens with volumes similar to those of domestic microwave ovens have considerably lower capital costs, e.g. the Rowenta 'Gourmet' portable electric oven with rotisserie costs less than £100 whereas a time-controlled microwave oven, a temperature-controlled microwave oven and a microwave-convection oven typically cost about £200, £300 and £400, respectively. Because the price differentials between microwave appliances and portable convection ovens are so great, it would appear that considerable modifications to the thermal design of the latter could be made without adversely affecting saleability. Thus the development of more energy-efficient portable convection ovens, which can achieve traditional culinary results[103] but with energy and time expenditures approaching those of microwave ovens, is desirable. Such ovens would tend to be bought not only by single-person households but also by those domestic groups who would otherwise purchase microwave ovens. Therefore the development of superior portable convection ovens is recommended.

SOLID-FUEL COOKERS

Due to the rapid increases in unit energy prices during the last decade, effort has once again been devoted to the improvement of solid-fuel cookers. Compared with the standard wood, peat and coal-burning stoves (widely employed before the 1960s), modern solid-fuel systems are attractive, compact and energy efficient (see Table 22). They provide, simultaneously if necessary, domestic central-heating, hot water and cooking facilities.

TABLE 22
Flue Losses from Fossil-Fuel Burning Appliances
(adapted from refs 27 and 31)

Appliance	*Percentage of fuel's energy lost via the flue*[a]
Open fire	80
Gas oven (externally heated)	63
Closed solid-fuel stove	45
Oil/gas central-heating system	40

[a] These typical values are only approximations: in a particular instance the percentage loss would depend upon the thermal load imposed on the heating/cooking system.

Air can be drawn in from, and combustion gases exhausted to, the ambient environment without taking air from within the building: by means of a heat exchanger, the exhaust can serve to pre-heat the incoming air. Thus a high rate of heat loss from the building due to the essential supply of air for combustion, need not be a prerequisite of using a solid-fuel cooker. Slow burning can be achieved with a thermostatically-controlled air supply damper, and most cookers incorporate a roasting/baking oven and a smaller slow-simmering oven, the temperatures of which are usually thermostatically controlled. Campbell[104] claims that recent slow-burning thermostatically-controlled radiant convector backboiler stoves are about 75% efficient. Furthermore, unlike most gas and oil-fired heating equipment, the efficiency of slow-burning solid-fuel stoves tends to increase as the burning rate decreases. Thus, an effective means of keeping an intermittently-used building, at say approximately 14°C, during unoccupied winter periods (i.e. to protect it from condensation), is provided by the solid-fuel stove.

The main advantage of solid-fuel cookers, according to Turner,[105] is their excellent low-heat cooking capabilities, yielding successful and repeatable results for foods such as bread, puddings and casseroles. It is claimed that solid-fuel fired ovens are better than electric and gas ovens, because heat is provided from all sides of the oven compartments in a similar fashion to traditional bakers' ovens.[106] However, grilling with a solid-fuel cooker is very difficult to control accurately, and the hot-plates (usually insulated when not in use) tend to be considerably oversized relative to most cooking pans, and therefore hob operations can be wasteful of energy. Furthermore, due to the high fuel-bed temperatures, relatively thick layers of thermal insulation are needed if sufficiently low external surface temperatures and low rates of heat loss are to be achieved. Also the householder needs the cooking facility to be operational when the central-heating system is not required (i.e. in summer). The latter is achieved in some designs, e.g. Simon Thorpe Ltd's 'Tiba',[107] by fitting separate flues for the boiler and cooker, each with its own damper. This helps to some extent to ensure that heat is supplied only when and where required.

A typical solid-fuel cooker is considerably more expensive to purchase than a comparable gas or electric cooker. However, the life of a solid-fuel appliance is much longer (~ 50 to 100 years for the cast-iron variety) and most manufacturers guarantee their equipment for 5–10 years.[108] Also various fuels can be employed—wood (costing approximately 50% less than smokeless coal on an equal energy-release basis) is normally used although oil, gas, coke, coal, peat, paper and refuse burning are feasible with most designs. (At present, the segregation and recycling of the components of household refuse at source is not widely practised: this may be an important aspect of domestic energy-thrift and a valuable source of domestic fuel in the future.)

In 1975 only 3% of pre-1975 dwellings used solid-fuel cookers and this was predicted to fall to 1·5% and almost zero by the years 1990 and 2000 respectively.[5] Nevertheless there has been a recent resurgence of interest in solid-fuel cooking and Vale and Vale[27] estimated that if the waste wood produced in Britain each year was burnt in closed solid-fuel stoves, all the space heating, hot water and cooking demands for 5% of domestic dwellings could be satisfied by this means.

Unlike fossil fuels, wood is a replaceable resource and so by careful planning reserves can be maintained. However, wood-burning appliances, especially slow-burning ones,[109] liberate several pollutants (including carcinogens such as benzo(a)pyrene and chrysene). High cost and practical difficulties militate against the fitment of electrostatic precipitators and sulphur dioxide scrubbers for cleaning the air exhausted from domestic solid-fuel stoves. Therefore, even though there is scope for increasing the amount of woodland in the UK, the widespread employment of solid-fuel cooking equipment is unlikely to recur because of difficulties relating to fuel supply and dry storage, as well as problems concerning pollution, convenience, fire risks and kitchen cleanliness.

Globally, about half of mankind uses wood as cooking fuel. More than 10^8 people live in situations where they are unable to obtain sufficient wood to satisfy minimal energy needs, and approximately a further 10^9 of the world population ($\sim 5 \times 10^9$) are affected by lesser fuel shortages.[110] Consequently these people spend much of their time searching for fuel, e.g. in rural Tanzania some villagers walk up to 50 km per day in order to collect wood.[111] The problems of supplying and distributing sufficient energy, food and water are often greater in the cities of the Third World—where cooking is usually restricted to one meal per day—primarily because of the high population densities.[112] It has been estimated that, by the year 2000, the wood supply for 10^9 people, living in LDCs, will be so critical that they will not be able to cook their food properly.[113] If this is allowed to happen, the number of people dying in Third World countries each day will increase enormously.

Deforestation (which usually leads to desertification) has accelerated recently, because of the rapidly increasing population of the LDCs and the increasing unit price trends of fossil fuels. This has had an immediate effect upon the local climates and general environments, placing agricultural potential and food production in great danger.[9] In India wood accounts for approximately 69% of the total energy consumed in the rural household sector,[114] but animal dung is also a major energy source—about 73×10^6 tonnes (~ 300 PJ) are burnt annually.[115] In Africa, the energy used for cooking can account for up to 75% of a country's total annual energy expenditure: the comparative UK figure is about 5%. Although the total amount of energy consumed annually by a person living in an industrialised nation can be up to 50 times more than that used annually by someone living in the Third World, on average about *three* times as much energy is utilised for daily cooking operations by a native of a LDC than by his counterpart in the developed world. Therefore, it is vital that energy is used more effectively for cooking purposes in the Third World.

Unfortunately, as local fuel supplies diminish, people are forced to: (i) use dried animal dung as cooking fuel which deprives the land of natural fertiliser; (ii) eat less food or eat it raw; and (iii) spend more time searching for suitable fuel, leaving less time available for work, which effectively decreases their food and fuel purchasing power. Thus in an attempt to decelerate falling living standards in LDCs, several relatively efficient wood-burning cookers have been developed. Preferably these should be constructed in the affected areas with local raw materials and labour, because the manufacture of cooking equipment by developed nations for sale in LDCs usually precludes their use by the poor (who clearly need them the most). Sadly, Cross[116] reports that many cooking stoves developed for use in the Third World do not necessarily lead to a saving of as much energy in practice as is indicated by laboratory experiments. Development of appropriate technology is therefore urgently needed to:

(a) improve the designs of 'mud-brick' or ceramic stoves, because many existing types tend to crack when hot, thus reducing their efficiencies and shortening their useful lives;[117]
(b) ensure that the size of the fuel-beds can be adjusted to accept available pieces of wood, remembering that cutting tools are often in short supply in LDCs; and
(c) reduce the outside surface temperatures of metal stoves to ensure a safer cooking environment.

To alleviate the Third World's present dependency on wood and charcoal for cooking fuel, the use of other biomass fuels (e.g. methane and alcohol), the introduction of appropriate hydro, geothermal and wind energy schemes, and the exploitation of less-traditional fossil fuel energy resources (e.g. peat and tar sand), are needed. This will require substantial financial, technological and educational support from industrialised nations, but even then the spreading of appropriate technology will not be an easy task, especially when it contravenes well-established traditions. For example, straight-forward education concerning the construction, operation and maintenance of 'new' energy-efficient cookers is needed, if the users are firstly to achieve consistent fuel savings relative to the traditional practice of cooking on an open fire, and secondly to improve conditions relating to health and safety. It is therefore unwise for members of developed nations to regard any of the aforementioned energy technologies as a panacea to the cooking fuel problems of the Third World.

KITCHEN VENTILATORS AND KITCHEN WASTE-HEAT RECOVERY

The processes involved in the normal occupancy of a house result in large amounts of water vapour being released to the internal environment. For example, a typical four-person family in the UK produces about 15 kg of water vapour per day; cooking accounting for approximately 13% of this.[118] However, the latter can be reduced considerably by keeping the lids on pots and pans (see Figs 37 and 38).

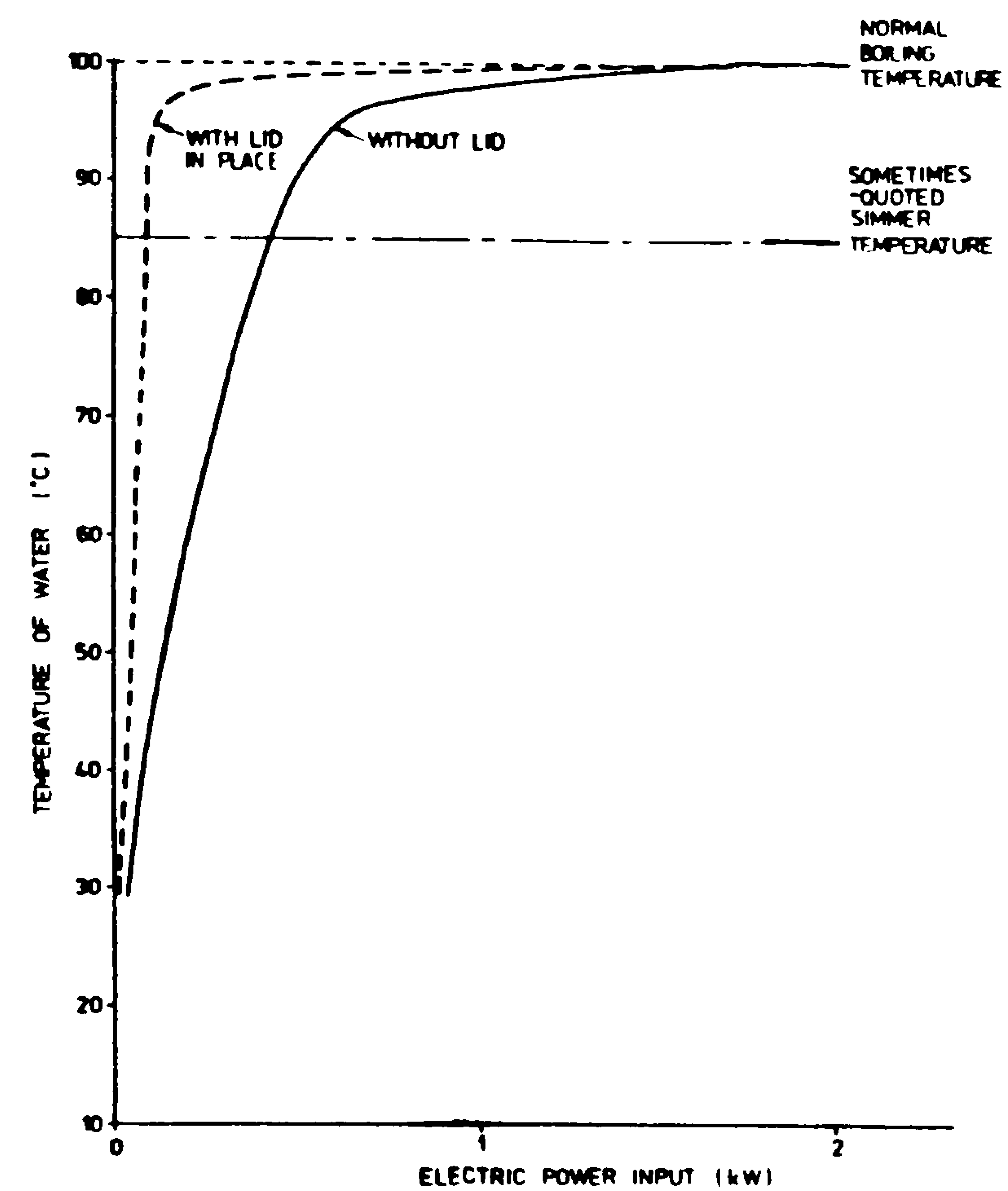

Fig. 37. Attainable temperatures as functions of power input to an electric hob using a saucepan with, and without, a fitting lid in place (adapted from ref. 119).

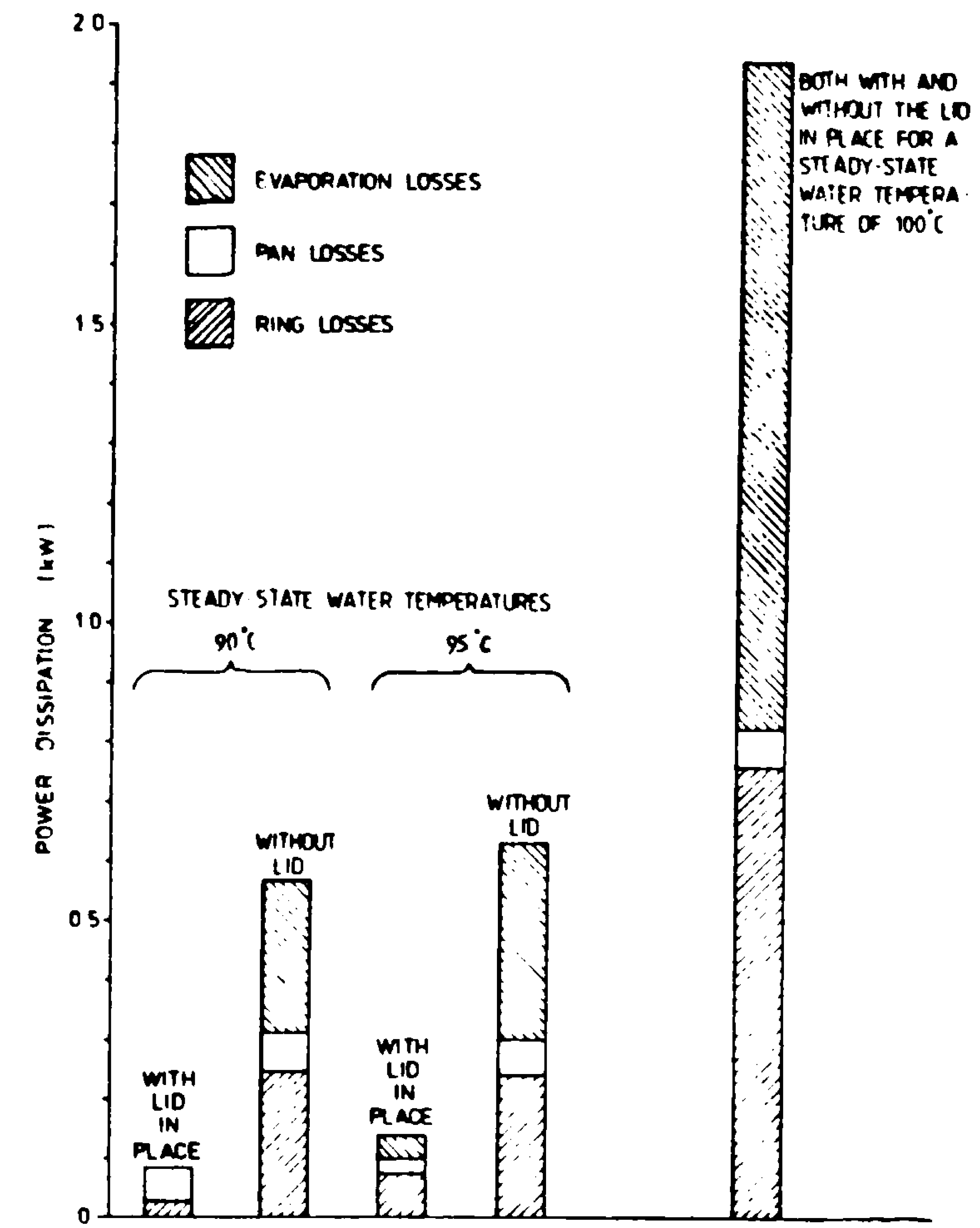

Fig. 38. Steady-state heat losses when heating water in a saucepan, with and without a fitting lid in place (adapted from ref. 119).

In order to improve the comfort of house occupants—as well as prevent the deterioration of the house fabric resulting from surface or interstitial condensation—excess water vapour, cooking odours, grease contaminated air and indoor pollutions ranging from oxides of nitrogen (produced by cooking) to radon (emitted by granite foundations) should be ventilated to the ambient environment. Thus investments in a kitchen window-fan or a 'cooker-hood' are usually worthwhile[120]—the latter being preferred because it provides a generous catchment area directly above the hob surface.

Domestic cooker-hoods fall into two categories: recirculating types and extraction devices. Manufacturers usually supply the recirculating variety, but these are often less satisfactory for several reasons:

(1) They do not remove water vapour from the kitchen: thus condensation is more likely to occur.
(2) A transverse flow fan is normally employed: for this to be effective, a high rotational speed is required and so objectionable noise is often generated.[121]
(3) Usually, nearly as much energy is used for superfluous hob illumination as is required to drive the blower motor.
(4) The incorporated (synthetic or charcoal) air filters tend to clog up quickly, and so their performances are impaired unless cleaned frequently. Thus without proper maintenance, the purity of the air after passing through the filter remains inadequate.
(5) Too much emphasis is placed on the visual appeal of these cooker-hoods rather than on their air-handling capabilities. For example, an attractive 'slimline' hood tends to have a small filter-to-fan spacing, which restricts the effective area of the necessarily (but usually inadequately) thin filter, thereby increasing the rate of filter blockage.

The more effective type of cooker-hood is the one which extracts the contaminated air from the cooking zone and ejects it to the ambient environment—a 'built-in' design intended for the domestic kitchen is shown in Fig. 39.[121,122] To exploit the chimney effect, a means of widening the exiting air flow passage is provided, and this is often sufficient, without having to use the blower, to satisfy the removal requirements when using only one or two pans. For high-demand periods, a relatively more effective variable-speed centrifugal blower can be switched on. (This may be achieved automatically by 'dew-stats' located

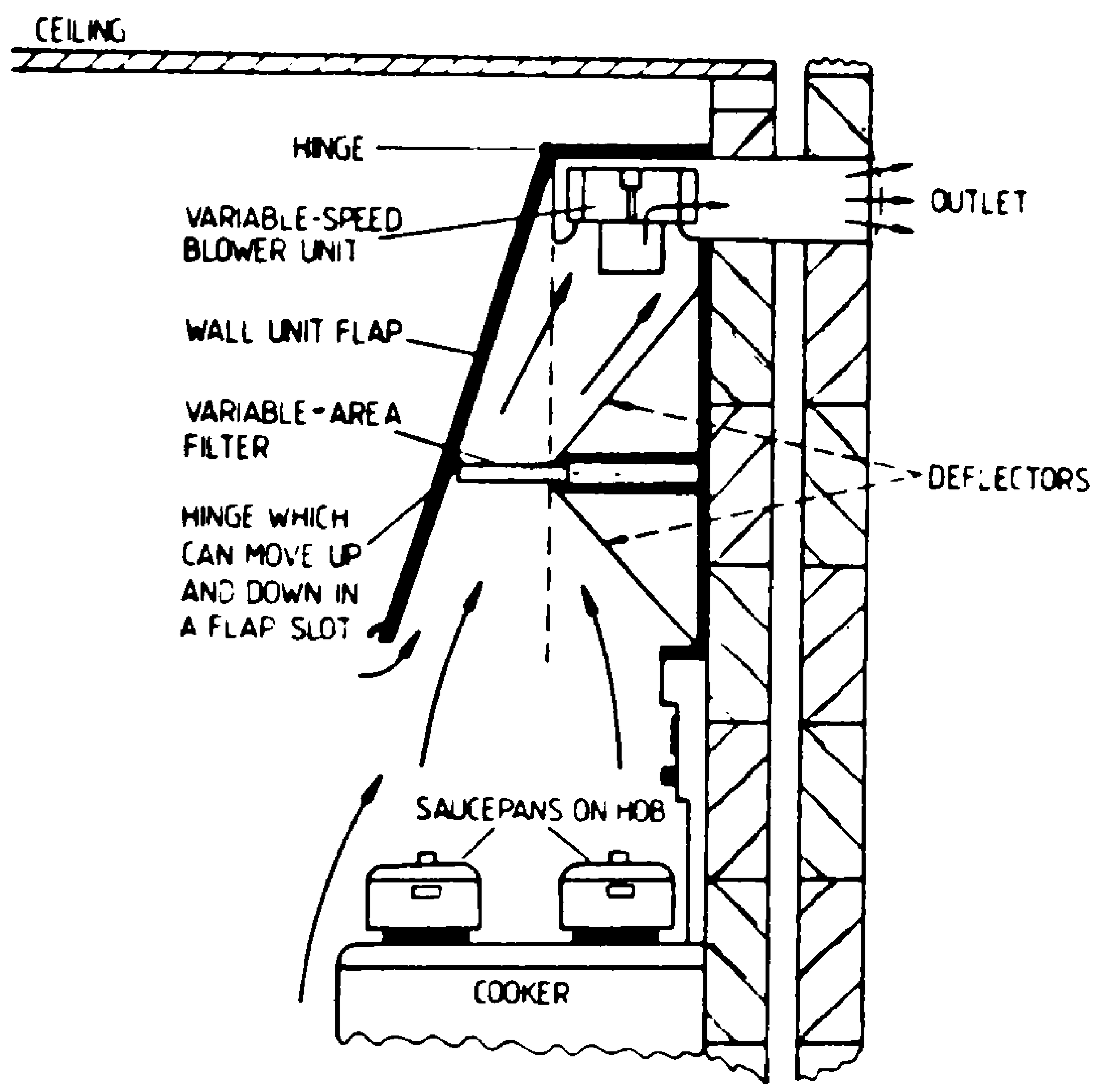

Fig. 39. A simple cooker-hood designed to exploit the chimney effect and thus discourage the operation of the blower unless essential The wall unit flap, when the cooker-hood is not in use, is vertical

on the inside of the kitchen window in order to avoid high air humidities within the kitchen.) However, this blower should be used only when essential so as to avoid energy wastage. By siting the blower and filter well above the immediate cooking area, noise levels are usually lower and a more uniform use of the filter—which is needed to protect the fan from collecting grease and dust particles that would otherwise reduce its performance—is achieved. The blower, filter and duct are hidden behind a standard kitchen-unit door (which has a horizontal hinge instead of the more usual vertical one) at the expense of cupboard space. The door can be pulled progressively outwards to widen the duct as required and can be closed subsequently to prevent unwanted ventilation, i.e. when not using the cooker. Therefore, it is relatively easy to achieve an attractive appearance for this type of cooker-hood, and so more financial investment can then be devoted to improving the energy efficiency of this increasingly popular domestic appliance. To this end, it is suggested that capacitor-start capacitor-run (CSCR) motors are used, which can, by careful design, operate at overall efficiencies in excess of 50%, in preference to the more widely adopted shaded-pole motors, that often have efficiencies of less than 20%. As can be seen from Table 23, an acceptable financial pay-back period will occur, for the assumed family of four, if this modification of the domestic cooker-hood blower unit is implemented. However, it is suggested that both the cooker-hood and fan-assisted oven shaded-pole motors are replaced, thereby achieving a primary energy saving of nearly 0·5 GJ per annum for each such household fitted with a typical fan-assisted oven and cooker-hood. Further bonuses achieved by using fractional horsepower CSCR motors are that they can operate at unity power factor and are exceptionally quiet compared with equivalent output shaded-pole motors.[124]

In catering establishments 25–30% of the energy consumed is used for space heating and ventilating purposes.[11] The need for air removal from above the cooking equipment is vital in order to maintain a reasonably comfortable and safe working environment. Therefore it is important to ensure that:

(a) ample moisture, smoke, odour and heat removal is achieved;
(b) filters are of sufficient area and thickness to condense the grease in the exhaust air and thus prevent such muck and other particulate matter from damaging the air-moving equipment; and
(c) flame traps are fitted if needed, to ensure that a fire cannot result from the ignition of the highly-combustible condensed grease.

Considerable savings can be achieved by using heat-exchangers and heat pumps to reclaim some of the heat that would otherwise be wasted in the exiting air (which usually has an average temperature of 30–40°C). For example, respective pay-back periods of 3·7 and 2·0 years have been achieved using plate heat exchangers when applied to (i) an institutional kitchen mainly carrying out hob operations that produce a low-temperature high-humidity exhaust, and (ii) a fast-food store mainly carrying out grill/fry operations producing a high-temperature low-humidity exhaust.[125] To make proper use of such heat-recovery systems, it is desirable to satisfy the following criteria:

(1) There should be an in-phase demand in the immediate vicinity for the recovered heat, e.g. a dining room which needs heating, or a hot-water system (the contents of which can be pre-heated with the recovered low-grade waste-heat).
(2) A knowledge of the contaminants likely to be present in the exiting air is required. (An expensive electrostatic precipitator may be

TABLE 23

Household Energy Thrift Achieved by Replacing Widely-Employed Single-Phase AC Shaded-Pole Motors by Equivalent CSCR Motors for Some Popular Domestic Appliances: Estimates Are Based on Usage by a Family of Four People[33,121-123]

Motor changed for stated appliance	*Power input to shaded-pole motor (W)*	*Power input to equivalent CSCR motor (W)*	*Estimated annual usage (h)*	*Annual primary energy saving (GJ)*	*Annual electricity cost saving E (£/year)*	*Estimated capital cost to consumer of the replacement, C (£)*	*Financial pay-back period for consumer = C/E (years)*
Cooker-hood	170	68	300	0·393	1·53	6	3·9
Oven fan	35	14	300	0·081	0·32	3	9·4
Convector heater	50	20	150	0·077	0·23	3	13·3
Hair dryer	20	8	50	0·008	0·03	2	66·7

Assumptions:

Average efficiences for the shaded-pole and CSCR motors are 20% and 50%, respectively. 1 kWh of electricity costs £0·05. The overall national efficiency of the electricity supply is 28%.

needed to filter out suspended grease and carbon particles from the extract of a kitchen, which is mainly carrying out grill/fry operations, before the air reaches the heat exchanger in order to prevent its fouling or blockage.)

(3) A correctly sized exhaust system should be used to ensure that the hot combustion gases are not carried away too quickly. Tests at the American Gas Research Institute revealed that gas cooker efficiencies can be reduced by up to 40%, if exhaust ventilation hoods are oversized—in terms of fan power and exhaust flow area—for a given cooking operation.[126]

Unfortunately in some large catering kitchens, ventilation rates of up to 60 air changes per hour are necessary in order to dissipate surplus heat, water vapour and cooking odours.[127] More commonly, ventilation rates of 15 to 30 air changes per hour are needed, but this still indicates that kitchens are often badly designed and the fitted cooking equipment operates inefficiently (partly due to a lack of energy awareness among users). Because of the high air-change rate in the kitchen (and the associated sucking of air from adjacent rooms) the overall space heating energy demand is large: thus inappropriately sized kitchen ventilators can be highly energy wasteful. Therefore *before* installing a waste-heat recovery system for the kitchen, it is important to ensure that energy-efficient cooking techniques are practised, equipment is operating at high efficiency and correctly sized exhaust systems (i.e. ones which can be matched to the cooking demands) are fitted. The design of the air-conditioning system should be modified if kitchen staff have to (i) open windows or use cooling fans in the vicinity of their work during the summer months, and/or (ii) use cooking equipment as a means of heating the kitchen during winter months. To expect catering staff to stop such energy-wasteful practices without providing proper environmental control within their working zones is illogical. During the interim period between now and the time when well-insulated energy-efficient cooking systems are introduced, it is desirable to employ induction hobs and microwave appliances to reduce cooling and ventilation loads within catering kitchens.

To use the waste heat recovered from a kitchen as a means of achieving a noteworthy reduction in energy expenditure, especially in domestic dwellings where cooking is a sporadic activity and in total only consumes about 8% of a household's annual energy supply (see Table 7), a means of completely controlling the ventilation within the building is desirable. Domestic energy-saving air-management systems (which include cooker-hoods) are available—with the additional benefits of reduced condensation levels and an improved indoor atmosphere throughout the house—having pay-back periods of less than 5 years (see Fig. 40). In the catering sector, considerable energy savings can also be achieved by reclaiming heat from (i) the condenser coils of cold storage equipment and (ii) the dishwashing facility.[129] The electricity consumptions used to wash 40 plates and 10 complete covers by a typical domestic dishwasher, traditional manual cleaning techniques, and a commercially used conveyor dishwashing machine (capable of cleaning 7500 plates per

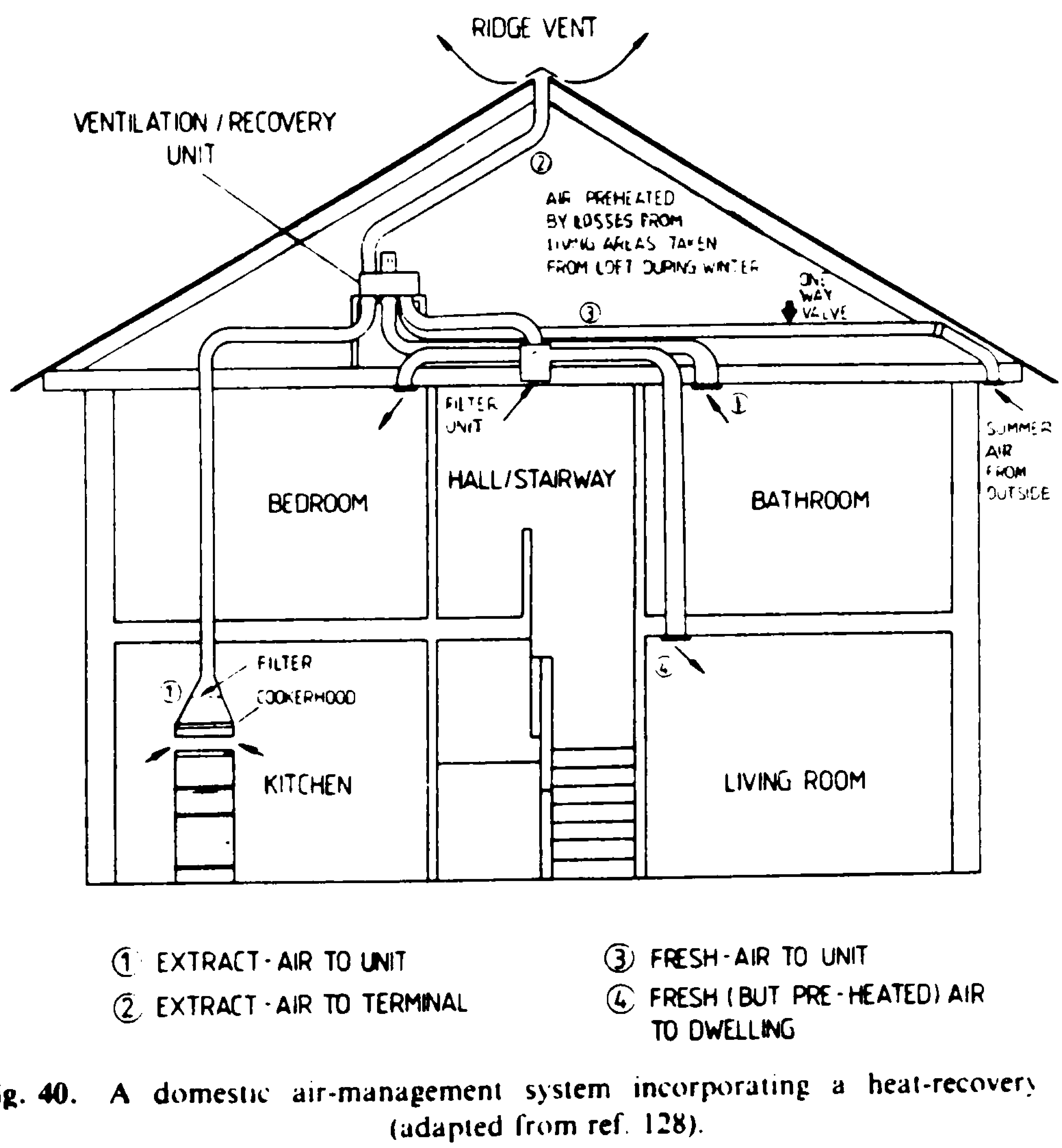

Fig. 40. A domestic air-management system incorporating a heat-recovery unit (adapted from ref. 128).

hour) fitted with an air-to-water heat pump, were alleged to be approximately 2·5, 1·0 and 0·3 kWh respectively.[130] This indicates that, at present, energy savings can be achieved by washing dirty utensils by hand in domestic kitchens, and by employing energy-efficient dishwashing machines with integral heat-recovery systems in commercial premises. Furthermore, the use of low temperature sanitising agents for cleaning purposes, in order to reduce the energy consumptions of water-heating equipment in the kitchen, is recommended. Indeed, dishwashing equipment which chemically sterilises used utensils may be more hygienic and consume less energy (by removing the need for the 'hot rinse') than more conventional techniques.[38]

EFFECTIVE COOKING

All energy-consuming appliances should be designed and selected on the basis of running costs and life criteria rather than mainly on the basis of capital cost. However, it is not only the efficiency of a device, but also the effectiveness with which it is employed that dictates how much energy is wasted. Much persuasive education is needed to overcome traditionally established wasteful practices so that energy thrift becomes part of the creative art of cooking. Recipe books should be written with the aim not only of achieving culinary masterpieces, but also of reducing rates of energy dissipation in the kitchen. Unfortunately energy thrift is too often misinterpreted as meanness. Thus the general public, and cooks in particular, require a more informed appreciation of:

(a) the need for energy-quality conservation;
(b) the choices open to individuals to reduce their own energy demands;[131] and
(c) the non-renewability of fossil-fuels and the need to control energy expenditures now, so that living standards do not fall in the future.

However, the social inertia that opposes the implementation of practical measures specifically designed to lead to the more effective use of energy in food preparation, should not be underestimated. Personal energy consumption is very much determined by one's lifestyle and inbred values, rather than by a conscious awareness of energy cost, use and efficiency.

Considerations when purchasing cooking equipment

Because the common cooker is one of the more expensive domestic appliances, the average consumer is unlikely to buy a new more energy-efficient design or change from a conventional electric cooker to a gas one just because of prospective running-cost savings. Cookers are frequently bought at the house-purchase stage, i.e. when one is adopting a new lifestyle. Thus it is important for the cook to define exactly both the amount and the type of cooking he/she is most likely to practise, and then the appropriate choice of cooking equipment can be made so that a saving of energy (and hence money) can be achieved. For example, a large family which is not usually together at meal times can reduce cooking energy expenditures by using a microwave oven in preference to a conventional cooker. On the other hand, a home-based family living in a rural community, with an adequate local supply of wood, will achieve energy savings by using a modern solid-fuel stove to provide space heating, hot water and cooking facilities.

There are many differences between British and Continental domestic cookers which should be appreciated when purchasing such equipment. Several nations give a higher priority to cooking (both its science and art) than is the custom in the UK and thus some European cookers are more energy efficient. For example, Stephan Witte's combination oven—a pyrolytic self-cleaning/convection/microwave appliance—has its oven compartment insulated with Microtherm.[132] Culinary differences arising in the various European countries have resulted in distinct evolution paths for domestic cooking equipment. For instance common British food dishes, e.g. a mixed grill, buttered scones or fruitcake, place different demands on cookers than soufflés or choux pastry, which are more popular on the Continent. A Continental cooker may therefore require its user to learn different techniques. From an energy viewpoint the main differences between British and most Continental cookers are:

(1) Continental gas ovens are usually externally heated: this is a major cause of energy wastage. It is alleged that Continental gas ovens can sometimes 'burn' the undersides of cakes and are less suitable for cooking large quantities, because hot and cool spots are created within the oven and these can adversely influence the quality of the end-product.[102] Also the temperature gradient is opposite in direction to a conventional internally heated gas oven,

i.e. the highest temperature zone is at the bottom of the oven compartment!

(2) Continental gas ovens cannot usually be set for very low-heat cooking (i.e. less than gas mark 1).

(3) Continental electric ovens have heating elements at the top and bottom of the oven compartment. This provides a different temperature distribution therein and improves the oven's energy-efficiency. The upper set of elements also acts as a grill, but when in use for this purpose, the oven door needs to be left open so leading to high heat losses. This procedure means that either grilling or baking/roasting can be carried out but not both both simultaneously. However, The Good Housekeeping Institute[133] reported that this type of oven heats up more quickly than the conventional British type, mainly because the upper elements are exposed.

(4) Continental gas grills are fitted inside the oven, and have lower rates of heat output: thus grilling operations may take longer.

(5) Some Continental ovens are fitted with solid shelves instead of rod-shelves. This causes some foods to be overcooked at their bases, but is good for cooking 'non-soggy' pastry.[102]

(6) Continental gas hobs are equipped with three or four different rated burners. Thus if the cook matches the heat load and pan size to the heat output and geometry of the respective burner, the Continental gas hob can be more energy efficient.

(7) Continental electric hobs usually involve high thermal-inertia hotplates. Compared with radiant rings, these are oversized and do not respond rapidly.

For many items of kitchen equipment (e.g. toasters) energy thrift receives a low priority, precedence being given to the unit's reliability and the consistency of the food item produced. However, it is recommended that minimum efficiency standards for cooking appliances should be introduced nationally. Manufacturers should exhibit prominently the power rating of each piece of equipment that they sell. The British Standards Institution should be encouraged to recommend that manufacturers specify, for example, the average steady-state power input to maintain an oven at say 200 °C. Tests carried out for nominally similar, fan-assisted ovens from different manufacturers showed that the hourly costs of maintaining oven temperatures at 200 °C vary considerably—see

Table 18. Such disclosures will help consumers to become more energy conscious when buying cooking appliances.[134] Also by knowing exactly how much energy each device consumes, one can more easily develop techniques which contribute towards reducing cooking costs.

If standard energy test procedures are to be developed for ovens and grills, it is essential that appliances are compared on the basis of energy consumed to cook certain typical food dishes (preferably in the most energy-efficient manner) rather than purely on a heat transfer basis. In this way, the consumer can judge equipment according to practical cooking efficiencies, i.e. on data that allow for pre-heat times, positioning of the food in the oven, the type of food container and the choice of the optimal technique of cooking (e.g. involving the minimum number of times the oven door has to be opened for spooning fat over a roasting meat joint). Furthermore, the purchaser must realise that better designed and more energy-efficient cooking equipment will generally cost slightly more. However, he should also be aware that often items such as radiant-ring reflectors are introduced partly to attract his attention. Unfortunately sometimes these have been designed into the cooker to add to its selling appeal at the expense of other energy-saving features that are less noticeable at the time of purchase. For example, one popular cooker has reflectors fitted beneath its radiant rings but has no 'tell-tale' lights to indicate that a ring is in operation. Many cooks achieve energy savings by glancing at such indicator lights, to check that the appropriate hob-heater has been switched off, when the cooking operation has finished: thus they should *always* be a basic feature of electric hobs (excluding 'light hobs').

Since the first oil crisis of 1973, energy-conservation attention has tended to be directed more towards the industrial sector, where large energy savings (in absolute amounts) are made more easily.[30] Generally domestic savings are difficult to quantify and rely heavily upon the user making determined efforts to use energy more efficiently. Essentially to achieve significant percentage savings in cooking energy expenditures, the cook must *plan-ahead.* Unfortunately this runs contrary to the recent trend towards the increasing use of convenience foods by consumers. The 'last minute' decisions usually preclude the adoption of more energy-efficient, yet slower, techniques such as defrosting frozen food at room temperatures (instead, the energy wasteful procedure of using a conventional or microwave oven for this purpose is often chosen). Therefore government aid, advice and encouragement is needed if consumers are to judge and use cooking equipment effectively. Some domestic energy-thrift measures have been stimulated by government actions, e.g. loft insulation grants, but little attention has been devoted to reducing domestic cooking energy consumptions. One positive measure would be to encourage builders of new houses and flats to install cooking equipment that suits their future owners' needs. By allowing the house purchase price to include the cost of the cooking appliances (e.g. as with the central-heating boiler), the owner will pay for his cooking equipment via his house mortgage. Thus he will then be more likely to buy equipment most suited to his *long-term* needs and this will encourage energy thrift. However for such a proposal to succeed, government inducement is needed (e.g. tax relief on the interest paid on that part of the mortgage used for repaying loans used for the purchase of energy-thrift kitchen facilities).

Improved management

The most rapid means of achieving a nationally-significant reduction in energy demand for cooking will probably occur by implementing energy-thrift procedures in food preparation.

In tests carried out at the US National Bureau of Standards Laboratory, six cooks each prepared nominally the same sequence of meals (i.e. adhering to the same menu and recipes): differences in energy consumptions of up to 50% in one day occurred between the procedures adopted by the cooks (see Fig. 41). Because the oven operations were so carefully prescribed, most of these variations can be attributed to different techniques and time expenditures when using the hobs. Such differences have been investigated independently by Brundrett and Poultney.[119] They found that maintaining a lid in place on its saucepan while simmering—with the contained liquid at approximately 85°C—decreased the necessary power dissipation by about 80% (e.g. see Fig. 37). This is achieved primarily by reducing the water vapour loss by a factor of about 100. If the contents of the pan are boiling vigorously at atmospheric pressure, there appears to be little difference in the steady-state rates of energy loss incurred whether or not the lid is on the saucepan. In general, to reduce the rates of energy wastage and the likelihood of producing condensation within the kitchen, liquids should be simmered rather than boiled for extended periods. Indeed, Enga[44] found that gas-hob efficiencies could be increased by up to 7% if the burners could be turned down sufficiently to permit simmering.

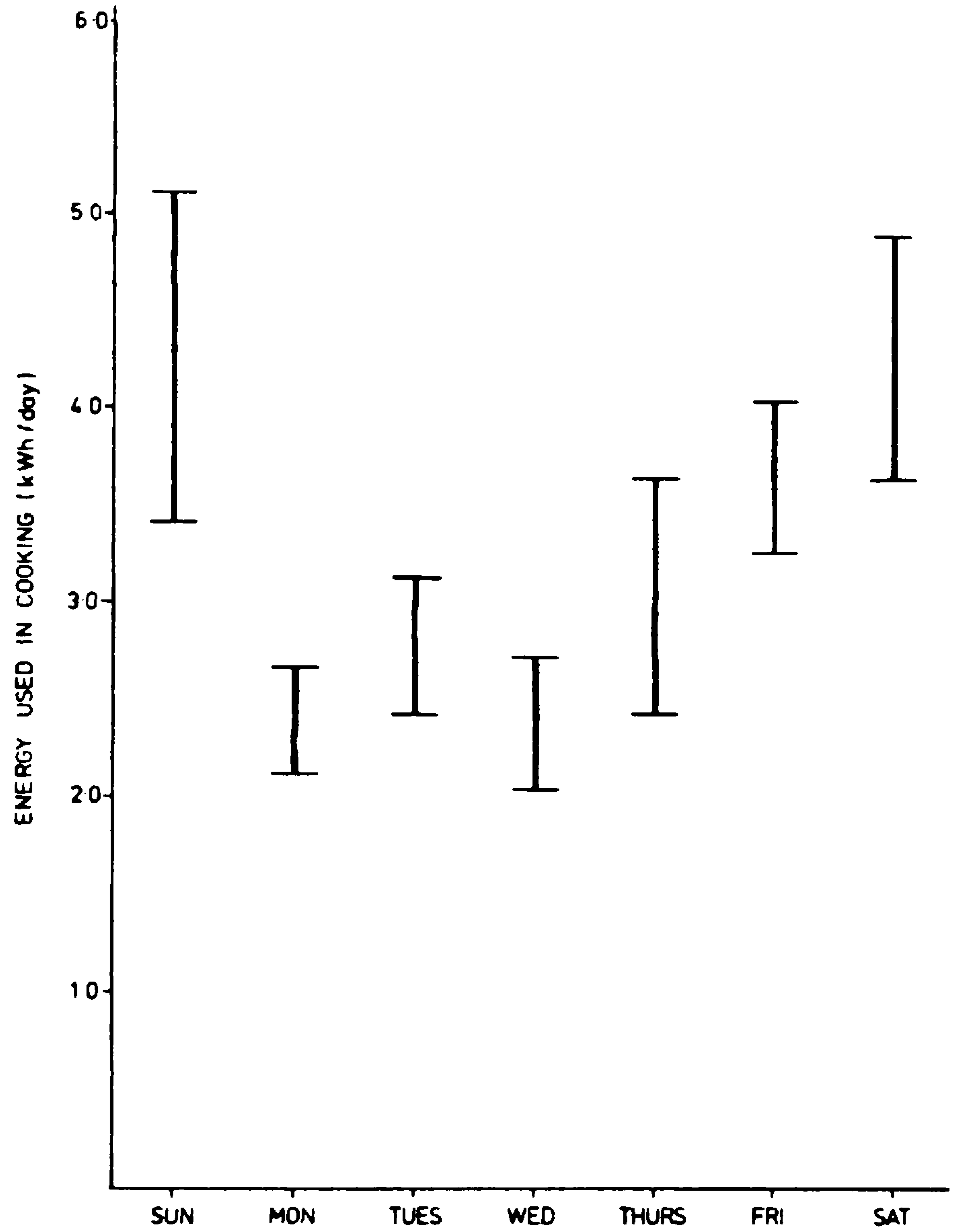

Fig. 41. Variations in the daily energy expenditures by six cooks preparing nominally the same meals with identical electric cookers (adapted from ref. 135).

Figure 42 illustrates a pan lid designed to help the cook develop energy-efficient hob techniques. To reduce the number of times the lid is removed while cooking, it is made from pyrex glass, thereby facilitating viewing: it may, however, require an internal 'wind-screen' wiper. This relatively heavy lid fits tightly onto the pan to ensure water vapour escapes only via a pressure-release adjustable vent. In order to remind the cook to reduce the power supply, the vent is designed such that it 'whistles' when the contents of the pan are at approximately 100 °C. This should prevent what Brundrett and Poultney[119] referred to as the over-enthusiastic boiling of food on the hob. An additional accessory is a 'paddle' which can be attached to the well-insulated lid-handle to permit the food, if suitable, to be stirred—by rotating the handle. Alternatively, if the handle incorporates a simple clockwork spring mechanism, the food could be stirred automatically without requiring the cook's attention. (At the start of the cooking operation, the handle would be wound up a chosen number of times corresponding to the required duration of the stirring.)

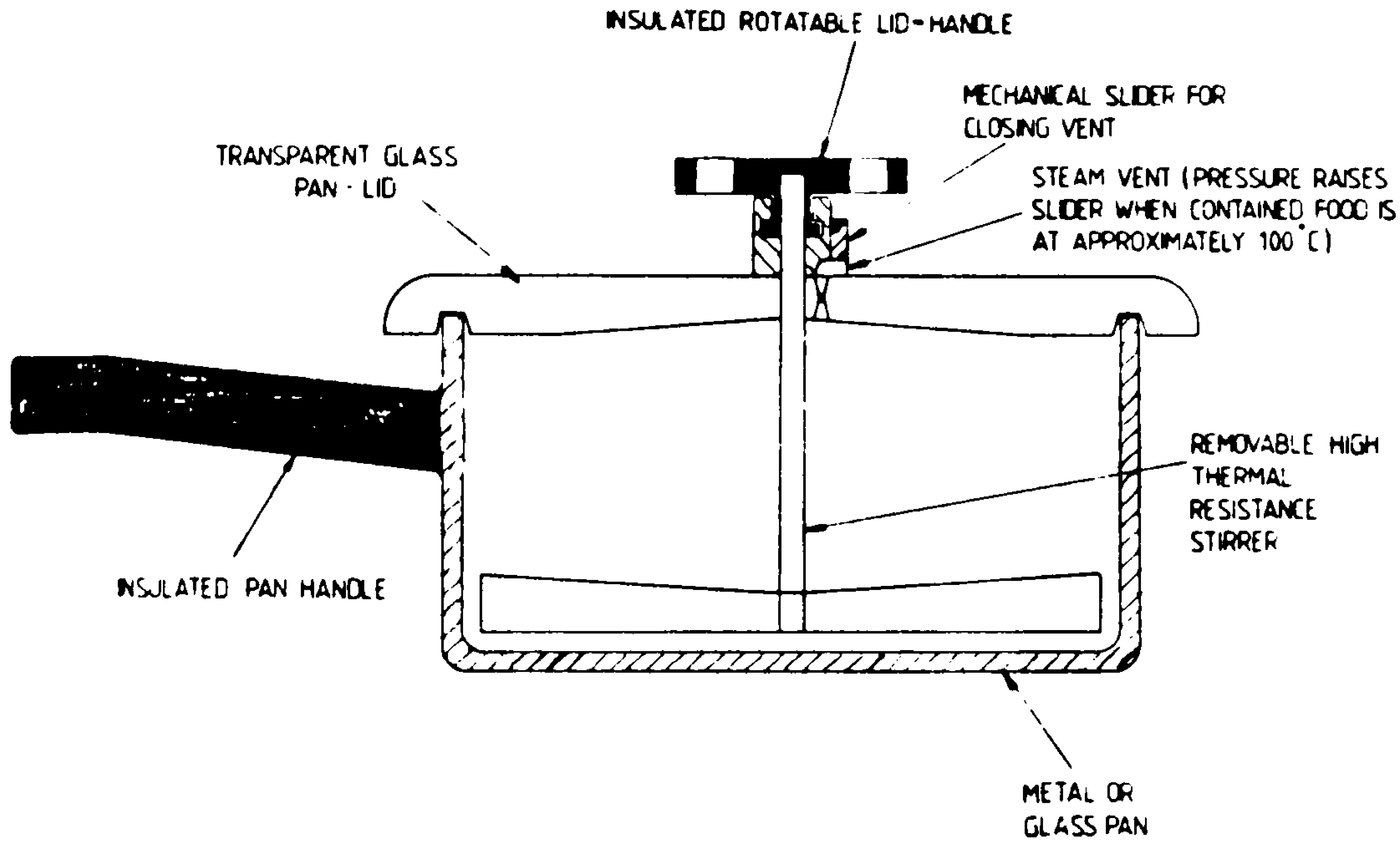

Fig. 42. A pan lid, which is designed to reduce evaporation rates.

Either method should enhance the energy-effectiveness of the pan, because high evaporative losses that are normally incurred, especially when preparing certain foods (e.g. soup or custard), will be reduced.

When cooking food in a shallow-fat frying pan, under a grill or on a griddle, a high 'turning over' frequency will reduce the necessary cooking period. If this action is not performed regularly such cooking methods can be unnecessarily wasteful of energy. Thus the use of temperature-controlled 'double-sided contact' frying pans or griddles, which sandwich the food between two electrically-heated metal plates, would lead to substantial energy savings and reduce cooking periods without requiring the cook to repeatedly turn the food over. Dakerskog[136] reported that double-sided frying can:

(i) achieve a given temperature at the centre of the food more rapidly (i.e. 20% faster when deep-fat frying and more than 50% faster when carrying out single-sided shallow-fat frying): and
(ii) reduce nutritional losses and colour changes that result from cooking.

As far as is feasible, the component foods for a single meal should be cooked simultaneously with the oven well-filled. Singer *et al.*[28] have shown that a beef and vegetable stew, potatoes, peas and an apple Charlotte, each in a separate receptacle but all cooked simultaneously in a traditional oven, require in total about 30% less energy than the conventional use of an oven and hob for preparing identical quantities of these same foods.

As an alternative to filling a standard size oven completely, a practice which is often unrealistic when cooking for only one or two people, it is suggested that domestic ovens are in future designed so that the heated volume can be arranged to be only slightly larger than the volume of the food being cooked. By ensuring that the part of the oven compartment activated is only marginally bigger than say the cake being cooked, the basic thermal energy-thrift rule—supply heat only when and where required—is satisfied and thus the cake is cooked relatively efficiently. A simple way of achieving this would be to supply tightly-fitting (when hot) insulated shelves that can isolate a chosen volume of the oven and then supply heat only to that zone (see Fig. 43). In Denmark, a small ($\sim 8 \times 10^{-3}\,m^3$) insulated oven which fits inside a conventional oven compartment has been developed by Norgard[81] based on the same procedure. Such modifications overcome the limitations of single or double-oven cookers (i.e. a fixed volume regardless of cooking load) because, when required, large or small quantities of food can be cooked efficiently, e.g. ranging from a 12 kg turkey to a single cake. Reduced pre-heat and cooking times should also be achievable with these systems. Further energy-conscious developments may involve providing the cook with the facility to thermally isolate sections within the domestic oven completely, in order to permit the simultaneous preparation of foods requiring different cooking temperatures. Also the feasibility of using the shelves as secondary heaters and employing them directly as baking sheets (or shallow roasting pans) should be investigated.

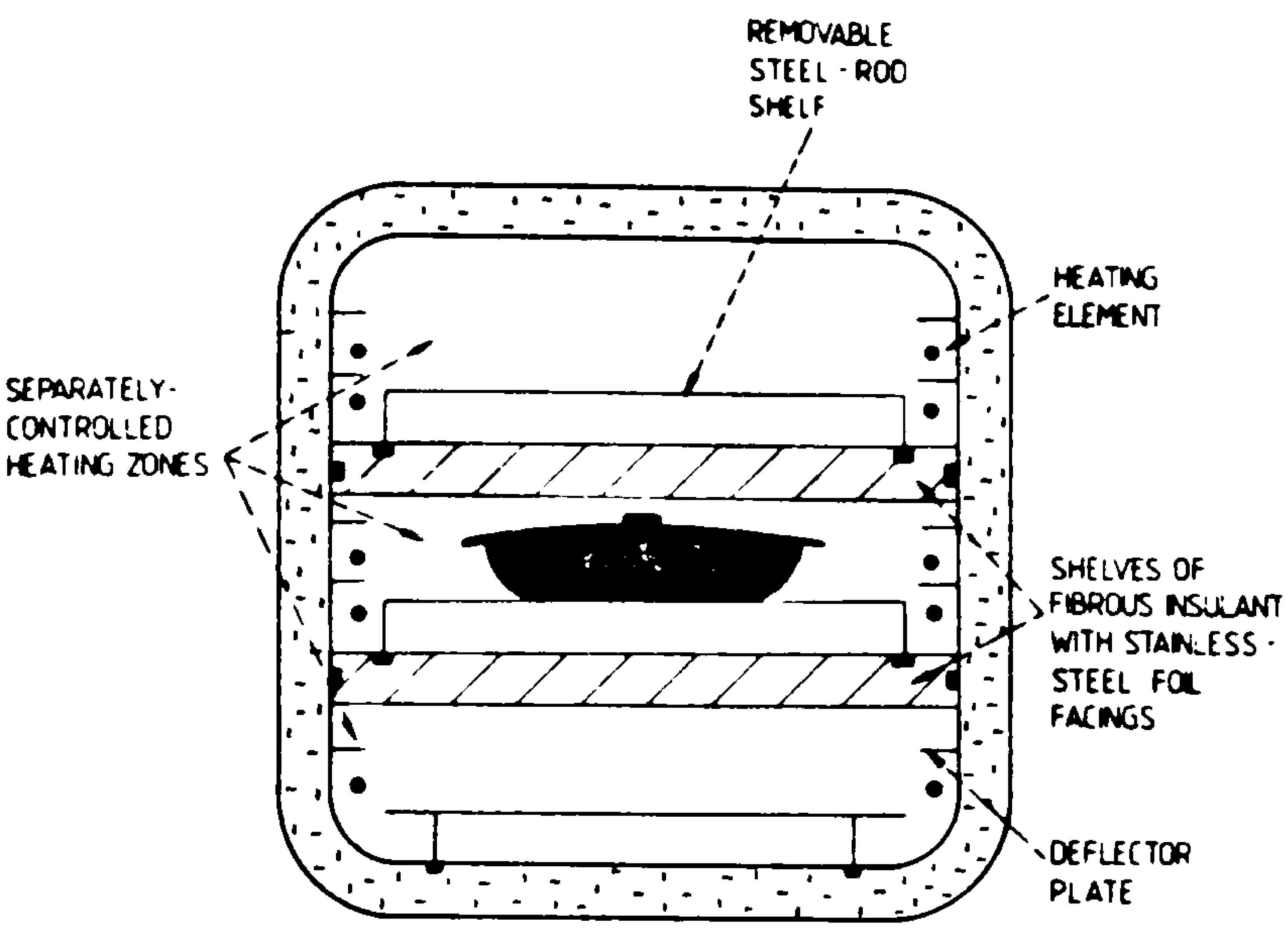

Fig. 43. A proposed oven which can be divided to ensure that the intentionally-heated volume is only slightly larger than the item being cooked.

Other recommendations for achieving energy thrift, as well as the better management of cooking systems and their ancillaries are:

(1) Adopt healthier diets. Avoid wasting energy, and abusing the quality, flavour and nutrient value of foods by overcooking. Use fresh vegetables, nuts and fruits, which are in season locally and need little or no cooking. However, although eating uncooked food is a basic energy-thrift measure, raw meat should only be eaten if it originates from within the Arctic Circle (e.g. walrus, seal and reindeer flesh) because only animals living there are free from the parasites and bacteria that set up disease in man.[137]

(2) Do not cook or re-heat food unless essential. The extra energy obtained by eating hot food instead of cold food is normally less than 5 % of the nutritional energy available in the food. Try to choose a cold liquid food in preference to a hot drink, but if the latter is required, it is better to use energy to prepare a nutritious beverage (e.g. cocoa) rather than one which has almost no nutritional value (e.g. tea). Furthermore, it is not necessarily correct to assume that a 'hot meal' is more nutritious than a 'cold snack' (e.g. see Table 24).

(3) When not being usefully employed for cooking purposes, ensure that all cooking equipment is switched off.

TABLE 24
Comparison Between the Nutritional Values of a Typical 'Cold Snack' and a 'Hot Meal' (adapted from ref. 17)

Nutrient	*Units*	*Cold snack*[a]	*Hot meal*[b]
Energy	(MJ)	2·85	2·71
Protein	(g)	27·01	26·25
Fat	(g)	34·80	28·85
Carbohydrate	(g)	68·76	74·60
Calcium	(mg)	688·5	159·0
Iron	(mg)	2·87	3·30
Vitamin A	(μg)	459·0	112·0
Vitamin B_1	(μg)	370·0	310·0
Vitamin B_2	(μg)	473·0	465·0
Vitamin B_6	(mg)	7·86	11·40
Vitamin C	(mg)	58·80	24·00
Vitamin D	(μg)	0·31	0·03

[a] This consisted of 113 g white bread, 14 g butter, 57 g cheese, 14 g lettuce, a 28 g tomato, 3 g instant coffee, 57 g milk and a 100 g orange.
[b] The composition was 71 g roast lamb, 57 g 'boiled' peas, 85 g fried chips, 113 g canned peaches and 85 g custard.

(4) Adhere to a regular maintenance schedule for equipment. Clean the oven compartments, door seals, gas burners, electric elements, all utensils (e.g. pans, baking trays, etc.) and cooker hood air-filters just after use, i.e. when still warm. Replace worn door seals, hinges and catch mechanisms, as well as burned-out elements, blower motors and indicator lights.

(5) Develop the skill to load and unload food and utensils rapidly from an oven in order to reduce convective losses, i.e. only open the oven door for as short a period as is essential.

(6) On conventional hobs, use Teflon-coated thick aluminium pans, copper-based or copper pans for general cooking, and cast-iron pans for slow cooking (see Appendix 4). Each should have a flat ground-base, a thermally-insulated handle and a tightly-fitting heavy lid. Switch off the energy supply to the hob-heater before removing the pan from the hob. The use of pans with their internal volumes segmented is recommended for cooking small quantities of different foods simultaneously.

(7) When carrying out hob operations on radiant rings, try to use pans with diameters approximately 3 cm greater than the active heat-source diameters. For small quantities of food, use small diameter pans and

employ the inner ring of a dual-circuit radiant ring or the smallest hob-heater available.

(8) On induction hobs, use pans which are designed to achieve maximum efficiencies (see Appendix 1). Choose porcelain enamelled-steel, stainless-steel clad carbon-steel, or cast-iron pans in preference to aluminium, copper, aluminium-clad steel, copper-clad steel, or glass pans.[53]

(9) Choose foods that do not require large amounts of energy in their preparation (i.e. select those which will cook with the minimum of supervision, e.g. casseroles, in preference to dishes like thick soups which require regular stirring and hence incur high evaporative losses).

(10) Pre-heat only the equipment needed just before use, as specified for the intended cooking operation. Generally, ovens need only be pre-heated for baking operations.

(11) When cooking with gas-fired units, ensure that the flames are even and completely blue, i.e. without yellow or orange regions.

(12) Cook at the lowest temperature that will achieve satisfactory culinary results. For example, cook a 1·82 kg sirloin roast at about 140 °C for 200 min. This will avoid a shrinkage reduction of up to 0·2 kg (about two servings), improve the flavour and achieve an energy saving[138] compared with the more usual method of cooking for 80 min at 220 °C.[92] Furthermore, cheaper cuts of meat become more acceptable digestively if they are cooked at low temperatures because their proteins coagulate more slowly. However, although meat, poultry and game benefit, in terms of edibility, from being cooked at sub conventionally-adopted temperatures, the 'slow-cooking' of vegetables only serves to increase the rate of destruction of their vitamins B and C. (It is desirable to 'boil' vegetables quickly by placing them in a pan of boiling water, replacing its lid and then simmering the contents at a temperature in excess of 85 °C for the minimum acceptable period. They should then be eaten as soon after cooking as is feasible.)

(13) Use the self-cleaning procedure for an oven infrequently. Woodson[99] reported that if the operation was limited to once per month the appliance's annual electricity consumption increased by only 30 kWh.

(14) Operate the blowers of kitchen ventilators only when essential, and use variable-speed motors properly to ensure that the ventilation rate matches the evaporation load.

(15) Adopt more scientific means for estimating the quantities of the constituents for a meal. Apply similar techniques to those employed for

TABLE 25
Some Equivalent Masses for Those Quantities Commonly Employed in Cooking (adapted from ref. 17)

Food	*Traditional measure*	*Approximate equivalent mass (g)*
Milk	1 glass	200
Steak	average	200
Potatoes	2 medium, boiled	110
Orange	1 medium	110
Apple	1 medium	85
Porridge oats	1 teacup	85
Tomatoes	2 medium	85
Sausage	1 large	55
Bread	1 thick slice, from large loaf	55
Egg	1	50
Flour	1 rounded tablespoonful	30
Bacon	1 large rasher	30
Breakfast cereal	1 helping	25
Cheese	1 cubic inch	20
Lettuce	2 large leaves	15
Biscuit	1 plain-sweet	10
Tea	per cup	5

baking a cake, i.e. weigh to achieve the required amounts of ingredients rather than make visual estimates because the latter often lead to both energy and food wastages (see Table 25).

(16) Where appropriate, prepare foods manually.

(17) Use the hob in preference to the oven for warming food.

(18) Use toasters and griddle plates rather than conventional grills.

(19) While cooking, keep windows and doors in the kitchen *closed* in order to prevent excessive draughts. Tests carried out in one kitchen showed that reducing the time the kitchen door was open from 30 to 7 s caused the convective heat loss (occurring via the exiting warm air) to fall by a factor of eight. (This occurs because during the first few seconds the exiting air is still accelerating.)

(20) Judge carefully the correct times at which to start heating each item of food, so that as far as is feasible, all components for a single meal are ready to eat simultaneously, exactly at the time required—i.e. none having to be kept warm, while waiting for the completion of cooking of

other items, before serving. (Use the oven-timer if fitted.) Do not maintain vegetables at high temperatures for long periods, because this reduces their nutrient content. However, when it is necessary to keep food warm, only employ well-insulated 'hot cupboards' and bains-marie, or alternatively a temperature-controlled microwave oven.

(21) In commercial premises, switch off (or turn-down) equipment during slack periods. Tests show that only approximately half the power dissipation is required to maintain oil in an electric fryer at 93°C compared with that needed to maintain the usual operating temperature of 177°C: the time taken to re-establish operating conditions is usually about 2 10 min.[139] Occasionally check the temperature of the oil to ensure that the thermostats and elements are functioning properly.

(22) Cook fresh foods in preference to frozen foods: as a rough guide it should be remembered that, on average, it requires as much energy to freeze food as it does to cook it. Cooking periods and energy consumptions increase considerably if food is cooked from its frozen state. For example, Bengtsson *et al.*[58] reported that the cooking periods required for roasting samples of frozen beef (initially at −20°C) were about 50% greater than those needed to thoroughly cook similar thawed samples from 5°C. Furthermore, nutrient losses tend to be significantly higher if foods are deep-frozen prior to cooking or re-heating, e.g. peas lose virtually no vitamin C when stored at 0°C for 6 months, but more than 50% when frozen at −9°C (as is common practice) over the same period.[140]

(23) When chilling cooked food, allow it to cool to room temperature in the ambient environment before placing it in the refrigerator or freezer.

(24) If frozen food is to be cooked, remove it from the freezer well in advance and allow it to thaw completely in a refrigerator before starting the cooking operation. This cascades the warming-up process, i.e. the frozen item reduces temporarily the cooling load of the refrigerator, before it is removed for cooking.

(25) Do not use conventional or microwave ovens for defrosting frozen foods unless shortening the food preparation time is given a higher priority than energy thrift.

(26) For microwave cooking use polysulphone cookware—see Appendix 3. If this is not feasible, then make the best selection from those non-metallic food containers available by placing each in the oven for about 30 s on maximum power. The one that remains comparatively cool at the end of the test period is to be preferred.[88]

(27) Be aware that some foods, e.g. steam puddings, 'scrambled' eggs or jacket potatoes, can be cooked in a microwave oven to at least equal culinary standards, much more rapidly and for less energy expenditure, compared with more conventional techniques.

(28) Develop energy-efficient hot-water management skills. The hot water thermostat should be set to a temperature that is suitable for the majority of cooking and washing purposes (e.g. 60 °C). On occasions when very hot water is required, some water should be taken from the hot water supply, boiled in a kettle and then mixed with water from the hot water tap to achieve the required quantity at the required temperature. The practice of cooling water from the hot water supply by adding water from the cold water tap should be discouraged because it is wasteful of energy. It is estimated that for each main meal consumed, between 0·005 m^3 and 0·018 m^3 of water is used for meal preparation, cooking and washing-up purposes. Thus when cooking, boil the required volume in a kettle, so that the least amount of water can be used in the appropriate size vessel for cooking. This practice (of using the least amount of water for cooking) also has nutritional benefits, e.g. it reduces the diffusion of soluble vitamins (see Fig. 44) into the cooking water. (When catering for a large number of people, the re-use of warm, nutrient-containing, cooking water will conserve both energy and nutrients.) Finally, when washing-up, do not wash items under a flowing hot-water supply, do not boil too much hot water in a kettle and only employ a dishwasher when it is well filled with 'used' utensils (which have already been 'scraped' clean).

In catering premises it is desirable to meter all electricity, gas, steam and hot-water consumptions. Preferably an energy-management control system for monitoring, and where feasible regulating, the space-heating requirement, electricity demand and overall power factor of the establishment, should be fitted. This will usually achieve a significant reduction in the annual energy bill. For example, a Kentucky Fried-Chicken group in Detroit saved 9 % of their annual energy consumption simply by installing peak-loading control devices to ensure that the highest demand equipment (e.g. air-conditioning compressors and automatic pressure fryers) did not start-up or surge simultaneously. Also the use of a heat exchanger between the waste warm water and the incoming water to the hot-water tank, served to pre-heat water and hence saved energy. Additional savings can be achieved by using highly efficient

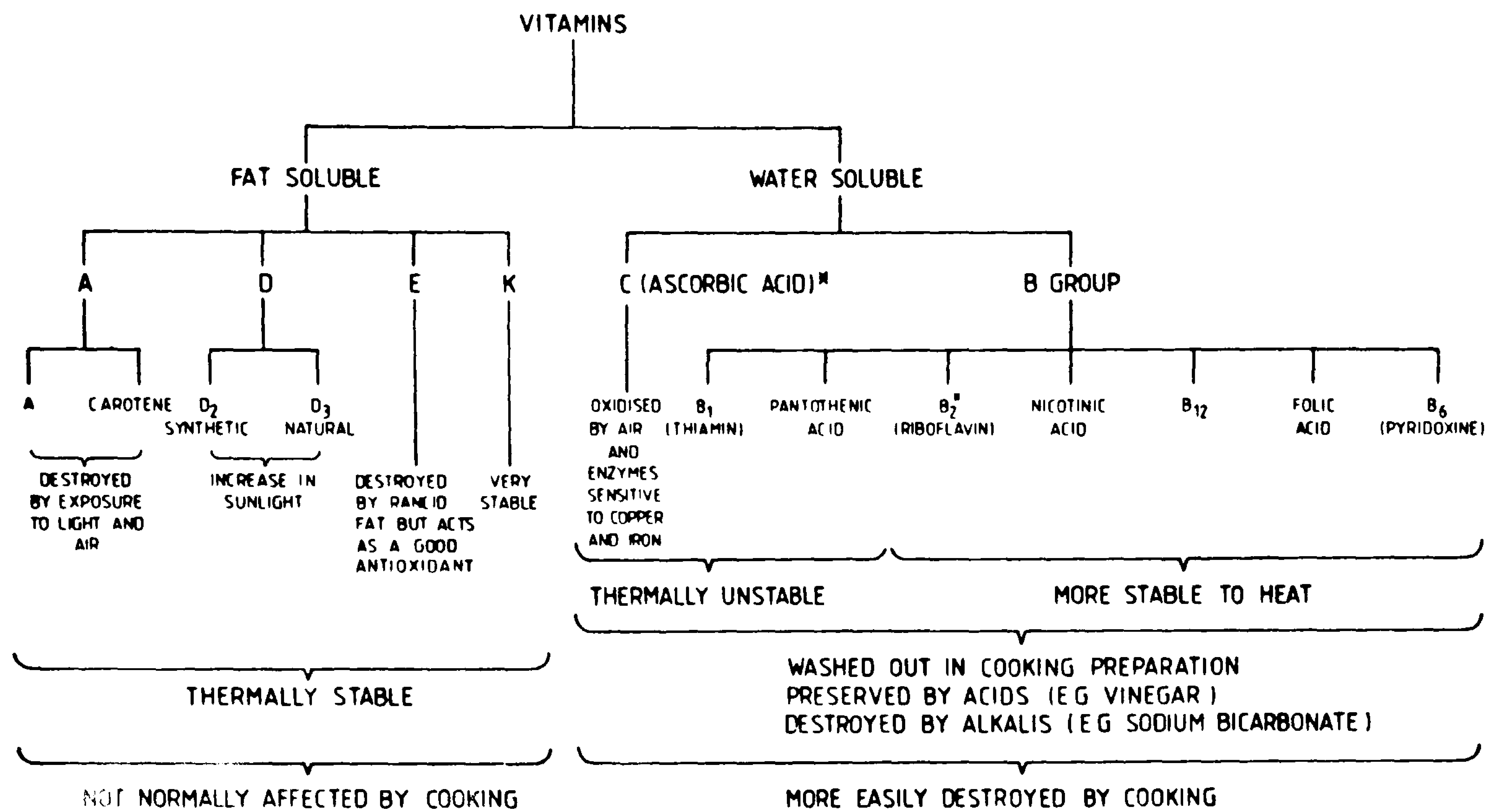

Fig. 44. Adverse effects of cooking upon the vitamin content of foods (after ref. 141). * Adversely affected by bright light, especially ultra-violet which is emitted by the commonly-used fluorescent lighting

(> 90 %), high power factor (> 0·9) three-phase blower motors to satisfy the high ventilation rates that are necessary in most catering kitchens. The electricity tariffs payable will be minimised (assuming no change in kitchen practices), if the *overall* power factor for the establishment is maintained at unity. This will also ensure that the size, cost and heat losses (when in operation) associated with the necessary transformers and electrical wiring will be minimised. Accurate voltage regulation may be worthwhile in large establishments, where the working lives and energy efficiencies of electrical appliances (such as motor and lighting equipment) can be improved, if the supply voltage is maintained within closer tolerances (e.g. ± 1 %) than is present practice (± 6 %). This has a beneficial knock-on effect because when, for example, motor manufacturers are certain that a motor will only be operated on a near-constant voltage supply, a lower cost, greater efficiency and a longer life motor can be designed.[99,142]

Although the task of reducing energy expenditures in commercial premises is often hindered by irresponsible catering staff who do not pay the energy bills, savings can be achieved simply by improved kitchen management. Ovens should always be filled: if space is available in an oven which is in use, consideration should be given to cooking foods which would otherwise be prepared at another time or by another technique (e.g. rice or sauces). High energy-demand equipment should be used sequentially rather than simultaneously and energy-intensive cooking operations, such as baking and roasting, should be carried out during non-peak demand hours. Also it is advisable to start the day's baking with foods that require the lowest oven temperatures and to stagger pre-heat times. Clearly it is the responsibility of the kitchen manager to ensure that his staff abandon their energy-wasteful practices. One of the manager's chief objectives is to ensure that equipment (including lighting) is switched off (albeit temporarily) when it is not needed: the ventilation rate within the kitchen should then be adjusted so that a comfortable average air temperature of about 18 °C is maintained. Unfortunately, recent surveys[11,35,143] found that:

(i) catering equipment was often abused and in poor working order;
(ii) virtually all catering kitchens had equipment which was either not functioning, working inefficiently due to inadequate or improper maintenance, surplus to requirements or unused;
(iii) caterers were dissatisfied with the repair and maintenance services proffered by manufacturers and their representatives;

(iv) equipment was often switched on in advance of cooking and left on continuously even though it was only used intermittently;
(v) dishwashers were frequently used when only partly full, lids were left off pans during cooking operations and automatic timers remained unused;
(vi) little attention was given to monitoring the use of electricity, gas, steam or water supplies; and
(vii) kitchens and catering appliances were often not ergonomically designed and few (if any) staff were aware of energy-saving practices.

To rectify these shortcomings, energy audits for all types of catering kitchens should be carried out. Attempts deserve to be made to correlate energy consumptions with (a) production, (b) man-hours of work and (c) expenditures on raw materials. Subsequently, the performances of kitchen equipment and the efficiencies of kitchen activities must be checked regularly.

Alternative methods

A simple demonstration of how improved management can contribute to energy thrift was given in 1980 by pupils at the Sir Charles Lucas School, Colchester. The traditional method for cooking an egg is by boiling water in a pan, and then immersing the egg in the boiling water for about 3 min. This requires the combustion of approximately 6 min of the gas supply. But a perfectly 'boiled' egg can be obtained by (i) placing the egg in a small volume ($\sim 5 \times 10^{-4} m^3$) of water in the pan and replacing its lid, (ii) bringing the water to the boil (and maintaining it there) using less than 3 min of the gas supply at the same setting as previously, and (iii) allowing the pan, with lid in place, to stand with the egg in the hot water for at least a further 6 min. By this method, the egg is not overcooked: the yolk's central region attains a maximum temperature of approximately 70 °C and thus it does not harden even though the albumin (i.e. the 'white') solidifies. A disadvantage is that the overall cooking period becomes 9 min, whereas the traditional method takes only 6 min. The lid should remain on the pan throughout the heating and cooling process and preferably more than one egg should be cooked simultaneously in a proportionally greater amount of water.

A similar procedure should be practised with ovens. Cooking should commence immediately the heating ensues. Switch off the heating well before the termination of the prescribed, traditional (i.e. pre-1973) 'cookbook' period, but allow the food to stay in the oven. The oven will remain for an appreciable time at a sufficiently high temperature so that the cooking can be completed satisfactorily. Furthermore, it should be remembered that most foods do not need necessarily to be heated to high temperatures in order to cook them satisfactorily (e.g. see Table 26). Usually the temperature required for cooking is below 100°C.[145]

Often increasing the food's temperature above its 'minimum cooking temperature' serves only to reduce its nutrient and water content.[137,146] However, the period of cooking also directly affects the edibility and nutritional value of the food, and so 'optimal temperature' cooking should be preferred to either 'minimum temperature' or 'minimum time' cooking. The optimal cooking temperature may be defined as the temperature that produces the most palatable end-product, with minimum mass and nutrient losses, but for acceptable expenditures of time and energy. Such temperatures have been determined for roasting (initially frozen or thawed) joints of beef, pork, lamb and veal.[147] Tests indicated that the optimal *oven* temperatures for these foods were between 150°C and 160°C, although the cooking period required depended on whether rare, medium or well-done meat was prepared.

TABLE 26

Temperature Considerations Involved in the Cooking and Storage of Food[137,144]

Temperature (°C)	*The result of maintaining the food at the stated temperature*
> 120	Rare infecting organisms (e.g. Botulism spores) are eradicated
> 70	Meat is 'well cooked'
> 63	The lean parts of meat, poultry and fish begin to shrink
60–85	The rate of destruction of vitamin C when 'boiling' vegetables is maximised
> 60	Egg 'white' is formed
> 60	Infecting organisms (e.g. bacteria of the typhoid, dysentery and salmonella groups) are eradicated
> 60 (at surface)	'Red' meat 'browns'
55–75	The effects of meat 'tenderisers', i.e. enzymes such as papain (which is found in the juice of papaya fruit), are maximised
20–40	The rate of mould growth on food is maximised
< −10	The growth of micro-organisms ceases
< −12	Milk is safely stored for at least one year

Exhaustive testing may be required to obtain optimal temperature values for all commonly-eaten foods, but considerable energy savings could be accrued from their implementation. Such action may militate against the cooking of certain high-temperature (> 150 °C) composite foods (e.g. cakes), which provide few nutrients for relatively high energy inputs and thereby support the quest to improve the quality of the British diet.

The use of more-appropriate equipment

An appliance designed to accomplish a specified cooking task will usually expend less energy than a traditional cooker employed to satisfy the same purpose. (However, the energy used in manufacturing each such replacement device should ideally be much less than 1 % of the total energy savings subsequently accrued throughout its working life.) A good example of a more energy-efficient appliance than the conventional oven is the well-insulated 'slow-cooker', which, because of its cheapness, simplicity and convenience is becoming popular. Cooking a 2·27 kg joint of meat during a 10-h period, using a slow cooker, expended only 0·75 kWh, whereas to cook the same joint, the energy consumptions ranged from 2·73 kWh, with what in 1976 was regarded as a highly-efficient conventional oven, to 4·59 kWh with a typical oven in use at that time.[28]

As an alternative to the conventional cooker, for the slow-cooking of stews or soups, the use of a 'hay-box' is feasible. This was favoured during World War Two and in its most basic form consisted of a cardboard box ($\simeq 1\ m^3$ capacity) lined with about $0{\cdot}5\ m^3$ of hay. The components of a stew, for instance, can be prepared as usual, then immersed in water which is boiled in a pot (with its lid on) for about 2 min on the hob, before being placed centrally in the hay-box. It can be left to cook in the hay-box for several hours and then placed on the hob once more in order to re-heat the contents for 2–3 min just prior to serving. The amount of energy expended in this way is relatively small, and because the initial capital cost is low, the hay-box would appear to compete favourably with the more versatile electric slow-cooker. The use of hay is preferred because it releases a more pleasing aroma than a box lined with a synthetic insulant, but neither is likely to become common in modern domestic kitchens. However, a 'polystyrene-box' (see Fig. 45) does improve the cooking capabilities of this method—e.g. a soup prepared in the above manner was removed from the box after 3 h: it was cooked and still too hot to

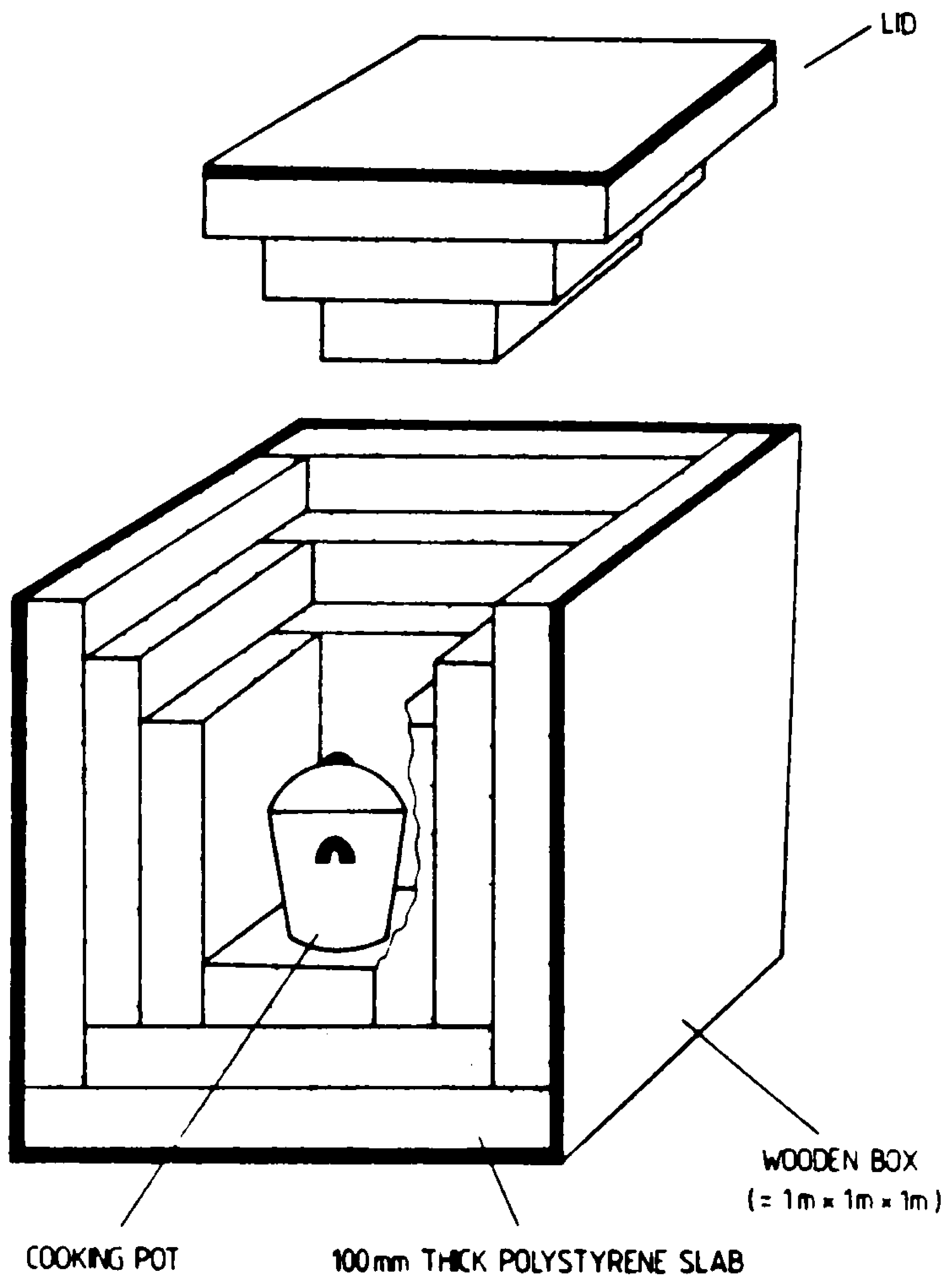

Fig. 45. An inexpensive 'polystyrene-box' which can be used for the slow cooking of pre-boiled liquid foods (after ref. 27).

swallow.[27] (Other foods such as porridge, milk puddings and casseroles can also be cooked satisfactorily by this technique.)

Portable, thermostatically-controlled, 'multi-purpose' cookers are capable of thawing, simmering, stewing, braising, roasting or baking small quantities of various foods. It is claimed that these appliances save electricity and cook in considerably shorter periods than are achievable with conventional ovens.[37] Maximum attainable cooking temperatures are in excess of 200 °C and the cooked products are alleged to be comparable with those achieved with conventional cookers. Their increased use, especially by single people, would therefore result in some reduction of domestic cooking-energy expenditures.

When cooking joints of meat or poultry, it is expedient to employ a rotisserie attachment which fits into the main oven. The rotation achieved via this system permits the meat to cook more quickly and uniformly than it does in a conventional roasting dish.[92] This is because (i) the spit increases the rate of heat transfer through the central region of the food, (ii) energy is not used to heat the roasting dish and the cooking fat therein, and (iii) the cooking operation needs less supervision (e.g. the oven door doesn't have to be opened for basting purposes during the cooking operation). However, a joint of meat (especially one with a high fat-content) has a low thermal conductivity and although its external surface may appear cooked, internally it may not have reached a 'safe' temperature (see Table 26). For example, it took 90 min for the centre of a 1·6 kg joint of beef to reach 62°C, when immersed in boiling water throughout the cooking period.[137]

Cover[148] showed that by inserting six nickel-plated copper skewers, which were approximately 15 cm long by 0·5 cm diameter, into each of the 15 (~ 5 kg) 'round' joints of beef roasted, an average reduction of 54 % in the periods required to cook 'well-done' meat was achieved. Nutritional losses were also reduced but subjective tests revealed that the meat was slightly less tender when cooked in this manner. Alternatively, an inexpensive heat pipe in the form of a thick pin, can be inserted into a joint of meat to lower the thermal resistance for heat passing to the interior of the joint. By such a measure, the necessary cooking periods can be reduced by up to 50 %.[149,150] Furthermore some heat pipes are fitted with temperature indicators to enable the cook to assess the state of the cooking operation more accurately. This permits much more precise temperature control of the food to be achieved while it is being cooked. Therefore the cooking efficiency and the culinary standard of the cooked food can be improved. Indeed, if the 'food temperature' is known throughout the operation, rather than just the oven temperature, it becomes easier for the typical cook to develop techniques which will enable him/her to prepare food consistently. Thus, future cookers should be equipped with a *food*-temperature indicator (which could be linked feasibly to an external buzzer to inform the cook that the food has exceeded the chosen temperature). This can be achieved by using a heat pipe fitted with a temperature dial for the cooking of some foods (e.g. meat joints), or by employing a robust thermocouple probe for other types of food (e.g. soufflés).

Energy consumptions may be reduced significantly and cooking periods shortened by up to 75 %[151] by using a 'pressure-cooker' instead of a normal pan. This applies especially if traditional cooking periods are long and the pressure-cooker is well filled.[28] However for short-duration cooking of only small thermal loads, conventional cooking, using a saucepan containing pre-heated water (from an electric kettle), is usually preferable.

Compared with a conventional potato-chip pan, the thermostatically controlled domestic deep-fat fryer is cleaner, more easily controlled and uses up to 75% less energy. In addition, the latter constitutes far less of a fire hazard. (It should be noted in this context that deep-fat frying is the major cause of fires in the kitchen: more than 16000 fires are caused annually in UK homes by 'chip-oil' or 'fat' catching alight.) Thus the use of domestic deep-fat fryers in preference to conventional systems is recommended.

The 'multi-purpose' cooker, deep-fat fryer, kettle and 'egg-boiler' all have their respective electric heating elements immersed in, wrapped around or directly below the liquid or food being heated. Each possesses a relatively well thermally-insulated low thermal-mass casing, which inhibits direct heat losses from the element to the ambient environment. Therefore these appliances are more energy-efficient than traditional systems. For example, the development of tall, visually appealing, moulded-plastic, automatic, electric kettles with graduated capacity scales has reduced the energy consumption of a basic cooking operation—namely the boiling of water. However little attention has been devoted to the optimisation of the design of the ubiquitous saucepan, which has been used for hundreds of years. To obtain satisfactory results for the minimum rate of energy expenditure, an optimal pan material (probably of composite or alloy construction) needs to be found. Nilsjohan Ltd[152] provided thermographic evidence that their stainless-steel pan with an aluminium core distributes heat more evenly than a more conventional aluminium-based steel pan. Alternatively, the practice of using a pan on a heated hob may be superseded by the use of a thermally-insulated, low-emissivity container with: a well-fitting lid; an internal electric element, that provides uniform heating; a temperature indicator; a variable-power control for precise boiling and simmering operations; and a motor or clockwork-driven stirrer, which may be of particular benefit to caterers.

Foods, which are now commonly 'boiled' on a hob, can be cooked via an electrolytic heating technique. This involves placing two electrodes in a cooking fluid, which is contained in a suitable (e.g. glass) vessel, and then passing an alternating current between the electrodes. As a result, the fluid (e.g. a weak salt solution as traditionally employed for cooking vegetables) and the food are heated. By 'boiling' potatoes, Svensson *et al.*[153] tested a commercial cooker system based on this principle. When compared with a more conventional technique it was found that: the necessary cooking periods were reduced typically from 25 to 5 min (depending on the salt concentration of the cooking water); the amounts of protein, minerals and vitamin C contained in the potatoes after cooking were often higher; and the aesthetic quality of the average potato was improved. Also water is expressed from the food when cooked electrolytically, and so 'soggy' potatoes cannot be produced.[153] Therefore the use of this type of cooker system may be particularly advantageous in the catering sector, where large energy and nutrient savings should be achievable (especially if the need to keep 'boiled' foods warm after cooking is avoided due to the relatively short cooking periods).

Energy-thrift education for consumers

A survey—see Table 27—undertaken during 1976 covering 2500 households in 11 cities of Texas, USA revealed that almost half of the respondents were not taking advantage of the portable appliances, e.g. deep-fat fryers, that they owned.[154] Such inaction was partly because the owners were unaware of all the energy-saving attributes or capabilities of

TABLE 27
The Frequency with Which Cooking Equipment Was Used by a Sample of US Domestic Owners[154]

Appliance	*Percentage of owners using the stated appliance*			
	Daily	*Weekly*	*Monthly*	*Seldom*
Microwave oven	60	40	0	0
Conventional oven	62·8	32·9	2·0	2·3
Toaster	67·3	20·3	2·3	10·1
Sandwich toaster	0	31·8	22·7	45·5
Pressure cooker	13·7	25·3	14·7	46·3
Portable oven	18·2	25·0	9·1	47·7
Deep-fat fryer	3·1	21·9	25·0	50·0
Rotisserie	1·9	15·4	11·5	71·2

these appliances. There is little reason to suppose that buyers are simply not interested in such details. For example, since the UK Ministry of Transport required the publication of details concerning the fuel consumptions of new cars, the discerning buyer has taken this into account when buying. Similar influences would probably have analogous effects eventually on purchases of cooking equipment if the energy efficiencies (explained via straight-forward examples relating to the cooking of typical foods) were outlined within the sales and maintenance literature that usually accompanies such appliances. The argument that consumers (especially domestic ones) are only interested in appearance, reliability, cleanability and size is commonly expressed by manufacturers, who are often unable to state the energy efficiencies of their appliances or would prefer them not to be published to avoid embarrassment. However, in times of depleting fossil-fuel reserves, this attitude is unwise: consumers do not deliberately waste energy, they use it in buildings, systems and equipment designed for them by others who should know better. It is clearly the responsibility of appliance manufacturers to provide product information, which includes energy consumption details for the potential customers. Furthermore, present advertising malpractices whereby, for example, new cooker-hobs are illustrated supporting uncovered pans containing rapidly boiling liquids, should cease.

It has been estimated that over 50 % of purchasers of electric cookers do not read the accompanying information booklets issued by manufacturers.[155] The reason why this occurs may be partly due to the consumers' dissatisfaction with these colourful brochures, because they are so full of sales jargon (much of which has little scientific justification) and recipes with illustrations showing, for example, cakes cooked by experts. Today in the UK, the provision of easily understood scientific data may be received with more interest. For example, this could be done by listing a dozen common recipes that can be cooked with the appliance, the corresponding methods of cooking, the energy consumed and its financial cost; and suggestions as to how the cooking methods could be modified to reduce the cost of the energy used, plus the approximate financial savings resulting from such improvements. Also the government should investigate such tests and provide long-term fuel consumption targets similar to those set for automobiles by the US government. This should ensure that, in future, cooker design is improved consistently.

When shopping for food, consumers are frequently provided with a huge variety of attractively-packaged items from which to choose.

However, such packaging: (i) sometimes reduces the keeping quality of the food;[156] and (ii) is often energy expensive to produce and subsequently dispose of when the food has been eaten (e.g. some non-biodegradeable materials have to be incinerated). Furthermore, scientific information—e.g. the optimal cooking method, the energy required for cooking and the food's nutritional composition (see Table 28)—should be provided on the package to influence purchasers' decisions. This would encourage individuals to be more selective when buying foods and may thereby be beneficial to the nation's health (see Table 5) as well as reduce its energy bill.

Substantial increases in the electrical energy required by consumers occur between 4 and 7 p.m., partly because of the popularity of cooking during this period. To help smooth out electricity production, it may be advantageous for the government to publicise this fact and increase the charge per kWh during this period, in order to encourage individuals to achieve energy savings and thereby contribute towards lessening the peak load imposed upon the electricity-supply network. The use of 'storage

TABLE 28

Nutritional Labelling of Food Packages, Similar to That Exhibited on a Can of Sardines Sold in the USA (adapted from ref. 157)

Food	Norway brisling sardines in olive oil
Mass	106 g
Chief ingredients	smoked brisling, olive oil and salt
Name and address of food manufacturer or distributor	
Serving size	106 g per person
Energy content	1·93 MJ (1·09 MJ excluding liquid)
Protein content	19 g
Carbohydrate content	1 g
Fat content	42 g (20 g excluding liquid)

The contents of this can provide the following percentages of the US recommended daily allowances for maintaining good health:

Protein	40	Vitamin A	4
Calcium	30	Vitamin B_1	0
Iron	10	Vitamin B_2	10
Phosphorus	30	Vitamin B_{12}	100
Magnesium	10	Vitamin C	0
		Vitamin D	100
		Nicotinic acid	30

cookers', which have been developed in Norway and Nepal,[158] may bolster attempts to achieve this. Such appliances store energy continuously and then release it in relatively large amounts when it is needed for cooking.

Unfortunately it is alleged that higher marks are often awarded in the UK to those home-economics students who, for example, skillfully mix, cook and ice a cake than to those who prepare a less demanding, yet healthier, and less energy-consuming cold-salad dish.[159] Influences such as this are the reasons why the public tend to adhere to traditional foods and cooking techniques even though these may be less healthy and more wasteful of energy than known alternatives. It is vital that schools impart energy-thrift habits to the younger generation because, when these people are older, they will encounter a far more difficult fossil-fuel scarcity situation than exists at present.

IMPROVED DOMESTIC-KITCHEN DESIGN

Most operations carried out in a kitchen involve cooking or washing-up: thus ample work-space should be provided in the immediate vicinities of these activities (e.g. see Fig. 46). The relative locations of food and utensil storage spaces are of less importance, although they must be of sufficient capacity and sited conveniently, e.g. frequently used cooking utensils should be fitted in raised positions close to the cooker. Ideally appliances, cupboards and work surfaces should be arranged so that the necessity to retrace steps randomly when performing kitchen activities is minimised. In attempting to achieve this, the logical sequence of preparing (and clearing away after) a meal should be considered, i.e.: acquiring and cleaning the raw materials, mixing, cooking, dishing-up and serving; then collecting used utensils, removing and disposing of food wastes, positioning utensils ready for washing-up, washing-up, temporarily stacking washed items, replacing cleaned items in their storage positions and cleaning the kitchen. The lay-out of the kitchen units and equipment should also ensure that the movements of individuals passing through the kitchen does not interfere with any work being carried out therein.

The environment created within a kitchen directly affects the people using it. Mean air temperatures should be maintained between 16 and 22 °C, excessive draughts (i.e. air velocities $>0{\cdot}15$ m/s on the ankles, or $>0{\cdot}3$ m/s on the face) should be eliminated, and preferably noise levels

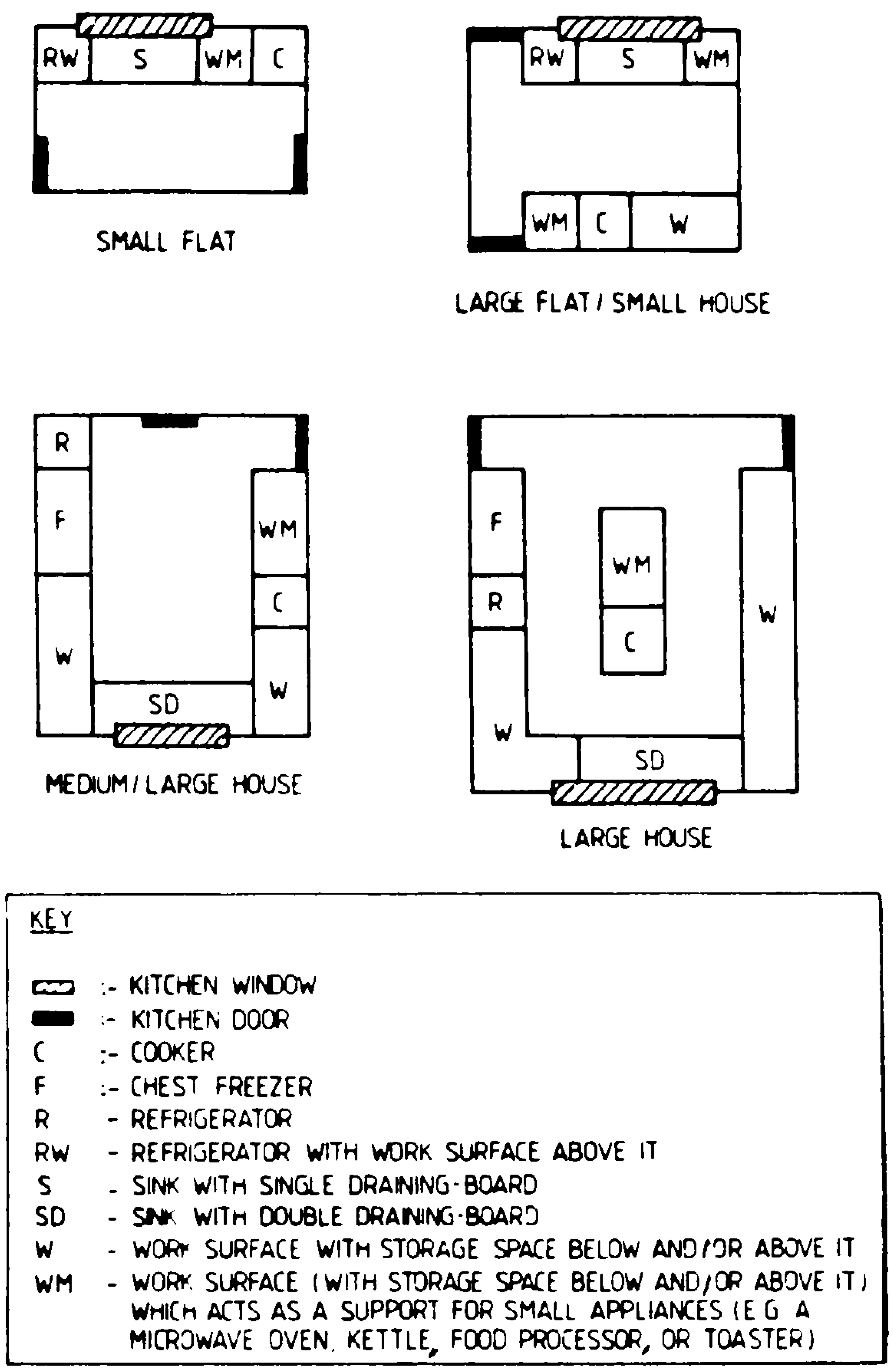

Fig. 46. Some plan views of ergonomically-designed domestic kitchens (adapted from ref. 160).

should be kept below 56 dB. In addition, factors such as the incorrect positioning of sinks, sub-optimal illumination and the storage of heavy items above head-height or below knee-height can, over long periods, cause excessive mental and physical effort to be expended by users. This often leads to mental stress complaints (e.g. headaches, impaired alertness and carelessness) which can jeopardise both the safety of operations carried out in the kitchen and the quality of the food served. Thus, kitchens should be designed with a view to maximising operational efficiency (i.e. the ratio between the useful effort expended and the energy consumed to achieve the considered kitchen activity). Facilities such as variable height work-surfaces or sinks, which can be better matched to the anthropometric dimensions of each user, may be included in the designs of future kitchens (especially commercial ones, where an improved working environment will usually lead to more cost-effective catering).

There is a growing trend towards developing the domestic kitchen so that it integrates with the other, more comfortable, living zones within the building. The siting of cooking and food preparation facilities in locations which are also suitable as eating zones is more common in US homes, but this will probably occur in future large UK dwellings because of the higher levels of convenience and the reduced energy expenditures thereby achieved.

In addition to the more usual economic and ergonomic factors that should be considered when designing a kitchen, attention should be given to the following:

(1) Always size kitchen units and other equipment to meet the predicted demand.

(2) Avoid positioning freezers and refrigerators immediately adjacent to or directly opposite cookers, dishwashers or other heat-liberating equipment.

(3) Choose high-efficacy, high-efficiency, fluorescent lighting in preference to conventional incandescent tungsten-filament lighting. Typically an illumination of about 400 lux is adequate for the domestic kitchen and a 1 m long twin-tube, 85 W fitting will usually be sufficient for a 10 m^2 floor area. Nevertheless it is expedient to design a kitchen to make full use of natural (i.e. free) daylight.

(4) Consider fitting raised built-in ovens (rather than built-under or free-standing types) because they tend to be simpler to use, easier to clean, better insulated (primarily to ensure that the kitchen units do not catch fire) and more out of reach of young children.

(5) Think carefully about the allocation of space within the kitchen. The installation of ample equipment will reduce the space available for storage, meal preparation and kitchen furniture. In the extreme, this may result in an increase in the frequency of shopping for food and cause irritation when using the kitchen. These factors lead to increases in energy consumptions.

(6) Consider fitting an air-management system. If a basic cooker-hood

is favoured, site the cooker on an external wall to simplify the installation of the outlet ducting. Preferably fit a heat exchanger to the exhaust duct in order to reclaim some of the heat from the exiting air. Do not vent air removed from the kitchen directly into the attic space because this will probably cause condensation there, so leading to rapid deterioration of the colder members of the wooden roof structure.

(7) Minimise the lengths of all non-ambient water-carrying pipes and then insulate them properly.

(8) Ensure that all electro-mechanical controls on a cooker: (i) can be adjusted accurately without difficulty in a safe manner; (ii) are clearly marked (preferably with coloured dials); and (iii) move in the same direction to increase rates of energy expenditures. Opt for equipment with (i) 'tell-tale' warning lights (which, for example, indicate that the oven is switched on, or that the hob surface is above its safe-touch temperature); (ii) robust and easily-operated door catches mounted on doors, which can be removed for cleaning purposes; and (iii) easily-removed hob-reflectors, oven shelves and drip-trays (if applicable). If a glass-ceramic hob is to be fitted choose one that has a lip around the perimeter of the hob-top: this will help prevent any spills incurred during cooking from flowing off the hob.

CONCLUSIONS

For kitchen operations, energy thrift can usually be achieved most easily by replacing old equipment with more efficient systems. Even by applying only our existing technical understanding to developing economically justifiable designs, it is probable that the annual energy consumption of the typical, domestic, electric cooker will decrease by over 50% between the years 1978 and 2000.[81] The increasing popularity of specific-purpose equipment, such as microwave ovens, infra-red grills and slow cookers, will also contribute appreciably to achieving energy thrift. Nevertheless, this 'new for old' policy will result in improvements occurring only slowly (especially in the catering sector) because, for instance, the average life for a free-standing cooker is about 15 years.

Generally a saving in energy consumption is insufficient incentive for the consumer to purchase new cooking equipment unless other improvements (e.g. shorter cooking periods, fewer cleaning difficulties and improved appearance) are available as well. For the individual, there is a natural reticence to incur rapid changes because of the valid economic desire to exploit existing capital investment to the maximum: this is the major problem with many proposed energy-thrift measures. However, caterers should appreciate that by reducing energy wastages, they will not only be saving money, but also improving the working environment within their kitchens.

Retro-fitting existing cookers with energy-conservation improvements in order to raise achievable efficiencies will occur only rarely. For the most immediate significant impact nationally, with respect to reducing the energy expended upon cooking, better management is recommended. Lawson[11] suggested that about 16 PJ per year could be saved in the British catering sector by adopting improved operational practices. If only 10% of the energy used for catering purposes in the domestic sector could also be saved, overall national savings would amount to approximately 44 PJ per annum (i.e. at least £250 × 10^6 at 1985 prices). To achieve this aim, a comprehensive and straight-forward programme of energy-thrift education for housewives, cooks and kitchen managers is needed. This will require all concerned to exercise considerable personal discipline.

The present approach, whereby individuals make purchasing decisions mainly on visual and first-cost grounds—partly because the cooking appliance and food manufacturing industries rarely provide adequate scientific data to support their claims—should be supplemented by other considerations. Food is too fundamental to human life, health and happiness to be considered an unworthy subject by intellectuals. For example, even the typical Briton (who tends to be casual about eating compared with most of his foreign counterparts) spends between 25% and 33% of his waking hours preparing, cooking and/or clearing away after meals.[161] Nevertheless, energy wastage prevails both on a national scale (e.g. storing vast quantities of food at sub-ambient temperatures in so-called 'food mountains'); and on an individual scale (e.g. performing hob operations without placing lids on the pans employed). In times of rapidly increasing human population, such malpractices are morally questionable because:

(i) many people living in both less-developed and developed nations are malnourished;
(ii) the world's existing food supply, which is sufficient to support the entire human population, is unjustly distributed;[162]

(iii) the amount of land that is suitable for food or energy farming is decreasing; and
(iv) fossil-fuel reserves are being depleted rapidly.

Thus for the prosperity of future societies, food and related matters (e.g. the energy and health factors involved in catering, food processing and agriculture) deserve to be given more rigorous and unified scientific attention.

APPENDIX 1: OPTIMAL PAN-BASE DESIGN FOR USE WITH INDUCTION HOBS

For effective cooking, the metal in a cooking utensil must offer sufficient resistance to the induced current flows to produce a large amount of eddy-current heating. In the frequency range 20 to 30 kHz, it is difficult to heat cookware made entirely from aluminium alloys or copper due to their relatively low surface resistivities. Stainless-steel has a much higher resistivity, but a lower thermal conductivity and thus it does not allow rapid lateral heat transfer to occur. Low-carbon steel is suitable for the pan base, but research has shown that a composite construction leads to a higher cooking effectiveness, e.g. see Fig. 47. A portable induction hob manufactured by Toshiba[163] overcomes some of the variations in heating performance when using different pans, by adjusting automatically the

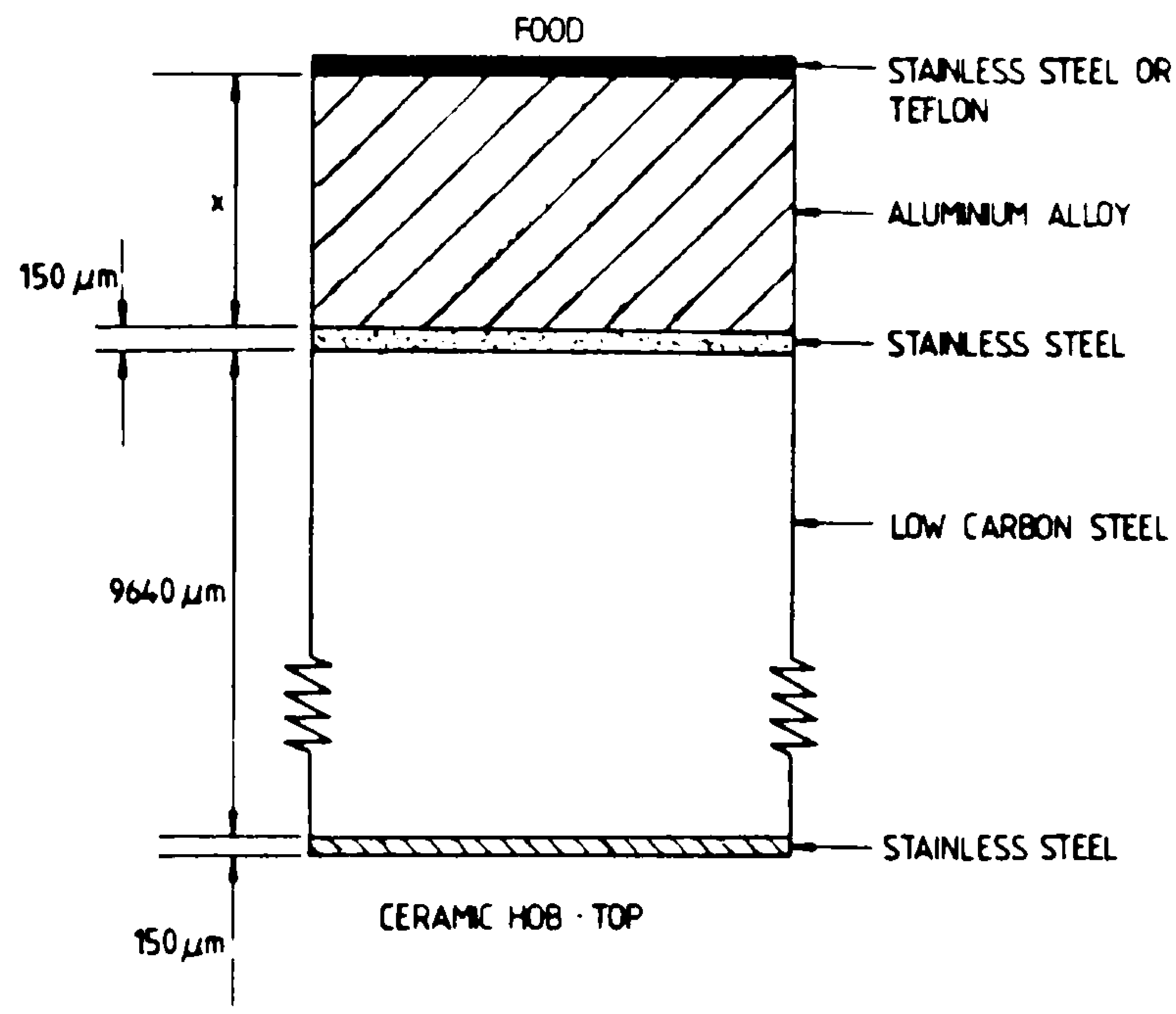

Fig. 47. Schematic cross-sectional plan view of a pan-base designed for use on an induction hob (adapted from ref. 53). Thickness x should be about 1500 μm for frying pans, but about 1020 μm for saucepans because lateral thermal conductivity is then not as important.

power taken from the mains supply according to the metal pan superimposed on the hob. Allegedly, it ensures that a thin-based pan is no more likely to overcook food at a particular setting than a thick-based pan at the same setting.

APPENDIX 2: MICROTHERM AS A THERMAL INSULANT

Microtherm is a mechanically relatively weak, thermal insulant. It has an average cellular size of approximately 0·1 μm, i.e. less than the mean free path of an air molecule. Thus internal convection is entirely suppressed, and even conduction through the air is inhibited because the pore sizes tend to be smaller than the mean free path of the trapped air at the considered temperature. Therefore Microtherm has a thermal conductivity *less* than that of still air, and considerably less than that of conventional glass-fibre oven insulant.[132]

APPENDIX 3: ENERGY-EFFICIENT MICROWAVE COOKWARE

At present, more than 1 million microwave ovens are sold annually in the UK and about half the purchasers buy special microwave cooking utensils.[164] Thus, from the energy-thrift viewpoint, it is important to ensure that only thermally efficient cookware is used. Ideally utensils should not absorb microwaves but be transparent to them. Independent studies, carried out in the USA, showed that of the five plastics subjected to comprehensive cooking tests (namely thermoset polyester, thermoplastic polyester, polysulphone, TPX and polycarbonate), the polysulphone absorbed the least amount of microwave energy.[165] Also polysulphone cookware was generally preferred to the other plastic containers tested because it:

(a) reduced cooking times;
(b) remained cool enough to handle after cooking;
(c) was less dense;
(d) withstood considerable misuse; and
(e) was more resistant to staining.

APPENDIX 4: MATERIALS SUITABLE FOR USE AS COOKING UTENSILS

The following materials form acceptable food utensils when carrying out general cooking operations: stainless steel, aluminium, iron and high-temperature glass. Tin-coated vessels may cause acidic foods (e.g. citrus fruits) to darken and develop a slightly metallic taste, but the salts that cause this are non-toxic and non-poisonous. Items cooked in aluminium containers absorb up to 12 parts of this metal per million parts of food although this is not harmful.[166] Chromium and nickel are dissolved from stainless-steel utensils but because this occurs in such minute quantities, no adverse physiological effects result.[167] Glass containers may be dangerous because they have very low emissivities and thus the cook cannot perceive the temperature of the hot container just prior to handling as well as he/she can when using a more conventional metal container. However, cooking utensils which partly consist of zinc (e.g. galvanised ones) should never be used.[168] This is because toxic salts are formed when organic acids contained in the food react with the zinc.[169]

To reduce oven-cooking periods, high-emissivity (i.e. dark and dull), oven dishes or pans should be used (e.g. see Fig. 13). Tests by Cornehl and Swartz[170] indicated that the end-use efficiencies of electric ovens ranged from 13·6% when using aluminium utensils, to 24·7% when employing cast-iron ones. The thermal efficiencies of commonly-employed utensils when used in such ovens vary considerably (see Table 29). However, because the aesthetic quality of the end-product depends partly on the

TABLE 29

Relative Thermal Efficiencies of Oven Cooking Utensils[171]

Utensil description	*Thermal efficiency of stated pan divided by that achieved by pan (A)*
(A) Darkened steel with its inside surfaces coated with two layers of white enamel	1·000
(B) Steel entirely coated with two layers of white enamel	0·877
(C) High-temperature glass	0·819
(D) Steel	0·678
(E) Aluminium	0·581
(F) Copper	0·576
(G) Tin	0·468

thermal properties of the material from which the cooking utensil is made, high thermal efficiency pans do not necessarily produce good culinary results. For baking cakes, steel, japanned-iron, anodised-aluminium and sheet-iron utensils achieved significantly shorter cooking periods and greater cake volumes, than copper, bright-aluminium, tinned-iron, stainless-steel and glass ones, although the latter group tended to produce cakes of superior texture, shape and eating quality.[172] If the food had been cooked at slightly lower oven temperatures when using the high-emissivity pans, improved culinary results may have been achieved. Consequently, experimentation with various materials, in order to determine the optimal design of utensil for a particular food or type of cooking, would appear worthwhile.

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OTHER RELEVANT CODES OF PRACTICE AND STANDARDS

CP 334: Selection and installation of town-gas cooking and refrigerating appliances.
Part 1: 1962. Domestic cooking appliances.

Part 2: 1966. Cooking installations for educational establishments.
CP 404: 1974. Installation of domestic heating and cooking appliances.
BS 1195: 1972. Kitchen fitments and equipment.
BS 1252: 1981. Specification for domestic solid-fuel free-standing cookers with integral boilers.
BS 3456: 1969. Specification for safety of household and similar electrical appliances.
BS 3547: 1962. Electrically-heated food conveyors and carriers.
BS 3588: 1963. Insulated food containers with integral insulation (including insulated tea urns).
BS 3705: 1972. Recommendations for the provision of space for domestic-kitchen equipment.
BS 4167: Electrically-heated catering equipment.
Part 3: 1982. Grillers, grillers on ranges, toasters.
Part 4: 1982. Deep-fat fryers.
Part 5: 1982. Steaming ovens.
Part 6: 1982. Bulk liquid heaters.
Part 7: 1982. Water boilers.
Part 8: 1982. Griddles and griddle grills.
Part 9: 1982. Boiling pans
Part 10: 1982. Sterilising sinks.
Part 11: 1982. Hot cupboards.
Part 12: 1982. Bains-marie.
BS 4177: 1967. Cooker control units rated at 30 A and 45 A for 250 V single-phase AC.
BS 4352: 1968. Electric catering equipment for educational establishments.
BS 4353: 1968. Gas catering equipment for educational establishments.
BS 4424: 1969. Methods for the thermal performance testing of insulated equipment for the transportation of portable foodstuffs.
BS 4874: 1983. Catering container dimensions.
BS 5175: 1982. Specification for the supply of commercial electrical appliances using microwave energy for heating foodstuffs.
BS 5258: 1975. Cooking appliances (Part 2).
BS 5313: 1983. Aluminium catering containers and lids.
BS 5314: Specifications for gas-heated catering equipment.
Part 1: 1976. Ovens.

Part 2: 1976. Boiling burners.
Part 3: 1976. Grillers and toasters.
Part 4: 1976. Fryers.
Part 5: 1976. Steaming ovens.
Part 6: 1976. Bulk liquid heaters.
Part 7: 1976. Water boilers.
Part 8: 1979. Griddle plates.
Part 9: 1979. Boiler pans.
Part 11: 1979. Hot cupboards.
Part 12: 1979. Bains-marie.

BS 5784: Specification for the safety of electrical commercial catering equipment.
Part 1: 1979. Particular requirements for range ovens and hob elements.

BS 5957: 1983. Recommendations for modules for the co-ordinating dimensions of catering equipment using containers designed according to BS 4874.

EN 153: 1980. Methods of measuring the energy consumptions of electric mains-operated household refrigerators, etc. (EEC Standard).

CHAPTER TWO

RELATING ENERGY-CONSUMPTION AND HEALTH-CARE

CONCERNS TO DIET CHOICES

Relating Energy-Consumption and Health-Care Concerns to Diet Choices

SUMMARY

A computer program is described which permits users to obtain rapidly an analysis of the approximate nutrient contents, nutritional suitabilities, and primary-energy expenditures on production and cooking of the foods that comprise their diets. These parameters can be stored, and subsequently retrieved so that the associated effects of transient changes (which may be intentional) to one's diet can be assessed. Such information is useful when attempting to formulate optimal menus, and should benefit medical practitioners when diagnosing treatments for the diet-related ailments of patients. Furthermore reductions in national and personal consumptions of primary energy for producing and cooking foods may be achievable as a result of employing this facility, because the software enables users to gain quantitative knowledge concerning the approximate energy expenditures inherent in their diets.

ABBREVIATIONS AND NOMENCLATURE

C	Specific heat capacity ($J\,kg^{-1}\,K^{-1}$).
CER	Primary energy requirement for cooking the food (J).
EE	Overall energy efficiency of a cooking appliance (i.e. the product of its end-use efficiency and the supply efficiency for the cooking fuel): $0 \leq EE \leq 1$.
i	Indexing parameter.
LDC	Less-developed country.

m	Mass (kg).
NEI	Nutritional and primary energy information.
n	Nutrient density (kg of nutrient per kg of food).
OER	Overall primary-energy requirement for producing and cooking the considered food (J).
PED	Production energy density ($J\,kg^{-1}$).
PER	Primary energy requirement for producing the food (J).
PRDA	Fraction of the recommended daily allowance of a nutrient that is satisfied by consuming the food (%).
RDA	Recommended daily allowance of a nutrient (kg). (Usually this is defined as the minimum mass of a nutrient that is recommended for daily consumption by a given type of healthy human, so that he/she can maintain satisfactory health. However the provision of ranges, i.e. maxima as well as minima of recommended daily intakes of nutrients for each type of human, is more desirable.)
u	Proportion of the total mass of a food which is inedible (%).
X	Extra energy required to *maintain* the mean bulk temperature of the cooking medium at the desired temperature throughout the cooking period, divided by that required to raise it to this temperature.
Y	Approximate overall energy usage of an average catering establishment (including an allowance for the estimated average amount of primary-energy expended on travelling to eat there), divided by that used by a domestic cook for preparing a similar meal.
ΔT	Temperature difference (K).

Subscripts

a	At the initial condition of the cooking medium.
f	Of the food.
M	Of the cooking medium.
s	Of the food system on which the consumer relies.
t	Total content.

GLOSSARY

Ascorbic acid	Vitamin C.
Body mass index	Ratio of mass to height for an adult human.
Cardiovascular	Pertaining to the heart and blood vessels.
Cerebrovascular	Pertaining to the brain and the heart.

Mortality risk index	Ratio of the risk of dying to the average risk of dying.
Nutrient density	Mass of a nutrient per unit mass of a food.
Obese	The physical state of an individual who weighs at least 20% more than the upper limit of the weight range recommended for maintaining satisfactory health for people of his/her height.
Output/Input energy ratio	Nutritional energy available at the point of consumption, divided by the process energy required to supply the food in the form that it is eaten.
Primary energy	Energy contained in the fuel at the point of extraction: this does not include solar energy.
Process energy	Primary energy used to nurture, harvest (or slaughter), process, transport, store and cook the food.
Production energy	Energy used to produce food, i.e. the difference between the process energy and the primary energy expended for cooking.
Pyridoxine	Vitamin B_6.
Riboflavin	Vitamin B_2.
Thiamin	Vitamin B_1.

THE CHALLENGE

It is estimated that mal-nutrition affects at least 50% of the world's population.[1] In global terms, *over*-nutrition as well as *under*-nutrition results in widespread human suffering and retards the advancement of the species (e.g. by lowering worker productivity), because non-optimal diets lead to numerous diseases.[2] Current expenditures of money and energy on treating patients with these diseases and on producing and preparing foods are excessive. Unfortunately the affluent and predominantly sedentary lifestyles of those in developed countries, have resulted in widespread complacency concerning the use of fundamental commodities such as food and energy. Thus, at present, the optimisation of dietary parameters, such as nutritional composition and primary energy consumption, is not attempted widely.

Having estimated the overall energy inputs for food production and delivery in Britain for 1968, Leach[3] suggested that the energy consumption of the food system amounted to approximately 21·4% of the UK's total primary-energy expenditure (see Table 1). The UK food system now accounts for about 25% of the country's total primary-energy consumption:

TABLE 1

A Breakdown of the Primary-Energy Inputs to the UK Food System for the Year 1968[3]

Food sector	*Annual primary-energy usage per person (GJ)*	*Percentage of national primary-energy usage per person*
British agriculture and fisheries	7·5	4·9
Food and fish imports	5·0	3·3
Food processing	8·7	5·7
Wholesale and retail	2·5	1·6
Domestic preparation and cooking	9·0	5·9
Total	32·7	21·4

this is not unexpected because: (i) the primary-energy requirement of the typical kitchen has risen substantially since 1968, due for instance to the increased employment of cold-storage and dish-washing equipment; and (ii) the energy intensity of the food processing sector has increased, mainly because demand for more varied and 'convenience' foods has grown. Unfortunately, even though such a vast amount of energy (i.e. ~2200 PJ) is expended annually on providing foods, the current diet of the typical Briton is nutritionally imbalanced (e.g. see Table 2). Consequently dietary changes are recommended for health reasons.

However, too few people appreciate the implications of these changes on the energy demands placed on the food system.[5,6] Popular literature

TABLE 2

The distinctive Features of the Average British Diet (Adapted from Ref. 4)

	Consumption of nutrients	
Inadequate	*Adequate*	*Excessive*
Starch	Protein	Saturated fat
Fibre	Pantothenic acid	Sodium
Folic acid	Ascorbic acid	Phosphorus
Polyunsaturated fat	Thiamin	Chlorine
Pyridoxine	Riboflavin	
Vitamin D	Nicotinic acid	
Vitamin E	Vitamin B_{12}	
Iron	Vitamin K	
Copper	Vitamin A	
Magnesium	Iodine	
Potassium	Calcium	
Selenium		
Zinc		

concerning proper nutrition[7-9] tends to neglect discussion of the effects of implementing the recommended dietary modifications upon primary-energy consumptions. Therefore developing a means of helping consumers to understand the primary-energy costs, as well as the nutritional values, of the foods that they eat is desirable. Eventually each person's diet could be optimised in a health-conscious and energy-efficient manner.

Food and health

In developed countries, obesity, cardiovascular disease, diabetes, hypertension and various cancers and allergies are common diet-related ailments, which attract general preventative recommendations from nutritionists and the medical profession. Unfortunately, information specific to one's own diet is usually sought or obtained only when a marked state of ill-health occurs. Commonly proffered preventative advice (e.g. diet-modification information) is based on the current eating and exercise habits of the 'average person'. However, because there is no typical human diet in an affluent society[10] this information may not be appropriate to one's own lifestyle. For example, if an individual is informed that average Britons should double their consumptions of iron, he may ask the following questions:

(1) Is my iron intake similar to that of the average person?
(2) How do I determine my daily consumption of iron?
(3) What is the minimum recommended intake of iron for a person of my age, sex, weight, occupation and state of health?
(4) How can I ensure that I eat more iron?

Questions (3) and (4) can be answered readily, because much scientifically-based literature concerning food, nutrition and diet is available to the typical reader. However questions (1) and (2) demand that the individual calculates the amounts of iron present in the foods that he eats. Such calculations are simple but lengthy, especially when one may wish to determine the consumptions of say 40 nutrients. Thus consumers are disinclined to examine quantitatively the nutritional aspects of their diets. This retards the implementation of dietary changes that may be necessary to ensure the maintenance of good health.

It has been alleged that some people avoid comprehensive consideration of the nutritional aspects of what they eat, because the advice they receive from medical practitioners concerning how diet affects their health is inadequate.[11,12] However the reasons why the UK is currently characterised by, for example: (i) the highest per capita death rate due to heart disease in the world, (ii) one of the worst death rates due to smoking-related and

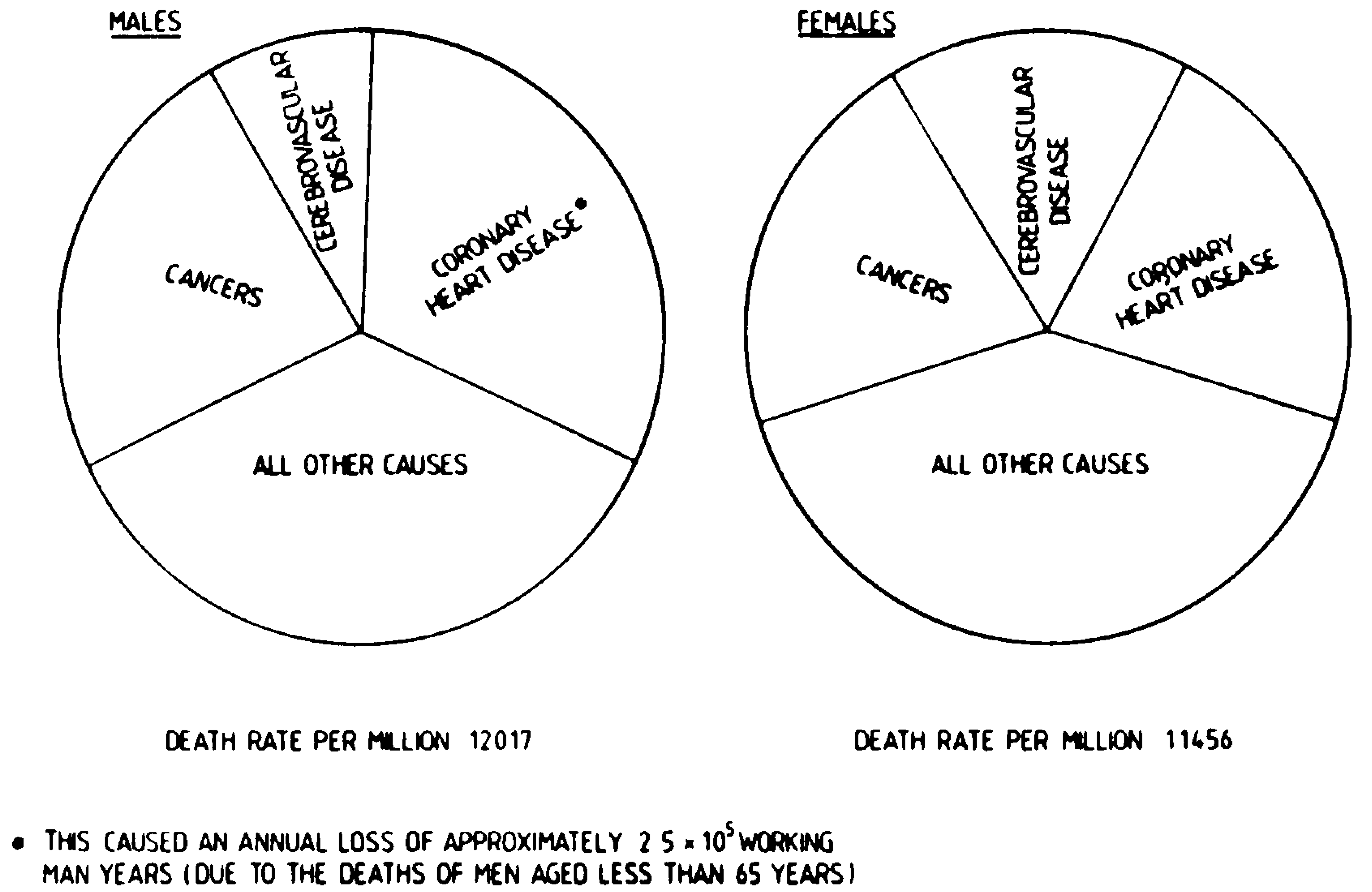

Fig. 1. Proportions of fatalities caused by diet-related diseases in England and Wales during 1982.[24]

alcohol-related illnesses in the developed world, and (iii) the shortest life expectancy for 45 year-olds in the EEC,[13] are intrinsic to the present British way of life (e.g. see Figs 1 and 2). As reported by Roseaman,[14] Britons pay relatively little attention to the subject of food, when compared with their counterparts in other developed nations. This may be due partly to the unwise, yet widely-held, belief amongst laymen that medical technology will solve all of our major health problems. Thus there appears to be an urgent need to improve preventative health/diet education in Britain.

Those food packages, which are labelled externally with the detailed compositions of their contents, are useful when attempting to calculate the nutritional details of one's diet. Nevertheless food manufacturers and Governmental organisations still exhibit considerable inertia to the comprehensive implementation of 'nutritional labelling' of foods and beverages. In the meantime, nutritionists warn of the fallacy of categorising foods into the two groups 'healthy' or 'unhealthy' (i.e. 'good' or 'bad'). Yet both ignorant and misinformed consumers tend to do this. Such action may be attributed mainly to four factors. Firstly, the science of human nutrition is complicated—most Britons are too confused by nutrient terminology and content per unit mass of food to attempt to unravel mathematically the overall healthiness of their diets. Secondly, traditional health advice is oversimplified and tends to group foods into 'good', 'bad' and unclassified categories. Consequently many consumers are disinclined to study

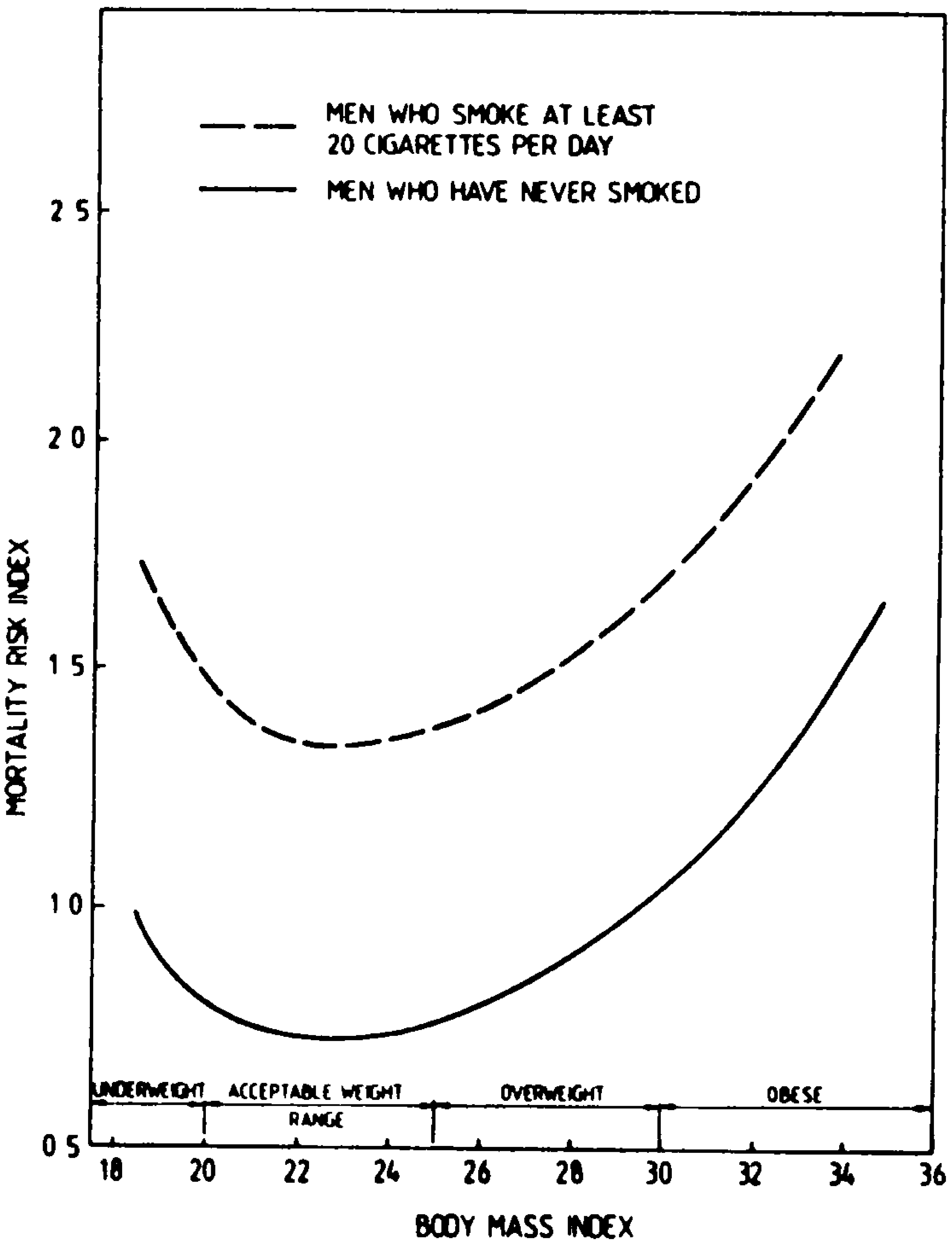

Fig. 2. The relationships between human mass, rate of cigarette-smoking and mortality for adult men in the UK.[61]

comprehensively the nutritional aspects of their diets, because they do not recognise the need to do so. Thirdly, because the sources of health-advice are diverse, the typical consumer may easily become misinformed from the often exaggerated claims of food advertisements in the media and currently-fashionable 'health-food' outlets.[15] Finally, attitudes concerning diet often tend to be apathetic. Unless people feel unwell, most are unlikely to devote much time or money considering the quality of their diets.[16] Ironically many mal-nourished individuals may reach middle- or even retirement-age before experiencing any serious illnesses resulting from their life-long poor eating habits. The effects of mal-nourishment in developed nations are rarely dramatic, unlike those of famine which is associated with LDCs.

Fundamentally food has a sensual, rather than an intellectual, appeal. Thus dietary changes are often made despite the advice obtainable from the literature concerning proper nutrition. For example, when individuals suddenly become aware that diet is fundamental to physical and mental health, many over-react by adopting a food fad. This involves adhering rigorously and slavishly to a certain type of diet, which is alleged by its originators or advocates to assure optimal long-term health. The consumption of vitamin, mineral and amino-acid pills is perceived by some as the panacea: consequently the rate of consumption of vitamin pills in the UK has trebled since 1981, and now results in expenditure of about £5 × 10^7 p.a.[17] However, a more careful selection of foods, together with regular eating and exercise habits would often be of greater health benefit to their consumers.[18] Unfortunately many quacks profess to be authorities on dietetics, yet recommend special diets which are often nutritionally-imbalanced and occasionally harmful to their long-term users.[19-22] Ironically those who adopt a food fad may attain a false sense of security concerning their health and thus be less inclined to seek medical advice when ill. Therefore it is vital that, as individuals become more aware of the nutritional aspects of their eating habits, they appreciate that no single food or pattern of food consumption is the optimal choice for all occasions. People can usually achieve balanced diets by modifying their existing eating habits rather than implementing wholesale changes. Such modifications need to be integrated gradually, and the appropriate means made available for consumers to realise the effects of dietary changes in the short-term (rather than having to wait to see if they experience any long-term health improvements or deteriorations).

Many factors act simultaneously to discourage people from adopting systematic diet analyses. Only the simplest method (i.e. the monitoring of nutritional energy consumption) is practised in anything like a widespread manner, usually so that excesses which increase bodily fat content can be avoided. This perpetuates the over-simplistic beliefs that some foods are good for you and some are not (due to their respective energy densities), and that so long as one's appetite (i.e. energy and water demand) is satisfied, one's health should be maintained. However an abundance of food does not necessarily assure that proper nutrition is achieved, because it is not only the quantity, but the quality of the foods consumed (i.e. the total mass of each nutrient eaten), which influences a person's health. It is unfortunate that even those individuals who appreciate this fact, and generally express strong concerns about the subject of nutrition, still fail to achieve optimal diets.[23,24]

Food and energy

The total nutritional energy value of foods and alcoholic beverages (provided for individuals living in the UK) has been estimated to exceed the nutritional energy consumption of the population by about 33%.[59] Although there is no readily available information concerning wastages within the current British food system, it is estimated that at least 15% more nutritional energy is purchased than is consumed in the domestic sector, to compensate for wastages (e.g. vegetable 'trimmings', spillages and uneaten 'left-overs') and the evaporation and 'burning-on' of foods during cooking. Thus if the energy wastages in British kitchens are to be reduced, careful purchasing, storage, preparation and cooking of foods (in amounts that match the demands placed on the kitchen) are essential.[25]

It is probable that consumers may be more inclined to attempt to limit their own energy expenditures upon cooking, as well as contribute towards reducing the nation's overall expenditures on food, once they are aware of the energy requirements for producing and cooking of foods. Therefore facilities for analysing the primary-energy requirements of foods prepared in the typical domestic kitchen may be well received, because financial savings should be achievable as a result of practising energy-conscious diet management. There are many techniques which can be employed in kitchens to limit energy expenditures when preparing and cooking foods.[26]

More energy is expended on cooking some foods, e.g. for 'boiling' potatoes, than on growing them.[27,28] Therefore energy-conscious cooking practices, e.g. modifying recipes and preparation techniques so that less energy is employed,[29] can have a significant effect on the overall primary energy requirement of an individual's diet. Conversely some foods (e.g. dairy and processed-vegetable products) are very energy-expensive due to (i) their position in the food chain and/or (ii) the energy-intensive methods of their production. Thus the energy efficiencies of the techniques employed to cook these foods have only small effects on their overall process energy requirements (i.e. the amount of primary energy expended during production and cooking).

From an energy-thrift perspective, the merits of developing different hybrids of certain foods (e.g. baked goods, confectionery and 'soft' drinks) are doubtful, if they require greater energy inputs during processing without providing any significant improvements in nutrient densities, when compared with their existing base products. However it is unlikely that food-processing organisations will take the initiative to halt the developments of new energy-expensive foods, because they operate in a highly competitive market, where a product's saleability usually depends upon its taste, appearance and overall cost rather than on its nutritional value per unit input of primary energy. Nevertheless consumers may influence food production and processing industries via their purchasing decisions, e.g. recent public concern for the amounts of additives used by the food-processing industry for preserving (and enhancing the taste and colour of) foods and beverages has led to the widespread provision of items containing few (if any) additives. Thus energy-conscious individuals may reduce the food system's annual energy requirement, by refusing to buy the more expensive derivatives of a base-product (e.g. by choosing a simple chocolate biscuit in preference to a multi-layered marsh-mallow biscuit, or fresh fruit instead of industrially-manufactured fruit-based beverages.

Rehkugler[30] studied the effects on the overall primary-energy requirement, of maintaining recommended daily nutrient allowances (RDAs) for certain diets. He concluded that:

(i) RDAs could be satisfied with minimum energy expenditures, if large amounts of relatively few foods were eaten;
(ii) cereals and fresh vegetables are energy-efficient foods and should be consumed if individuals are to reduce the primary-energy expenditures that are inherent in their diets;
(iii) a varied diet was relatively energy-expensive; and
(iv) high nutrient-quality diets tended to increase the primary-energy consumption of the food system.

A better diet would lead to improved health as well as an extended life expectancy and so the Earth's population would increase. More buildings and transport facilities would then be constructed and this would usurp even more agricultural land, thereby forcing agricultural techniques to become more energy-intensive (e.g. by increasing the use of fertilisers, pesticides and pumped-irrigation systems, so that crop yields per unit area may be increased). For such reasons, the energy demand of the food system tends to increase.[31] Conservational measures (e.g. the greater use of organic manure to satisfy partially the escalating demand for fertilisers) may retard the growth of the food system's annual energy requirement, but generally if humans are to improve the nutritional quality of their diets, the use of high-grade energy supplies will tend to increase.[3,6,32]

Therefore consumers should share the responsibility for controlling energy expenditures on food, with those who operate and manage farms, food-processing industries and food outlets. To achieve this during the present period of rapidly diminishing fossil-fuel reserves, and when the human population, energy intensity of food processing and general concern for health and diet are increasing, individuals must improve their understanding of the energy and health implications of their diets.

Comprehensive quantitative diet-analysis is well-suited to the utilisation of computer software (in conjunction with a personal computer), which has been designed specifically for a computer novice to examine his/her diet (and the effects of changing it). Although computer-based facilities have been developed to assist dieticians when analysing the nutrient intakes of their patients,[33-37] it appears that no appropriate micro-computer programs (which provide dietary data concerning primary-energy densities as well as nutrient contents) exist for individuals who may wish to attempt analyses of these aspects of their (or their family's) diets *at home*. Because of the fundamental nature of food and nutrition, the existence of such a facility would, if readily available, encourage people who would not otherwise use computers, to study the nutritional values and energy expenditures of their diets. Furthermore, as Britons become more computer-literate domestic employment of computers is likely to become more common. Therefore, in future, the use of this type of educational software may become an integral part of a healthy energy-conscious lifestyle.

SOFTWARE AND DATA-BASE DEVELOPMENT

Computer software, which provides its users with information concerning the nutritional and primary-energy aspects of their diets, is hereafter referred to as NEI software. Essentially, it relies upon the use of an accurate data-base of appropriate food properties. For each food, this source of information should include nutrient density values as well as data which permit the calculation of the energy expenditures on producing and cooking the food. For demonstration purposes, a data-base for 40 foods was created in the present project to facilitate the analysis of a restricted diet—see Appendix 1. If NEI software is to become commercially viable, the details of at least 500 foods should be described because Britons have widely-varying diets (although it should be remembered that an individual usually consumes less than 25 different foods per day). Furthermore a facility for the user to be able to update the data-base with details of additional foods is desirable. Nowadays, the use of a disk-based data-base of this required size on a micro-computer poses few problems, mainly because of the large memory/storage capability that is available with most current designs of personal computer, unlike those that were commonly-used in the domestic sector 5 years ago.

The data-base for the computer program was developed, in two stages, to permit the calculation of (i) nutrient intakes and (ii) primary-energy expenditures.

Nutritional information

Various sources of information concerning the nutrient contents of commonly-eaten foods exist.[38-43] These were used to generate representative nutrient-density values for the foods described in the data-base.

The nutrient content of a food may vary significantly. The compositions of samples of a 'natural' food (e.g. eggs, hazelnuts, chickens or apples) vary with (i) the climatic and geological nature of the area where they are grown, (ii) their species (e.g. there are 30 different types of banana), (iii) the agricultural techniques employed during cultivation, (iv) their age or maturity, and (v) the type and period of transportation, storage and cooking undertaken before consumption. The nutritional make-up of a 'composite' food (e.g. bread, chocolate, chutney or gravy) may fluctuate even more, because of additional factors such as variations in the proportions of the ingredients used and the processing methods employed. For example, the mineral (e.g. sodium, iron and calcium) content of foods which are cooked in water or prepared by adding water will vary, because the mineral content of water depends partly upon geographical location. Therefore consumers should remember that published values of nutrient densities only approximate to those of the foods that they eat. However this should not dissuade individuals from attempting to analyse their diets, because significant nutrient excesses or inadequacies can still be identified and the relative effects of implementing dietary changes assessed.

The recommended daily consumptions of several nutrients for various types of human are available—e.g. see Table 3—these must comprise a basic part of NEI software. Wastages resulting from (i) poor health and (ii) energy abuse, should be reduced significantly if this form of health/energy education is readily available to and for all members of society regardless of age, sex, weight, occupation or culture. People who adopt dietary energy intakes which are significantly above their RDAs, are profligate consumers of food (and hence primary energy) because they ingest only a small fraction of their excess food—the majority is simply wasted. Therefore the facility for individuals of non-optimal weight to program in their desired nutritional energy requirement per day is desirable, so that they can analyse the effects of unconventional energy intakes on the overall nutritional values and primary-energy requirements of their diets.

Unfortunately, details concerning some nutrients (e.g. the densities of fibre, saturated fat and amino-acids) for many foods are as yet incomplete.[43] Also RDAs for several nutrients are not defined clearly. But achieving optimal intakes of many of these sustainers is, at present, crucial to the maintenance of optimal long-term health for individuals living in industrialised nations. Therefore, if it is to be viable, NEI software must be developed (when the necessary data become available) to include algorithms which facilitate analyses of these nutrients.

Computation of actual nutrient contents per portion of food consumed involves the summing of simple multiplications. For example, the total iron content (n_t) of a cheese and lettuce sandwich would be calculated as follows:

$$n_t = \frac{\sum_{i=1}^{i=4} m_i n_i (100 - u_i)}{100} \qquad (1)$$

where, for example[42]

i = 1:	Cheddar cheese	$u = 0$, $m = 0{\cdot}02$ kg and $n = 4 \times 10^{-6}$;
i = 2:	lettuce	$u = 20$, $m = 0{\cdot}01$ kg and $n = 9 \times 10^{-6}$;
i = 3:	butter	$u = 0$, $m = 0{\cdot}01$ kg and $n = 2 \times 10^{-6}$;
and		
i = 4:	wholemeal bread	$u = 0$, $m = 0{\cdot}09$ kg and $n = 2{\cdot}5 \times 10^{-5}$

Hence the iron content, n_t, of this snack = 2·422 mg.

Consequently the percentage of the RDA for iron can be calculated (i.e. so that the user can ascertain what fraction of his/her recommended daily intake of this mineral will be provided by eating the aforementioned snack):

$$\text{PRDA} = \frac{100 n_t}{\text{RDA}} \qquad (2)$$

e.g. for a pregnant woman (see Table 3), it can be deduced that PRDA $\approx$ 19%, in this example.

Such calculations can be performed for the various foods described in the data-base, so that information relevant to one's entire diet can be obtained. Although recording daily food intakes (in terms of type and mass) is irksome (and hence highly susceptible to human error), it should be regarded as an essential discipline by those who wish to learn more about their diets. To assist users, data are provided so that daily household amounts (e.g. numbers of slices of bread or leaves of lettuce, and cups of water) can be converted into mass units. However, further efforts to improve this prototype NEI program are needed, so that less time is expended when attempting diet-optimisation procedures, i.e. the visual presentation and prompting generated by the coding must be made entirely unambiguous so that it can be used successfully even by the computer novice.

Cok[36] analysed the nutritional aspects of the diet of a 69 year-old man (who had recorded the amounts of food that he consumed over a two-week period) via digital computational techniques. Significant daily variations in his dietary intakes occurred, e.g. within a period of one week, his daily consumptions of nutritional energy and cholesterol ranged from 9·9 MJ to 15·8 MJ and 0·157 g to 0·356 g respectively. Generally, misleading results are generated when a person's diet is analysed over a period of only one day. Consequently the NEI program should be employed each day for *at least* one week, if an understanding of the transient behaviour (in nutritional terms) of a diet is to be gained. Significant nutritional inadequacies and excesses of the average daily food consumption over this period can then be

TABLE 3
Recommended Daily Dietary Intakes of Various Nutrients for Different Categories of Human[44]

Age ranges (years)	Nutritional energy (MJ)	Protein (g)	Calcium (mg)	Iron (mg)	Vitamin A (μg)	Thiamin (mg)	Riboflavin (mg)	Nicotinic acid (mg)	Vitamin C (mg)	Vitamin D (μg)	Folic acid (μg)
Boys											
0–1	2·2–4·1	12–24·5	600	6	450	0·3	0·4	5	20	7·5	50
1	5·0	30	600	7	300	0·5	0·6	7	20	10	100
2	5·75	35	600	7	300	0·6	0·7	8	20	10	100
3–4	6·5	39	600	8	300	0·6	0·8	9	20	10	100
5–6	7·25	43	600	10	300	0·7	0·9	10	20	—	200
7–8	8·25	49	600	10	400	0·8	1·0	11	20	—	200
9–11	9·5	56	700	12	575	0·9	1·2	14	25	—	200
12–14	11·0	66	700	12	725	1·1	1·4	16	25	—	300
15–17	12·0	72	600	12	750	1·2	1·7	19	30	—	300
Girls											
0–1	2·1–3·8	12·5–23	600	6	450	0·3	0·4	5	20	7·5	50
1	4·5	27	600	7	300	0·4	0·6	7	20	10	100
2	5·5	32	600	7	300	0·5	0·7	8	20	10	100
3–4	6·25	37	600	8	300	0·6	0·8	9	20	10	100
5–6	7·0	42	600	10	300	0·7	0·9	10	20	—	200
7–8	8·0	48	600	10	400	0·8	1·0	11	20	—	200
9–11	8·5	51	700	12	575	0·8	1·2	14	25	—	300
12–14	9·0	53	700	12	725	0·9	1·4	16	25	—	300
15–17	9·0	53	600	12	750	0·9	1·7	19	30	—	300
Men											
18–34 Sedentary	10·5	62	500	10	750	1·0	1·6	18	30	—	300
18–34 Moderately active	12·0	72	500	10	750	1·2	1·6	18	30	—	300
18–34 Very active	14·0	84	500	10	750	1·3	1·6	18	30	—	300
35–64 Sedentary	10·0	60	500	10	750	1·0	1·6	18	30	—	300
35–64 Moderately active	11·5	69	500	10	750	1·1	1·6	18	30	—	300
35–64 Very active	14·0	84	500	10	750	1·3	1·6	18	30	—	300
65–74	10·0	60	500	10	750	1·0	1·6	18	30	—	300
75 and over	9·0	54	500	10	750	0·9	1·6	18	30	—	300
Women											
18–54 Most occupations	9·0	54	500	12	750	0·9	1·3	15	30	—	300
18–54 Very active	10·5	62	500	12	750	1·0	1·3	15	30	—	300
55–74	8·0	47	500	10	750	0·8	1·3	15	30	—	300
75 and over	7·0	42	500	10	750	0·7	1·3	15	30	—	300
Pregnant	10·0	60	1 200	13	750	1·0	1·6	18	60	10	500
Lactating	11·5	69	1 200	15	1 200	1·1	1·8	21	60	10	400

identified accurately and assistance obtained when attempting to quantify desirable changes to the diet. The latter may be achieved by using the program, in two ways, to list, in ascending order:

(i) the amount of each suspect nutrient provided by each of the foods eaten, or
(ii) foods described in the data-base, which contain significantly high or low concentrations of each considered nutrient.

Method (i) is preferable because the user can attempt to improve the nutritional balance of his diet by simply adjusting the relative proportion of the foods that he is in the habit of eating. However in the event that a certain nutrient is consumed in amounts that differ considerably from those recommended to sustain good health, access to the data-base (i.e. via method (ii)) is desirable. Thus the NEI program was developed to supplement method (i) with method (ii), so that operatives can predict quantitatively the effects of changing their diets before actually doing so. Where appropriate, the amount by which each item in the current consumption of foods needs to be adjusted, so that RDA values can be satisfied, is displayed. Consequently the user can determine suitable changes in his/her diet. Finally, the effects of implementing diet-modification information obtained from NEI software, dieticians, doctors or the scientifically-respectable literature can be assessed by analysing a future week's diet, and then comparing the overall average nutrient intakes for both weeks.

Process-energy expenditures

Generally, published values suggested for the typical process-energy expenditures which are involved in the production and cooking of foods, are usually only accurate to within $\pm 20\%$. This is because food systems are complex, and so a number of assumptions and approximations have to be made when attempting to quantify the direct and indirect primary-energy inputs. Although several energy-accounting analyses for foods have been carried out in the USA,[27,45-48] few comprehensive attempts appear to have been undertaken for the UK food system. Because process-energy data from various sources can be misleading (due to the different assumptions and methodologies adopted), the NEI data-base was based originally on the data proffered for Britain by Casper *et al.*[49] and Leach.[3]

Primary-energy efficiency ratios for the processes involved in producing and cooking foods are expressed usually in terms of the primary energies expended per unit of (i) nutritional energy, (ii) protein, or (iii) a vitamin or mineral, which are available to the consumer. From these parameters, many

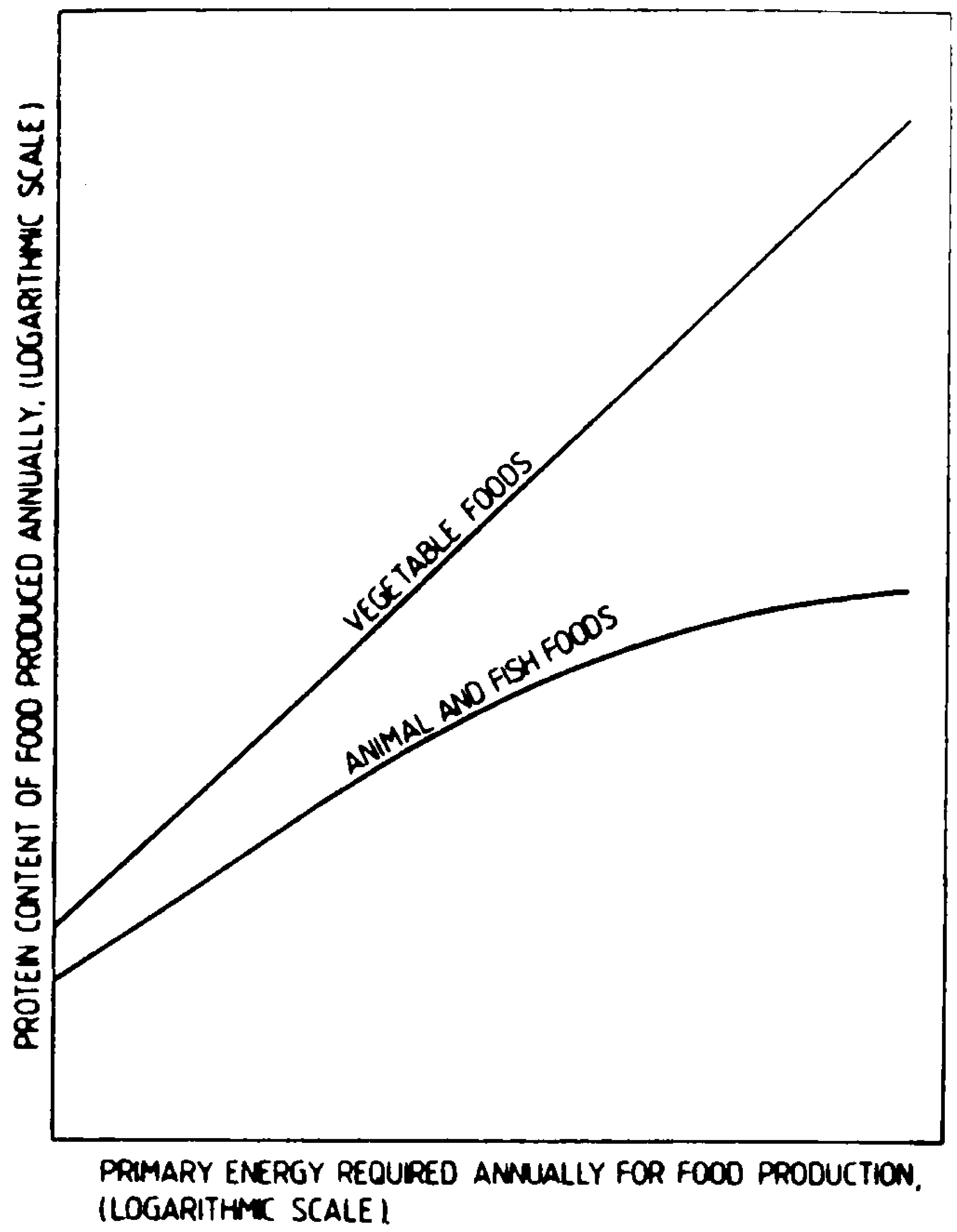

Fig. 3. The difference between the primary energy requirements for producing protein via propagation of vegetable and animal/fish foods.[62]

interesting examples of energy utilisation in the food-supply system can be gleaned,[3,32] e.g.:

- Approximately 2200 times as much energy is required to produce a can of 'diet soft-drink' than is available nutritionally by drinking it.
- On average, the primary energy required to produce 1 kg of edible plant protein is only 10% of that used to manufacture a similar amount of animal protein.
- If tomatoes are grown instead of oranges, about twice as much ascorbic acid is made available to consumers per unit of primary energy input.

Because a large part of the food production of developed countries is represented by animal products, analyses of agricultural energetics have shown that nutritional energy is produced mainly by the profligate use of primary energy.[50] Generally, animal products require significantly larger amounts of land and energy inputs per unit of protein or nutritional energy than plant foods (e.g. see Fig. 3). Approximately 42% of the world's annual production of plant protein (i.e. $\sim 5 \cdot 9 \times 10^{10}$ kg) could be made available for human consumption if it were not fed to livestock.[32] These animals are then

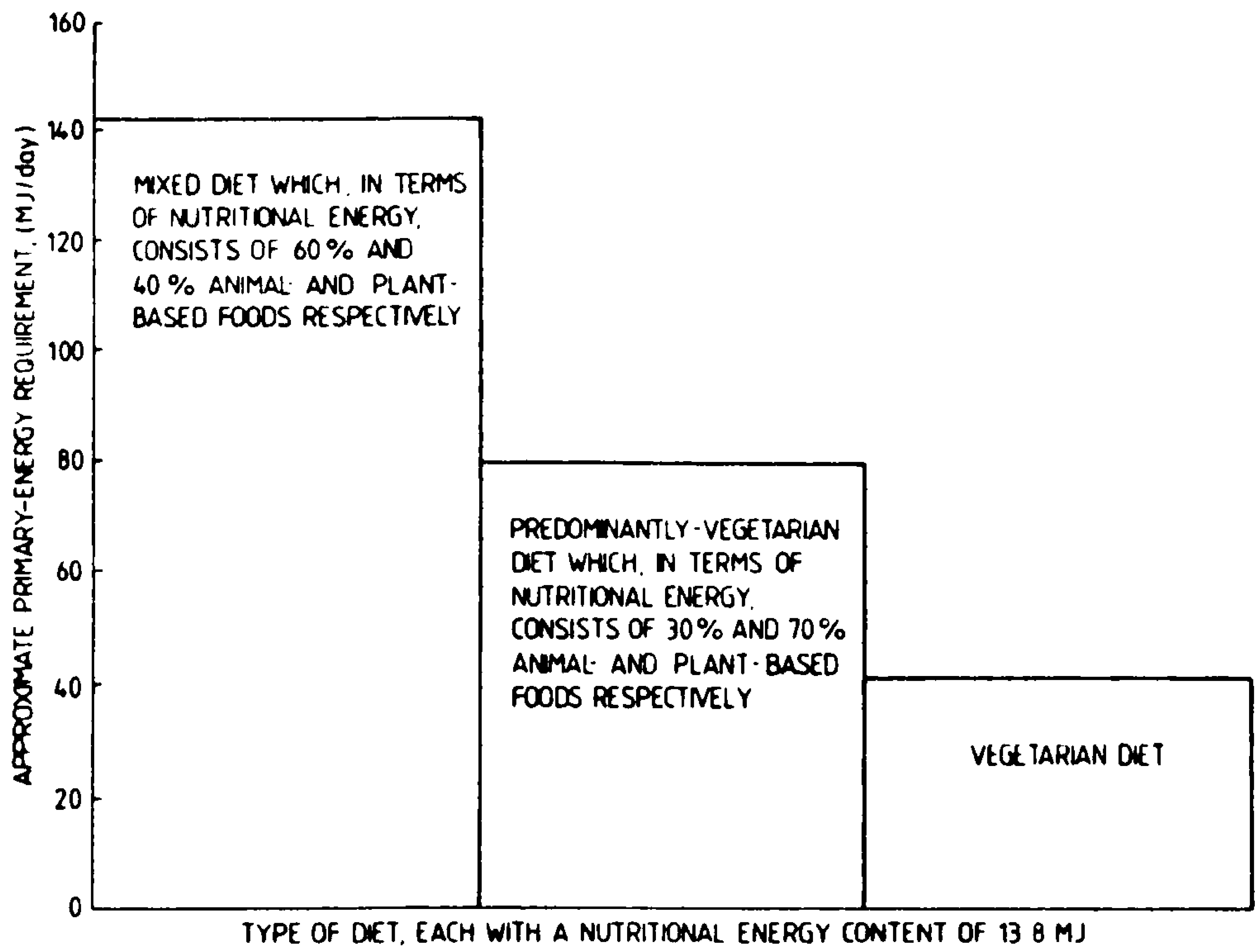

Fig. 4. The primary energy requirements for providing three different daily diets of identical nutritional-energy content in the USA (adapted from Ref. 32).

slaughtered, processed and stored, mainly for human diets, at a very high energy cost. If a vegetarian diet was widely adopted, the aforementioned quantity of plant protein could be released for direct human consumption (and the waste used as fuels). Consequently primary energy expenditures on the food system would be reduced substantially (e.g. see Fig. 4). For example, Leach[3] concluded that, in theory, more than $2{\cdot}5 \times 10^8$ people could be fed on a diet consisting of vegetables and cereals if the land currently used by farm animals in the UK was converted to crop production. (The British population at present is about $5{\cdot}5 \times 10^7$). However, plants are devoid of vitamin B_{12}, deficient in either one or two of the eight amino acids which are essential for human health, and have low nutritional energy densities. Therefore a highly energy-efficient nutritionally-balanced plant-based diet should comprise many different plant foods (which must be eaten in relatively large amounts) plus some supplementary animal-foods. Nevertheless, meat should be regarded increasingly as a luxury food. If present consumption rates continue, the psychological effects, of a sudden rise in unit energy prices and/or a more uniform distribution of the world's food supply, on many consumers in developed nations could be devastating, because they will need to adapt to a marked shift in food production (i.e. from animal and fish foods to unprocessed vegetables and fruits).

Efforts to achieve optimal diets often tend to over-simplify the objective of satisfying the balanced dietary nutritional requirements for the least expenditure of primary energy, by placing too much emphasis on effectiveness parameters such as the aforementioned energy-efficiency ratios (i), (ii) and (iii). Thus a food system which minimises the energy requirement for supplying energy and protein needs may be created at the expense of providing adequate quantities of other essential nutrients.[30] A more satisfactory aim for NEI software may be to calculate an overall value for the energy effectiveness of a user's diet, by summing the energy expenditures involved in the preparation of the required food (i.e. from the farm or sea to the point of consumption). Subsequently the operative should attempt to minimise this total, whilst maintaining RDA values, i.e. the individual may use the program to examine his diet in the light of the information presented (and if necessary to modify it), rather than be forced to adopt a less palatable optimal dietary regimen.

Unfortunately, the accurate evaluation of energy-efficiency parameters is hampered by several uncertainties. For example, if the contents of a can of peas are cooked then slightly less cooking energy but more primary-energy is expended, than if the same amount of 'frozen' peas was purchased and cooked (assuming that their respective storage periods prior to cooking were similarly short). However as the storage period prior to cooking increases, the use of the 'frozen' peas becomes less desirable from an energy-thrift viewpoint. This is because prolonged sub-ambient storage of foods is energy expensive and so the total primary-energy expenditures involved may exceed those expended for alternative preservation processes such as canning. From the perspective of the health-conscious consumer, the canned peas contain smaller amounts of nutrients than the same mass of 'frozen' peas. Thus consumption of the latter is preferable. Although the data-base can deal with the nutritional implications of this example, calculation of the actual primary-energy costs can be achieved only if the consumer provides information concerning storage periods or dates of purchases. This requirement necessitates a precise analysis of one's lifestyle, which some may consider unnecessarily intrusive. Therefore approximations are made by the program whenever users are unable or unwilling to provide information concerning storage periods. Ultimately, conventional food-shopping techniques may be abandoned for the more amenable and energy-efficient method of ordering food from distributors via a computer. Consequently a means of obtaining details concerning purchase dates should be available for NEI software. In the meantime, it is advisable for users to limit their food-shopping activities (e.g. to one regular collection per week), unless shopping trips are partly undertaken for meeting people or physical and mental exercise (e.g. by old-age pensioners).

Most countries import foods to diversify or supplement their own indigenous supplies, partly because they would incur large energy bills if they relied solely on local propagation. Nations practise different techniques when growing and processing foodstuffs, thus the production-energy densities of similar foods can vary considerably world-wide. Energy use in different parts of the food systems of nations may vary, e.g. about 80% of the primary energy used in Swedish agriculture is expended on tractor fuel and fertiliser, whereas 79% of the total primary energy consumption of Dutch agriculture is used for heating greenhouses.[51] Furthermore, as the Earth's population is increasing rapidly in the LDCs, energy inputs per unit of agricultural land there are growing despite the general trend of rising unit energy prices. Thus production-energy data derived for food systems outside the UK are not wholly appropriate to British diets. Therefore it is essential that production-energy densities for foods contained in the data-base of the NEI program are appropriate to the food system of the nation in which the user resides. The primary-energy requirement for producing a food may then be calculated as follows:

$$\mathrm{PER}_f = m_f\ \mathrm{PED}_s \tag{3}$$

Only a few studies have suggested values for the energy expenditures on cooking foods derived from practical investigations.[28,52–55] Unfortunately manufacturers are not as yet forced to display the energy efficiencies of the kitchen appliances that they sell in the UK. Also the energy requirement for cooking a certain type of food varies considerably according to the cook. Consequently, the amount of energy used in apparently similar cooking equipment (stimulated by the same energy source) to perform nominally-identical cooking operations varies significantly. This is because the efficiences of cooking appliances vary between manufacturers, as do the techniques employed by their users when performing nominally-identical cooking operations. In this context it should be realised that the primary-energy requirement to simmer water at 90°C in a pan, when the cook employs a well-fitting lid, is only about 15% of that required if the lid is not used.[56] Hence the computer program has been constructed to use energy-efficiency data for various types of commonly-employed cooking equipment,[25,57] so that the approximate cooking-energy requirement for the food considered may be estimated, i.e.:

$$\mathrm{CER}_f \approx \left[\frac{(m_f C_f\,\Delta T_f) + (1 + X)(m_M C_M\,\Delta T_M)}{\mathrm{EE}}\right] \tag{4}$$

Specific heat capacities for foods[58] are not generally available for bulk temperatures above about 40°C. Thus the data-base utilises values which are appropriate strictly only during the initial part of any cooking period. The change ΔT_f in mean bulk temperature for a food, i.e. the difference between its final and initial mean bulk temperatures, varies with the type of cooking activity practised, e.g. for microwave heating $\Delta T_f \sim 55°C$ whereas for toasting $\Delta T_f \sim 105°C$, assuming the initial mean bulk temperatures of the appropriate samples of uncooked foods were about 15°C. Values of ΔT_f and ΔT_M were estimated for the various cooking operations that are commonly undertaken in domestic kitchens. The variable X in eqn (4) represents an estimate of the additional energy expended on maintaining the cooking medium at the required temperature (i.e. $T_a + \Delta T_M$), so that an adequate thermal gradient is provided between the medium and the food item throughout the cooking operation. Usually this additional energy requirement is small, unless foods are cooked in comparatively large masses of fluids for prolonged periods.

An appreciation of the energy costs of preparing foods can be gained, provided that the computer is informed (interactively) of the types of equipment and cooking processes that were employed during preparation. If the foods are prepared at home, this requirement poses few problems, but when 'eating out', energy expenditures on foods are much more difficult to quantify. According to Singer *et al.*[29] the commercial caterer typically expends 6·5 times as much energy as the domestic cook per similar meal prepared. Corresponding studies to determine this ratio for kitchens in the USA suggested a value of 3·1.[60] Furthermore, energy expenditures on travelling to and from food-service establishments may be significant, e.g. an individual may use about 60 MJ of fuel for a 20 km round-trip to eat a 6 MJ meal in a restaurant. Thus preferences for eating-out result in particularly energy-profligate (as well as financially-expensive) diets. Allowances for this additional 'travelling-to-eat' expenditure augment the aforementioned ratio. Although performance data for commercial-catering equipment is limited, a further allowance was made for the variations in the overall efficiencies of average domestic and commercial cooking-equipment (employed for producing similar end-products). Consequently a ratio, Y, with a crudely estimated value of 2·5 was deduced; this facilitated approximate calculation of the primary energy expenditures on cooking, for diets partly consisting of foods that were prepared by food-service establishments. Taking this factor into account, eqn (4) becomes:

$$\mathrm{CER}_f \approx Y\left[\frac{m_f C_f \Delta T_f + (1+X)(m_M C_M \Delta T_M)}{\mathrm{EE}}\right] \tag{5}$$

Then the overall energy requirement for providing a food can be determined from eqns (3) and (5):

$$\mathrm{OER}_f = \mathrm{PER}_f + \mathrm{CER}_f \tag{6}$$

Because of the aforementioned factors, the values of OER_f are only approximate: in particular, they are subject to significant errors if foods from catering establishments are considered. However, they provide a means of comparing the energy demands placed on the food system for different foods, diets, and cooking appliances. Essentially, if NEI software is to be developed for commercial exploitation in the UK, then rigorous investigations into the energy costs of producing and cooking foods (by employing both domestic and commercial catering appliances) must be carried out.

DISCUSSION AND RESULTS

The weekly diet under consideration (see Appendix 1) was described interactively in several instalments, each consuming approximately 10 minutes of personal-computer time. The period required for analysing the weekly data thereby created, from health and energy perspectives, was approximately 35 minutes. This enabled a better diet to be formulated (see Appendix 2) which satisfied RDA values more closely and achieved some savings in primary energy (see Table 4). Thus the overall period required when attempting to determine an optimal diet in both nutritional and energy terms need not be excessive, unless the user's current diet is particularly unhealthy or his/her dietary and/or cooking preferences abnormally restrictive. When compared with the period otherwise required to calculate and analyse (i) the nutritional details of a diet, (ii) the energy expenditures involved in its preparation, and (iii) the effects of dietary-changes on (i) and (ii), from the appropriate literature it would appear that NEI software offers both a rapid and convenient means for self-education on the subject of energy-efficient nutrition.

Efforts were made to reduce the estimated primary-energy expenditures inherent in the diet described in Appendix 1 (i.e. diet A). For instance, a 43% saving in primary energy could be achieved by drinking cold water instead of Coca Cola. A more realistic strategy for the user was to decrease the consumption of the latter by 75%, and to satisfy the resultant deficit in liquid intake by drinking approximately three and seven extra cups of tea and cold water per week respectively: this substitution alone would result in a primary-energy saving of about 32%.

The nutritional imperfections of diet A that were studied by using the program (i.e. deficiencies of vitamin A, ascorbic acid and iron) were rectified in an energy-conscious manner. The lack of vitamin A and iron in the original diet could be corrected by increasing the consumption of vegetables, but this would raise cooking-energy expenditures significantly (i.e. see Table 5). Consequently, the consumption of a small quantity of liver per week was preferred. This was supplemented with fresh fruit (e.g. one banana or apple

TABLE 4
Nutrient and Primary-Energy Data for the Original and Modified Diets (see Appendices 1 and 2)

Dietary parameter	*Amount associated with diet A*	*Amount associated with diet B*	*Recommended daily intake of nutrient**
Protein (g)	90·8	98·0	60
Calcium (mg)	927·1	925·9	500
Iron (mg)	9·1	10·1	10
Vitamin A (μg)	533·0	1 452·8	750
Thiamin (mg)	1·0	1·1	1·0
Riboflavin (mg)	1·7	1·9	1·6
Nicotinic acid (mg)	31·4	37·0	18
Ascorbic acid (mg)	28·1	32·7	30
Vitamin D (μg)	6·3	6·4	†
Nutritional energy (MJ)	8·8	8·9	9·0
Domestic cooking-energy expenditure (MJ)	9·3	10·3	—
Total cooking-energy expenditure (MJ)‡	14·5	10·3	—
Production-energy expenditure (MJ)	76·3	49·4	—
Total primary-energy expenditure (MJ)	90·8	59·7	—
Output/Input energy ratio	0·10	0·15	—

* For an overweight adult male aged 35 years, with a sedentary occupation, who wishes to maintain temporarily a nutritional energy intake of approximately 10% less than that recommended for similar individuals of optimal weight.
† No dietary source of vitamin D is usually needed, unless the individual stays out of sunlight.
‡ Assumes that all foods were cooked in amounts suitable for one person in separate appliances/utensils (e.g. fresh water was taken from a cold-water supply for each preparation of 'boiled' vegetables).

each day), which also rectified the deficiency in ascorbic acid. Additional efforts to reduce primary energy expenditures whilst maintaining RDA values involved avoiding eating sausages and chips that were cooked outside the domestic kitchen, and reducing the consumptions of chocolate and coffee by approximately 25%. To overcome the nutritional deficit caused by the latter, increases in the daily intakes of bread, butter, cheese, peanuts, tea and hot-water were preferred primarily because of their relatively low process-energy densities, the personal choices of the user, and the constraints imposed by the data-base.

The diet thereby formulated (see Appendix 2) was regarded as an optimum by the person under investigation. (This diet was designed for a particular individual: those described in Appendices 1 and 2 are

TABLE 5
A Breakdown of the Primary-Energy Expenditures Involved in Cooking the Foods, Which Comprised the Cooked Part of Diet A

*Electrical cooking appliance employed**	*Food eaten*	*Mean daily energy expenditure for cooking (MJ)*
'Radiant-ring' hob	Gravy	0·06
Grill	Pork sausages	0·19
'Radiant-ring' hob	Chips	0·28
Grill	Cheese	0·19
Grill	Sardines	0·20
Grill	Pork chop	0·20
Oven (not fan-assisted)	Roast beef	0·32
'Radiant-ring' hob	Boiled carrots	0·34
Oven (not fan-assisted)	Roast chicken	0·35
'Radiant-ring' hob	Tomato soup	0·38
'Radiant-ring' hob	White fish	0·55
Toaster	Toast	0·64
'Radiant-ring' hob	Boiled sprouts	0·68
'Radiant-ring' hob	'Baked' beans	0·69
Oven (not fan-assisted)	Roast potatoes	0·72
'Radiant-ring' hob	Boiled peas†	1·03
'Radiant-ring' hob	Boiled potatoes	1·08
'Jug-kettle'	Boiling water for beverages	1·40
Commercial fryer	Pork sausages	2·50
Commercial fryer	Chips	2·72
Total		14·52

* All equipment is designed for domestic use, unless stated otherwise.
† Initially frozen at −20°C.

inappropriate for the majority.) Unfortunately an increase in that user's cooking-energy bill of 11% was predicted if the modified diet (i.e. diet B) was adopted (e.g. see Tables 4, 5 and 6). This was due to the chosen means of satisfying:

(i) the deficit in liquid intake by drinking extra (hot) tea as well as cold water, in place of the rejected energy-expensive beverages, coffee and Coca Cola;
(ii) a vitamin A deficiency (i.e. by eating cooked liver); and
(iii) the requirement for fried sausages and chips on day 5 (see Appendix 2).

This shortcoming may be rectified partially if salads (which include raw carrots) and cold water are consumed during the summer instead of liver and tea. RDAs may be satisfied and an overall reduction in primary-energy

TABLE 6
A Breakdown of the Primary-Energy Expenditures Involved in Cooking the Foods, Which Comprised the Cooked Part of Diet B

*Electrical cooking appliance employed**	*Food eaten*	*Mean daily energy expenditure for cooking (MJ)*
Radiant-ring hob	Gravy	0·06
Grill	Cheese	0·19
Grill	Pigs' liver	0·17
Grill	Sardines	0·20
Grill	Pork chop	0·20
Oven (not fan-assisted)	Roast beef	0·32
Radiant-ring hob	Boiled carrots	0·34
Oven (not fan-assisted)	Roast chicken	0·35
Radiant-ring hob	Tomato soup	0·38
Grill/radiant-ring hob†	Pork sausages	0·46
Radiant-ring hob	White fish	0·55
Radiant-ring hob	Chips	0·57
Toaster	Toast	0·64
Radiant-ring hob	Boiled sprouts	0·68
Radiant-ring hob	'Baked' beans	0·69
Oven (not fan-assisted)	Roast potatoes	0·72
Radiant-ring hob	Boiled peas‡	1·03
Radiant-ring hob	Boiled potatoes	1·08
Jug-kettle	Boiling water for beverages	1·57
Total		10·29

* All equipment is designed for domestic purposes.
† Food was cooked by grilling and frying on day 2 and 5 respectively (see Appendix 2).
‡ Initially frozen at −20°C.

expenditure of at least 34% afforded, provided that fresh, locally-grown, vegetables are eaten.

The predictions for diets A and B indicated that significant amounts of energy were used for boiling water whilst cooking vegetables and preparing hot beverages. Therefore significant cooking-energy savings should be achievable, if the thermal designs of hob-heaters and their associated cooking pans are improved. However, cooking energy expenditures tended to be small compared with expenditures on production, unless food from catering establishments was consumed. If attempts were made to carry out each cooking task involved in preparing diet B to a similar culinary standard by using the most energy-efficient domestic cooking-system, it was predicted that primary energy expenditures for cooking could be reduced by 55% (e.g. see Tables 6 and 7). Unfortunately this saving is unlikely to benefit the

TABLE 7
A Breakdown of the Primary-Energy Expenditure Involved in Cooking the Foods Which Comprised the Cooked Part of Diet B, by Using the Most Efficient (in Terms of Primary Energy) Domestic Cooking Appliance Commonly Available

Cooking appliance employed	*Food eaten*	*Mean daily energy expenditure for cooking (MJ)*
Gas hob	Gravy	0·03
Gas grill	Cheese	0·04
Gas grill	Pigs' liver	0·04
Gas grill	Sardines	0·05
Gas grill	Pork chop	0·05
Gas grill	Toast	0·13
Gas grill/Gas hob*	Pork sausages	0·15
Gas hob	Boiled carrots	0·16
Electric oven (fan-assisted)	Roast beef	0·18
Gas hob	Tomato soup	0·18
Electric oven (fan-assisted)	Roast chicken	0·19
Gas hob	White fish	0·25
Gas hob	Chips	0·26
Gas hob	Boiled sprouts	0·32
Gas hob	'Baked' beans	0·32
Electric oven (fan-assisted)	Roast potatoes	0·40
Gas hob	Boiled peas†	0·48
Gas hob	Boiled potatoes	0·50
Gas hob	Boiling water for beverages	0·88
Total		4·61

* Food was cooked by grilling and frying on day 2 and day 5 respectively (see Appendix 2).
† Initially frozen at −20°C.

typical user, because few domestic kitchens are equipped with a wide range of cooking facilities (e.g. gas hobs, microwave ovens and fan-assisted electric ovens). Nevertheless, consumers may become more discerning when buying cooking equipment, if they are made aware of the effects of using different types of appliance on their fuel bills before making a purchasing decision. Then appliance manufacturers may receive direct encouragement for improving the thermal designs of domestic cooking equipment.

CONCLUSIONS

The primary energy demand placed on industrialised food-systems could be reduced significantly, if consumers gave a high priority to selecting energy-efficient foods and using the most appropriate energy-efficient appliance for each cooking operation. Financial savings may be accrued if attempts are made to limit their cooking-energy expenditures, but this may lower the nutritional quality of the individual's diet unless he/she is prepared to eat more raw vegetables and fruits, as well as increase his/her consumption of cold water.

NEI software provides a rapid means for an individual to determine the overall health-value and energy effectiveness of his/her diet. The prototype computer program developed in this investigation enabled relatively nutritious and energy-efficient (but restricted) diets to be formulated. To maximise the energy savings achievable, it is advisable to include energy-thrift recommendations for kitchens[25,26] within the software and its associated literature, because the underlying assumption of the method of energy analysis described herein is that individuals utilise 'average' appliances to prepare foods via 'identical' procedures. In reality, it is not only the efficiency of a cooking appliance but the effectiveness with which it is employed that determines the energy requirement to cook a certain mass of food. Inclusion of appropriate utilisation ratios in the analysis was not feasible because users of the program are unlikely to know the necessary details (e.g. the proportion of the oven's available capacity that was utilised or the number of times the oven door was opened during cooking). Thus, to prevent under-estimation of energy savings due to this human variation in cooking practices, it is vital that cooks become aware of (and then attempt to implement) energy-effective cooking techniques. The percentage reductions in energy expenditures that may be predicted by NEI software, if diets are modified in an energy-conscious manner, should then approach those achievable in practice.

The concept of NEI software is still somewhat futuristic because of the lack of recent and comprehensive data concerning food production and cooking energy expenditures, and the limitations of current knowledge concerning optimal nutrition (i.e. the inter-relations between dietary nutrient intakes and disease). Nevertheless the objective of providing a means for individuals to achieve personally-desirable healthy diets for the minimum expenditure of primary energy must be pursued, because the long-term effects of poor diet and energy mis-use may be disastrous for several nations now and for many of our descendants during this period of rapidly depleting fossil-fuel resources and rising world population. Unfortunately most of the world population may never gain the opportunity to use nutritionally-balanced varied diets similar to those achievable in the UK, because (if living standards in the already-developed societies are to continue) the Earth simply cannot maintain the increase in demand for fossil fuels caused by the operation of such a food system. Consequently, on-going attempts to (i) limit energy consumptions by improving the designs of food appliances (especially those used in LDCs), and (ii) modify diets from an energy-conservation perspective may be most pertinent for the prosperity of future generations.

Computer-based facilities for obtaining quantitative information concerning diets should be developed further, because individuals who are in a position to study their food consumptions in such detail are also likely to be among those who are most able to implement energy-efficient, health-conscious modifications to their current diets. The latter involves practising personal restraint when selecting and preparing foods. This may not necessarily result in substantial reductions in personal financial expenditures on food and cooking, but, in national terms, large primary energy savings should ensue.

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APPENDIX 1

The original weekly diet, A, formulated for analysis, from a restricted database of 40 common foods, was as follows:

Food	*Mass of food consumed (g)*						
	Day 1	*Day 2*	*Day 3*	*Day 4*	*Day 5*	*Day 6*	*Day 7*
Baked beans	0	100	0	0	0	80	0
Beef (roasted)	0	0	0	0	0	0	65
Biscuits	50	40	60	25	25	60	25
Bread (white)	0	0	100	0	0	0	80
Butter	15	10	10	25	20	0	20
Carrots	0	0	40	0	0	0	0
Cheese (Cheddar)	0	0	55	0	0	80*	55
Chicken (roasted)	0	0	110	0	0	0	0
Chips	0	0	0	0	175†	150	0
Chocolate	100	130	50	130	100	50	50
Coca-cola	660	660	600	660	660	0	0
Coffee (instant)	15	15	15	15	15	10	5
Cornflakes	0	0	30	0	0	30	20
Custard	0	5	0	0	0	0	0
Fish (white)	0	0	0	120	0	80	0
Gravy	20	0	20	0	0	0	20
Ice-cream (vanilla)	50	0	0	0	0	0	50
Lettuce	0	0	8	0	0	0	0
Marmite	7	5	0	5	5	0	5
Milk	100	65	250	50	50	300	200
Peanuts (roasted)	50	50	0	100	0	0	0
Peas (boiled)	50	0	0	50	0	0	60
Pork-chop	100	0	0	0	0	0	0
Pork sausages	0	80	0	0	60†	0	0
Potatoes (boiled)	150	125	0	175	0	0	0
Potatoes (roasted)	0	0	110	0	0	0	130
Sardines	0	0	0	0	80	0	0
Soup	0	0	0	0	200	0	0
Sprouts	0	0	40	0	0	0	30
Sugar	0	0	15	0	0	15	15
Tea	10	0	0	5	5	10	5
Toast	75	50	0	50	130	75	50
Water (cold)	500	250	250	250	250	250	250
Water (hot)	1 250	850	750	1 000	1 000	1 000	500
Wine	0	0	0	250	0	0	250

* This amount of cheese was grilled, whereas other consumptions apply to raw cheese.
† This food was prepared in a catering kitchen.

APPENDIX 2

The modified weekly diet (i.e. diet B) derived from an analysis of the original diet (i.e. diet A) is described below. Adoption of this diet is not recommended, because it was developed by considering intakes of only 10 nutrients (see Tables 2 and 4)

Food	*Mass of food consumed (g)*						
	Day 1	*Day 2*	*Day 3*	*Day 4*	*Day 5*	*Day 6*	*Day 7*
Apple	80	0	80	0	80	0	0
Baked beans	0	100	0	0	0	80	0
Banana	0	80	0	80	0	80	80
Beef (roasted)	0	0	0	0	0	0	65
Biscuits	50	40	60	25	25	60	25
Bread (white)	0	25	100	0	100	50	100
Butter	15	15	10	30	40	10	40
Carrots	0	0	40	0	0	0	0
Cheese (Cheddar)	0	0	65	0	0	80*	65
Chicken (roasted)	0	0	110	0	0	0	0
Chips	0	0	0	0	175	150	0
Chocolate	100	50	50	50	100	50	50
Coca-cola	330	330	0	0	150	0	0
Coffee (instant)	15	10	10	10	10	5	5
Cornflakes	0	0	30	0	0	30	20
Custard	0	5	0	0	0	0	0
Fish (white)	0	0	0	120	0	80	0
Gravy	20	0	20	0	0	0	20
Ice-cream (vanilla)	50	0	0	0	0	0	50
Lettuce	0	0	8	0	0	0	0
Liver (pigs)	0	30	0	0	0	0	0
Marmite	7	5	0	5	5	0	5
Milk	100	65	250	50	50	300	200
Peanuts (roasted)	100	100	50	100	0	0	0
Peas (boiled)	50	0	0	50	0	0	60
Pork-chops	100	0	0	0	0	0	0
Pork sausages	0	80	0	0	60	0	0
Potatoes (boiled)	150	125	0	175	0	0	0
Potatoes (roasted)	0	0	110	0	0	0	130
Sardines	0	0	0	0	80	0	0
Soup	0	0	0	0	200	0	0
Sprouts	0	0	40	0	0	0	30
Sugar	0	0	15	0	0	15	15
Tea	10	5	5	10	15	15	15
Toast	75	50	0	50	130	75	50
Water (cold)	500	500	500	500	500	500	500
Water (hot)	1 250	850	750	1 000	1 250	1 000	1 000
Wine	0	0	0	250	0	0	250

* This amount of cheese was grilled, whereas other consumptions apply for raw cheese.

CHAPTER THREE

ENERGY-EFFICIENT FOOD-PREPARATION FACILITIES

SUMMARY

The catering industry is one of the more energy-profligate sectors of the British economy, if assessed according to the ratio of the amount of energy used divided by that needed if efficient systems and practices were employed to achieve the same quality of end-product. Consequently worthwhile energy-thrift opportunities exist for reducing energy consumptions in British kitchens, whether associated with canteens, cafes, restaurants or hotels. To facilitate encouraging the implementation of these improvements, detailed energy-conscious recommendations are proferred in this survey with respect to the structural and ergonomic designs of food-preparation facilities. Also advice which should enable caterers to select (and demand from appliance manufacturers) more energy-efficient equipment for initial installation in, or when refurbishing, their kitchens is presented. By the economically-justifiable introduction of these proposals, it is predicted that a reduction in overall energy usage in the British catering sector of at least 25% (i.e. about £1.25×10^8 p.a. at 1987 prices) may then be achieved.

NOMENCLATURE, ABBREVIATIONS and GLOSSARY

A	Area formed by one of the frozen-food store's bounding surfaces, m^2.
a	Total radiating area of the store's typical occupant, m^2.
C	Specific heat capacity, $Jkg^{-1}K^{-1}$.
COP	Coefficient of performance for the refrigeration system.
D	Number of decks required.
d	Proportion of operating period that the equipment is energised, $0.0 \leqslant d \leqslant 1.0$.
E	Overall energy requirement for cooking, J.
H	Heat input to the food during cooking, J.
h	Convective heat transfer coefficient, $Wm^{-2}K^{-1}$.
i	Indexing parameter for the food item, i, to be stored.
j	Indexing parameter for the bounding surfaces of the frozen-food store.
k	Thermal conductivity of a building component, $Wm^{-1}K^{-1}$.
$\dot{L}$	Rate of heat dissipation by the lights in the frozen-food store, W.
LH	Latent heat of fusion for the food, Jkg^{-1}.
l	Number of portions of the food that can be cooked per cooking pan.
$\dot{M}$	Rate of heat dissipation by motor-driven equipment, which is used in the frozen-food store, W.
m	Mass, kg.
N	Number of air changes per hour in the sub-ambient store, hr^{-1}.
n	Number of people occupying the frozen-food store.
P	Power requirement, W.
p	Number of pans that will fit into a single deck of the oven.
(pf)	Power factor of the compressor associated with the refrigeration system, $0.0 < (pf) \leqslant 1.0$.
$\dot{Q}$	Rate of heat dissipation, W.
r	Proportion of customers expected to choose that item of food, %.
S	Expected serving rate, hr^{-1}.
T	Temperature, K.
t	Cooking period, hr.
U	Thermal transmittance, $Wm^{-2}K^{-1}$.
u	Period required for the food to cool to the environmental temperature of the sub-ambient store, s.
V	Volume of the store, m^3.
v	Total period during which the frozen-food store is occupied divided by the total working period for the kitchen.
X	Extra energy required to maintain the mean bulk temperature of the cooking medium at the desired temperature throughout the cooking period, divided by that required to raise it to this temperature. (Usually X approximates to the period during which the heating system is stimulated after the cooking medium has reached the desired temperature, divided by the initial period of continuous energisation necessary for it to attain that temperature).

x	Thickness of the wall, which forms one of the store's bounding surfaces, m.
y	Number of bounding surfaces.
z	Number of foods to be stored in the sub-ambient environment.
ε	Average emissivity of the clothed occupant, $0.0<\varepsilon<1.0$.
η	Overall efficiency, $0.0<\eta<1.0$.
η'	End-use efficiency, $0.0<\eta'<1.0$.
η''	Production-plus-supply efficiency for the fuel, $0.0<\eta''<1.0$.
ρ	Density of air, kgm^{-3}.
σ	Stefan-Boltzmann constant, $5.67\times10^{-8}\ Wm^{-2}K^{-4}$.

Subscripts

A	Of air.
a	Of the catering appliance.
B	Per batch of food.
C	For cooling.
c	Of the compressor.
d	Pertaining to the food as it enters the sub-ambient store.
E	Pertaining to the useful power requirement for operating the sub-ambient temperature food store.
e	Of the maximum temperature attained by the cooking medium.
F	Of the food.
f	At the freezing point of the food.
h	Of the frozen food.
i	At the initial condition of the food.
j	At the initial condition of the cooking medium.
k	At the mean condition of the food once cooked.
M	Of the motor-driven equipment in the frozen-food store.
p	Of the operatives.
s	Of the store.
t	Of the just-thawed food.
V	Pertaining to the apparent power requirement for operating the sub-ambient temperature food store.
W	Of the store's building fabric.
in	At the inside surface of the frozen-food store.
out	At the outside surface of the store.
	Of the artificial environment within the general kitchen zone.

Abbreviations

CFP	Centralised food production.
CFPU	Centralised food-production unit.
COP	Coefficient of performance of the refrigeration unit.
CPA	Critical path analysis.
HVAC	Heating, ventilating and air conditioning.
IUFoST	International Union of Food Science and Technology.
OECD	Organisation for Economic Co-operation and Development.
PERT	Programme evaluation and review technique.
pf	Power factor.

Glossary

Magnetron	A thermionic valve in which electrons, released from a central cathode, gyrate in an axial magnetic field before being collected by a series of slots situated around the adjacent concentric anode.
Smoke Point	The oil temperature beyond which continued heating will result in smoke emissions from the oil/air interface.
To bread	The process of covering food with bread crumbs before it is fried or grilled.

THE PROBLEM AND THE OPPORTUNITY

In the UK, the catering industry (i.e. approximately $2.3x10^5$ individual establishments producing in total at least $5.5x10^9$ meals annually) incurs an unnecessarily-high fuel bill of about £5 x 10^8 p.a. Direct (e.g. cooking and freezing foods) and indirect (e.g. manufacturing cooking appliances) energy inputs to this industrial sector amount to about 1% and 3% of the UK's annual primary-energy usage respectively (Singer et al, 1976; Lawson, 1983). A survey, conducted by Conway (1985), indicated that 96% of the respondents from a sample of catering managers (employed by a large contract-catering organisation) believed that significant reductions in fuel consumptions within their kitchens were feasible. Yet the task of reducing energy bills within the food-service sector, by implementing appropriate energy-thrift measures, remains in its infancy. Complacency concerning the rational use of energy in kitchens is still rife world-wide!

Energy expenditures usually account for about 10% of the total cost of a meal prepared in a non-domestic kitchen, and this percentage is tending to increase (Howard, 1979; Barclay and Hitchcock, 1984). The costs of utilising the facilities, typically provided by restaurants, hotels and cafes in industrialised nations, vary considerably — those in the UK being relatively high (e.g.see Table 1) — yet significant savings could be achieved by implementing appropriate energy-thrift measures. Thus it is particularly important for the British catering-industry, which is expected to expand substantially during the next 25 years, to develop a comprehensive energy-thrift campaign. This will help improve the long-term cost-effectiveness as well as bring the food-service sector more 'into line' with other industries, which have already reduced their annual fuel expenditures.

Unfortunately much of the energy expended during storing, preparing, cooking and serving food is wasted without achieving any useful purpose. Some catering establishments expend much greater quantities of energy per meal served than others (e.g. see Tables 2,3 and 4). This is due partly to the variety of catering activities undertaken (e.g. see Table 5), but fundamentally there are three main inter-related factors, which lead to energy profligacy within food-service:-

* Poor designs of kitchens.

* The utilisation of poorly-designed, inefficient or inappropriate equipment.

* The common employment of improvident catering practices and inadequate equipment-maintenance procedures in kitchens.

By analysing each of these mal-practices from an energy-thrift perspective, targets for achieving reasonable but significant overall savings may be established. (Because remedies for the latter malfeasance have been discussed in detail elsewhere (Probert and Newborough, 1985; Sutcliffe Catering Group Ltd., 1986; and Batty et al, 1987), the present investigation concentrates on the first two of the aforementioned categories of energy mis-use). The rewards for applying a comprehensive energy-thrift strategy in kitchens may be summarised as follows:-

* Lower operating costs.

* More comfortable environments for the workers.

* A stimulus for catering-equipment manufacturers to design better and more energy-efficient kitchen appliances.

* Altruistic contributions towards (i) delaying the exhaustion of the Earth's finite reserves of fossil fuels, (ii) reducing Britain's annual energy bill, and (iii) lessening the amount per annum of thermal and chemical pollution of the ambient environment.

Therefore it is desirable for the catering sector to start monitoring and controlling its use of energy. It is imperative that long-term targets, to reduce energy expenditures, are introduced so that the impacts of any sudden increases in unit-fuel prices can be reduced. In view of the world's major dependence upon oil for at least the next 20 years, and the volatile nature of energy prices, deferment of decisions concerning energy thrift is now financially unwise and will probably reduce the catering industry's growth rate significantly. The financial savings achievable by practising energy-thrift tactics in the food-service sector have been demonstrated by Trusthouse Forte plc: this organisation, by adopting a two-year maximum pay-back criterion for financial investments in energy-thrift measures, reduced its annual expenditure on energy by 57% in 4 years (Anon. 1986a). There is little reason to suppose that percentage savings of this magnitude cannot be matched (and in some cases exceeded) by caterers, restaurateurs and hoteliers throughout the industry.

TABLE 1

Comparative financial expenditures within the 'hospitality' industries of various nations during 1981 :adapted from OECD, 1983 and Unklesbay and Unklesbay, 1985.

Country	Per capita expenditure throughout the stated country in restaurants, hotels and cafes, divided by the magnitude of the same parameter for the UK	Proportion of the approximate total per capita expenditure spent in restaurants, hotels and cafes of the stated country (%)
United Kingdom	1.00	11
United States of America	0.81	5
France	0.78	7
Canada	0.77	6
Finland	0.59	6
Italy	0.49	7
Sweden	0.32	2
Greece	0.23	5

TABLE 2

Typical average total energy costs incurred by various British food-service establishments during 1982. The data exclude consideration of cold snacks and cold beverages (Lawson, 1983).

Representative catering establishment	Average energy cost per meal served in the stated establishment, divided by the average energy cost per meal served in a typical snack bar
Snack Bar	1.0
Coffee Shop	1.8
Employee Canteen	2.4
University Refectory	2.7
Steakhouse (limited menu)	4.5
Traditional English-Restaurant	4.8
High-Class Restaurant	6.8
Hotel Restaurant	9.0

TABLE 3

Analysis of the British catering-industry, according to the annual rates of either meal production or energy consumption (adapted from Lawson, 1983).

Type of catering establishment	Percentage of the total number of meals produced annually	Percentage of the total annual energy expended for producing meals
Hospital-staffs' restaurants*	0.6	0.6
'Steak houses', and limited-menu restaurants	0.7	1.3
Store restaurants, 'coffee shops' and speciality restaurants	2.7	2.2
Public houses	9.7	5.6
Traditional English-restaurants	4.3	9.1
Educational catering-facilities	11.0	13.1
Snack bars	31.6	13.9
Hotel restaurants	4.1	16.6
Employee catering-facilities	32.6	34.8
Other catering establishments	2.7	2.8

* N.B. This does not include the meals prepared for patients.

TABLE 4

Typical energy consumptions in two characteristically-different catering establishments when producing nominally-identical food items, i.e. fried chicken (adapted from Dwyer et al, 1977).

Kitchen activity	Energy expenditure (MJ kg^{-1} of food) in a :-	
	Cafetaria*	Fast-food store*
Frozen storage	13.47	0
Refrigerated storage	0	2.30
Warming and breading chicken	0	0.85
Deep-fat frying**	18.99	2.69
Food-holding	2.17	0.85
Total	34.63	6.69

* Pre-cooked, frozen, 'breaded' chicken was used by the cafetaria, whereas the fast-food store employed chilled chicken, which was breaded by staff prior to cooking.

** Because of its diverse menu, the cafetaria employed a versatile, conventional, deep-fat fryer for producing the fried chicken, unlike the fast-food establishment which utilised a specific-purpose pressurised deep-fat chicken-fryer. The values stated in the Table apply to the production of 72.7 kg and 19.1 kg of chicken in the cafetaria and fast-food store respectively.

TABLE 5

Typical requirements placed on the main types of catering facilities by their users.

Type of individual to be served	Objective and nature of the catering operation
Industrial employee	To provide at approximately mid-day a restricted variety of meals, which customers can select, collect and purchase rapidly. Usually operated on a 5-day week.
College student	Similar to that associated with industrial catering, except that the dining periods for students are relatively more flexible and so the peak demand upon the kitchen is lower for the same rate of daily demand. Operated on a 5-day week, but usually with long seasonal-holidays.
School pupil	To provide a restricted-menu mid-day meal rapidly, usually at two or three sittings, in an area which is unlikely to be reserved solely for dining. Operated on a 5-day week, but with long seasonal holidays.
Hospital patient	To provide all meals for partially or wholly incapacitated individuals situated in a number of relatively non-compact dining areas. Operated on a 7-day week.
Institution patient	To prepare all meals for physically and/or mentally sub-normal individuals, some of whom may wish to participate in meal distribution activities. Operated on a 7-day week.
Aircraft/train passengers	To provide foods and beverages to individuals in a manner which complements the basic service. Cooking facilities are usually minimal because of space restrictions. Operated on a 7-day week.
Leisure-seeking individual	To provide a variety of meals to particularly discerning customers often during unsocial hours. Demand patterns are usually highly variable when compared with other types of catering. Normally operated on a 7-day week.

KITCHEN DESIGN

The operational efficiency of any kitchen depends partly on its design, i.e. on the decisions taken before construction commenced. Once the kitchen serving a restaurant, canteen or hotel has been built, the prospects for achieving large energy-savings subsequently in a commercially-viable way are correspondingly limited. For example, extensive heat-recovery within a kitchen is not always justifiable economically as a retrofit option. Thus it is important to analyse, in depth at the design stage of the kitchen, the implications that alternatively proposed building designs would have on the energy expenditures incurred when the catering facility is in operation.

There is evidence to suggest that kitchen designs tend to be traditional and have evolved only in a formalised manner. Furnival (1977) described the environment of a typical traditional British kitchen as 'very hot or very cold, noisy, greasy, steaming and poorly lit, with little access to natural light and fresh air'. To some extent, these conditions still prevail in many existing kitchens. Thus efforts to improve the designs of such work-places are highly desirable. Unfortunately, it would appear that there has often been a lack of thinking from first principles, partly due to insufficient energy knowledge among kitchen designers (Sutcliffe Ltd., 1983). This may be caused by inadequacies within the syllabuses of educational courses designed specifically for training food-service professionals, as well as the traditional low esteem given to catering by organisations which achieve little or no financial gains by operating food-service facilities for their employees.

Relinquishing the responsibility for designing and equipping a kitchen to an appliance manufacturer is a common practice: this has led to many kitchens being over-equipped. Then both capital and operational expenditures may be excessive (Thomas, 1947). Initial specifications tend to be unscientific - often too little thought is given to fundamental productivity and quality matters such as the number of sittings for meals per day, the types of food to be prepared, the method of service, the distances travelled by the catering staff within the building, the expectations of the customers/patients and the expected operating life of the establishment (Fisk et al, 1963; Montag and Tamashunas, 1969; Sutcliffe Catering Group Ltd., 1983). Furthermore, the employment of inadequately qualified or biassed consultants, may have led to some of the industry's current over-spending on energy. Although associations have been set up in the UK by manufacturers and distributors of catering equipment, none exists for designers of food-service facilities. Clearly, in the long term, an association formed by kitchen-design consultancies could introduce approved design methodologies and so provide many benefits for its members and their clients.

The present scenario indicates that the instigator of a new kitchen should attempt to establish a co-operative liaison (e.g. via a quality circle) involving caterers, dieticians, architects, building-services engineers, interior designers, energy engineers, builders and (if possible) prospective customers for the food, when designing the catering facility. Current wisdom suggests that the architect should be the arbiter for this design team : however, if minimising the establishments operational costs is the paramount aim, the appointment of a professional energy technologist, who specialises in kitchen design might be more expedient.

There are many reasons for the traditional lack of concern for ergonomic design and energy management within the food-service sector, several of which are associated directly with the nature of the industry. Essentially the hospitality industry has always been very labour intensive and suffers a high turn-over of labour (~75% p.a.), compared with other industries. A false, but common, belief among kitchen managers and chefs has evolved : it implies that catering should be regarded solely as an art and as such would not benefit from being treated by scientific analyses (which could help in predicting, for example, optimal lay-outs and work-flow patterns). Because service labour is usually abundant and associated wages are relatively low, the management is more inclined to permit increases in the labour force, rather than instigate design analyses and then implement the structural, spatial and/or equipment changes that may be recommended, even though the total cost over the lifetime of the kitchen will then be higher. Usually, in order to limit labour costs, the employment of extra skilled staff is avoided: instead the hiring of unskilled staff and the purchase of robust labour-saving (but not necessarily energy-saving) appliances, which require relatively little expertise to operate, are preferred. The latter is widely viewed as highly desirable, although comparative life cycle cost assessments are not always undertaken (Milson and Kirk, 1980).

In recent years, the increasing employment of otherwise unemployed unskilled or semi-skilled workers has enabled overall labour costs to be limited (e.g. by increasing the proportion of part-time staff). A recent survey indicated that although the total profits of the UK catering industry exceeded £10^9 in 1986, about 70% of its employees received wages which were below the Council of Europe's 'decency threshold', i.e. about £3 per hour (Chappell, 1987). Indeed, because many skilled kitchen staff have opted for alternative careers, in which higher salaries are attainable, the catering industry is staffed increasingly by (i) the young and inexperienced; (ii) the over-50's, who have few opportunities for starting new careers elsewhere; and (iii) mothers, who prefer part-time work. Ironically these groups of people are among those Britons least likely to be concerned with avoiding energy mis-use during their working activities. Many of them are not responsible for paying their domestic energy bills and so they instinctively but unintentionally thwart the adoption of energy-efficient kitchen practices. Thus it is likely that, unless adequate educational programmes and financial incentives are provided by employers, energy-thrift practices will only rarely be implemented. Although large reductions in operational costs are achievable by good house-keeping practices and the wise use of equipment within kitchens, low-quality staff are unlikely to achieve energy-savings targets consistently. Therefore the designs of kitchens (and the catering appliances therein) need to be improved now, in order to limit the energy profligacy of the incompetent, the inadvertent and even the disobedient.

The primary objective when developing a 'low-energy' design for a kitchen should be to minimise the exergy losses per meal served. However, determining the optimal design of kitchen is complicated mainly because of:-

i) the varying daily demands placed on the catering facility;
ii) the sporadic nature of most activities within the kitchen; and
iii) the frequent use of inefficient, heat-liberating, equipment within a relatively small working zone.

Moreover, because a single truly representative standard kitchen cannot be specified (as may be appreciated from Table 5), only general recommendations can be proferred. Nevertheless the implementation of such advice should enable the annual energy consumption of the food-service sector to be reduced significantly.

To obtain a low energy-demand catering-facility, three interdependent features should be considered:-

(I) The structural design of the kitchen and the specifications of the building's environmental-services (e.g. ventilation, heating, cooling, dehumidification, lighting and heat-recovery systems).

(II) The ergonomics of the kitchen's interior, (e.g. the optimal lay-out of the stores, preparation areas and catering equipment).

(III) The procurement of energy-efficient kitchen appliances for installation in the kitchen.

I. THE KITCHEN BUILDING

British catering establishments often have poorly insulated, low thermal-mass structures with relatively large areas of glazing (e.g. see Appendix 1). Such designs incur large space-heating losses during winter and require substantial cooling during summer. Because the costs of achieving adequate environmental conditioning are only rarely fully met, an uncomfortable environment within the kitchen is usually tolerated during some work periods. Unfortunately inefficient attempts are frequently made by the employees to achieve comfort conditions for themselves, e.g. by using cooking equipment to heat the environment at the start of a work period.

If the kitchen-design team intends to fit an air-conditioning system (which will provide cooling or heating as required) in the kitchen, the following recommendations should be implemented in order to reduce the building's overall energy requirement for maintaining a comfortable indoor climate:-

* Insulate thermally the kitchen (i.e. by appropriately treating wall-cavities, floors and roofing) from the external environment. Compatible with their functional requirements, minimise the dimensions of all pipes, tanks and ducts that will contain non-ambient temperature fluids, and then insulate them properly.

* Fit porches around self-shutting or revolving external doors and, where appropriate, reduce air infiltration by draught-proofing doors and windows.

* Never provide doors and windows based on the premise that 'if it gets too hot, the doors and windows can be opened'. In kitchens which prepare day-time or evening/night-time meals, attempt to fit sealed windows predominantly on the east and west sides of the main work-zones respectively. By so utilising direct solar radiation (when available) the establishments annual air-conditioning bill will be reduced.

* Where feasible, plant shrubs around the kitchen building, and construct an external ground-periphery from grass instead of concrete or tarmac. This will reduce heat gains during warm weather, because (i) the grass has a relatively high reflectivity (Hunn and Calafell, 1977), and (ii) the shrubs will help maintain a low ground-surface temperature via evaporative cooling and shading. Also appropriately-situated coniferous and deciduous trees will afford some protection against prevailing winds and direct solar radiation respectively.

* Do not build the kitchen:-
  i) unnecessarily far away from where the food is to be served;
  ii) with large areas of fenestration which face a prevailing cold wind: ensure, by means of a suitable overhang, that shading from above is provided for any south-facing windows to counteract the effects of higher intensities of solar radiation at high altitude angles during summer.
  iii) with ceilings which are more than 3.5m above the floor;

iv) in any particularly wind/rain-swept location;
v) towards the top of a multi-storey building where mean wind speeds are relatively high; or
vi) so that it has a large ratio of perimeter to floor area: a kitchen building with a square floor is conducive to energy-thrift, and will facilitate solving many of the problems involved in making internal alterations that become desirable as technological and social trends affect the demands placed upon the kitchen.

All internal surfaces should be constructed so that they are smooth and impervious to water, grease, acids, alkalis and scouring agents, thereby permitting a high standard of hygiene to be maintained (Douglas, 1979; Lawson, 1980). Walls above head-height and ceilings should be built to achieve acoustic absorption, because noise levels in kitchens can often exceed 70dB during peak-activity periods, when sound intensities of less than 50dB would be desirable for the occupants (Kotschevar, 1967). Each zone of the kitchen must have floor drainage,but this should be covered as much as possible to avoid excessive humidification of the indoor environment. Glazed doors, windows and angled 'sky-lights' must be provided with drip channels and drainage outlets to ensure that any condensation is removed automatically in a controlled manner (e.g. see Appendix 1). Ideally, doors and windows should be positioned so that they are flush with interior surfaces in order to improve their cleanabilities. Automatic, electrically-operated, partially glazed, sliding doors are usually preferable to swing doors because they help facilitate more rapid entry to and exit from the kitchen, reduce the likelihood of accidents, and always ensure that adjacent zones are separated effectively when access between them is not required.

Underground Kitchens

From an energy-thrift viewpoint, kitchens are better positioned below ground-level (e.g. with their floors about 2.5m beneath the horizontal air/ground interface, where the subsoil temperature remains at approximately 10°C throughout the year in the UK). This ensures that heat losses to the ground from the building remain relatively small and nearly constant, regardless of the above-ground weather conditions, thereby limiting the kitchen's air-conditioning requirement. The surrounding earth acts as an effective thermal insulant. Also, because much of the kitchen is not visible above ground, the problem of designing the building with a reasonably attractive appearance is simplified. However underground facilities must be designed to avoid flooding during freak rainstorms and moisture incursion from the surrounding earth. Nevertheless, provided that the site is well suited geologically, reduced maintenance costs (and fire insurance premiums) are usually incurred because of the inherent protection from the weather that is afforded to underground structures (Morelend, 1975; Parizek et al, 1975).

An underground or partially-buried kitchen is considerably cheaper to operate, because the facility's energy demand for achieving comfort conditions is, in general, smaller and its internal temperature behaviour is less erratic than that of the same kitchen if located above-ground. The financial savings for sub-surface food-facilities can be enormous (e.g. see Table 6). The percentage savings achieved by using underground buildings in the UK are not as great as those appertaining to the central regions of the USA because the British climate is far more equable (i.e. winter heating and summer cooling loads are considerably smaller). However the operator of a properly-designed entirely subterranean kitchen in the UK may expect to achieve a reduction in his overall energy bill for the kitchen of at least 25%, relative to the corresponding above-ground kitchen.

Much of the reluctance to use completely underground rooms for human activities is based on the supposed emotional disturbances experienced in windowless military buildings during World War Two. However, more recent studies have suggested that evidence to support these allegations is inadequate and open to doubt (Chryssafopoulus, 1962; Larson, 1965; Collins, 1975). In particular, children educated in an underground school over a ten-year period were found to experience no detrimental physical or mental health effects: in fact the work of some pupils actually benefitted from 'underground schooling'. Support for the widespread introduction of underground schools among associated teachers and parents was almost unanimous (Lutz, 1976). Therefore the construction and use of underground food storage and preparation facilities would appear to be both feasible and attractive from psychological, financial and energy-thrift perspectives. Far-sighted kitchen designers should consider the possibilities of (partially or fully) underground construction when planning the introduction of large kitchens or central food-production units for 'cook-freeze' or 'cook-chill' catering systems. A dining room may be constructed, or vegetation grown, above the kitchen. Thus the underground-kitchen concept may appear particularly attractive in urban areas, where charges for land, rent and rates are becoming exorbitant.

TABLE 6

Financial savings achieved by building a food-storage facility completely underground instead of above-ground in central USA (Bligh and Hamburger, 1974).

Type of storage facility	Percentage savings achieved with respect to:-	
	Capital cost	Operational cost
Dry-goods	75	90
Refrigerated food	73	92

Centralised Food Production

Where a regular demand for many similar meals (e.g. 10,000 meals per day) exists locally (e.g. from a hospital, a university, or a group of factories in one urban area), financial (and sometimes energy) savings can be achieved by operating a centralised food-production (CFP) system. This involves constructing a single large kitchen, which acts as a central food-production unit (CFPU), for preparing, cooking and (if necessary) temporarily storing the food (using production line methods) until it is distributed in thermally-insulated containers to 'finishing kitchens' sited at the points of consumption. The work-schedules of those employed in the CFPU usually approximate to those of normal office-workers, i.e. the catering staff do not need to work unsocial hours, unlike many of their counterparts in traditional kitchens (Cowell, 1980). Also, because the finishing kitchens require fewer workers (especially skilled ones) and less equipment, only about 60% of the total workspace otherwise required for the satisfactory operation of traditional kitchens is needed (Electricity Council, 1977). Therefore CFP systems are particularly advantageous in city areas where space is at a premium. Furthermore, improving the operational efficiency (on an energy consumed per meal served basis) of one CFPU is far easier than attempting to increase the efficiencies of several smaller traditional kitchens. For example, because production rates are less variable throughout working periods, HVAC demands are less erratic than those of conventional kitchens and so the use of an energy-management system to regulate ventilation, heating, cooling and lighting is relatively simple for CFP facilities.

There are two main ways of operating a CFP system:-

i) freezing the food to about -20°C after cooking, and then distributing it for re-heating (within 3 months) in the finishing kitchens - the 'cook-freeze' technique; or

ii) chilling the food rapidly to about 3°C after cooking and then conveying it for re-heating (within 4 days) to the finishing kitchens - the 'cook-chill' method.

Although the rapid distribution of hot food to the various outlets (where it is served almost immediately) is preferable to methods (i) and (ii) from an energy-thrift perspective, the complicated planning and organisation (in both the CFPU and finishing kitchens) that are necessary for such an operation to be successful militates against its use. It is only feasible if the transport periods involved are short, because considerable organoleptic and nutritional degradations of the food ensue if the food is kept warm for more than 2-3 hours. Nevertheless, if the containers used to store the food temporarily are designed properly, and transportation begins immediately after cooking, then hot-food distribution should be satisfactory and favourable in nutritional and energy terms respectively.

Because most foods degrade bacteriologically unless cooled rapidly after cooking -- (it is recommended that if they are to be stored then they should be cooled to their desired storage temperatures within 1.5 hours) -- the associated refrigeration equipment to achieve this tends to be expensive (DHSS, 1980). Blast-cooling (using refrigerated air) and rapid cryogenic cooling (usually accomplished by the expansion of liquid nitrogen) of foodstuffs are excellent means with respect to satisfying hygiene and nutritional requirements, but very energy-expensive. Alternative techniques such as vacuum-sealing cooked foods, so that they can be cooled via water chillers instead of blast chillers can yield energy savings. Nevertheless, attempts to reduce financial expenditures by allowing foods to cool to near-ambient environmental temperatures before being placed within blast-chillers/freezers must not contravene health guidelines: these stipulate that items should enter such devices within 30 minutes of completing the cooking (DHSS, 1970, DHSS, 1980). However, recent studies suggest that the rate of freezing foods is less critical to food quality than was previously thought (Jul, 1984). Thus efforts to determine optimal rates of freezing, and temperatures for the storage of different frozen foods from an energy-thrift perspective are desirable (Houwing, 1984).

Hu et al (1979) compared the energy consumptions of a cook-freeze system with those of a conventional catering facility, when employed to provide 17,000 to 21,000 meals per day (see Table 7). The CFPU achieved an average energy-saving of 42% for preparing the different foods, but the overall mean energy expenditure for CFP (i.e. on cooking, freezing, storing and re-heating the foods) was 21% greater than that for the conventional system. However, when foods which required no cooking or freezing were prepared by CFP, average energy savings of 46% were achieved, when compared with the conventional catering system.

TABLE 7

The energy expenditures involved in providing diners with different foods by a cook-freeze catering system, compared with those incurred by a more traditional facility (Hu et al, 1978).

Item of food	Energy expended per portion, (MJ), (including re-heating) via:-	
	Centralised Food Production	Traditional Production
Roast pork	1.57	1.41
Roast beef	1.50	1.09
Barbecued chicken	1.45	1.40
Southern fried chicken	1.12	0.98
Salisbury steak	1.03	0.96
Fried beef patties	0.79	0.38
Meat sauce for spaghetti	0.60	0.33
Chili con carne with beans	0.57	0.37

Fundamentally, the cook-freeze system is more expensive in energy terms than the cook-chill one because:-

i) the food is cooled initially by up to 100°C, whereas with the cook-chill process the temperature reduction required is less than 80°C;

ii) foods are maintained at sub-ambient temperatures usually for much longer periods when operating a cook-freeze CFP system; and

iii) more energy needs to be provided for re-heating (i.e. the latent heat of fusion for water has to be supplied to thaw the ice within the food).

The cook-freeze system is limited to foods that can be cooked, frozen and then re-heated without affecting adversely their quality. With either technique there are some foods which cannot be prepared by CFP techniques (e.g. sandwiches and toast) without resulting in an inferior product being supplied to the customers. Therefore some extra staff and equipment must be employed in the finishing kitchens for preparing items such as salads, sauces and bread-based foods. However the operation of a cook-chill system can be adjusted easily to meet variations in customer demand, whereas because most foods can be kept frozen for prolonged periods without undergoing substantial nutritional-degradation, the cook-freeze system tends to require more advanced planning concerning the number of portions to be cooked per unit time. Consequently the necessary storage volume is smaller for a cook-chill system and so the capital outlay for constructing the kitchen is slightly less. Generally it would appear that the employment of a cook-freeze system is inappropriate from an energy-thrift perspective.

The Kitchen's Environmental Services

Maintaining a comfortable environment within an operating kitchen is difficult, due mainly to the extremely variable thermal loads. For example, a typical kitchen may experience:-

* High peak rates of energy consumption.

* Localised high rates of heat gain.

* Significant infiltrations of ambient environmental air during peak periods.

* Large amounts of water vapour being released as a result of the cooking and dish-washing operations.

* High concentrations of odours in a zone which is often adjacent to the dining room, where a near-odourless, low-noise (i.e. <50dB) environment is desirable.

The installation of an adequate environmental-conditioning system is therefore desirable if comfortable working conditions are to be maintained economically. Mean air temperatures and humidities in general kitchen areas should be maintained between 18 and 23°C, and from 40 to 70% respectively. Ideally draughts (e.g. air streams with velocities > 0.3 ms^{-1} impinging on the face and > 0.15 ms^{-1} on the ankles) should be eliminated. However, because the problem of creating comfort conditions within a kitchen is largely one of heat removal, it is likely that, during peak-demand periods, excessive air temperatures (e.g. >25°C) and air speeds (e.g. >1 ms^{-1}) will occur. Adequate rates of air removal near cooking appliances are desirable, primarily because of the poor thermal design of typical catering appliances, e.g. the temperatures of the external surfaces of currently-used ovens, when in operation, are often 20 to 70 °C above room temperature (Probert and Newborough, 1985; Skjoldebrand, 1985). The ensuant effects of the radiative heat fluxes emanating from operating cooking equipment (i.e. the high mean-radiant temperature of the kitchen) suggests that the air's optimal temperature, in the locality of cooking equipment, may be low - e.g. <15°C.

If the kitchen is not entirely detached from the main building, it is desirable to ensure that up to 20% more air is extracted from the kitchen by the ventilation system than is supplied to it directly from the ambient environment. Thereby the infiltration of air from adjacent dining areas will inhibit steam, cooking odours and heat from diffusing into these zones. Traditionally, ventilation requirements for catering establishments were estimated according to the type of catering practised and the volume of the kitchen. However the rate of of air removal from a kitchen depends upon the sizes, efficiencies, locations and typical usage patterns of the catering appliances installed (see Table 8). Therefore bespoke ventilator hoods are desirable so that only the minimum amount of air necessary is withdrawn from above a certain appliance or group of similar appliances.

TABLE 8

Recommended exhaust air-flow rates from the immediate vicinities of various items of fully-operating catering equipment (CIBSE, 1985).

Appliance	Exhaust air-flow rate required when the stated appliance is fully utilised, ($m^3 s^{-1}$)*
Bains-marie	0.20
Sinks for sterilising utensils	0.25
Grills	0.25-0.30
Steam cookers	0.30
Boiling pans	0.30
Pastry ovens	0.30
Ranges	0.30
Fish fryers	0.45
Salamanders and steak grills	0.45

* Usually these values should be reduced by one-third during cold weather.

One of the most common causes of energy-wastage in a kitchen is the employment of a ventilation system, which is not (or cannot) be controlled accurately to meet the instantaneous ventilation requirement (e.g. see Appendix 1). The latter changes significantly throughout the working period due to the intermittent nature of the cooking activities. Failing to turn down (or switch off) the ventilation (automatically or manually) during periods when equipment is idling or dormant serves to increase operational expenditures on space-heating and electricity. To help overcome this, it is desirable to use either (i) a variable-speed control for the ventilation blowers, or (ii) a multi-blower system (i.e. where three or four small blowers can act independently in parallel instead of one large one) so that the air-flow through the building can be altered appropriately. This should enable significant energy savings to be achieved, e.g. if exhaust air-flow rates are reduced by 50%, the electricity requirement of the associated blowers will decrease by a factor of eight. However, during cooking, exhaust air velocities should be maintained above 7.5 ms^{-1} so that the rate of dirt settlement on the cooker hood is minimised, and a means fitted for routing condensate away from the associated metal surfaces.

A large proportion of the total energy expended within a typical British kitchen is for heating and ventilation (see Table 9). Unfortunately, high ventilation rates are usually required (e.g. see Table 8), because most cooking appliances are poorly insulated and/or not used in an energy-thrift manner. Sixty air-changes per hour have been observed (O'Brien, 1981), and Avery (1985) reported that often 30 and 20 air changes per hour prevail in small and large kitchens respectively, when less than half of these rates of ventilation would suffice. Many old-fashioned cooker-hoods (which are still in use) open directly to the ambient environment and so warm air is lost from the kitchen without any attempt being made to reclaim any of its potentially-recoverable heat. Consequently heating demands are higher than they need be. Therefore it is desirable to employ ventilation systems which attempt to satisfy the demand for high airflow rates only in the immediate vicinity of heat-liberating equipment without exhausting large quantities of relatively uncontaminated air from the rest of the kitchen. Unfortunately, for the successful operation of a simple re-circulatory ventilation system, which (when appropriate) reduces the ventilation rate, frequent cleaning of the associated contaminant-removal equipment (e.g. carbon filters) is needed. However, 'compensated air make-up ventilation hoods' (e.g. see Fig. 1) may be employed to draw air from an adjacent dining area and the ambient environment as well as from above the catering appliances, in order to achieve exhaust flow rates which are sufficient to prevent excessive deposition of grease and other muck on the associated ducting, instead of sucking out only warm kitchen air. Consequently the space-heating demand of the kitchen is reduced : manufacturers usually claim pay-back periods for such systems of about two years (Stott-Benham Ltd., 1985). Alternatively, 'side-pieces' (see Fig. 2), which effectively join cookers to their ventilation hoods, may be installed so that lower volumetric air-extraction rates and

TABLE 9

Comparative energy consumptions of the various processes involved in the operation of a typical catering kitchen in the UK.

Process	Percentage of total annual energy expenditure in the kitchen *
Storing, preparing, cooking and serving the food	30 - 50
Heating and ventilating the kitchen	25 - 40
Lighting the kitchen	10 - 15
Miscellaneous (e.g. dish-washing and refuse-compacting machines	< 20

* These values have been derived from studies concerning British kitchens by Lawson (1983), Conway (1985), Sutcliffe Ltd. (1986) and Batty et al (1987). They are inappropriate for the food-service sectors of many other nations mainly because of culinary, climatic and energy-management differences.

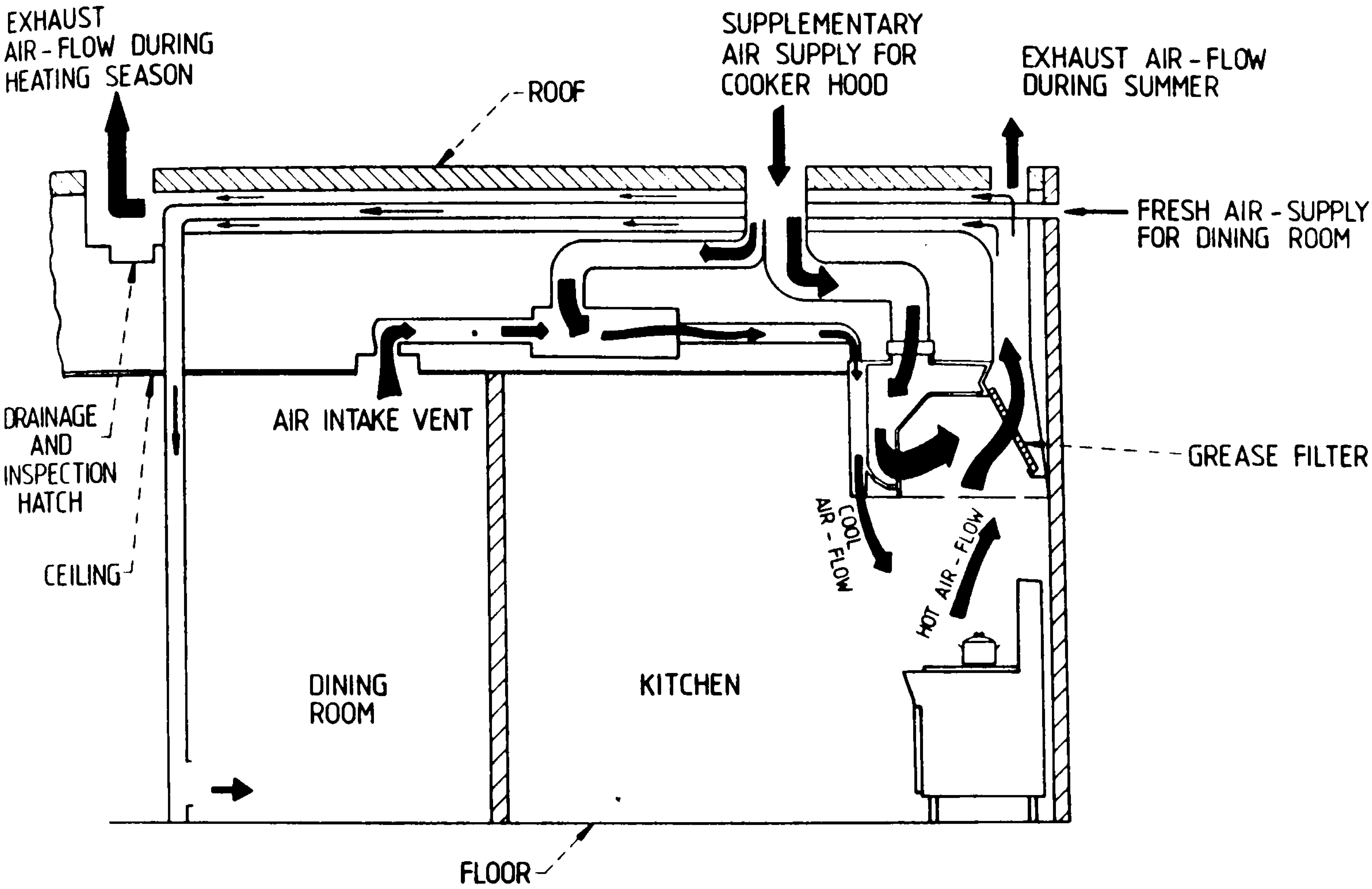


Fig. 1 A schematic representation of a kitchen ventilation system, which (i) satisfies exhaust air-flow requirements by utilising fresh air and stale air from the dining room as well as from the kitchen; and (ii) pre-heats the fresh air supplied to the dining room (when required) by extracting heat from the air leaving the kitchen via the cooker hoods. (The dimensions of the ceiling to roof separation are exaggerated in the drawing, relative to the room height in order to illustrate more clearly the ventilation system).

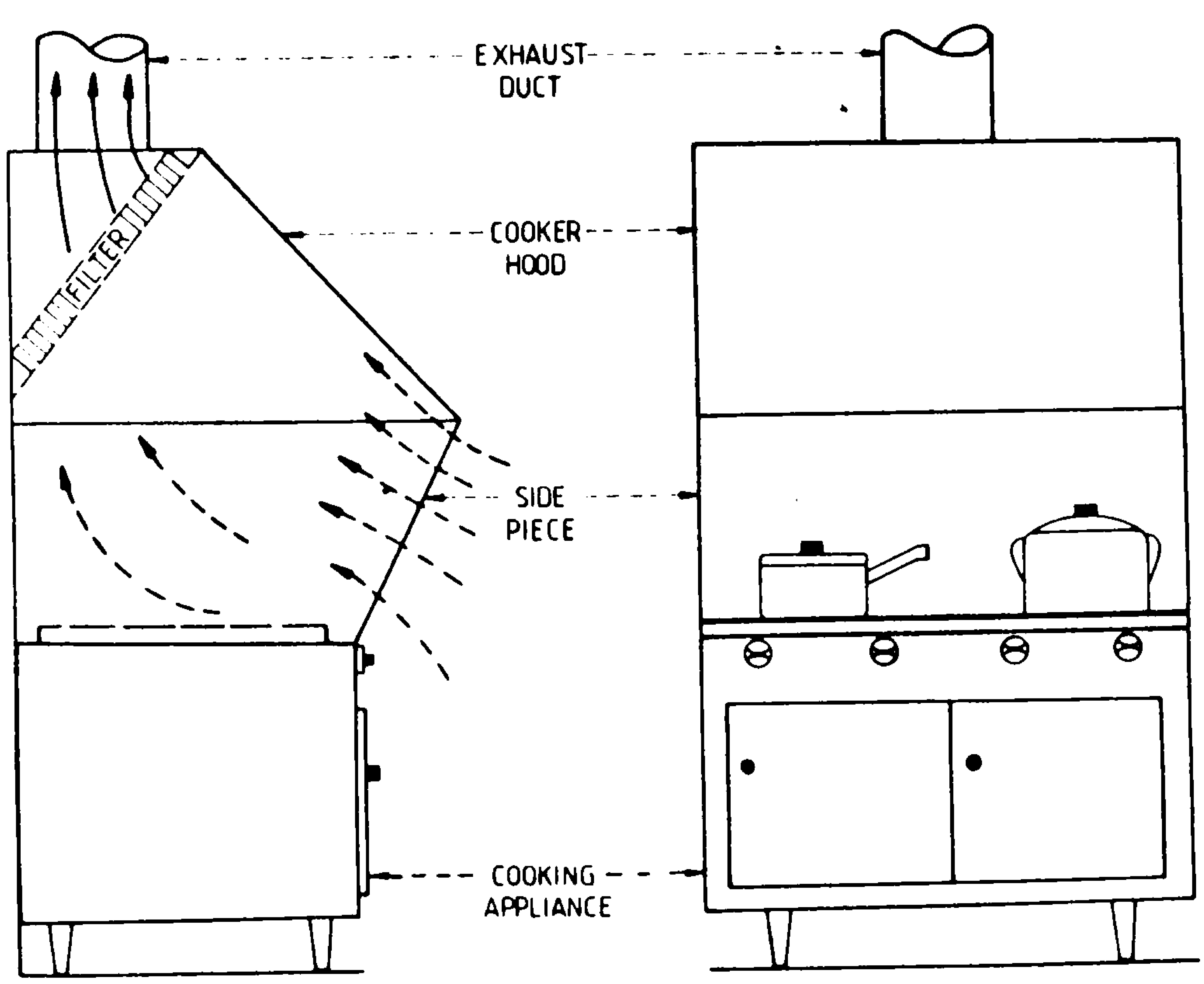


Fig. 2 Schematic side and front elevations of a cooking range, which is connected to its ventilation hood via transparent plastic side-pieces (Greenheck Fan Corporation, 1981).

fan-power demands can be achieved (Greenheck Fan Corporation, 1981). The visual and cleaning problems posed by the presence of the side-pieces may be overcome by using an air-curtain (which is generated by auxiliary air blowers attached to the ventilation hood), although a corresponding energy penalty must then be payed. Such techniques attempt to ensure that contaminated air, arising from the food being cooked, is extracted without exhausting large quantities of relatively clean air from the kitchen. Usually, side-pieces are cheaper and more effective, especially in poorly-designed kitchens where through draughts are excessive. (Transparent toughened-glass ones can be fitted if desired).

Unfortunately kitchen staff often rely on cooking equipment for heating their working environment. For example, gas hob burners are sometimes switched on at the start of the working day, and allowed to remain on throughout this period, in order to heat the kitchen. (However, such equipment is intended for heating food and not for space-heating). Thus an acceptable indoor air temperature is produced in an energy wasteful and often uncontrolled manner.

Appropriately-sited air-extraction blowers, and a rapid-response heating system consisting of an air heating facility for controlling the thermal environment of the storage, preparation and dining zones, together with 'high-level' radiant heaters for the cooking area are usually desirable. Kitchens which have high ceilings may be fitted with supplementary de-stratifying fans, so that space heating expenditures may thereby be reduced. Also the recommended use of summer and winter uniforms (of low and high thermal resistances respectively) for catering staff may be advantageous, provided that the relatively light-weight summer clothing incorporates appropriate ribs of insulant to protect, in particular, the arms of those who use the cooking appliances. When compared with other worker-pacifying techniques, which attempt to motivate operatives to maintain production during thermally-uncomfortable conditions (such as providing refrigerated water for drinking and permitting gas-fired hobs to be used for space heating), the implementation of such a policy is relatively inexpensive in energy terms.

Waste-Heat Recovery and Environmental Cooling

Once the design of a building's structure and its environmental-conditioning system have been decided, the feasibilities of using energy-recovery systems (e.g. heat exchangers, heat pipes and heat pumps) to extract heat from the outflows of warm air and water from the kitchen should be assessed. This reclaimed energy may then be utilised for heating the kitchen (and/or rooms adjacent to it), or for pre-heating hot water prior to its entry to the boiler (Tompsett, 1979). However before contemplating the installation of any means of recovering what would otherwise be wild heat, it is particularly important to ensure that the following higher priorities will be satisfied:-

i) Energy-efficient catering techniques only will be practised.
ii) All the equipment will operate at high efficiency.
iii) The ventilation rate can be adjusted to meet the actual ventilation requirement for each work-zone within the kitchen.
iv) An effective thermal barrier exists between the dining room/servery and kitchen (e.g. by separating door(s) closing automatically after the traffic has passed).
v) The hot-water system is sized correctly. A comprehensive survey (Jones 1983) of restaurants, hotels, schools, hostels, offices, and stores revealed that the sizes of the gas boiler plants and associated water-storage systems, which were installed for water heating, were often too large. Boilers were up to eleven times oversized and storage capacities up to nine times too large.

Conway (1985) reported that about 40% of the heat generated within a kitchen was exhausted via its ventilation system. Thus considerable savings may be achieved if heat, that would otherwise be wasted, is reclaimed from the air withdrawn by cooker-hoods (which usually has an average temperature of $35 \pm 5\,^{\circ}C$). Interest among manufacturers of heat exchangers in reclaiming heat from catering facilities is increasing. For example, a heat-recovery system incorporating heat pipes to extract energy from the exhaust air-flows of a kitchen, associated with a motorway service-station, achieved a reduction in the space heating requirement of 50% (Thomas, 1984). Subsequently space heating was only necessary during early morning periods. A Department of Energy Demonstration Project (Anon., 1984) has been instigated for an educational catering-facility, which employs a closed loop air-to-glycol/water heat-recovery system (see Fig. 3). Initially a pay-back period of about 3.5 years was predicted, but mainly because of (i) the inconsistent manner in which catering students use the kitchen, and (ii) the need to optimise the operation of the programmable washing-facility for the heat-exchanger coils, a revised pay-back period of more than six years appears probable. Nevertheless, it is considered that this type of system would offer shorter pay-back periods when installed in commercially-operated catering establishments, where working activities are more consistent.

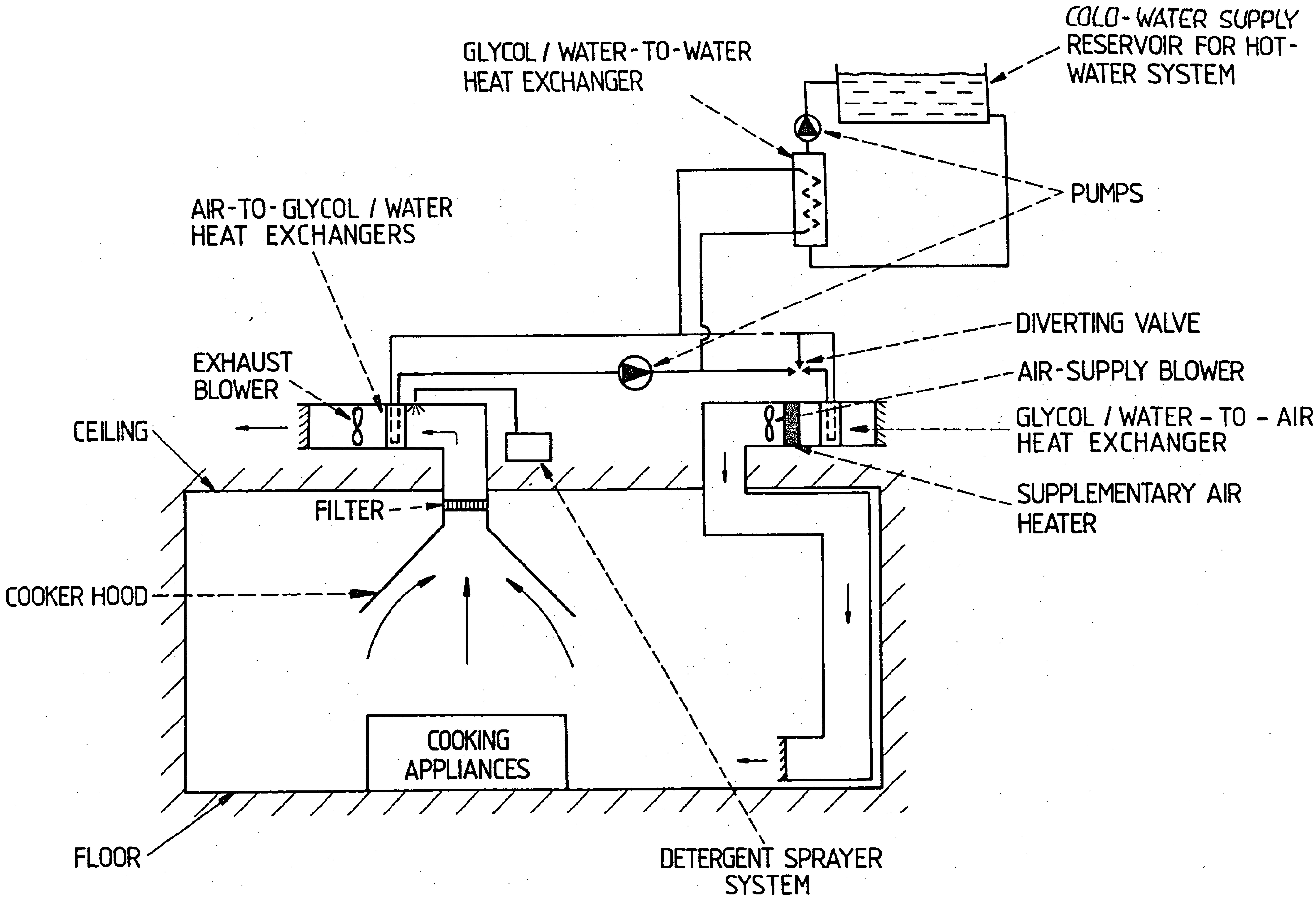


Fig. 3 Schematic representation of a heat-recovery system fitted to the kitchen of the Department of Hotel, Catering and Institutional Management at Plymouth College of Further Education (adapted from Anon., 1984).

The commercial feasibilities of providing environmental cooling and dehumidification in British kitchens may be improved, if operational expenditures are reduced by reclaiming heat wherever commercially justifiable (e.g. waste-heat recovery systems could be used to reclaim heat otherwise lost via cooker hoods, waste-water outflows and the vents of gas and, where appropriate, electric ovens). Although costly, attempts to reduce the characteristically-high air temperatures and humidities within kitchens from, say, 35 to 25°C and 85 to 70% respectively, during high demand periods in hot weather, will aid productivity, help prevent accidents occurring and reduce the need for workers to take rests while nominally on duty, as well as encourage them to be more amenable to energy-thrift. Research shows that (i) kitchen staff are 10-25% more productive if their working environment is air-conditioned during summer, and (ii) 15% more useful work is performed when the mean indoor air temperature is maintained at 24°C instead of 32°C (Avery, 1985).

Cost effectiveness may be improved if chillers are employed which have integral heat-recovery systems for their associated compressors and condensers (Kumar, 1979). However the installation of alternative or supplementary cooling systems, which permit reductions in electricity expenditure compared with conventional vapour-compression chillers, deserve to be considered for large kitchens. For example, cold water (stored at say 7 °C in large tanks beneath the insulated floor of a kitchen) may, when appropriate, be circulated through finned collectors in the kitchen to obtain cooling and dehumidification. The return flows of water may then pass through subterranean heat-exchangers, which promote heat transfers from the water to an organic material of low freezing point. Consequently low-grade waste heat is extracted from the water which is then returned to the storage tanks. During periods when cooling is not required, the temperatures of the water and the phase change material will gradually decrease to that of the surrounding earth and so the depth at which these media are stored affects the system's efficiency. Alternatively, means for achieving evaporative cooling of kitchen roofs may be utilised. These systems are well suited to poorly insulated catering establishments with roofs which tend to reach high temperatures (i.e. above 30°C) during summer. Typically, during the first part of the working day, conditions in such a kitchen become increasingly uncomfortable, because the rate of heat loss via the roof diminishes as its temperature rises. Thereafter if the roof attains a mean temperature of more than about 40°C, direct radiative heating of the staff within the kitchen becomes a significant and uncomfortable feature. In order to avoid these problems, simple thermostatically-controlled external sprayers, which (usually for intermittent periods of less than one minute) sprinkle water on the outside surface of the roof when its temperature exceeds approximately 30 °C, may be fitted (Patterson, 1981). Although data concerning British kitchens, which are cooled via these techniques, are scarce, it is likely that electricity bills will be reduced substantially, when compared with expenditures for driving the compressors and blowers associated with conventional air-cooling chillers, because 'maximum demand' charges will be less.

Lighting

The levels of illumination which are necessary within a catering establishment vary considerably (see Table 10). It is desirable to make full use of natural (i.e. free) daylight, and to ensure that the internal surfaces of the floor, walls and ceiling have reflectivities of about 0.3, 0.5 and 0.9 respectively (Lawson, 1980). Dark shadows must not be created because cleaning and inspecting operations can then become less effective (e.g. sufficient illumination should be provided above sinks so that users' shadows do not occur and so hinder activities). Conversely because of the high reflectivities of stainless-steel, aluminium and chromium-plated steel surfaces within the kitchen, over-illumination is undesirable — it often results in glare, which can be dangerous and tiring for the operatives. Thus careful consideration should be given to the positions of the cooking appliances and serving equipment relative to those of the luminaires, e.g. cooker-hood canopies and ducts must not inhibit the illumination of hobs.

Flush fitting, high efficiency, fluorescent tubes should be used in preference to conventional incandescent lamps, because electricity expenditures will then be reduced - typically by a factor of about four (e.g. see Table 11). However, the aim of utilising high-efficiency lighting may have to be compromised in the servery where the colour-rendering and food-warming capabilities achieved with different lighting systems become more important to the fundamental process of selling food. Nevertheless, external lighting and security-lighting may be achieved efficiently by using high-pressure sodium lamps. Regular maintenance of lights (e.g. cleaning the shades and dust-covers, and replacing 'starters' and tubes) is essential if a high luminous efficacy is to be maintained : therefore easy access to the lighting must be provided.

When a kitchen lay-out is being designed to fit into an existing facility, there are several methods available for limiting lighting costs:-

* Use more efficient means of lighting (e.g. replace incandescent lights with fluorescent ones).

* Avoid excessive ilumination — where feasible reduce it from previous levels (e.g. see Table 10). If fluourescent tubes are to be removed, ensure that their ballast inductors are also disconnected because otherwise these will dissipate heat when energised.

* Introduce zonal lighting for the various work activities, so that high levels of illumination are only used where required: this will probably require the installation of more light switches.

* In zones where the demand is irregular, or where precision work is carried out, provide local lighting that can be dedicated to each specific activity.

* Fit a means of controlling automatically the lighting levels for

outside normal working periods: e.g. install time-switches or external photocells to switch-off security lighting as soon as natural lighting becomes significant.

* Raise the reflectivities of some internal surfaces (e.g. by fitting smooth light-coloured tiles on walls).

* Train staff to (i) use and maintain the new lighting systems properly, and (ii) make sure that they switch-off lights whenever feasible.

Lighting constitutes a highly expensive form of heat input to the upperstrata of the kitchen. This may be slightly beneficial during cold weather, but it increases the air conditioning load in summer. Unfortunately the implementation of strategies to remove this heat input, by extracting air over the luminaires during warm conditions, may be discouraged by the problems caused by the accumulation of grease and other airborne particles (produced within the kitchen) which would then occur on the luminaires.

TABLE 10

Recommended illuminations within catering establishments (adapted from: Smith, 1978; Lawson, 1980; O'Brien, 1981; Avery, 1985; and Kotschevar and Terrell, 1985).

Zone	Approximate illumination, (lux) *
Corridors	100
Dining rooms	50 - 250
Stores	150 - 250
General cooking areas	300
General preparation areas	400
Dish-washing zone/Servery	400
Precision-work zones	600

* These values apply for the usual activities undertaken. For cleaning purposes, illumination levels should be raised to at least 350 lux.

TABLE 11

Typical efficiencies for commonly-employed lighting systems (Smith, 1978).

Lamp	Power input (W)	Luminous efficacy ($lm\ W^{-1}$)	Overall efficiency (%)
Incandescent	100	7–13	2.5–4.5
Fluorescent	40	30–54	8.5–15.0
High-pressure sodium (for outdoors)	400	72–103	14–20

Further Energy-Saving Techniques

Electricity is the most expensive form of energy used by catering establishments. Therefore it is desirable to smooth-out (i.e. lower) the peaks of electrical demand, and ensure that the kitchen's overall power factor is maintained close to unity. Opportunities exist for reducing electricity bills by employing only relatively efficient electric motors. For example, three-phase, single-phase capacitor, or brushless d.c. motors are usually recommended for air-moving purposes; whereas the use of small portable a.c. 'cooling' fans should be discouraged, because about 85% of the energy supplied to them is wasted as heat. To install motors, compressors and heaters with power ratings that are greater than necessary (based on the idea that they will be more reliable and function over a longer period) is unwise. Electrical equipment should always be operated as near to its full design load (which usually corresponds to achieving the maximum efficiency and power factor for motors) as is feasible. Furthermore, in very large kitchens (e.g. a cook-chill catering facility, which supplies several finishing kitchens) reclamation of heat from large equipment may be worthwhile.

The installation of an automatic power-factor correction facility, to ensure that the establishment's overall power factor is optimised regardless of the demand placed on the kitchen, will not usually be justifiable economically, unless the kitchen uses mainly electrical equipment which operates consistently with an overall power factor of less than about 0.8. Thus it is desirable for caterers to demand information from manufacturers concerning the likely power factors, as well as the typical efficiencies and power ratings, of the appliances that they have fitted into their kitchens (e.g. induction hobs operate at a power factor of less than 0.7 unless integral corrective capacitors are installed). Then estimates of the probable variations in electrical demand (in kVA) for the kitchen can be predicted at the design stage of the kitchen.

Reducing electrical loads during peak-demand periods (which usually occur 2-4 hours before, as well as during, the periods when the meals are served) is difficult. If feasible, high energy-demand equipment (e.g. large ovens, fryers and hobs) should be used sequentially rather than simultaneously, and energy-intensive operations (e.g. baking and dish-washing) should be carried out during non-peak hours. It is advisable to start the day's baking with foods that require the lowest oven temperatures, and/or the longest cooking periods, and to stagger essential pre-heat periods. Furthermore, the use of off-peak electricity to reduce annual energy bills is expedient. For example, timers should be fitted to dish-washing equipment which can then be operated automatically during the night. (By means of similar controls the internal air temperatures within frozen-food stores may be lowered to say -25 °C in order to achieve a lower energy consumption for refrigeration, at say -20 °C, during the daytime).

Automatic 'load-shedding' (i.e. where non-essential loads are switched off for a few seconds or minutes to ensure that the electrical demand does not exceed momentarily a certain limit, and thereby cause the kitchen's electricity consumption to be charged entirely at a higher tarriff) is feasible. It is possible to practise load shedding with devices such as ovens, griddles, mixers, ventilation blowers, compressors and dish-washers, but fryers, and steam-raising cooking equipment should only be switched off for very short periods. Pay-back periods, for load-shedding control systems fitted to kitchens which operate mainly electrical equipment, are usually less than three years (Scriven and Stevens, 1982).

Finally, utility meters should be installed to monitor energy and water/steam usages within kitchens. These will permit catering managers to evaluate simple energy-efficiency ratios (e.g. energy consumption per menu) and then assess their endeavours to achieve energy-thrift, relative to previous attempts made by themselves and their counterparts in other similar kitchens. Unfortunately, at present, energy-consultants usually find that the task of improving the operational efficiency of a food-preparation facility is thwarted by the absence (or deficiencies) of previous records concerning energy consumptions for the establishment (Batty et al, 1987).

II. ACHIEVING THE OPTIMAL LAY-OUT FOR A KITCHEN

The relative positions of catering appliances, storage facilities and work zones affect each kitchen's effectiveness. Catering establishments are usually more labour-expensive than they need be, due to their poor internal lay-out (Sutcliffe Ltd, 1985). Essentially, kitchens which have not been well-designed ergonomically tend to be characterised by low operational efficiencies, because they are labour intensive. As well as inducing fatigue, inappropriately-positioned and wrongly-sized facilities can cause workers to operate with a greater risk of slipping and/or falling over, so possibly spilling food on to the floor, which then needs to be cleaned (i.e. both time and effort are wasted). Therefore it is desirable that the implications of any proposed lay-out plan for the kitchen on the establishment's annual expenditures on labour and energy should be considered at the initial design stage.

The size of a kitchen should depend largely on the amount and capacities of the necessary catering equipment to be installed. Typically, kitchen staff spend 10-20% of each working day walking between work-zones. Unfortunately over-sized kitchens are not uncommon, yet these lead to excessive expenditures of energy and time by staff, because the distances travelled within them are too great (Montag and Tamashunas, 1969). Also such kitchens cost appropriately more to build, heat, ventilate, cool, illuminate, clean and maintain. The combination of high capital expenditure and excessive running costs makes these kitchens unattractive economically.

A catering establishment which serves simple one- or two-course set meals, mainly prepared from frozen convenience foods, requires less equipment, labour and work-space than a traditional kitchen serving four- or five-course meals selected by customers from an extensive menu. However, existing kitchens are often overcrowded with equipment, which is rarely fully utilised. If this has been installed at the expense of work-space, then staff will be hindered and operational efficiencies may be low as a consequence. Such under-sized kitchens can be as expensive to operate as over-sized ones, as well as possibly being more dangerous.

Fundamentally, the kitchen lay-out should ensure that staff only need expend the minimum amount of effort to achieve the desired results. For example, the kitchen, servery and dining areas should be constructed on a single level, and wherever activities can be performed with less fatigue while sitting, employees should be provided with seats. Ideally, appliances, stores, sinks, cupboards and work surfaces should be arranged so that:-

i) the necessity to retrace one's steps when performing kitchen activities is minimised; and

ii) the movements of individuals entering, leaving or passing through the kitchen do not interfere with one another or the work being carried out therein.

Factors such as the incorrect positioning of sinks, work-surfaces and lighting and the storage of heavy items above head-height or below knee-height can, over long periods, cause excessive mental and physical fatigue. This often leads to mental stress (resulting in headaches, impaired alertness and carelessness) and absenteeism, which can jeopardise both the safety of operations carried out and the quality of the food served. Thus a kitchen should be designed with a view to maximising its operational efficiency.

Unless the kitchen lay-out has been planned properly, it is likely that staff will inadvertently obstruct one another and sometimes be required to travel devious paths to obtain food, equipment and utensils. Ample space must therefore be provided for kitchen activities in accordance with the number of meals served per dining period and the type of catering practised (see Figs. 4 and 5). However there is no unique method for determining the optimal space requirement for a kitchen.

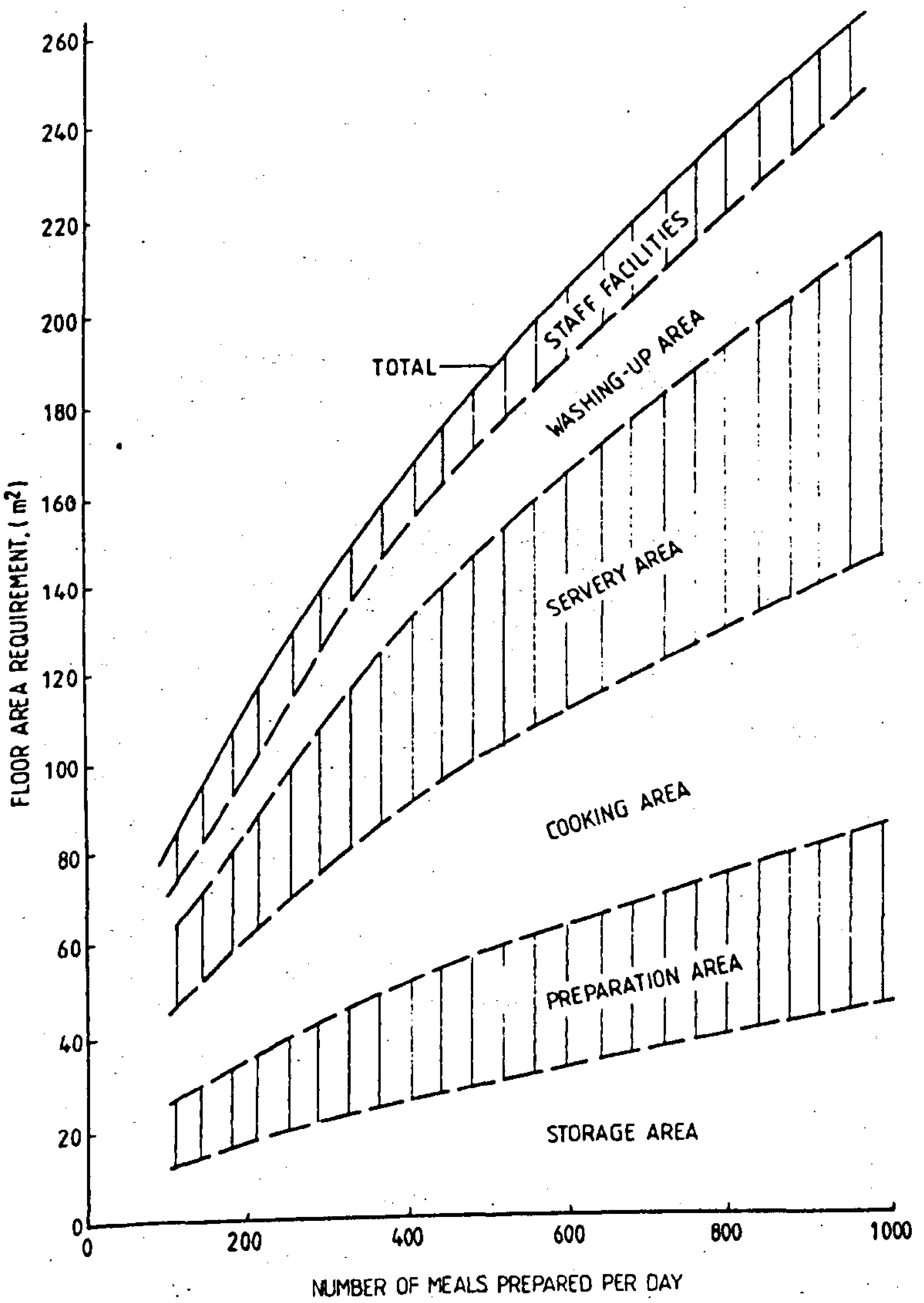


Fig. 4 The approximate relationships between the space requirements of the various work zones within a traditional kitchen and the number of meals that it serves per day (Lawson, 1980).

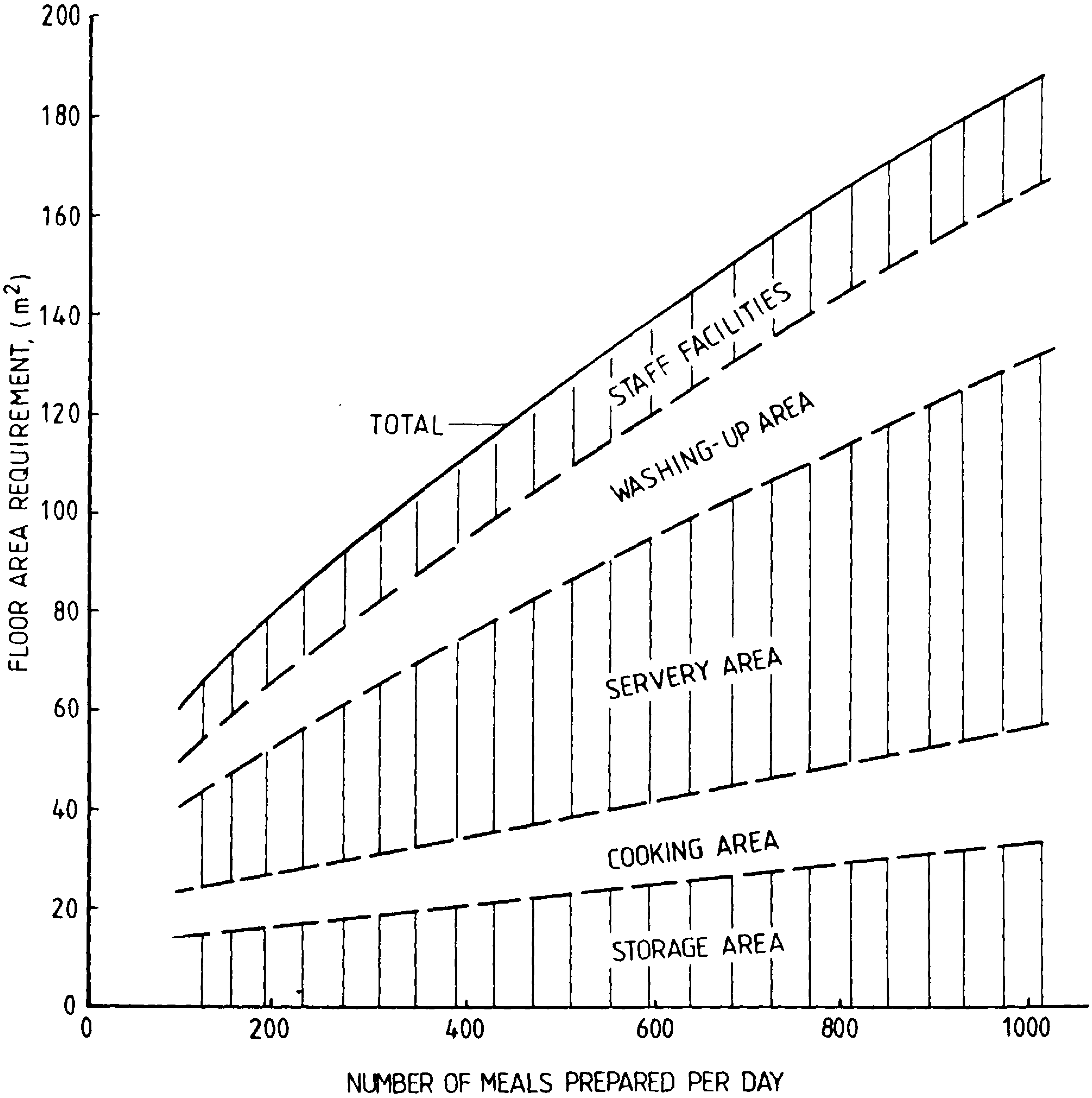


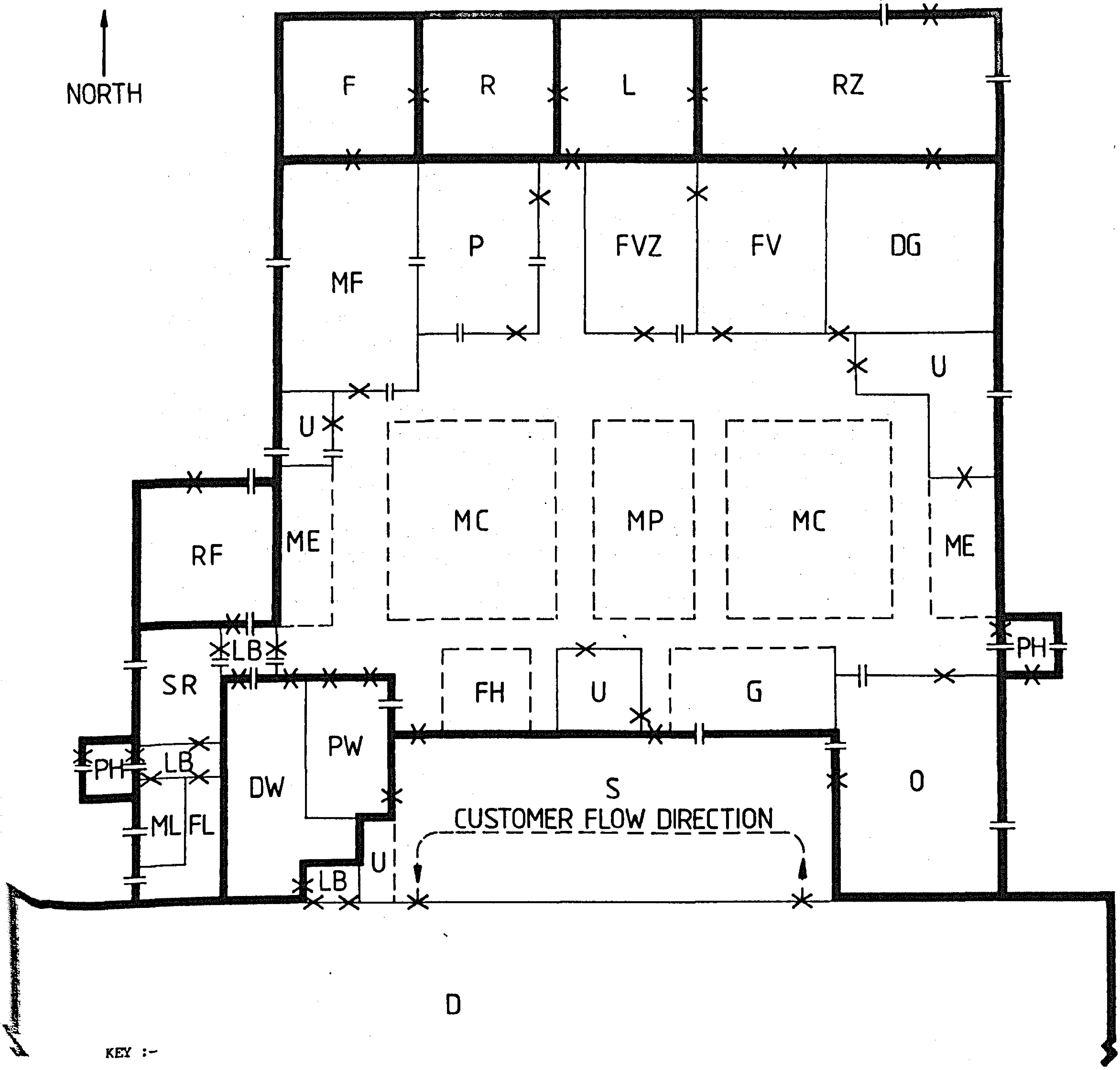
Fig. 5 The approximate space requirements of the various work zones within a finishing kitchen (Lawson, 1980).

Each work zone within the kitchen should be assessed separately and the necessary appliances and utensils located logically within it. Work zones which have the greatest mutual interaction should be sited contiguously (e.g. see Fig. 6). If the work activities are considered in their logical sequence (i.e. receive, store, prepare, cook, serve and clear away), it becomes evident that the primary work-flow, or traffic paths, should always run in parallel (e.g. see Fig. 7), and where cross-flows occur, extra space should be allocated. Failure to do so will probably result in an unnecessarily high frequency of accidents, employee dissatisfaction and energy wastage. Usually one-way traffic routes within the kitchen (which simplify analysis at the design stage) are not adopted in practice, because each worker tends to choose the shortest route to his immediate destination. Nevertheless, where feasible, exits and entrances to the work-zones within kitchens should occur through different doors, in order to avoid mishaps.

Work-study reports prepared for similar existing kitchens provide a useful guide for the designer who tries to achieve an optimal lay-out. If he is aware of the inherent failings of other kitchens, attempts can then be made to plan a kitchen which is more convenient, efficient and cost-effective. Various techniques, such as CPA, PERT, travel analysis and activity-sampling analysis (Peddersen et al, 1973; Kazarian, 1979; Kotschevar and Terrell, 1985), can be employed to examine and then optimise the methods and movements involved in catering work, but although kitchen designers, planners and managers are often aware of these techniques, such methods are implemented only rarely.

When undertaking a work-study assessment of the operation occurring within a kitchen, the opinions of some of the more knowledgeable members of the catering staff should be sought. Generally, the opinions of chefs and catering managers are particularly valuable when designing kitchens (Furnival, 1977; Kazarian, 1979). However, in order to obtain quantitative data for optimisation purposes, the typical daily activities and travel patterns of each operative should be observed and recorded (e.g. see Table 12). From this, any excessive distances between items of equipment frequently used in sequence, inordinate periods spent moving foods or traversing walk-ways, and the inadequacies of an individual's performance (especially with regard to energy use) can be identified more easily.

Once all the data for a time-and motion study have been collected, optimal locations for each work-zone and its associated equipment can be determined. For this assessment, consideration should be given to the labour costs incurred in the kitchen (e.g. it is more logical to site a mixer closer to the head chef than to one of his lower-income junior cooks, assuming that each on average uses the mixer the same number of times per day, because the head chef will then waste less time and effort walking to and from that appliance). Productivity indexes, with respect to expenditures of time and effort, may be deduced (e.g. see Table 12). By assessing how these vary among the



KEY :-

: Wall designed to achieve a high degree of thermal and/or acoustic insulation.
: Internal wall designed to provide a high degree of thermal isolation.
: Designated boundary for groups of equipment.
= : Sealed window(s).
x : Automatically-sliding door.

D : Dining room.
DG : Dry-goods store.
DW : Dish-washing zone.
F : Frozen-food store.
FH : Food-holding equipment in kitchen.
FL : Females' lavatory.
FV : Fruit and vegetable store.
FVZ : Fruit and vegetable preparation zone.
G : Rapid-cooking equipment.
L : Larder.
LB : Lobby.
MC : Main cooking zone.
ME : Mobile equipment parking-bay.
MF : Meat-and-fish preparation zone.
ML : Mens' lavatory.
MP : General preparation zone.
O : Administrative office.
P : Pastry-preparation zone.
PH : Porch.
PW : Pot-washing zone.
R : Refrigerated-food store.
RF : Refuse store.
RZ : Receiving zone.
S : Servery.
SR : Staff-relaxation room.
U : Utensil store.

Fig. 6 Schematic plan of a traditional kitchen (associated with an industrial catering facility), designed primarily from an energy-thrift perspective.

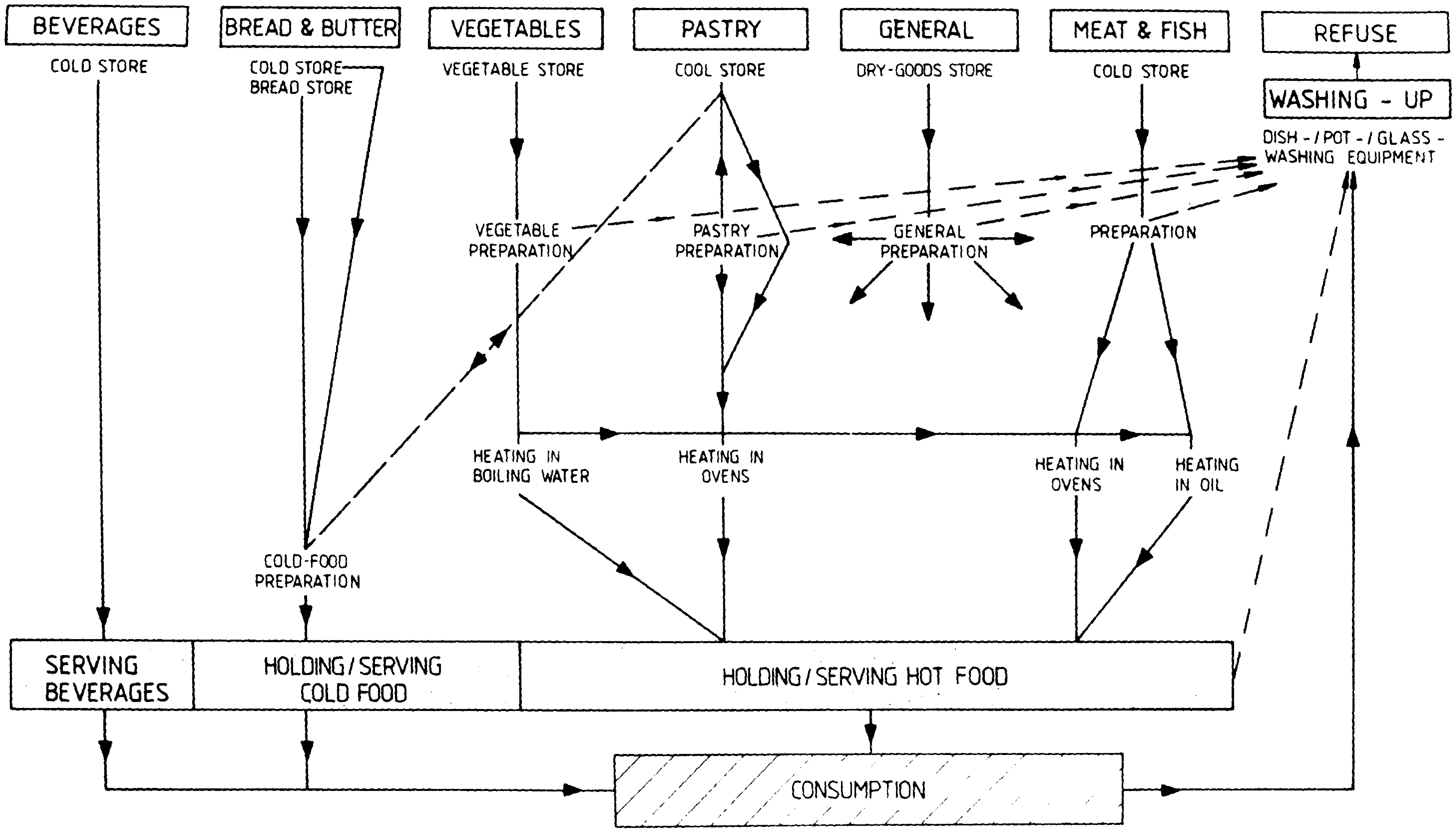


Fig. 7 The primary work-flows in a traditional kitchen.

TABLE 12

An Activity Table for a Kitchen Worker Having a Labour-Cost Index* of 75% when Preparing a Small Number of Set Meals, over a Nominal 15 Minute Period.

DESCRIPTION OF ACTIVITY CONSIDERED		DISTANCE TRAVELLED BY WORKER, ASSOCIATED WITH THIS ACTIVITY, (m)	TIME TAKEN FOR THE CONSIDERED ACTIVITY, (s)	OBSERVERS' COMMENTS
Ignite gas supplies associated with griddle and hob.		4	15	Hob burners ignited approximately 230 seconds too soon. Griddle-lid not used
Collect fish from refrigerator and take to work-surface.		10	26	Inadequate gap available for the cooling environmental air to flow around the condenser coils at the rear of the refrigerator.
Prepare fish.		2	120	No seat available for worker.
Collect frozen vegetables.		17	38	Door of frozen-food store remained open whilst the food was collected.
Collect pans.		10	25	Pans were positioned too far away from hob and work-surface.
Fill pans with water and place on hob.		6	30	Cold-water introduced into pans instead of hot water. Lids not in place on pans during pre-heating.
Collect the containers in which the food (once it is cooked) will be placed.		8	20	Conveyance distance was excessive.
Prepare griddle and position fish on it.		6	55	Approximately half of the cooking surface remained unused.
Clean the used work-surface.		8	45	Highly dependent on worker's attitude.
Place vegetables in pans.		5	10	Lids not placed on pans during cooking operations.
Collect trolley from parking bay and load with empty containers		24	60	Return journey complicated due to indequate width of even the most suitable gang-way.
Check food. Turn fish over on the griddle.		2	80	Griddle lid still not used.
Unload food into containers and switch off cooking equipment.		4	160	One hob-burner not switched-off.
Deliver containers to servery, place them in food-holding equipment and return the trolley to the parking bay.		26	165	Unloading of trolley made awkward due to lack of space.
Total Activity		132	849	Inefficiency due to poor kitchen design and energy-profligate operative
Productivity Index for total activity**	Per metre travelled	0.568		Could be increased by at least 8%
	Per minute expended		0.088	Could be increased by at least 13%

* The cost of employing the worker divided by that of the most highly-paid worker in the considered kitchen, (%).

** The labour cost index divided by the total distance travelled or time expended by worker.

kitchen staff, management will be able to determine appropriate target values for improving their establishment's operational efficiency.

Avery (1973) reported some observations concerning the catering staff in a hospital kitchen (which provided 250 meals per dining period). It was to be refurbished to satisfy twice this demand. The sum of the mean distances travelled by all the kitchen staff with the original lay-out amounted to 30.6 km per day. Subsequently two new lay-outs were proposed independently. These were based on (i) conventional design methods and (ii) the conclusions of a work-study investigation, which had attempted to determine the optimal kitchen lay-out. Results indicated mean daily cumulative distances (for all kitchen staff) of 55.0 km and 28.2 km for designs (i) and (ii) respectively. Thus by implementing the conclusions drawn from the work-study report, a reduction in the distances travelled by operatives in the kitchen was achieved despite a 100% increase in the number of meals being produced per day!

In order to achieve an improved lay-out, the operations involved in meal production must be analysed in detail. The use of facilities may be considered under three category headings:-

i) Receiving and storage facilities.

ii) Preparation and serving zones.

iii) The lay-out of catering equipment.

RECEIVING AND STORAGE FACILITIES

The amount of storage space required in a kitchen varies with the type and amount of catering practised, as well as with the frequency of food deliveries to the establishment. The energy-expensive trend towards the increased employment of frozen, processed convenience-foods in recent years has led to the capacities of of sub-ambient stores being increased, while those associated with conventional vegetable stores have declined. However, adequate and efficient storage is essential for the smooth running of any catering establishment. When menu planning and stock control are carried out via computer techniques, improvements in the kitchen's operational efficiency can ensue. Indeed, the future employment of computer systems in the catering industry will assist kitchen designers and facilitate much tighter management control of the overall operation, especially for CFP.

Fundamentally, the locations of storage areas should be decided as a result of analysing the requirements for:-

i) access and handling; and
ii) environmental control.

The unloading of food from supply vehicles as well as its weighing and transportation by kitchen staff to storage areas, should be capable of being accomplished relatively easily without kitchen operations being disrupted. If this is not achieved simply, workers will (i) tend to arrange unofficial yet readily accessible places, usually in walk-ways, where items can be stored temporarily; (ii) expend more energy subsequently moving them to their final storage areas, when it is convenient to do so; and (iii) in the meantime experience difficulties traversing the partially-blocked walk-ways and carrying out activities in the affected areas. Also, the external doors of the receiving area should be sized so that vehicles can be unloaded with the minimum of effort, and possibly an air curtain should be provided to inhibit infiltration of ambient air during unloading periods. The stores themselves should contain workspaces and be conveniently situated so that staff can locate, sort and collect the required items of food easily and rapidly, e.g. those items which are used more frequently should be stored between 0.7m and 1.5m above floor level (Douglas, 1979).

Sensitive controls of temperature, humidity and rate of ventilation for a storage zone are essential, because foodstuffs can decay quickly if their environment is unsuitable. It is particularly important to inhibit the ingression of sunlight and steam because there is an optimal combination of storage temperature and humidity for each type of food (e.g. see Table 13). Thus, because most of the kitchen is incompatible with the requirements for food storage, the construction of separate, well insulated, self-contained stores abutting on to the north and/or north-east walls (in the northern hemisphere) of the building, with sealed electrically-operated doors and balanced ventilation systems, is desirable. Interior lighting should be energised automatically only when someone is in the store.

Careful weighing of components is desirable if composite foods are to be prepared consistently. Also with such stricter monitoring, reductions in food wastages should be achievable. This may encourage the assessment and modification of recipes, menus and diets from an energy-efficiency perspective (Unklesbay and Unklesbay, 1980; Newborough and Probert, 1987). The allocation of a small area for weighing the food taken from storage areas should be worthwhile in a large kitchen. If one operative is responsible for the accurate weighing of all foods used before they are taken for cooking or serving purposes, financial savings should ensue, because (i) weighing food in individual work zones consumes the cook's time and would involve the presence of several scales placed on otherwise usable work-surfaces, and (ii) the likelihood of pilfering foods would be reduced.

TABLE 13

Desirable storage conditions for various foods (Pyke, 1974).

Type of stored food		Recommended storage temperature, (°C)	Recommended humidity within the store, (%)
Dairy produce	cheese	2	65 - 70
	butter	0 - 2	80 - 85
	milk	0 - 2	50 - 95
	eggs	-2 - 0	85 - 90
Fish	smoked	4 - 10	50 - 60
	fresh	0 - 4	90 - 95
	mildly cured	-3 - 1	75 - 90
Meat	bacon	1 - 4	85
	beef	0 - 1	88 - 92
	lamb	0 - 1	85 - 90
	pork	0 - 1	85 - 90
	veal	0 - 1	90 - 95
Fruit	melons	7 - 10	85 - 90
	apples	-1 - 0	85 - 90
	blackberries	-1 - 0	85 - 90
	cherries	-1 - 0	85 - 90
	peaches	-1 - 0	85 - 90
	pears	-1 - 0	85 - 90
	raspberries	-1 - 0	85 - 90
	strawberries	-1 - 0	85 - 90
Vegetables	new potatoes	10 - 13	85 - 90
	cucumbers	7 - 10	90 - 95
	old potatoes	3 - 10	85 - 90
	asparagus	0	90 - 95
	carrots	0	90 - 95
	cabbages	0	90 - 95
	cauliflowers	0	90 - 95
	celery	0	90 - 95
	lettuce	0	90 - 95
	spinach	0	90 - 95
	onions	0	70 - 75
	sprouts	0	90 - 95
	tomatoes (ripe)	0	85 - 90

In conventional kitchens which produce at least 50 meals per dining period, the storage facility should ideally consist of five main sections:-

i) a vegetable and fruit store;

ii) a store for dry goods (e.g. flour, sugar and dehydrated fruit);

iii) a sub-divided store for foods to be held at just above, and considerably below, 0°C;

iv) stores for utensils; and

v) a sub-divided refuse store.

Vegetable and Fruit Storage

Care must be taken to site these stores as close as is feasible to the receiving and vegetable preparation areas within kitchens, because vegetables (especially potatoes) tend to have relatively high densities and thus require large expenditures of human effort when being moved in typically required quantities. For example, personnel in a kitchen serving 600 meals at lunchtime usually have to transport and process about 0.5 tonnes of food. In large kitchens, the use of conveyor systems, wherever foods have to be transported over a fixed route should be considered (e.g. gravity-fed potato peelers). Because most fresh vegetables tend to dry out at above 12°C, and turn yellow/brown above about 20 °C, they should be stored in a cool, ventilated room at a relative humidity of at least 85% (see Table 13). The inlet and exhaust air-flow rates should be sufficient to ensure that about three air changes per hour ensue.

Storage of Dry Goods

Most dry goods (such as groceries) should be stored at 10-15°C, in a low-humidity environment which is ventilated at a rate of about two air changes per hour. To satisfy the daily requirements for commodities such as salt, spices, sugar and jam, it is often convenient to have a smaller 'daily issue' or 'cook's store', which is separate from the dry-goods store. Usually ventilated cupboards, situated conveniently in the kitchen and servery are sufficient, but the ingression of steam from the cooking and washing zones must be inhibited.

Cold Storage

This may take two forms: chilled-food stores and frozen-food stores. The former (i.e. involving refrigerators and cold rooms) should be used for perishable foods held temporarily at 0-5 °C and at about 80% relative humidity, whereas frozen-food stores are suitable for the prolonged storage of food at approximately -20°C. It is logical to site the frozen store at the rear of the cold room and thermally insulate both of them adequately so that the power consumptions of the associated compressors are kept low (e.g. see Appendix 2). A sub-ambient store of monolithic construction is desirable so that infiltration of warm air and moisture can occur only via its door (Brennan et al, 1976). The capacity of the cold-storage facility should be decided early in the design process: the need for other stores becomes less as the popularity of frozen foods increases. However, keeping foods at sub-zero temperatures for prolonged periods is very energy expensive and so frozen storage facilities should not be oversized.

Roussos (1984) reported that the rates of heat gain to cold stores via doors increased significantly with door height and period of opening (e.g. see Fig. 8). Thus it is desirable for the doors fitted to frozen-food stores to be no taller than they need to be. Sub-ambient food stores may be insulated effectively by injecting polyurethane foam into the cavities which isolate the cold environment from the kitchen. Specific attention should be given to the thermal design of the roof situated above the sub-ambient store, so that solar heat gains may be inhibited (e.g. a ventilated roofspace with a low-emissivity exterior surface is desirable). Generally, energy-thrift can be achieved if :-

i) The equipment is sited well away from windows and heat-liberating appliances (e.g. cooking systems, dish-washers and pipes carrying hot fluids).

ii) All food items are trimmed of inedible matter and contained in the least amount of packaging before they are placed on racks (not solid shelves) in the appropriate sub-ambient temperature environment. They should not be packed so closely as to inhibit convection completely within the store. Large stores should be fitted with blowers to circulate the cold air around the food containers.

iii) The surface area-to-volume ratios for the food containers placed in a cold store should be high to promote heat exchanges (e.g. the heights of frequently used containers should not exceed 50mm).

(iv) Preferably, 'reach-in' freezers should have individual sections, which can be used for storing different foods separately. It is wise to employ separate, labelled receptacles, each containing similar items, within large stores, so that only those which need to be accessed are affected significantly by the heat gains incurred

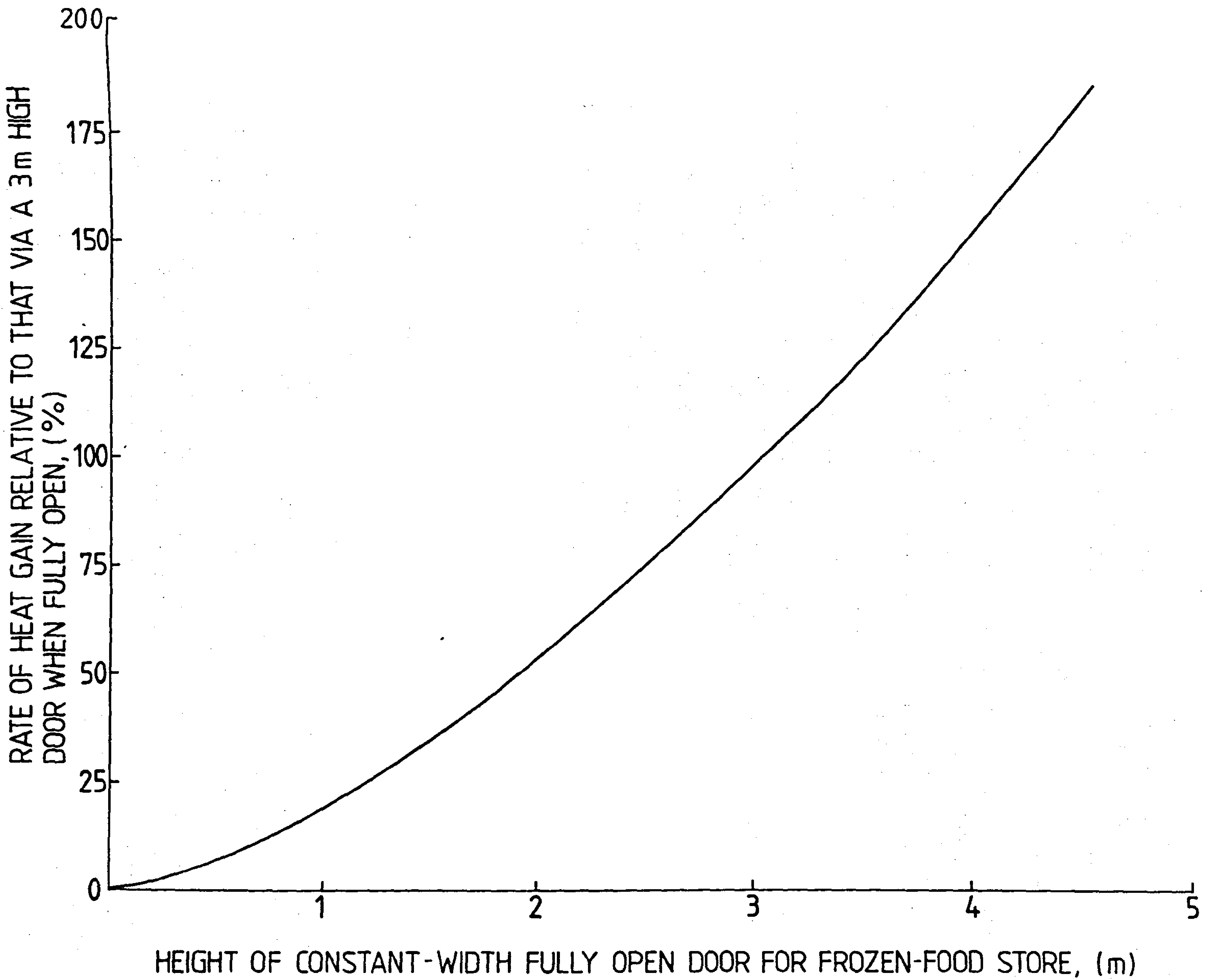


Fig. 8 The relationship between the rate of heat gain from the kitchen environment at 25°C) via a fully-opened 1.8m wide door of a cold-storage facility (which had an internal temperature of -30°C), and the height of the store's door (adapted from Roussos, 1984).

when the store is entered for the removal of some of these items.

(v) Equipment is fitted with self-shutting external doors, which switch-off the store's internal lights automatically. Preferably, walk-in stores should be fitted with transparent plastic strip curtains, to inhibit convective heat gains during the short periods when the doors remain open.

(vi) Equipment is defrosted (when necessary) manually or by re-circulating some of the otherwise wasted heat, emitted from the associated compressors and condensers, rather than automatically by internal heaters. (The internal temperature of the sub-ambient environment should be displayed prominently in the kitchen).

(vii) Work-surfaces are placed close to the cold-storage facilities, and/or trolleys are used to facilitate rapid loading and unloading of food items.

Furthermore, the efficiency achieved depends on the care taken by employees not to leave the store's door open longer than is necessary and to seal (in plastic bags) foods, which contain considerable quantities of water, because otherwise ice forms on the evaporator thereby lowering the appliance's COP and increasing its energy consumption. Usually the employment of a microprocessor-based control system (which, for example, attempts to minimise the daily energy consumptions by only switching-on the optimal combination of compressors to satisfy the varying refrigeration load) in kitchens having a large cold-storage facility, is expedient from an energy-thrift perspective (Watson, 1979).

Well-insulated larders abutting on to north-facing walls (in the northern hemisphere) are recommended for storing foods and thawing out (or holding) cold foods, which are not required immediately. Their use is desirable from an energy-thrift viewpoint, because unlike employing refrigeration equipment they do not require the expenditure of a high-grade energy supply. Furthermore, the feasibility of employing underground sub-ambient food stores should be assessed by kitchen designers, because of the associated cost benefits (see Table 6).

Utensil Storage

Kitchen utensils should be located near to where they are most likely to be used. In preparation zones, it is convenient to site kitchenware at the rear of the work surfaces and cleaning materials in ventilated cupboards away from where food is handled, but close to sinks and utensil-washing facilities. Consideration should be given at the design stage to the ratio of men to women likely to be employed in the kitchen, because ideally all items should be stored at heights which are compatible anthropometrically with the average employee. Observations by Sutcliffe Ltd (1985) and Knight (1986) suggest that the average height of kitchen staff is usually significantly below the national average, mainly because of the predominance of female workers in catering.

Waste Disposal

Provision for waste disposal is essential: segregated dry refuse areas (e.g. separate covered receptacles for vegetable matter, putrescibles, metal cans, glass and paper/cardboard) should be sited outside the kitchen building, and well away from the cooking and storage areas, preferably in a well-ventilated insect/vermin/animal/ bird-proof room. To achieve energy-thrift, attempts must be made to limit the wastages from the kitchen, and plausible commercially-viable methods for using kitchen refuse as a fuel source, composting (or providing animal feed from) food wastes, recycling bottles and reclaiming scrap metal should be investigated. The use of refuse-compacting equipment raises the kitchen's energy bill, but because it reduces (i) the cost of waste transportation and (ii) the problems of unpleasant odours and rodent infestation in the refuse storage area, it may yield long-term benefits for some large establishments. However, the installation of a partially-refrigerated refuse store should be avoided, although it is sometimes advocated. In the equable British climate, ventilated refuse stores are usually adequate if they are protected from the ingression of sunlight and waste heat from the kitchen.

PREPARATION FACILITIES

Kitchen staff often spend more than 60% of their time preparing foods for cooking and serving (Avery, 1973). Therefore the provision of ample work-surfaces in convenient positions within each work-zone is essential. Work-surfaces and sinks generally account for about 10% of the total floor area: these should be fitted about 0.05m below elbow level, i.e. about 0.9m and 0.7m above floor level for standing and seated average-male workers respectively. Ideally, to ensure that the least effort is expended when undertaking preparation activities, an individual work-station should conform to the anthropometric dimensions of the human operative. Thus it is desirable for the kitchen to be equipped with mobile adjustable-height work-surfaces and appliances (Giampietro, 1977).

Activities at a work-station should proceed in one direction and those items which a worker uses most frequently, placed within easy reach (e.g. see Fig. 9). Avery (1985) suggested that, in order to minimise necessary movements, most preparation tasks should be performed within radii of about 0.41m from each of the worker's elbows and within about $\pm 30^{\circ}$ of his/her straight-ahead view. By providing a rotatable seat around which a number of mobile, ring-segment, work-units (consisting of adjustable-height, tables and sinks) can be assembled, preparation activities may be performed effectively in a logical circular sequence and at a convenient position within the kitchen (e.g. see Fig. 10). On completion of an associated activity, each work-unit can be unfastened and moved to its next appropriate location (e.g. a store of peeled potatoes may be delivered to the cook, whilst their peelings and other residues are wheeled to the refuse store for disposal). Once cleaned, each of these mobile work-units can be returned to its parking bay until required for another activity. Furthermore, the provision of ergonomically-designed kitchen tools is also desirable if expenditures of human effort are to be reduced. For example, Kotschevar (1985) reported that if a knife was fitted with a handle which formed an angle of 161° rather than the more usual 180° with the sharp edge of its blade, users would need only to pivot their wrists through 4° instead of 11° when performing typical cutting operations in planes which are perpendicular to the food's upper surface.

Decisions as to where the preparation areas should be situated in a kitchen, and how large they should be, are usually made on the maximum rate that food passes through each work-zone. The need for work-surfaces to be immediately adjacent to the equipment which has to be employed is of paramount importance when a large mass of food has to be prepared frequently, e.g. when potatoes are peeled, chipped or fried. Sinks for draining 'boiled' vegetables should be positioned adjacent to hobs and steaming ovens,and similar facilities provided close to the frying equipment for draining (i) conventionally -prepared chips prior to frying, and (ii) recently fried food.

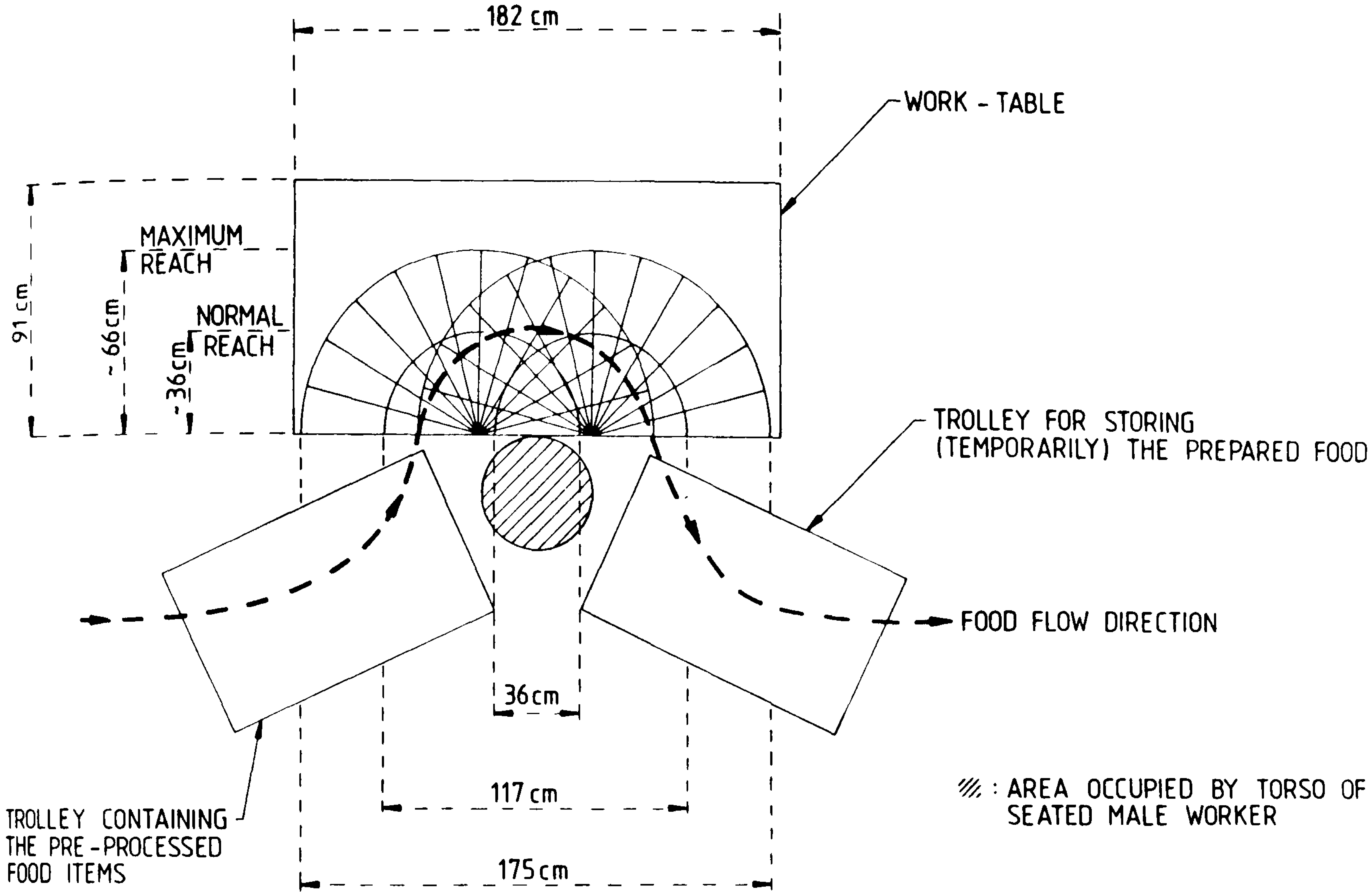


Fig. 9 An ergonomically-designed work-station for an average male kitchen operative (adapted from Richard, 1973 and Kotschevar and Terrell, 1985).

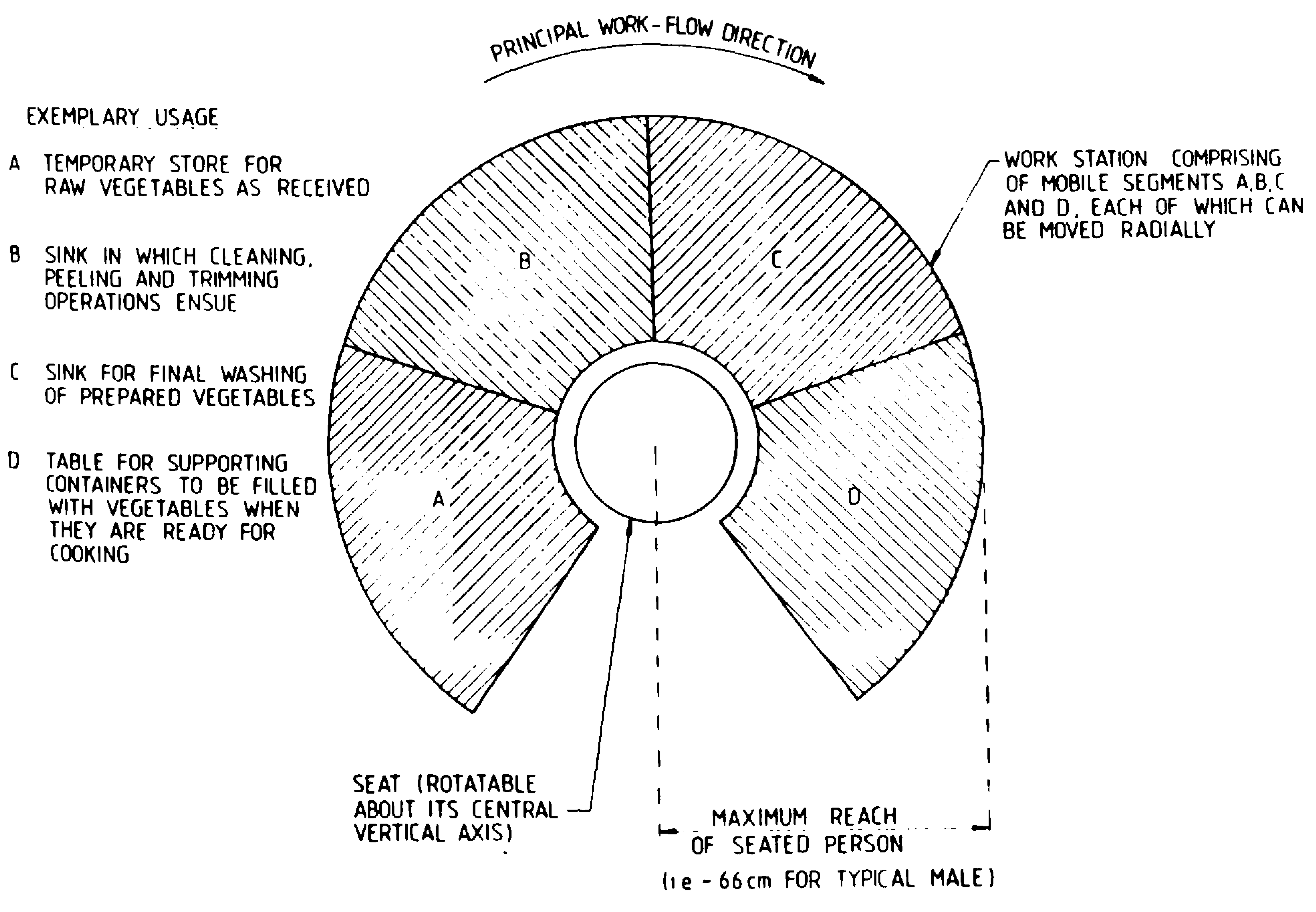


Fig. 10 A mobile circular-ring work-station assembly, arranged to simplify associated preparation activities.

Consideration must also be given to the degree of employment of frozen convenience foods, because, for example, if only frozen chips are to be used, then a far smaller preparation area and a lower labour requirement are needed compared with those for the conventional practices of peeling and chipping fresh potatoes. Use of convenience foods will usually reduce capital costs and space requirements by about two-thirds, as well as approximately halve the associated labour costs (Fisk et al, 1963; Peddersen et al, 1973).

Proper control of the thermal environments of preparation zones is essential if hygiene and food-quality standards are to be satisfied. The environmental temperatures in which vegetable and salad preparation occur should remain below 20 °C, while meat and pastry preparation activities should be performed at not more than about 15 °C and 18 °C respectively. Therefore it is logical to separate these preparation areas into separate self-contained zones, whilst leaving enough free work-surfaces in the general cooking zone to facilitate the final preparation of cooked items before their delivery to the servery (e.g. see Fig. 6).

The Utensil-Washing Facility

This usually consists of pot-washing and dish-washing sections: it uses about 75% of the water consumed in a typical kitchen (Malmstrom et al, 1980). Dish-washing involves the cleaning of crockery and cutlery that has been used in the dining room, whereas pot-washing involves cleaning pots, pans and other utensils used within the kitchen. Fortunately dirty items returned from the dining room can be cleaned more easily and hygienically by machine than by hand. Thus the dish-washing area should be arranged so that there is a logical sequence of cleaning operations (i.e. clearing trolleys and trays, scraping plates, refuse disposal, stacking and racking items, loading and unloading the dishwasher and then removing the cleaned items for storage elsewhere). Where feasible, it is desirable to use a conveyor system for removing trays from within the dining area to the kitchen. Provided that customers are amenable to this method, labour costs can be reduced and the dish-washing and tray-washing operations can be automated. However, pot-washing often necessitates the use of manual washing-techniques and extra sinks for soaking items which cannot be cleaned thoroughly immediately. The undersides of these sinks should be insulated thermally, and covers placed on them whilst items are left to soak. However, pot-washing machines are available commercially: some of these are alleged to reduce expenditures of human effort by as much as 50%, be cost-effective if more than 45 pans are washed per session and improve standards of hygiene when compared with manual washing techniques (Watson, 1986).

It is wise to construct the utensil-washing facility so that it forms a separate self-contained zone, which is within easy reach of the dining room and cooking zones (e.g. see Fig. 6). Too much humidification of the kitchen atmosphere and excessive noise levels within the general kitchen area should thereby be prevented. To achieve similar objectives, the kitchen should be sectioned off effectively from the servery. This may result in increased employment of bains marie and hot cupboards in order to meet the predicted demand, because communication difficulties between the cooks and servers are likely to ensue if they cannot see or hear one another. Therefore an effective communication system between the kitchen and servery must be fitted if ambiguities arising between waiters, servers and cooks are to be avoided. Then, increased use of food-holding devices will be inhibited and good environmental isolation between the kitchen and the servery/dining area can be achieved. Admittedly it may be cheaper to construct a building so that the servery and kitchen are largely unseparated, but because these zones have such different air-conditioning requirements, the HVAC plant would probably end up being oversized (e.g. see Appendix 1). Furthermore, the environmental quality of the dining area will be improved if the kitchen is well isolated from it (e.g. see Fig. 6). Thus reducing the operational energy costs of the facility need not be the sole benefit gained from such a design strategy.

EQUIPMENT LAY-OUT

Because catering equipment occupies so much of the floor area (i.e. 30%) of a kitchen, it is essential that it is properly arranged so as not to impede the work flows. In small kitchens, equipment can be placed against walls to save space, and so only short lengths of waste pipes and ducts are then necessary. However, 'island grouping' is more practical in premises serving at least 100 meals per session. This involves positioning work-surfaces and sinks chiefly around the kitchen's periphery and then fitting the catering appliances in (preferably small) islands close to their associated preparation areas on the outer periphery. For example, a mixer for mashing cooked potatoes should be located near to the island containing the hob, steam kettle or boiling pan used for cooking the potatoes.

The separate grouping of 'wet' and 'dry' equipment is expedient, i.e. placing hobs, kettles, bains marie and steaming ovens contiguously,whilst arranging assemblies of fryers, grills, toasters and ovens elsewhere. Cooking appliances, requiring or generating steam when in use, should be positioned adjacent to one another so that the necessary services can be provided economically. Then equipment containing hot fat should be located well away from that containing water or steam. Such groupings are convenient, because the wet equipment, which is used mainly for cooking vegetables, can be situated close to the vegetable-preparation section; and the dry equipment near to the servery, so that the grilled and fried foods can reach the diners rapidly. Furthermore, this should enable bespoke air heat-recovery systems to be fitted, because the cooking zones are then better defined.

Because accidents are more likely to occur if individuals are required to stoop, generous allocations of free space must be provided around ovens and tilting equipment. If gaps between equipment are necessary for access, these should be at least 1m wide where staff are obliged to work back-to-back, and about 1.5m wide if trolleys have to pass through. To avoid accidents, trolleys should not be permitted to pass close to tilting equipment, and they should have an adequate parking space when not in use so that traffic routes do not become congested. Sufficient space should also be provided around appliances (i.e. so that cleaning and maintenance operations can be carried out without disrupting significantly other kitchen activities).

Before deciding which catering appliances should be purchased, it is important to define exactly what demand the kitchen is expected to satisfy (Thomas, 1947), i.e. mainly in terms of the number and types of meals served per session and how much these are expected to change in the future. To assess the typical demands that will be placed on equipment, simple formulae can be deduced for various types of cooking/serving appliance. For example, the number of decks, D, (in a 'deck-oven' assembly) that are required to satisfy a certain rate of customer demand, S, for a given type of food/meal during dining periods, may be deduced from the following equation:-

$$D = \frac{S\, t_B\, r}{100\, \ell\, p} \qquad (1)$$

where t_B is the cooking period per batch, ℓ is the number of portions of food that can be cooked per cooking pan, p is the number of pans that will fit into one deck, and r is the percentage of customers expected to opt for this food/meal.

Generally once the size of each food portion, the serving rate, the cooking period per item or batch of items and the popularity of the food/meal have been determined, the kitchen's equipment requirements can be predicted acccurately. The overall primary energy consumption, E, incurred by the kitchen appliances during a typical working period may then be estimated as follows:-

$$E = \sum (P\, t\, d)_a \left(3600/\eta''\right) \qquad (2)$$

where 0.5< d <0.7 for typical cooking systems (Taylor, 1987). Alternatively

$$E = \sum \frac{H}{\eta_a} \qquad (3)$$

where, for thawed items of food,

$$H = m_F C_t (T_k - T_i) + m_e C_e (T_e - T_j)(1+X) \qquad (4)$$

or, for frozen foods,

$$H = m_F \left[C_h (T_f - T_i) + C_t (T_k - T_f) + LH \right] + m_e C_e (T_e - T_j)(1+X) \qquad (5)$$

Values for the approximate overall energy efficiency, η, for typical kitchen appliances are listed in Table 14.

TABLE 14

The approximate typical overall energy efficiencies of some kitchen appliances (Van Zante, 1973; Osepchuk, 1975; Erickson, 1977; Belling and Co. Ltd., 1978; Thorn Domestic Appliances, 1978; Scheidler and Kristen, 1980, Bell and Jones, 1981; American Gas Association, 1983; British Gas Corporation, 1983; Lawson, 1983; American Gas Assocciation, 1984; American Gas Association, 1985; Stierlen-Maquet, 1985; Newborough et al, 1987).

Type of appliance		Typical overall efficiency, (%)*
Ovens	Conventional electric	5
	Conventional gas	6
	Fan-assisted electric	6
	Microwave	6
Hobs	Ceramic, electric resistance heaters	16
	Electric hot-plates	16
	Electric 'radiant' rings	18
	Ceramic, induction heaters	22
	Unenclosed gas burners with automatic ignition	41
	Improved gas hob**	63
Grilling/Frying equipment	Traditional electric griddle	4
	Traditional electric fryer	5
	Conventional electric grill	5
	Fan-assisted electric grill	9
	Conventional gas grill	30
	Conventional gas fryer	34
	Improved gas-fired griddle**	55
	Improved gas-fired fryer**	72
Miscellaneous equipment	Electric 'convection' steamer	3
	Small portable cooling fan	5
	Electric pressure steamer	5
	Electric 'pop-up' toaster	6
	Traditional electric dishwasher	7
	Electric dishwasher with integral heat-recovery	13
	Electric kettle	23

* Assumes production plus supply efficiencies, η'', of 28% and 92% for electricity and natural gas respectively. All the values in the Table relate to the typical operation carried out by the appliance or have been derived from tests which involved raising the mean temperatures of known thermal loads through fixed intervals with the stated appliance. In practice, many factors will affect the efficiency of a catering appliance: these include the thickness of insulant applied, the suitability and accuracy of the control system employed, the management effectiveness of the cook, the duration of the cooking period, the initial temperature of the cooking medium, and the mass, temperature and water-content of the food to be cooked.

** See American Gas Association (1983, 1984 and 1985).

A knowledge of the energy consumptions of the appliances fitted will also be needed if the air-conditioning system is to be sized correctly. Unfortunately, appliance manufacturers do not proffer such information readily. Indeed, although efficiency labelling for some types of energy-consuming appliances is common practice in Germany, Canada and the USA, it may take several years before British caterers can simply peruse energy-performance details in the same manner that prospective car buyers can. Furthermore, food-service operators are often inhibited from calculating the energy implications of their prospective purhasing decisions, by (i) the diversity of units used when selling energy within the energy supply industry (e.g. electricity is sold in kWh, natural-gas in therms, coal in tonnes and fuel-oil in litres); and (ii) the absence of information concerning exergies. Such factors serve to confuse: they often deter non-engineers from even attempting comparative operational energy-cost calculations. For these reasons, only general advice can be suggested to assist in determining what, and how much, equipment should be fitted. At this juncture one of the best ways forward is for each catering organisation to generate data files on the energy performances of the equipment that it uses currently. Precise energy-consumption data (i.e. energy requirements per item of food or meal served and for maintaining a certain mass of water/steam/oil/air at a given temperature/pressure) may be determined best by an independent organisation. By testing equipment while undertaking a specified task, a better means of comparing the energy consumptions of similar, commercially-available, appliances can be achieved.

The following measures or options are advisable when equipping a kitchen:

* Purchase energy-efficient cooking systems (see later). Remember that although more efficient equipment is relatively expensive to buy, savings can be achieved subsequently because expenditures on cooking and air-conditioning are less. (The additional capital expenditure may be reduced by utilising money returned from the sale of existing less efficient or inappropriate appliances).

* Install a central energy-distribution and management system to supply all of the kitchen appliances. This will simplify initial installation of the electricity, gas and steam supplies, whilst permitting some central control of their usage, e.g. the stirrers associated with boiling pans can be energised intermittently at desired intervals, instead of continuously.

* Fit extendible flexible energy-supply pipes/leads to appliances, so that they can be moved during cleaning and maintenance, and ensure that each appliance can be switched off without affecting the operation of another system. Although the appliances should be manoeuvrable, they must be located securely during operation to avoid dangerous or awkward situations (e.g. ensure that the user of a freezer doesn't have to prevent it from moving when food is being loaded or unloaded).

* Install an automated water-dispensing system, which provides operatives with the exact amounts of water (via conventional taps) when required.

* Usually prefer the installation of two small appliances rather than a single large one, in order to obviate under-utilisation of equipment when demand is low. Avoid purchasing equipment which offers more facilities than are likely to be employed.

* Opt for modular cooking systems, which lend themselves easily to the addition of further units.

* Prefer raised ovens to range-ovens (i.e. those which are mounted below hobs, griddles and work-surfaces) because cooking and cleaning operations should then be less difficult.

* When purchasing gas-fired appliances, choose those which are fitted with durable spark-ignition devices.

* Ensure that all appropriate appliances (e.g. ovens, fryers and pressure-cooking systems) are fitted with timers, and/or food-temperature sensors, which terminate automatically the power dissipation when the food has reached the desired temperature, (and, if appropriate, switch it on again only for sufficient time to maintain the required temperature). Remember that if a cooking appliance is designed so that its operation demands relatively little supervision from the cook, then energy savings are more likely to be achieved consistently. Thus prefer microprocessor-controlled appliances, e.g. conveyor ovens, which can be programmed so that the speed of the conveyor and the temperature of the oven's heating system can be defined accurately (Hussman-CTX, 1986).

* Make certain that all electronic, electro-mechanical and mechanical conrols on catering devices :- (i) can be adjusted accurately without difficulty in a safe manner; (ii) are clearly marked (preferably with hard-wearing coloured dials); and (iii) move in the same direction to increase the power inputs. Opt for equipment with (i) green 'tell-tale' warning lights (which, for example, indicate that the oven is switched on, or that the hob surface is above its safe-touch temperature); (ii) robust easily-operated door-catches mounted on doors, which can be removed for cleaning purposes; and (iii) easily-removable oven racks, oven-linings, hob reflectors, pan supports and drip-trays (if applicable). Avoid appliances with unconventional controls, e.g. dial pointers which move in an anti-clockwise direction when their associated rotary controls are turned clockwise. Always ensure that a sufficient number of indicators are fitted so that temperature, pressure, power-input and malfunctions (if appropriate) are observable readily.

* Prefer chest freezers to upright ones, because infiltration of warm air occurs more readily when the doors of the latter type are opened.

* Ensure that menus and preparation schedules are reassessed regularly, so that under-utilised or unused equipment can be either better utilised or replaced by more suitable systems. Remember demands on equipment will change as customers modify their diets. In the extreme, if the kitchen is not adapted to satisfy these alterations,it will become ineffective financially.

* Before buying appliances, make certain that maintenance services will be available if they malfunction. Persistent use of equipment which is in a poor state of repair usually results in substantial wastages of time and energy. Therefore meticulous planning for the preventative maintenance of equipment should always be undertaken when designing a catering facility.

III. ENERGY-EFFICIENT CATERING EQUIPMENT

Caterers use high-grade energy supplies to stimulate processing-appliances (e.g. preparation, cooking and refrigeration equipment) so that ultimately food can be made edible (or more palatable) for their customers. Usually the capital investment in equipment is small, compared with the costs of operating the kitchen (i.e. expenditures on labour, food and energy) over the working lives of the appliances installed (Giampietro, 1980). Hence the prudent selection of equipment is a pre-requisite to cost-effective catering. Unfortunately, the currently high annual energy consumption of the British catering industry is due primarily to its (often involuntary) employment of inefficient equipment. From an energy-thrift standpoint, commonly-employed catering equipment tends to be poorly designed, e.g. the thicknesses of thermal insulant applied to ovens are often inadequate, and the control systems associated with many appliances are not well designed with respect to energy efficiency and ergonomics (Sutcliffe Ltd., 1985; Kotschevar and Terrell, 1985). Because most existing food-service facilities will still be in operation during the early part of the 21st century, when fossil-fuels will be much more expensive than they are today, energy-saving technology (which can be adapted easily into kitchens) must be developed now, if future annual energy costs for catering are to be curtailed. Thus, as unit costs of energy rise, caterers will increasingly require information which will enable them to (i) be more discerning when buying equipment, and (ii) demand that appliance manufacturers improve the energy efficiencies and ergonomics of their products.

In general there are 5 categories of kitchen appliances, namely those used for storage, preparation, cooking, serving and cleaning. Usually the most energy-consuming equipment within a conventional kitchen is that used for cooking purposes. Thus the subsequent discussion will concentrate on the performances and design failings of cooking appliances.

COOKING EQUIPMENT

Fundamentally the intended purpose of a cooking system is to heat food, i.e. it should be a 'heat-containing' device rather than a 'heat-liberating' one. The cook chooses to practise a particular type of cooking so that characteristic changes (in flavour, aroma, colour, tenderness, volume, mass, water-content and nutrient-content) may be obtained. The correct combination of these yields the desired end-product, and ideally this should be achieved in the most energy-efficient manner possible. However, until recently the latter objective has received scant attention from equipment manufacturers , and so widely used cooking appliances still tend to be very inefficient in energy terms (see Table 14).

The British catering equipment industry is partly responsible for energy profligacy in the food-service sector. Admittedly the development of cooking systems which have labour-saving attributes (e.g. improved cleanability and reduced cooking and maintenance periods) has increased during the last decade, but few R & D programmes to maximise the energy efficiencies and improve the ergonomics of these appliances appear to have been instigated. Traditionally, technical changes have resulted from concerns for rapidity of cooking, food quality, hygiene, appearance and durability. However, design optimisation in terms of energy efficiency, ergonomics, reliability and capital cost is becoming more desirable. Nevertheless, at present, it still seems appropriate to recommend the implementation of the aphorism " don't cook the cook - cook the food" to designers of catering equipment. In future, energy-thrift should form a fundamental part of the design strategies of manufacturers of food-service equipment, because caterers will search increasingly for more energy-efficient, controllable, safe and reliable cooking appliances for installation in kitchens.

It is desirable that caterers compare appliances with respect to their expected energy performances when contemplating purchase, and only buy high-efficiency systems. However, because catering equipment is not usually tested independently (see Appendix 3), manufacturers claims concerning their new appliances with 'energy-saving' features often cannot be substantiated coherently in terms of comparative energy performances. For example, Unklesbay and Unklesbay (1982) justifiably questioned the validity of one manufacturer's test results (which indicated energy savings of 29-40% for a forced-convection gas oven when fitted with a means of reclaiming some of the heat otherwise lost via its flue), because of the unscientific and misleading manner in which the data were made available to prospective buyers. Furthermore, some promoters of equipment often mislead customers by suggesting that those versions of a certain appliance, which have lower power inputs than is normal are more energy-efficient. Clearly, if expenditures on energy are to be reduced, senior food-service personnel must attempt to influence manufacturers now, since the majority of cooking appliances are designed for operational lives of at least 10 years.

Although the energy efficiency of the considered equipment influences some purchasing decisions, much apathy still exists. This is due partly to the disparity in the unit prices of the two main cooking fuels; natural gas being considerably cheaper than electricity in unit-energy terms. (If unit gas prices were increased to equal those of electricity per kWh of heat forthcoming, then the current annual energy bill of the catering industry in the UK would grow to about £1.2×10^9). As local natural-gas supplies dwindle, this price differential will gradually diminish, because (if customer demand does not decrease) the gas will have to be produced via the more expensive process of coal-gasification.

Most commercial catering organisations are financially responsible for the energy expenditures that they incur. Conversesly contract-catering companies experience little or no incentive to reduce the energy consumptions of the kitchens that they operate, because their clients pay all the utility bills. Unfortunately, the policies of many owners of industrial canteens may inhibit the introduction of more energy-efficient appliances, even if recommended by the contract-catering companies operating these kitchens. Usually the organisation operates its catering facility on two budgets: one for the construction of the establishment plus purchasing the equipment to be employed therein, and the other for paying the fees of the contract-caterer and the operational costs incurred. Generally, few industrial owners seem willing to increase the first budget, when more efficient (yet relatively expensive) appliances become available to replace existing energy-profligate or unrepairable appliances, even though by such purchases the annual operating costs of the establishment would be reduced. Ironically, although the kitchen will operate perhaps for 60 years and the catering equipment employed therein will be changed completely three or four times during this period, a maximum pay-back period criterion of less than 3 years is usually required when considering the replacement of existing appliances by less energy-consuming ones. Furthermore, during refurbishment, old or defunct catering appliances are replaced, but often in an attempt to reduce capital expenditures, the building's structure and its HVAC equipment are not modified to conform to an energy-thrift perspective. Consequently, although a gradual trend towards the use of more energy-efficient catering equipment may occur (see Appendix 3), overall energy expenditures will, in many cases, tend to remain unnecessarily high because energy-conscious modifications to the building's fabric and HVAC system have not been implemented. Unfortunately, since the employee catering sector forms the largest part of the British catering industry in terms of energy use (see Table 3), overall national energy savings may tend to be inhibited. However, it is expected that by 2000 A.D. most of the clients of contract-catering companies will insist that the operational energy expenditures incurred by their kitchens be paid by the caterers (Sutcliffe Ltd., 1987). (This applies already for hospital catering within the National Health Service). Thus it would be wise for contract-catering organisations, to consider carefully the types and amounts of catering equipment that they will install. If future planning neglects the importance of such energy considerations, many food-service establishments may discover suddenly that they have to replace some equipment part way through its useful life in order to offset escalating energy bills. Therefore by studying the energy consumptions of catering appliances now, catering professionals will be helping to assure the long-term profitabilities of their organisations.

HOBS AND BOILING EQUIPMENT

Conventional unenclosed or 'open' gas-hobs (e.g. see Fig. 11) are at least twice as efficient as standard electric hobs, provided that the burners are ignited only when required, e.g. via spark-ignition devices (see Table 14). However the electricity consumptions of radiant rings and hot-plates can be reduced by employing pan-sensing devices (Terai et al, 1984), which, for example, reduce or terminate heating when the pan is no longer in contact with the heater. Despite modern practice, it is not advantageous (in energy terms) to employ gas/electric heaters which are mounted beneath ceramic hob-tops, or hot-plates/solid-top boiling tables. The standard ceramic hobs for electric systems (see Fig. 12), including the slightly more effective ceramic 'light' (or 'halogen') hobs, are up to 20% less efficient than radiant rings. Gas-fired burners with a ceramic hob placed above, tend to spread the heat over the entire area of the hob-top: this reduces their effectiveness when compared with open gas-hobs.

A large natural-gas or electrically-heated solid top boiling table, as is commonly employed in catering establishments, is highly inefficient and difficult to control because of its high thermal inertia. However, the energy-conscious practice of ensuring pan-base areas exceed energised heat-source areas (Probert and Newborough, 1985) is difficult to achieve. Hence commercial hob operations tend to be more wasteful of energy than domestic ones. Slight improvements in the energy efficiency of a solid-top boiling table can be achieved, for example, by fitting spheroidal-graphite sheets above the burners instead of cast-iron ones (Enga, 1984), but essentially the design of solid top boiling tables results in deplorable energy wastages to the internal environments of kitchens.

Gas hobs tend to be left on by their users during periods when no cooking is taking place. This is partly because automatic-ignition systems are still only rarely fitted due to their poor reliability when subjected to typical usage. Consequently kitchen staff are disinclined to switch off the burners, because they would otherwise need to expend extra time relighting the gas manually, which can be an additionally troublesome operation especially during peak-demand periods. Although built-in electric-spark generators (Curran et al, 1981) are fitted as standard to domestic gas appliances, many types of catering equipment are still employed without such facilities. Nevertheless, the use of gas-fired catering appliances, which are fitted with spark-ignition devices, is desirable from an energy-thrift perspective, especially if they replace continuously-lit pilot lights.

Recently, design improvements for gas burners fitted to commercial cooking appliances have permitted substantial energy savings to be achieved. Hobs, griddles and fryers have been developed which achieve greater efficiencies (see Table 14) by using heating systems in which the fuel/air mixtures are fed to semi-insulated burners by means of variable-speed d.c. blowers (American Gas Association, 1985). Furthermore, gas-fired 'integrated cooking systems', which permit part of the energy which would otherwise be wasted, via the flue of one appliance, to be utilised by another or for pre-heating water, are under development.

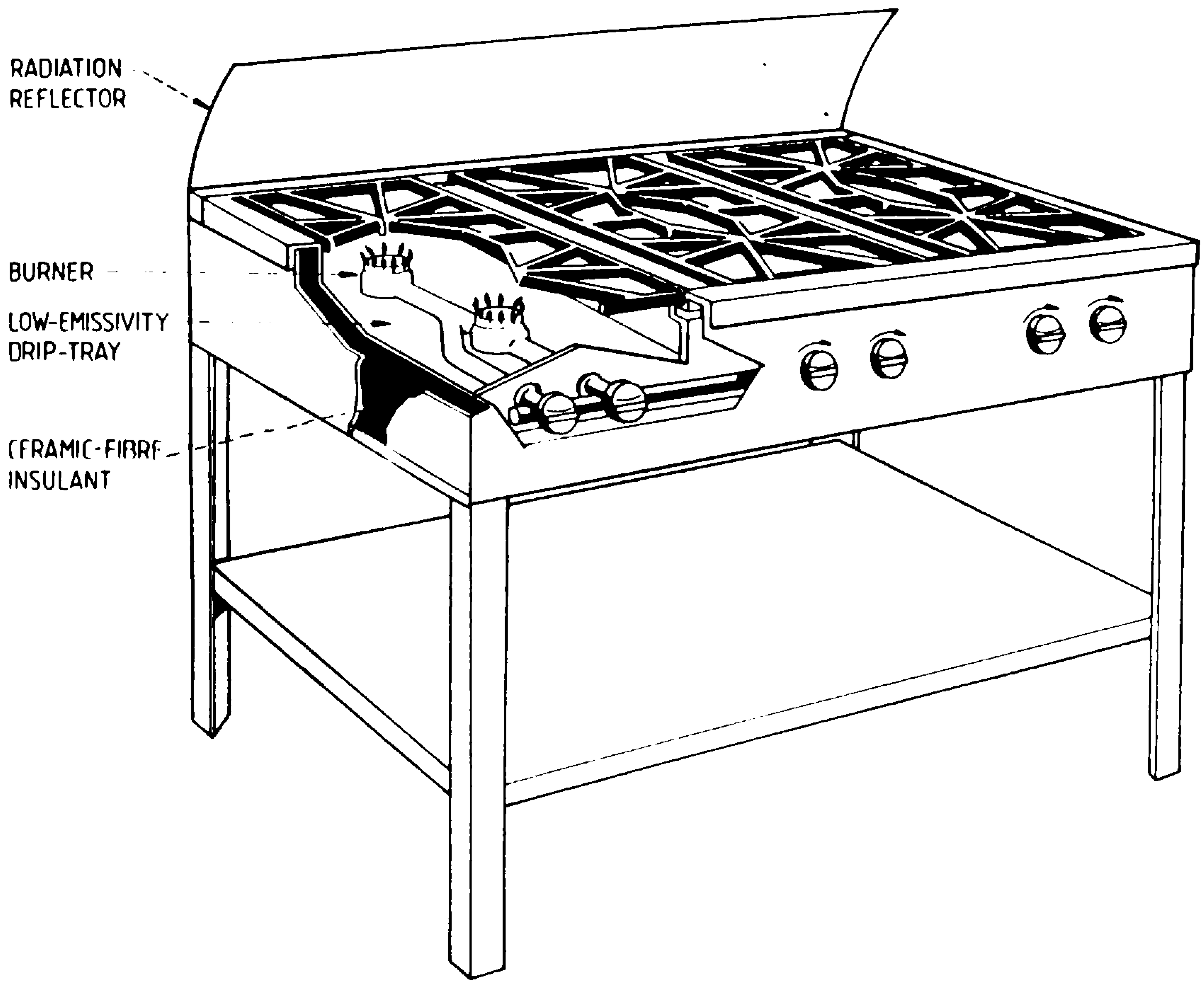


Fig. 11 A natural gas-fired open-top boiling table, incorporating some basic modifications to reduce the rates of heat loss to the kitchen.

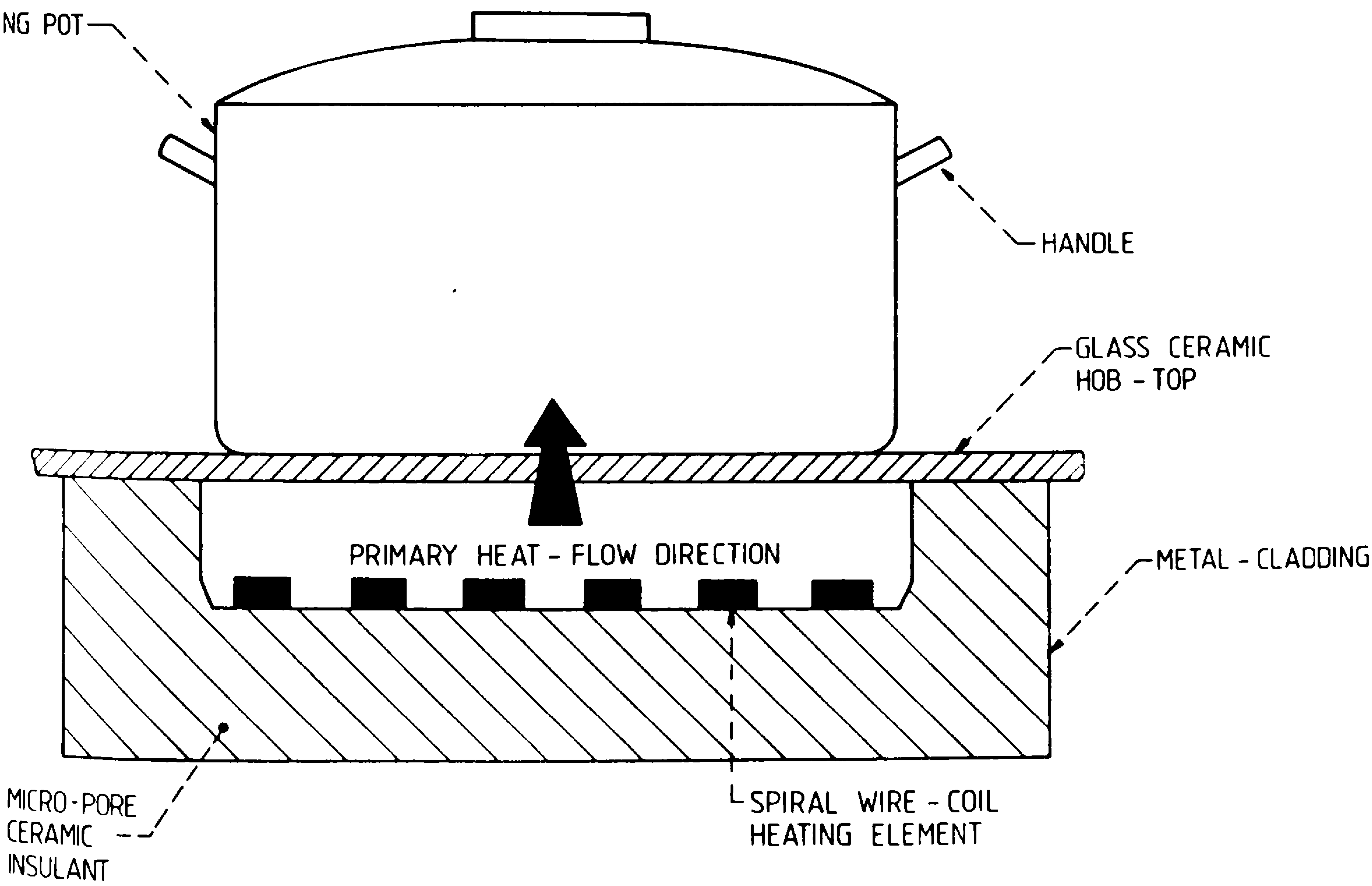


Fig. 12 A cross-sectional view of a conventional electrically-heated ceramic hob.

Induction Hobs

Usually energy savings of around 50% can be achieved by using induction hobs (which generate heat in the superimposed ferromagnetic pan electromagnetically, by the dissipation of eddy currents therein) instead of conventional electric hobs (Stangard Ltd., 1984). Financial pay-back periods of less than 3 years and often shorter than two years (where induction hobs have been installed in all-electric kitchens) are usually achieved. Robust, mobile, high power-output (i.e. up to 5kW), microprocessor-controlled versions, designed specifically for the food-service industry are now available. A most significant benefit for caterers who use induction hobs, is that the local environmental air temperatures are then much lower, when compared with employing gas or conventional electric hobs. If a pan is removed from the hob, the power dissipation is reduced automatically to a nominal rate without the cook's supervision. Thus summer cooling and ventilation loads for the kitchen can be reduced substantially: this should result in a more comfortable working environment for a greater part of the year. Productivity may thereby be improved slightly.

The recent purchase of The English Induction Cooking Company by Trusthouse Forte exemplifies the importance with which Britain's major hotel and catering company views induction-cooking appliances (Anon., 1986a). It has been predicted that eventually Trusthouse Forte will install induction hobs in all of its kitchens, because the associated environmental air temperatures and the probabilities of serious fires within the kitchen are then reduced significantly (Stangard Ltd., 1986). Nevertheless, at present, it is debateable whether or not the replacement of open gas-hobs by induction hobs is worthwhile financially if the sole objective of the designer is to reduce the annual energy costs.

However, from an energy thrift perspective, there is little to commend the use of the other electric hobs. In energy terms, some of the recent developments of electric hobs seem to have taken the wrong direction (e.g. placing 5mm of low thermal-conductivity glass ceramic between a conventional coiled-wire electric heater and the pan has not improved the overall energy efficiency yet it has increased the appliances capital cost). Preferences for ceramic hobs, because of their improved cleanability, would be better justified if they were used only as surfaces for supporting properly thermally-insulated pans, which had integral thermostatically-controlled heating systems. But such systems still need to be developed for commercial usage. Meanwhile it should be remembered that any efforts made by designers to increase the effectiveness of electric hobs will be counteracted by the low national supply efficiency (i.e. ~ 28%) for electricity. Nevertheless, it is feasible that this handicap may be overcome, to some extent, in CFPUs and continuously operating facilities (eg. motorway service-stations) if local combined heat-and-power generation systems come into more widespread use. The efficiency of energy release from the fuel used should be improved dramatically (i.e. to approximately 80%) : the heat reclaimed from the generator could be employed for pre-heating ovens as well as for raising steam, space-heating and pre-heating water.

The following recommendations are proffered to assist caterers when purchasing hobs, so that energy expenditures can be reduced:-

* Choose induction hobs in preference to all other electric hob-heaters.

* Prefer 'open' gas hobs to all other hobs, but be aware that as the unit price differential between gas and electricity is gradually eroded, the use of induction hobs instead of gas equipment will become increasingly attractive financially.

* If large quantities of food are to be boiled or simmered, prefer thermally insulated, low emissivity, cylindrical steam-heated kettles and 'boiling pans', which have well-fitting lids. One test indicated that a 5.3kW electric solid-top hob consumed 41.9% more energy than a 10.8kW, 44 litre, 'steam-jacketed' kettle (fitted with an integral steam generator) when each was used to raise 34.5kg of cold tap water to 91°C (Dover Corp., 1982). However be aware that the power inputs per unit volume for some boiling pans are insufficient for preparing high-quality end-products of certain foods, e.g. many of these appliances require 50-60 minutes to cook potatoes, whereas an optimal heating system would facilitate cooking in only 20-25 minutes (Bengtsson, 1980). To this end, boiling pans utilising thin-film heaters (which achieve uniform area-heating at high power densities) have been developed (Taylor, 1987).

OVENS

Conventional gas ovens are inefficient cooking systems, mainly because they must be vented to ensure adequate and safe combustion of the fuel. Unfortunately, some of the older types of gas oven do not employ dampers, which automatically reduce the area of the flue when the fuel is not being burnt. Consequently, heat losses tend to be excessive when using such ovens. Externally-heated gas ovens, with burners beneath the oven compartment's floor, usually consume 20-30% more gas than their internally heated counterparts (Flood and Enga, 1983). Although the latter designs are preferred by British manufacturers, the employment of foreign-made externally-heated gas ovens is a significant cause of energy wastage in UK kitchens. Nevertheless, energy-saving improvements to the designs of internally heated gas ovens are feasible, e.g. it has been reported that the cross-sectional areas of the flues of gas ovens can be reduced by up to 75%, thereby achieving energy savings of 10-20% when operating under steady-state conditions (Enga,1984). Generally, the end-use efficiencies of gas ovens are lower than those of electric ones. For example, fan-assisted gas ovens were found to use 130-230% more energy than electric ovens of similar capacity (Hu et al, 1978). However, in primary-energy and running cost terms,ovens fuelled by natural gas are usually more desirable than ones stimulated by electricity, although these advantages can be counteracted by the relatively large flue-losses, which increase the kitchen's cooling load in summer.

Conventional electric ovens (i.e. those which heat food by buoyancy-driven convection) also tend to be unnecessarily wasteful of energy (see Table 14). Fortunately relatively efficient electric ovens, which cook foods via forced convection, infra-red and/or microwave techniques are now employed to a greater extent in British kitchens. Nevertheless significant energy savings could be achieved economically if appliance manufacturers improved the designs of their ovens (Probert and Newborough, 1985). Unfortunately though, some current kitchen activities militate against attempts to improve oven efficiencies. For example, some drop-down oven-doors are designed to support loads of at least 100kg, because it is realised that workers tend to stand on them when cleaning cooker hoods. Thus, the overall thermal mass of the door and its operating mechanism is far greater than it should be from an energy-thrift perspective. Also the door seal is more likely to be damaged if exposed to such severe mechanical treatment, and the door itself will be unlikely to fit the oven closely, after several months of such abuse.

Hu et al (1978), having conducted an energy-consumption survey concerning 720 military dining facilities (serving 312,987 individuals), reported that ovens were by far the most used and most energy-consuming devices, when compared with other cooking appliances, employed in the associated kitchens. Although the results of this study are not wholly representative for all catering facilities, it is considered that efforts made to improve the thermal efficiencies of ovens will be most pertinent for achieving energy-thrift in non-domestic kitchens.

Better designed ovens incorporate the following features:-

* Ample thermal insulation (which should be protected from moisture ingression) fitted around the oven compartment. A 100mm thick blanket of glassfibre or rockwool insulant, or a 30mm thickness of micropore insulant would be recommended for most ovens, although an infra-red oven would need to be insulated with about a 40mm thick layer of Microtherm because of the higher temperatures achievable therein. The insulant layer placed in between the inner and outer leaves of the oven door should be slightly thicker than these values, in order to reduce the direct heating of personnel in the immediate vicinity whilst the food is cooking.

* Door catches and door seals which prevent convective losses. Such unwelcome ventilations occur when the doors distort due to the large temperature differences between their inner and outer leaves. (It is not uncommon to observe cooks using ovens which were designed without door seals or even door catches!)

* Door hinges, which are mounted on the outside surfaces of the oven casing and door, in order to prevent thermal shorting of the oven compartment via its hinges.

* Self-shutting doors, which do not have glass windows. If semi-glazed doors are regarded as desirable, then those with double- or triple-glazed windows of small area which have perforated reflective-coatings on the warmest surface of the coolest pane should be chosen.

* Removable, easily-cleaned, doors and inner linings.

* Illumination systems which can be switched on and off as required by the cook, but are extinguished automatically when the oven doors are closed.

* Low-emissivity external surfaces. Thick chromium-plated steel may be used on the outer leaves of oven doors, because of the resulting combination's relatively low emissivity, specific heat capacity and effective thermal conductivity.

* No protuberances which act like heat-exchanger fins.

Forced-Convection Ovens

A fan-assisted oven cooks food more efficiently (see Tables 14 and 15) and/or rapidly than a conventional one, mainly because it promotes relatively high rates of convective heat transfer to the food and achieves a more uniform internal temperature distribution within its oven compartment. Furthermore reductions in rates of heat loss to the kitchen of 50% have been claimed, if a fan-assisted gas oven is fitted instead of a conventional gas system (Erickson, 1977). However forced-convection cooking does become less effective in reducing the cooking period required as the volume of the food items increases (American Gas Association,

TABLE 15

Energy consumptions for cooking potatoes to a mean internal temperature of 95°C via typical catering appliances (Collison and Wilson, 1977).

Cooking procedure	Mass of potatoes to be cooked, (kg)	Mean temperature of the cooking medium (°C)	Energy consumption	
			End-use ($MJkg^{-1}$)	Primary* ($MJkg^{-1}$)
'Boiled' in water	1	100	2-14**	7.1-50
Deep frying	0.25 0.75	185 185	7.5 3.0	26.8 10.7
Baking in a free-convection electric oven of 6.4kW power input	4 4	176 232	5.3 6.25	18.9 22.3
Baking in a forced-convection electric oven of 5.6kW power input	3 3 3 3 5	121 176 232 288 176	1.8 2.8 3.22 3.7 1.8	6.4 10.0 11.4 13.2 6.4
Baking in a forced-convection electric oven of 11kW power input	10 10	121 288	1.9 4.0	6.8 14.3
Baking in an indirectly-fired forced-convection gas oven of 29.2kW power input	10 10	121 260	5.4 7.2	5.9 7.8

* Assumes national supply efficiencies of 28% and 92% for electricity and natural-gas, respectively.

** The energy consumption for 'boiling' potatoes depended upon the size of the pan, the amount of water it contained, and whether or not its lid was employed.

1967). Also, although the increased air-speeds promote rapid heating, they increase the rates of moisture loss from the food, especially in electric ovens. Thus steam/water-injection facilities are fitted to some types of fan-assisted oven so that excessive moisture losses from foods (especially if they are being roasted) can be avoided. Alternatively, forced-convection cooking processes may be optimised by adjusting the ratio of convective to radiative heat transfer occurring within the oven compartment. This can be achieved by regulating the air-speeds according to the type of food and the duration of the cooking period (e.g. see Table 16).

It has been suggested that, when baking in a forced-convection oven, the cooking period should be identical with that required by a conventional oven (i.e. the mean air temperature in the fan-assisted oven should be reduced) in order to prepare a high-quality product (Collison and West, 1980; Skjoldebrand, 1985): this should permit significant overall energy savings to be achieved, when compared with conventional buoyancy-driven convection ovens. Respective energy savings obtained for fan-assisted electric and gas ovens are alleged to be 1-5% and 8-20% when compared with their conventional electric and gas counterparts (Chiogioji and Oura, 1982). Due to the greater efficiencies and cooking capacities per unit volume of fan-assisted ovens, their use is desirable if limiting the size of the kitchen is a main design aim. (Alternatively less energy efficient 'reel' ovens, which rotate the food containers within the oven compartment, usually on a ferris-wheel, are sometimes employed to achieve the same objective in large kitchens). Further, by employing (where appropriate) forced-convection 'cook and hold' ovens, which assess the temperature of the food being cooked, caterers will not only be able to reduce energy expenditures for cooking, but also maintain foods at acceptable temperatures with less energy input (e.g. see Fig. 13).

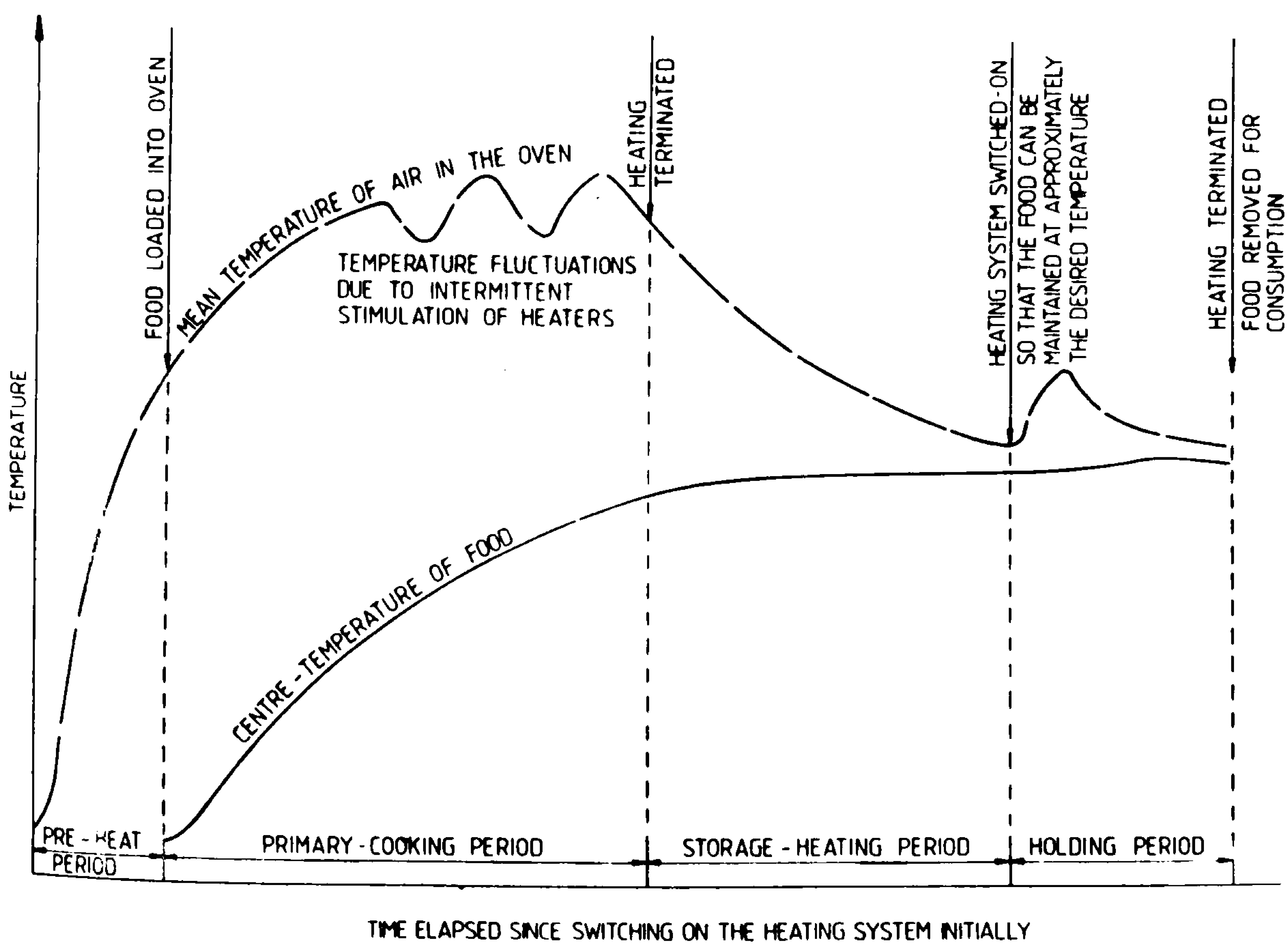


Fig. 13 A diagrammatic representation, on approximately linear scales, of the thermal response of a cook-and-hold oven.
Note :- Provided that the oven's temperature can be raised at a rate which is adequate for the required cooking operation, a period of pre-heating (i.e. with no food in the oven) should be unnecessary for non-baking operations.

TABLE 16

Preferred air temperatures and velocities for performing cooking processes in a fan-assisted oven (Skjoldebrand, 1985).

Properties of air within the oven compartment	Mean air temperature, (°C)	100-125		150-200		200-250		>300	
	Measured air speed, (ms^{-1})	5	7-9	5	7-9	5	7-9	5	7-9
Oven-cooking Process	Roasting meat (<20mm thick)							√	√
	Roasting meat (>20mm thick)				√				
	Baking					√*			
	Boiling	√*							
	Re-heating			√					

* High-humidity atmosphere desirable.

Microwave Ovens

Microwave ovens (e.g. see Fig.14), since their inception 40 years ago, have been used increasingly by caterers for rapid-heating operations. Because heat is generated within the contained food (via vibration of endogenous polar molecules of water and fat), cooking with microwaves is often more efficient than infra-red heating, as occurs in conventional electric ovens. Cooking periods and nutrient losses tend to be reduced and energy savings achieved when compared with the use of conventional ovens. However, the end-use efficiency of microwave cooking depends largely upon (i) the efficiency of the system's magnetron; (ii) the intensity and uniformity of distribution of microwaves in the immediate vicinity of the food being cooked; (iii) the transparency (to microwave radiation) and shape of the food container employed; (iv) how full the oven is when used; and (v) the thermal and dielectric properties of the food.

Conventional microwave ovens have limitations, e.g. the cooked food cannot be browned or crisped and so it often appears less appetising to the consumer. More expensive, 'microwave-convection' ovens - which permit infra-red and/or forced-convection heating with microwave cooking - may be used to achieve traditional appearances of the cooked food (Mealstream, 1985), but penalties are then paid in terms of energy consumption and cooking periods. Drew and Rhee (1979) reported increases in energy consumptions of 114-146% for heating four, 85g, beef patties in a microwave oven with a food-browning facility, when compared with using a conventional microwave oven for the same purpose. However, energy savings of 39% were achieved when the former system was used instead of an alternative method which involved heating the food in the conventional microwave oven and then browning it under an electric grill. Another draw-back of microwave cooking is that foods of significantly different specific heat capacities and dielectric constants cannot always be cooked satisfactorily together because the rate of heating in each is different. Consequently complete meal preparation using a standard microwave oven can become a more complicated operation and so less advantageous than the cooking or re-heating of just a single type of food. Furthermore, the preparation of frozen foods in a conventional microwave oven presents some disadvantages to caterers. For example, the energy field within the oven becomes distorted when frozen food is heated (i.e. the recently thawed layers of food are heated preferentially, because water absorbs microwave radiation more readily than ice). Therefore, initially, radiation needs to be applied intermittently so that the food becomes thawed evenly, before it is subjected to continuous heating. Because this prolongs re-heating periods, the prospects for operating economically a kitchen in which microwave ovens are used to prepare rapidly large quantities of pre-cooked frozen foods, so that food-holding requirements may be reduced, are poor. However because this type of catering system is potentially attractive to fast-food establishments, specific-purpose conveyorised microwave ovens have been developed for facilitating rapid re-heating (i.e. in about 2 minutes) of identical packages of pre-cooked frozen foods (Sale, 1978). The energy savings achieved by using such ovens depend on the resultant reductions in demand placed on other cooking and food-holding appliances during meal production.

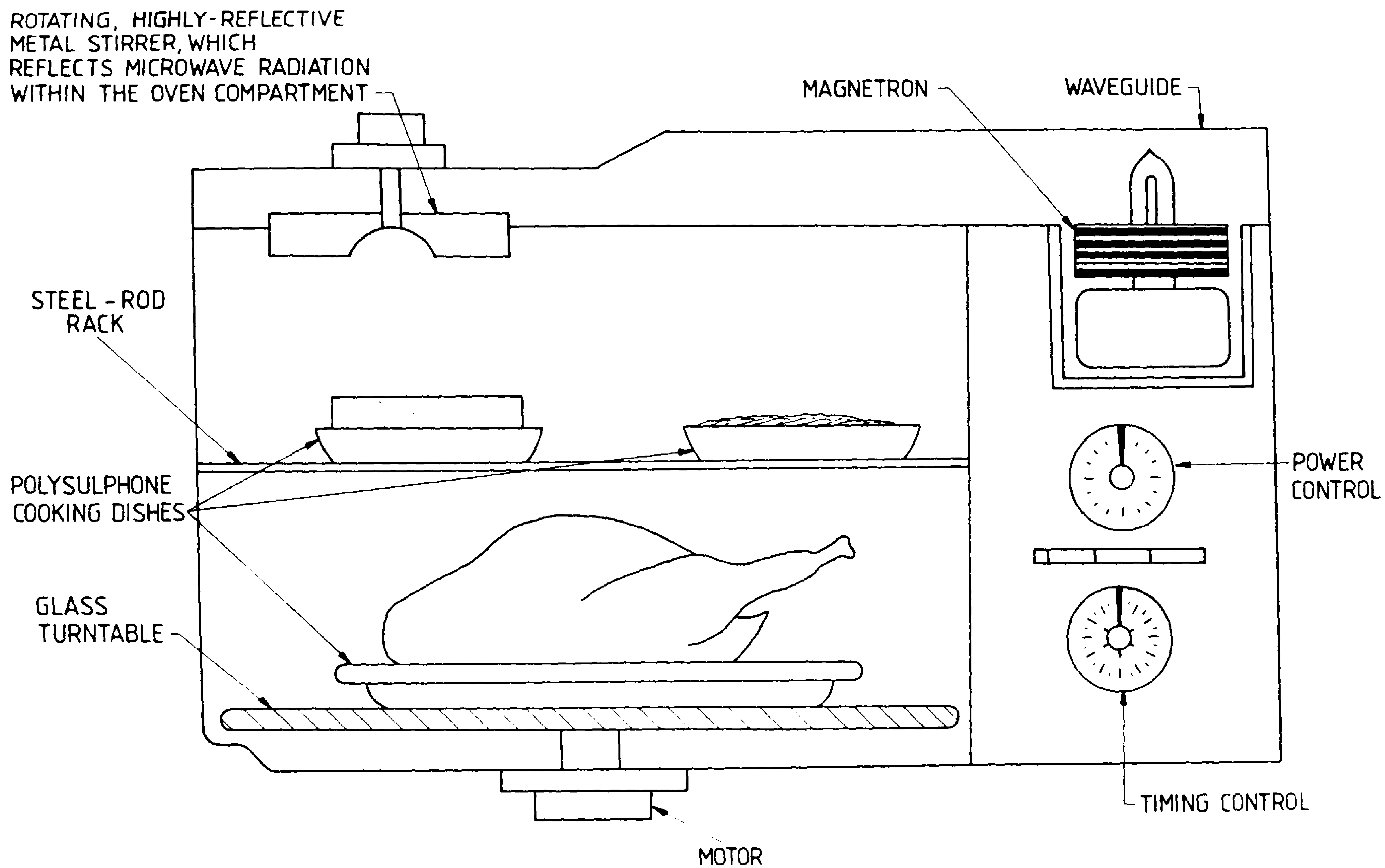


Fig. 14 A schematic view of a standard time-controlled microwave oven.

Temperature-controlled, variable power-output microwave ovens should be preferred to fixed or variable power-output traditional time-controlled ones. If the temperature of the food is allowed to control the duration of the cooking period directly, the cook can achieve consistent results more easily. Temperature-controlled ovens usually incorporate a probe, which can be placed on, or inserted into, the food to allow its temperature to be monitored. Consequently the over-cooking of food need not arise when using this type of oven. Furthermore such microwave ovens can maintain foods at a chosen mean temperature far more accurately than conventional ovens, i.e. they can provide a 'cook and hold' or 'boil then simmer' facility (e.g. see Fig. 13).

Large microprocessor-controlled combination-ovens (which provide microwave, forced-convection and steam-cooking facilities) are particularly useful for caterers. When microwave radiation is utilised in large conveyorised combination ovens, non-contacting photoelectric infra-red detectors offer a more practicable and hygienic means of sensing the food's temperature than conventional probes. This technique has been proposed for controlling electric toasters (Newborough et al, 1987), but is rarely appropriate for regulating cooking systems which heat thick or irregularly-shaped pieces of food via infra-red radiation (e.g. see Fig. 15), because the difference in temperature between the inner and outer regions of the food can often become too great and so cause the outer surface to be over-cooked when the inner regions remain under-cooked. Conversely, when heating foods with microwaves, this temperature difference is far smaller due to the nature of the radiation (Ohlsson, 1975), and so the measured temperatures of the outer surfaces provide accurate indications of the core temperatures. Therefore, the supplementary means for browning the food's surfaces (e.g. infra-red heating elements) can be energised without jeopardising the quality of the end-products. However, Smith (1986) reported that, when utilising this control technique for heating moist foods via microwave radiation, the evaporation of water from the foods' surfaces caused erroneous surface temperatures to be indicated. This occurred because (i) water vapour condensed in the line of sight of the infra-red sensor, and (ii) the foods' surfaces were at lower temperatures than their sub-surfaces due to superficial evaporation. It is alleged (Smith, 1979; Smith, 1986) that a suitable and rapid means of overcoming these problems is to combine microwave heating with 'jet-impingement convective heating', i.e. the impingement of high-velocity, high-temperature, vertical air-jets on the food so that rates of convective heat transfer can be increased (by a factor of up to ten when compared with more conventional forced-convection heating).Energy-efficient conveyor-ovens operating on this principle are available commercially (Hencke, 1985; Enersyst, 1986).

Data collected concerning domestic microwave oven operations, show that time-controlled appliances usually payback (relative to the continued use of conventional systems) in 6-15 years from the time of purchase, depending upon the degree to which they are employed as replacement cooking systems for conventional ovens and hobs. Temperature-controlled microwave ovens should offer consumers a shorter pay-back period, and thus the investment should be worthwhile for caterers, especially if re-heating pre-cooked foods is a prevalent practice (e.g. as in snack bars, cafes or finishing kitchens), provided that they make efforts to ensure that the ovens are always well filled.

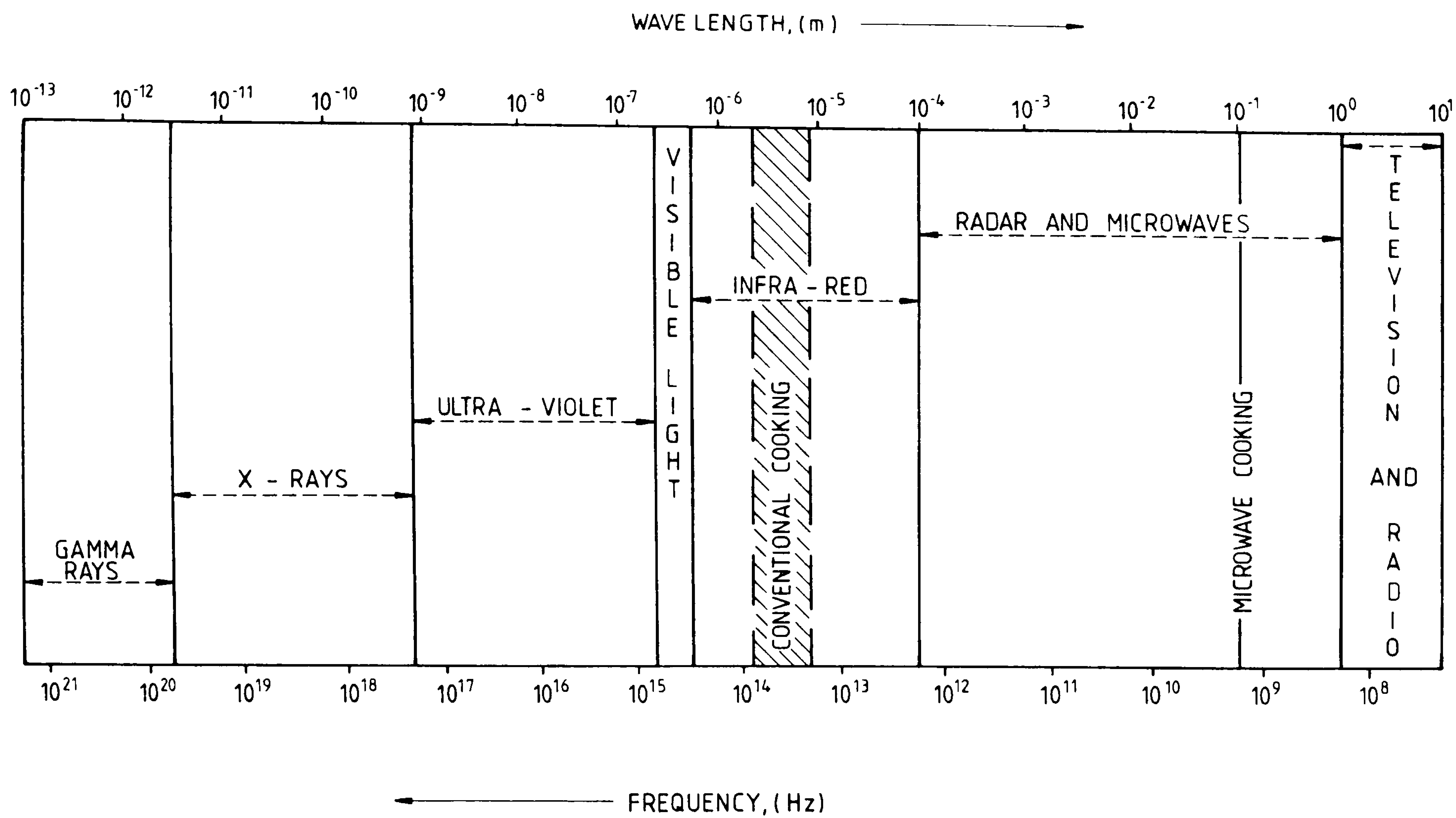


Fig. 15 The electromagnetic spectrum.

GRILLING, GRIDDLING AND FRYING EQUIPMENT

Many cooking appliances exist for performing the rapid heating that characterises frying and grilling operations. The recent trend towards 'fast food' has increased the demand placed on such systems. Unfortunately unless they are used in an energy-wise manner, they can all be highly energy profligate. In order to limit energy expenditures when cooking in a shallow-fat frying pan, under a grill or on a griddle, the food should be turned over frequently. Double-sided grilling equipment, direct resistance-heating grills, fan-assisted grills and deep-fat fryers can be used to avoid this labour-intensive operation of 'turning over' , although in culinary terms the food is then usually slightly different from that prepared by more conventional techniques (e.g. nutritional losses, colour changes and smoke emissions are reduced). However, the financial benefits (due to reduced energy and time requirements) for the caterer may be significant if he chooses such alternative cooking systems. A given temperature at the centre of a food item can be achieved by double-sided grilling approximately 20% and 50% faster than when cooking by deep-fat frying and single-sided frying respectively (Bengtsson and Dagerskog, 1977). Furthermore, direct resistance-heating can be advantageous in energy terms, e.g. Smokaroma Inc. (1986) described a small burger-cooking appliance which allegedly reduces energy consumptions by up to 90% when compared with more conventional grills/griddles.

Conventional electric grills tend to be inefficient (see Table 14), although substantial energy savings can be achieved, when cooking small quantities, if a dual-circuit element is employed. Fan-assisted electric grills facilitate achieving significant savings mainly because (i) the grill-door has to be closed during cooking, and (ii) energy is not wasted during the otherwise necessary operation of turning the food over. (The latter may be achieved in conventional grills, simply by fitting heaters at the top and base of the compartment). Generally, fan-assisted grills, griddles, infra-red grills, double-sided contact grills, toasters and low thermal-mass gas grills are preferable to conventional electric grills with respect to energy thrift. However the energy efficiencies of most electric grilling and toasting appliances could be increased significantly if (i) thermal leaks from the cooking zones to their external casings are inhibited, (ii) convective air-flows between the heaters and the food are suppressed, and (iii) the designs of the reflectors behind the radiation emitters are optimised (Newborough et al, 1987).

Tests undertaken by Flood and Enga (1983) indicated that gas griddles used about 8% less energy than gas grills for similar tasks, although the ubiquitous gas grill was improved if a 'duplex' burner control (which permits the use of only 50% of the grill-burner when cooking small quantities) was fitted. If the surface of a griddle is segmented, each segment being reserved for one type of food and controlled by its own thermostat, then a variety of items can be cooked simultaneously and hence relatively efficiently: this is particularly advantageous for the caterer who needs to cook only a few of each of a wide variety of foods. Furthermore, the underside of a griddle's heating system should be properly insulated and its cooking-surface should be of low-emissivity (e.g. steel plated with a thick coating of trivalent chromium) to reduce radiative heat losses at typical cooking temperatures (i.e. 120-200 °C). The use of an insulated lid to reduce heat losses during pre-heating and cooking is desirable provided that it does not affect adversely the culinary quality of the food produced. Sometimes quartz heaters are fitted to the undersides of griddle lids so that the conductive heating achieved by the griddle can be supplemented by radiative warming from above: reductions in cooking periods and operating temperatures are thereby achievable. A cooking range offering a thermally well-designed oven, hob and griddle may, in particular, benefit the energy-conscious operator of a small kitchen, partly because each section is likely to be fully utilised when in operation.

From an energy-thrift perspective, a thin-based low thermal-mass griddle is preferable, but the variation of temperature across its cooking surface may be great enough to present problems when griddling many similar foods. In order to improve the temperature uniformity across the cooking surface, 'vapour chamber' griddles (e.g. see Fig. 16), which exploit the principle of the heat pipe, have been developed (Basiulis, 1973). These require about 10% less energy per cooking operation than conventional gas or electric griddles and provide a cooking area of near-uniform surface temperature, i.e. typically uniform to < ±3 °C compared with < ±17 °C and < ±30 °C for modern and traditional electric griddles respectively (Schoman, 1960; Roberts et al, 1980). Further benefits may be achieved if the uniformity of power input across the heated area of the cooking surface (or heat pipes), as provided by the high-temperature heating system, is improved. Andersson (1985) indicated that a prototype low thermal-mass 'heat-foil' griddle (which utilised 0.5mm thick foil heating elements) achieved substantially reduced pre-heat and surface-temperature recovery periods when compared with conventional griddles (see Fig. 17). Alternatively, the development of an 'induction griddle', which generates heat uniformly in a semi-insulated ferromagnetic plate, attached either directly to the cooking surface or to the underside of the heat-pipe in a vapour-chamber griddle, may be worthwhile. Lampi et al (1980) suggested that the cooking facilities in a kitchen could operate on an enclosed heat-pipe network, supplied by a central heat source. Each branch of the network (i.e. for the griddle, fryer or oven) would be supplied (as required) with hot vapour, which would

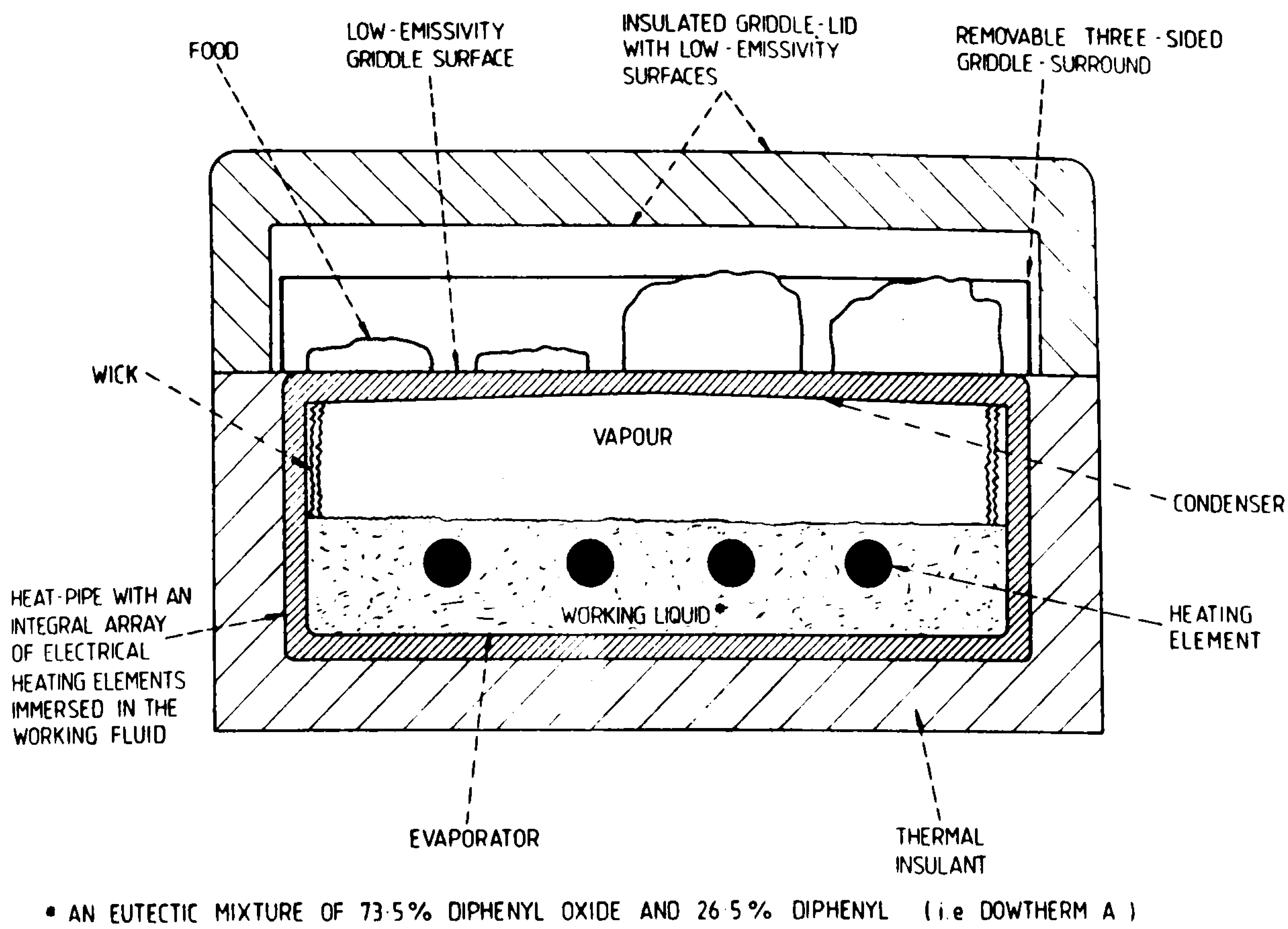


Fig. 16 A schematic cross-sectional view of a thermally-insulated vapour-chamber griddle with a fitting lid : the system achieves an almost uniform cooking-surface temperature.

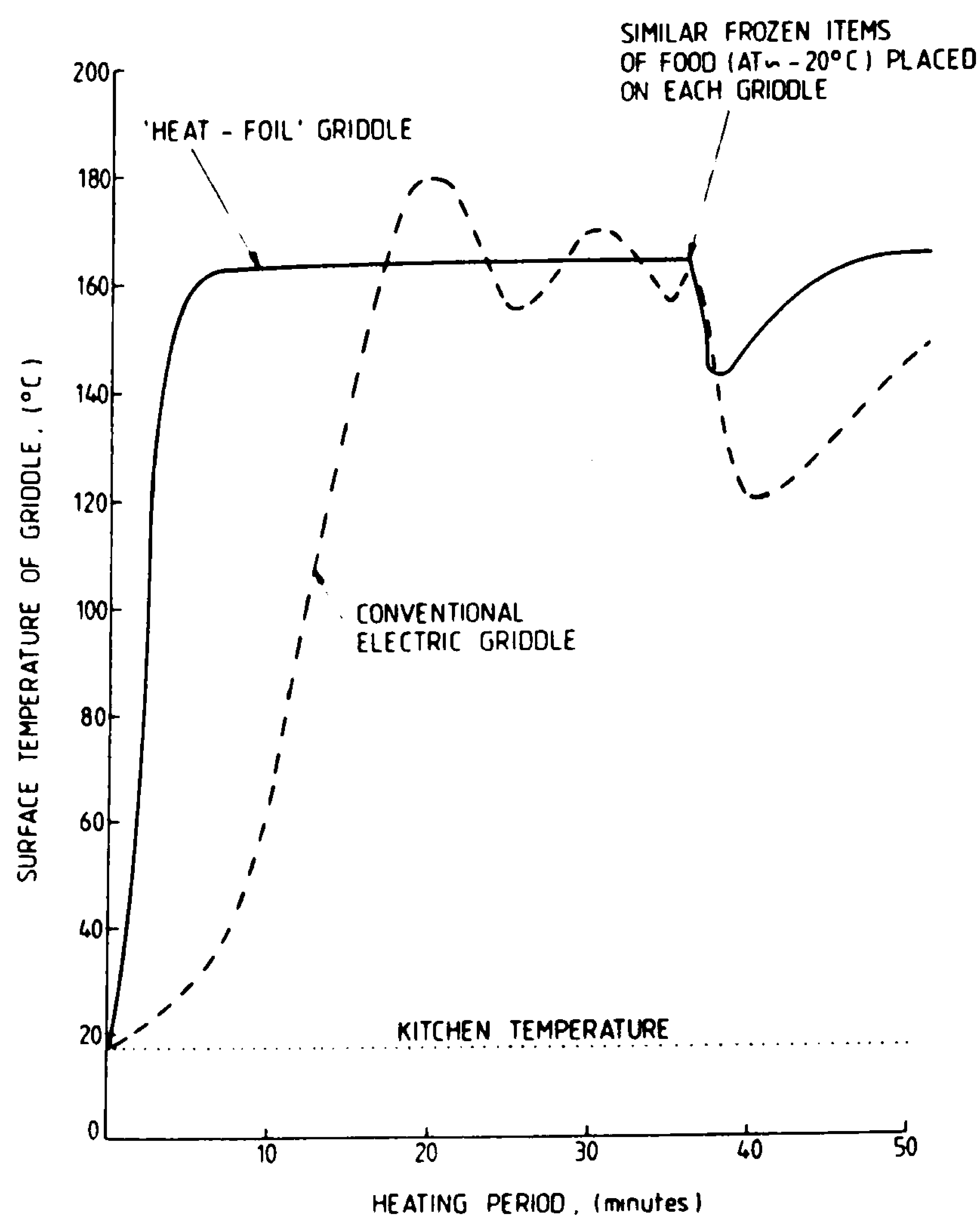


Fig. 17 The rapid thermal response of a prototype, low thermal mass griddle compared with that of a conventional electric griddle (Andersson, 1985).

then condense on the absorbing sides of the cooking surfaces - the condensate being subsequently returned to the heat source.

When compared with conventional gas grills, gas-fired infra-red grills (in which usually the burners heat a perforated ceramic sheet, so that this may re-radiate heat onto the underlying food) are alleged to reduce cooking and pre-heat periods by about 50% and 95% repectively. Electric versions utilise rapid-response infra-red quartz tubes, which when compared with conventional electric grilling and toasting equipment, achieve 10-75% energy savings according to the food being cooked and its required cooking period. The overall efficiencies of these infra-red appliances are likely to be similar, although the continuous heat input to the kitchen during cooking from the electrically-heated version will probably be significantly less. Both devices lend themselves to the adoption of simple control systems, which ensure that the power supply is terminated immediately the grill pan is removed (i.e. so that heat is supplied only when and where required). Furthermore, the temperatures of the top and bottom heating-elements in some infra-red cooking systems (especially those which involve a conveyor system to facilitate production of many similar food items of near identical quality) can be controlled independently (Hussman-CTX, 1986) : this is advantageous when determining the optimal means of grilling foods. However, if these appliances are under-insulated or their reflective internal surfaces deteriorate, the associated heat losses can be excessive, when compared with, for example, ovens and griddles, because cooking-zone temperatures of up to 400°C are achievable. The use of rotisseries (which may be designed to incorporate heat pipes) in infra-red ovens/grills should be encouraged, although if items are being cooked via this technique to attract custom (e.g. as in spit-roasting systems), then the glass doors should be double- or triple-glazed, and fitted with interstitial perforated radiation reflectors.

Fryers

Foods can be fried by either (i) total or (ii) partial immersion in oil at temperatures between 150 °C and 200°C. Thermostatically-controlled deep-fat fryers with lids and 'cool zones' above their bases, (which allow waste-food particles to collect where it is too cool for them to carbonise and so degrade the cooking oil - see Fig. 18), or conveyorised fryers are usually employed to accomplish process (i), and large frying pans, griddles and bratt pans utilised for achieving process (ii). It is desirable to display the mean temperature of the fat during cooking, because strictly the user must not allow this to fall below 150°C when the fryer is loaded with food, if excessive fat absorption by items during the prolonged cooking period is to be prevented. In order to reduce the energy consumption and the rate of degradation of the oil due to the attainment of high temperatures, it is desirable to employ fryers with accurate fail-safe control systems which incorporate thermoelectric, rather than traditional thermomechanical, temperature sensors). On no account should cooking fats be allowed to reach their 'smoke' points: these are mainly in the range 220-245°C for frying oils.

Due to the relatively high temperature of the contained cooking medium, a deep-fat fryer offers the opportunity to cook foods rapidly, e.g. 'fried potatoes' or frozen chips can be cooked in about six and two minutes respectively. Energy savings may be achieved by substituting fried items for boiled items, although Collison and Wilson (1977) reported that usually energy could be used more effectively by baking potatoes at low temperatures in a forced-convection oven (see Table 15). However, it should be remembered that when items of identical mass and volume are fried or baked instead of boiled, the required cooking periods may be greater. This is because the presence of (predominantly steam and carbon dioxide) boundary layers (around the food) reduce the rates of heat transfer to the food. For example, according to Dunning (1953), shortly after being immersed in (i) oil (at 190.6 °C), or (ii) air (at 110.0 °C), potatoes formed surrounding boundary layers, which reduced their respective superficial thermal-conductances to about 17% and 12% of that measured for a nominally-identical potato when it was heated in boiling water (at 100 °C). From this, two fundamental energy-thrift cooking practices (Probert and Newborough, 1985) can be identified :- (i) ensure that the foods to be cooked have a large ratio of surface area-to-volume, and (ii) stir the (non-boiling) fluids used for cooking.

A fryer which provides a high rate of heat input per unit volume of fat employed is usually preferred, but often low efficiencies are tolerated because the appliance has very little (if any) thermal insulation. To reduce (i) evaporative losses and (ii) the rate of fat degradation (Pyke, 1974), 'pressure fryers', which operate at lower temperatures (e.g. 115 °C to 165°C) with an internal pressure of 60 kNm^{-2} to 230 kNm^{-2} above atmospheric during cooking, are becoming increasingly popular. These hold the steam expressed from within the food under excess pressure, so that the oil is forced into closer contact with the food. When compared with the performances of conventional fryers with fitted lids, Avery (1985) reported that the pressure fryers reduced cooking periods by about 13%, although manufacturers often claim at least 30%. Automatic, microprocessor-controlled pressure fryers are highly desirable, because (i) the heating periods and cooking temperatures can be controlled automatically according to the cooking demand (i.e the temperature of the fat after the food has been loaded into the fryer); (ii) the power supply is reduced/terminated automatically during non-demand periods; and (iii) such fryers eliminate any possibilities of the fat igniting due to mis-management. Dwyer et al (1977) indicated the advantages, in energy terms, of frying thawed foods in specific-purpose pressure fryers, as occurs in many fast-food outlets, rather than heating pre-cooked frozen food in conventional multi-purpose fryers as commonly employed in cafeteria (see Table 4).

Considerable savings can be achieved by improving the designs of deep-fat fryers. For example, Avery (1974) reported that a 25% reduction in power input was achieved when fryers fitted in the kitchens of certain US Navy submarines were insulated properly. Further to this, reductions in cooking periods of up to 17% were achieved by covering the hot fat during cooking. However scope still exists for increasing the efficiencies of conventional fryers (e.g. see Fig. 18) by :-

i) utilising an alternative to the often impractical fryer-lid to inhibit evaporative heat losses and oxidation of the oil during both cooking and non-cooking periods, (e.g. by floating a blanket of sufficiently large hollow ceramic balls on the surface of the oil); and

ii) developing heating systems which ensure more uniform heating of the oil.

The tilting skillet or bratt pan (see Fig. 19) is a commonly-employed device because of its versatility: it may be used for shallow-frying, griddling, braising or boiling large quantities of foods. Unfortunately the most common design is inherently inefficient with respect to energy use: a large uninsulated, metal cooking box with a heated base and a lid which often needs to be open during cooking, is an energy-profligate appliance. Therefore bratt pans should (i) be properly insulated, and (ii) offer the facility to use only a portion of the base (and its heater) when cooking small quantities. Where feasible, reductions in energy usage can be achieved by ensuring that the appliance's lid is shut. For example, when their lids were closed, a 7.4kW electric bratt pan and a 33.4kW (including that dissipated by the continuously operating integral pilot light) gas-fired version, achieved energy savings of 8.6% and 5.1% respectively, for pre-heating to a cooking surface temperature of 177°C, and maintaining this temperature for a period of one hour without any food being placed on the cooking surface (Market Forge, 1982). As with all frying equipment, it is particularly important for the cook to ensure that, when in operation, these appliances are well filled with food, because the demands placed on the electricity or gas supplies during heating are high.

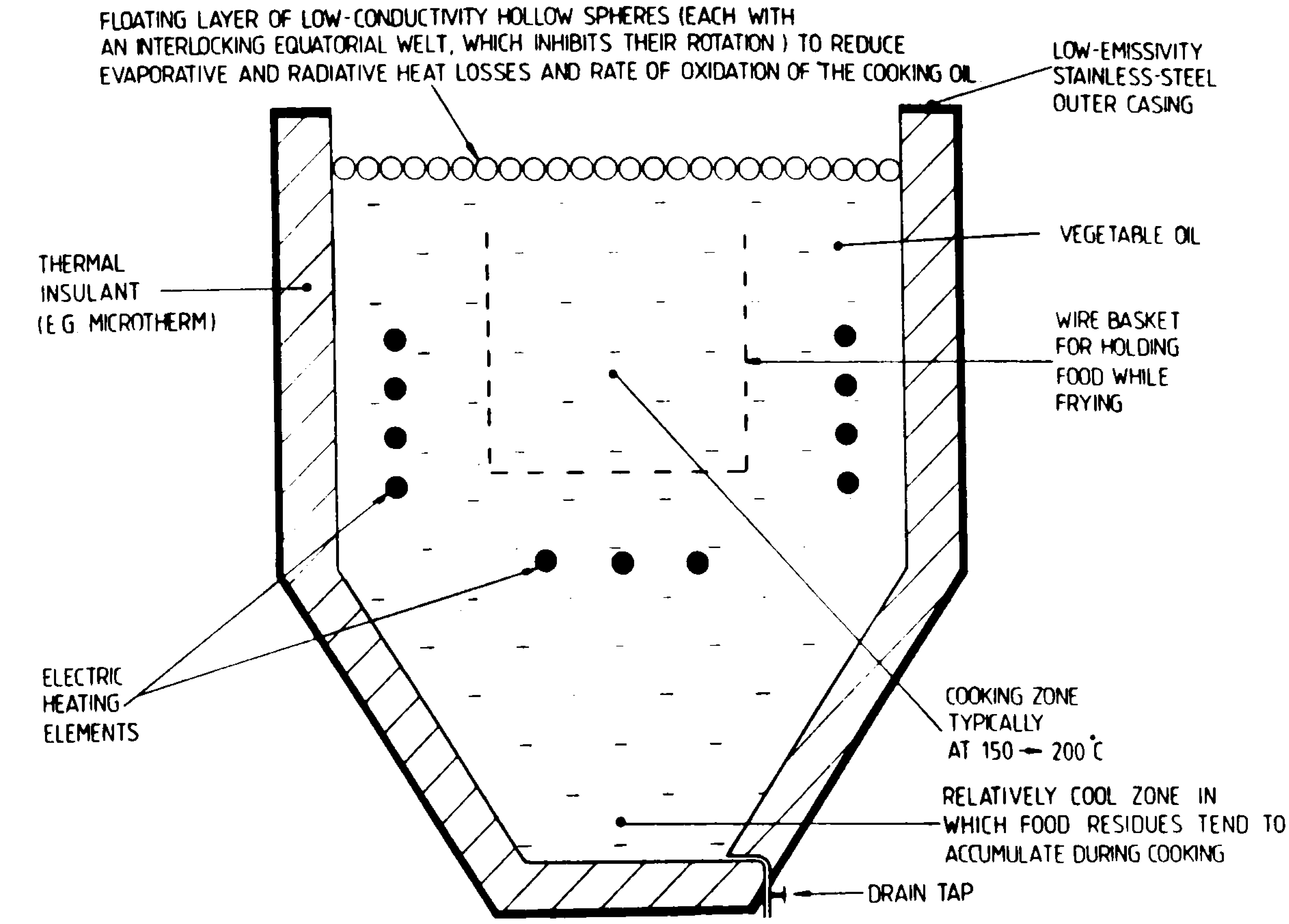


Fig. 18 A schematic cross-sectional view of a thermally-insulated electrically-heated deep-fat fryer.

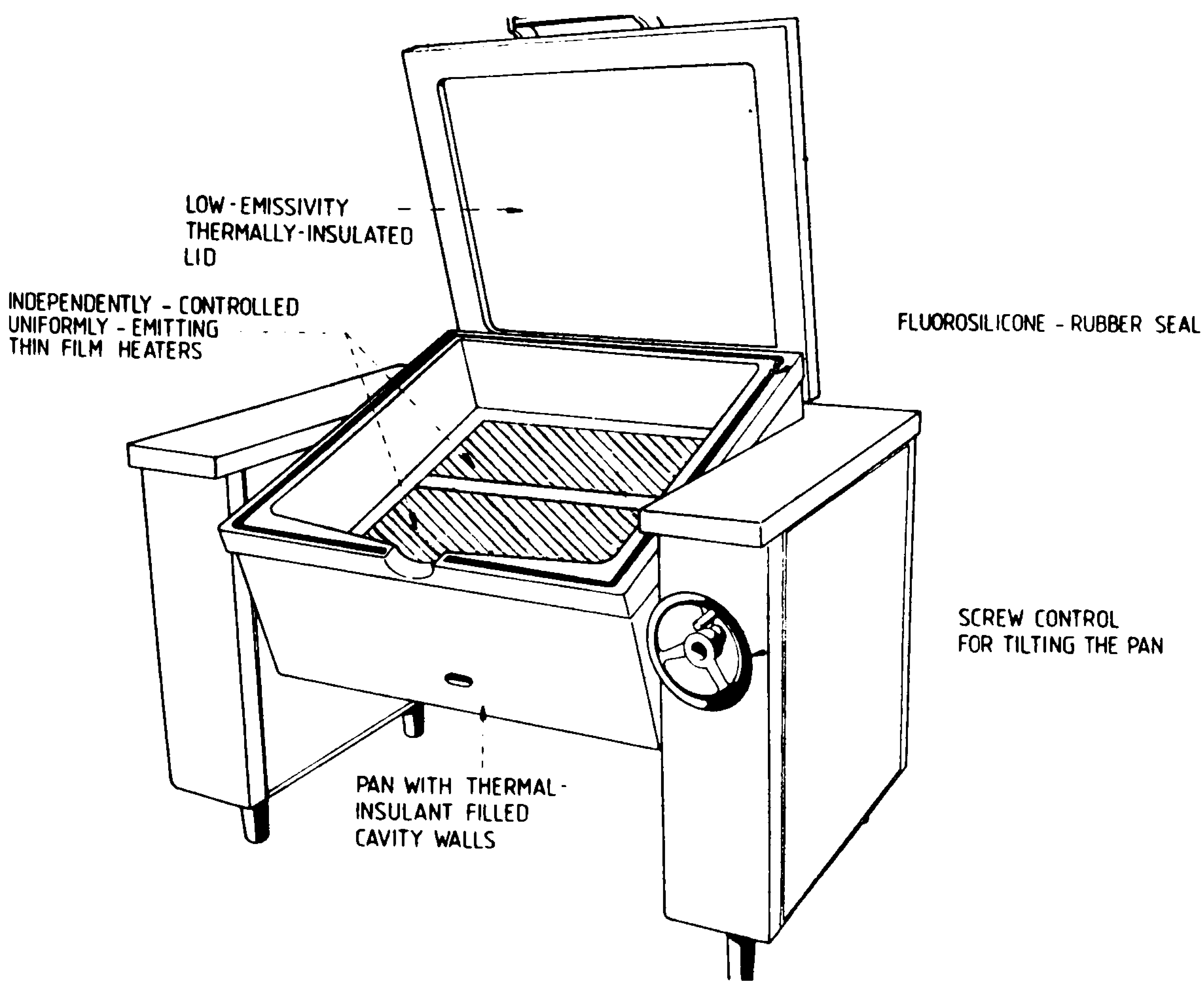


Fig. 19 A typical bratt pan, which has been modified to include some simple energy-thrift features.

PRESSURE COOKING AND STEAM HEATING EQUIPMENT

Heating foods via oil, water or steam, maintained at a higher than atmospheric pressure will usually reduce energy consumptions significantly and shorten cooking periods (by up to 75% in the case of a conventional domestic pressure cooker). Thus the use of these techniques allows foods to be prepared just prior to the serving time: such a practice reduces 'food-holding' requirements. Furthermore, when cooking under pressure and/or in steam, the food's dimensions, flavour, colour and nutrients are retained much better than when cooking by more traditional techniques. Although items cannot be browned via steam-cooking, this type of heating can be employed for pre-cooking foods rapidly before they are placed in an oven or under a grill for finishing purposes. Nevertheless, if steam-cooking systems develop leaks, or condensate and air are not vented away adequately, their efficiencies can be reduced drastically.

'Pressure steamers' - e.g. see Fig. 20(b) - which operate above atmospheric pressure can be employed for rapid cooking: the consequential reductions in energy consumptions, work loads and floor space (compared with using hobs and ovens) are substantial. An often quoted disadvantage for the cook, when using these appliances, is that food cannot be viewed during cooking. However because the thermal response of the cooking medium is virtually constant for similar cooking loads, the necessary period for heating is well defined and so consistent results should be achieved easily.

Pressure steamers are characteristically more energy efficient than 'pressureless steamers' (Unklesbay and Unklesbay, 1982). The latter can only facilitate cooking at 100°C, whereas temperatures of up to 121 °C are achievable with standard pressure-steamers. Because pressurized cooking compartments are sealed, only a relatively small mass of water needs to be converted to (and maintained as) steam for food-heating purposes. Conversely pressureless steamers require a constant mass-flow of dry steam, which is usually circulated around the cooking compartment by means of a fan. Unfortunately, air trapped within a pressurized cooking system will tend to reduce the convective heat-transfer coefficient associated with the food/fluid interface. However, because the temperature of the steam is high, the overall heating effectiveness is usually improved (see Table 17).

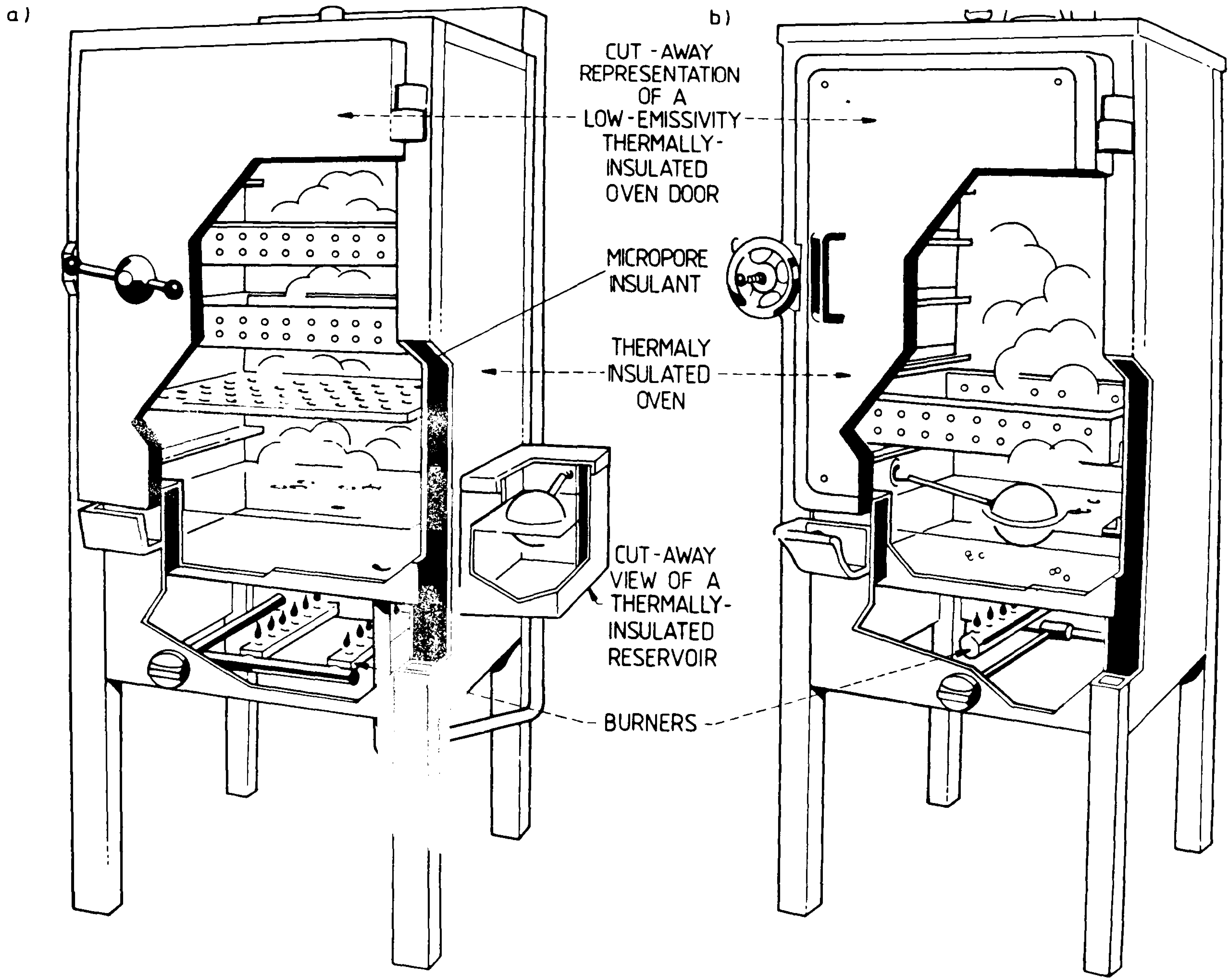


Fig. 20 Thermally-insulated self-contained gas-fired steaming-ovens operating at (a) atmospheric pressure, and (b) about twice atmospheric pressure respectively.

TABLE 17

A comparison of time, electricity and water expenditures for 'pressure-less' and 'pressure' steamers when used to cook 10.2kg of frozen mixed-vegetables (Hobart Corp., 1982).

Appliance*	Mass of water required, (kg)	Electricity consumption, (MJ)	Cooking period required, (min.)
Pressure Steamer	4.0	10.8	10.2
Pressure-less Steamer	7.5	16.2	15.4

* Both appliances had an integral means of generating steam.

'Steam-jacketed kettles' can be used to cook vegetables, stews, sauces and hot-cereals, although the culinary quality of certain individually-large items (e.g. potatoes) thereby prepared may be poor if the temperature gradient between the heated sides of the kettle and the internal temperature of the food is too great initially. Because dry steam, usually at a temperature of up to 143°C (depending on its pressure) is circulated around the sealed walls of the kettle, it can heat large quantities rapidly and reduce the problems of sticking or burning-on associated with conventionally-heated 'boiling pans'. Harrod et al (1984) reported typical horizontal and vertical temperature variations of less than 4 °C and 1°C respectively for near-boiling water when heated in an efficient steam-jacketed kettle. However, they indicated that (i) the aspect ratio (i.e. height to diameter) for the kettle was critical if uniform convective mixing was to be achieved, and (ii) the accumulation of condensate at the base of the heated cavity was the major cause of the prolonged heating times (i.e. extended by 40-100%) which characterised many steam kettles in Swedish kitchens.

If the steam kettle is thermally-insulated and fitted with a lid, typical respective energy savings of about 50% and 25% are achievable (Avery, 1986). However when the appliance is not fitted with a thermostatic control, large quantities of steam (emanating from the food and its cooking medium) are likely to enter the kitchen environment. Therefore a means for ensuring that foods can be simmered in a steam kettle should always be fitted. If this practice is adopted widely, cooks will probably need to adjust the amounts of water they use to 'boil' vegetables. Traditionally, enough water was added to compensate for substantial evaporative losses (which resulted from maintaining the cooking water at its boiling temperature), so that a sufficient quantity of nutrient-rich water remained after cooking for preparing the required amount of gravy. Thus the amount of water added initially for cooking vegetables should be reduced, because otherwise hot-water may have to be drained away or 'boiled-off'.(Unless essential to the quality of the end-product, the latter activity represents a most undesirable and profligate waste of energy!).

The steam for heating cooking appliances is usually generated from (i) an integral, heated reservoir of water; or (ii) the boiler plant associated with the kitchen. Use of the latter type of steam-driven catering appliance occurs especially in kitchens serving large manufacturing industries and institutions. The self-contained versions enable a more effective use of energy to be achieved, e.g. a 176 litre steam-kettle (supplied by a separate 24kW electric boiler) required 31.9% more energy to boil 145 litres of cold water, than one of identical capacity but with a built-in 24kW steam generator (Dover Corp., 1982).

'FOOD-HOLDING' DEVICES and CONTINUOUS-COOKING SYSTEMS

Keeping cooked food warm for long periods should be avoided because this lowers the organoleptic and nutritional qualities of the product, and increases the kitchen's overall energy requirement. Ideally the food should be served immediately after it is cooked (i.e. the rate of production should exactly equal the rate of consumption by diners). However, holding periods of up to 7.5 hours have been cited (Holynski et al, 1984). When already-cooked items need to be maintained at acceptable above-ambient temperatures, i.e. above 65 ^{o}C, it is logical to use only well-insulated devices which can hold and/or despatch food without incurring substantial heat losses (De Fielliettaz Goethart et al, 1980). Unfortunately, because too little thermal insulation is applied to most current designs of hot cupboard and bain marie (e.g. see Fig 21), high rates of heat loss are incurred whilst the food is being kept warm. It is particularly desirable for food-holding units to be provided with time switches to prevent the common practice of switching them on too early. Properly-designed food-holding appliances would reduce pre-heat periods, as well as the continuous heat input required to maintain the food at a chosen temperature. Indeed an easily-sealed, highly-insulated, 'hot-box' with no internal heating system may satisfy many food-holding requirements, provided that the food is taken from the cooking equipment and placed in the hot-box immediately.

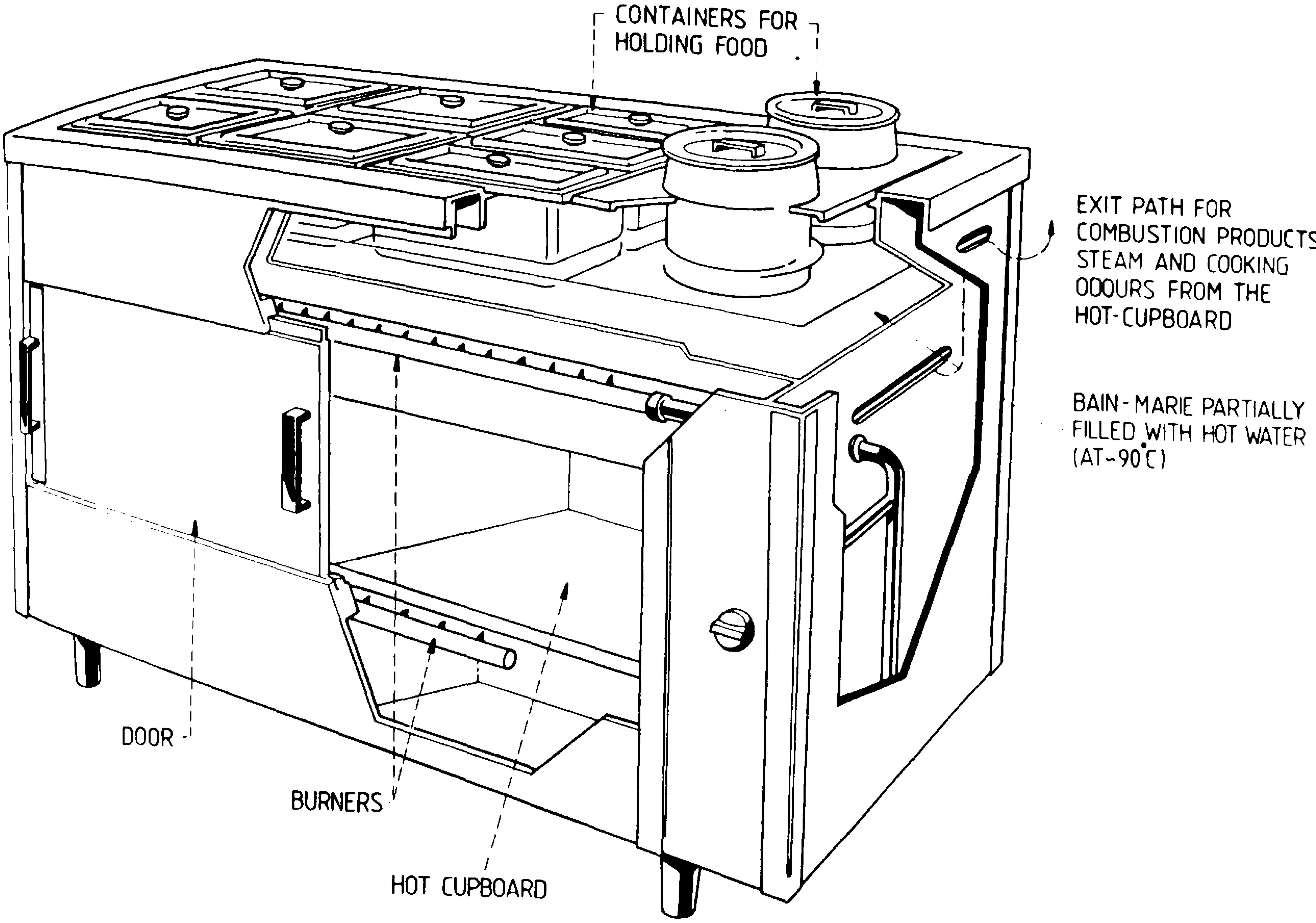


Fig. 21 A conventional gas-fired hot-cupboard supporting a 'closed-top' bain-marie.

To reduce energy expenditures, mass-production techniques can be applied in large kitchens. During meal times, such kitchens are characterised by a demand curve similar to that shown in Fig. 22(a): traditionally, all the food likely to be consumed is cooked before the start of the eating period, and the various constituents are kept warm until required. Hu et al (1978) reported that the staff of one military dining facility, who started to prepare breakfast at 4.15 a.m., switched on all the equipment likely to be used for preparing that meal at 3.00 a.m., including two conveyor toasters which were not used until 2.15 p.m! Similarly, many industrial-catering facilities still operate with a schedule which allows lunch-time meals to be prepared by about 10 a.m. (Batty et al, 1987). However, properly organised kitchens tend to keep food warm for minutes rather than hours, but even then energy expenditures and nutrient losses incurred during food-holding periods can be excessive. The total amount of food required can be cooked more economically in several batches under strictly-controlled conditions (Cutcliffe and Strank, 1971) - e.g. see Figs 22(b) and 23. In order to simplify planning, and avoid complicating the kitchen activities, specific purpose continuous-cooking equipment can be employed to cook and despatch large quantities of food in very small batches continuously (see Fig. 24). Such systems are particularly suitable for centralised food-production units.

If used properly, the continuous cooker eliminates the need to keep food warm (Fischer, 1977). Also cooking periods can be reduced

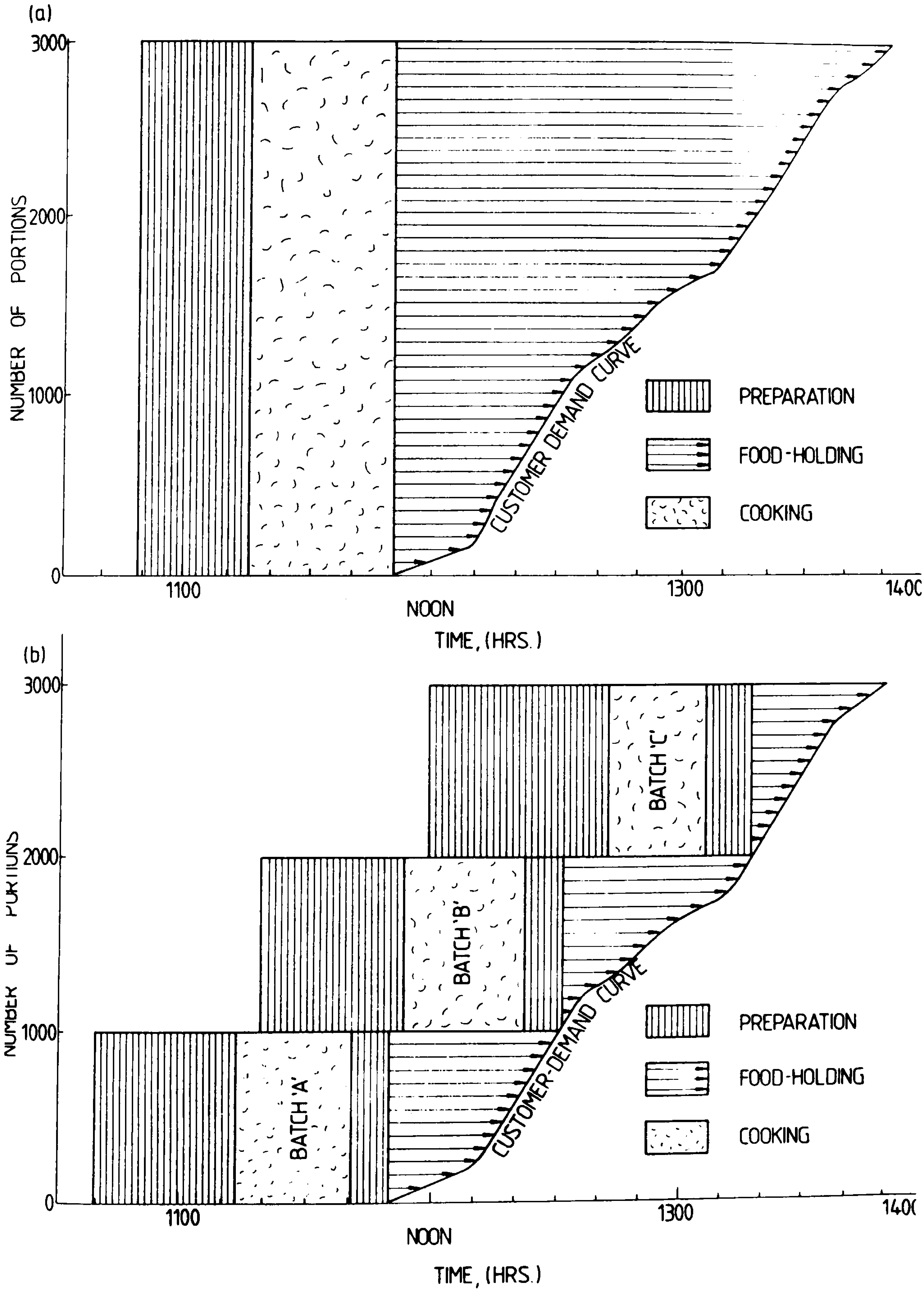


Fig. 22 Diagrammatic representations of cooking and food-holding demands for kitchens preparing identical meals via (a) traditional single-batch cooking, and (b) multi-batch cooking (adapted from Fischer, 1977).

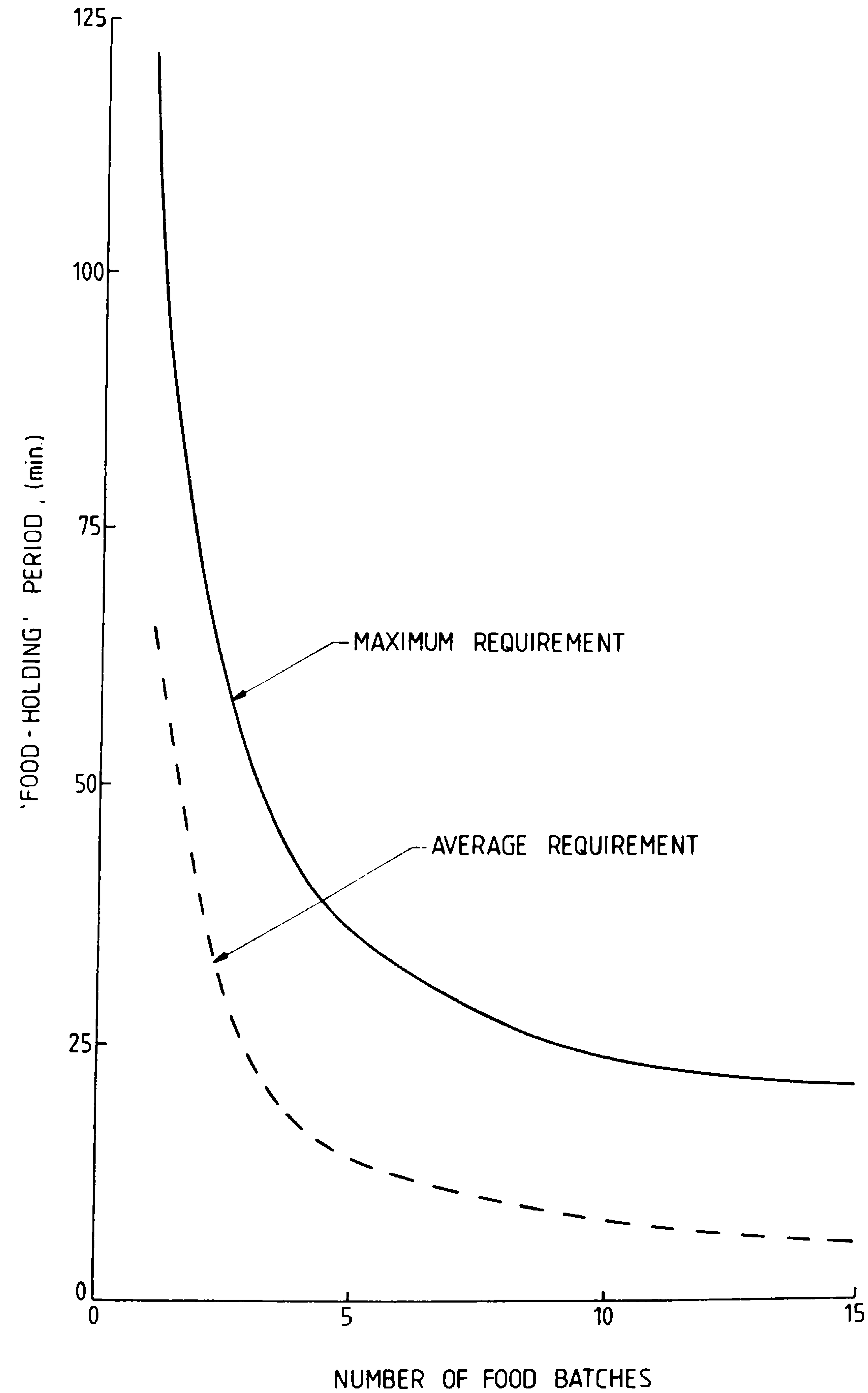


Fig. 23 A relationship between the typical average and maximum food-holding periods required (for one kitchen) and the number of batches of food cooked during meal production (Fischer, 1977).

primarily because each similar portion of a particular food has a near identical temperature-time history when cooked. This overcomes the situations that arise traditionally when, for example, staff try to cook uniformly large quantities of vegetables. If simmered in a boiling pan, or in a jacketed kettle supplied with high temperature steam, the vegetables closest to the heat source tend to be cooked before those near the centre of the vessel. Thus, they need to be stirred occasionally (which if done manually increases evaporative heat losses and possibly damages the food) to ensure that the end-products are cooked evenly. Therefore food quality can be improved, and power dissipations per food portion reduced to a near-constant level during cooking, by using continuous cooker systems instead of conventional ovens, grills, fryers, steamers and boiling apparatus. The installation of a continuous fryer to replace 30 conventional fryers in one large kitchen, reduced labour requirements and cooking periods by about 90% and 62% respectively (Scott-Smith, 1981). Furthermore, Unklesbay and Unklesbay (1982) reported that the peak energy demand of a continuous steamer was only 66% of that for a group of steam-jacketed kettles employed for preparing the same amount of similar food : a heat saving of 1.06 GJ was achieved over the cumulative two-hour cooking period!

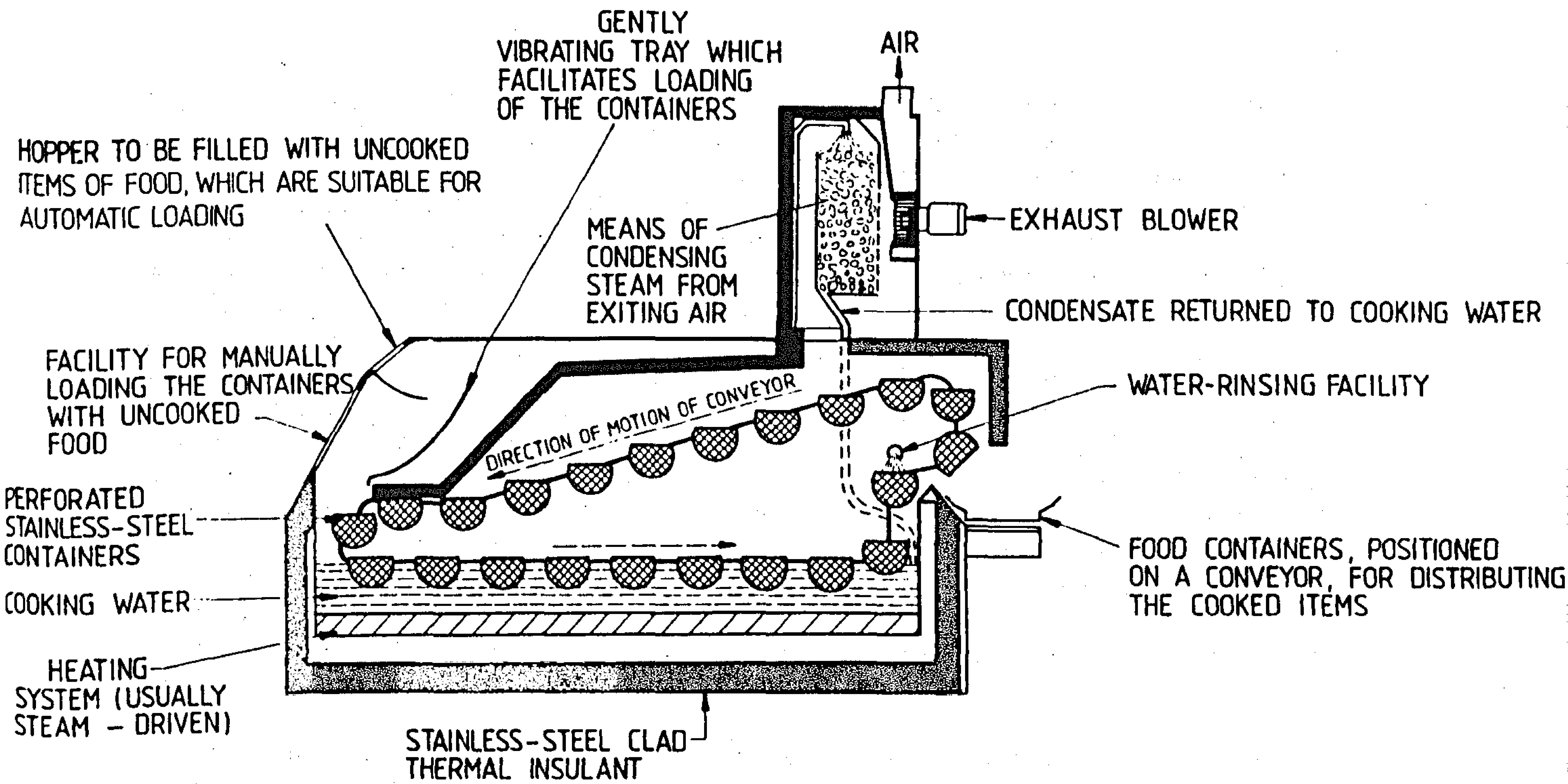


Fig. 24 A continuous cooker system for boiling foods in small quantities (adapted from Fischer, 1977).

MISCELLANEOUS CATERING EQUIPMENT

The widespread introduction of utensil-washing machines into kitchens during the last 30 years has reduced the catering industry's labour costs and improved the levels of hygiene considerably (Poledor, 1980), but raised its annual energy bill. Typical traditional dish-washers tended to operate with end-use efficiencies of only about 25% (Stierlen-Maquet, 1985). Recently, increasing the energy efficiencies of these appliances has become a major concern for some equipment manufacturers. Energy-saving control systems which, for example, ensure that the booster-heater (for the hot-water supply) and the exhaust blower associated with the dish-washer are only energised when a dish rack resides in the machine have been widely fitted: they often achieve pay-back periods of only about 6 months (Scriven and Stevens, 1982). Also, insulated dish-washing machines with integral heat-recovery systems (e.g. heat pipes and heat pumps) and facilities to re-circulate and re-use water are now available: investments in these usually achieve pay-back within two years (Harvey, 1982; Stroder, 1982; Skroder, 1985 Stierlen-Maquet, 1985; Hobart, 1986). Once much of the heat from the high-temperature waste-water has been extracted, it is desirable to pipe the water to the automatic refuse-disposal facility (if fitted) to reduce the fresh water requirement.

The use of water softening agents and lower temperature detergents for cleaning purposes, in order to eliminate the need for booster-heaters in the dish-washing zone, is recommended. However, utensil-washing machines which operate at low temperatures, usually require an integral means of drying the items (once they have been washed) with hot air. To some extent, this counteracts the benefits in energy terms of low-temperature washing/rinsing, although scope may exist for lowering the relative humidity of the utensil-washing zone so that items will dry more rapidly as they leave such equipment.

Thorough rinsing of items with fresh water, as achieved in dish-washers, is preferable to manual washing in sinks, because many detergents are mildly carcinogenic. However where hot water is required for cleaning (or cooking) purposes, it is desirable to use well insulated, thermostatically-controlled, water boilers which provide small quantities (e.g 10-50 litres per hour) of hot water (at about 65°C) and are situated in those areas of greatest need within the kitchen. This should remove the expensive requirement for keeping a large quantity of water or steam at high temperatures, often in a relatively distant boiler (and the intermediate piping), and encourage staff to employ hot-water supplies more prudently. Furthermore, because catering establishments characteristically expend large amounts of energy for heating water, the feasibility of employing solar pre-heating systems to reduce annual energy costs should be investigated. Fortunately many industrial catering facilities have flat roofs which are well suited to the application of evacuated-tube solar collectors for water-heating purposes.

The heat input to zones within a kitchen by refrigeration equipment has tended to grow in recent years, as frozen convenience foods have become increasingly popular. Although the instantaneous heat input from refrigeration equipment is usually much smaller than that of cooking equipment, the total annual dissipation of cold-storage devices within a kitchen can be significant, because they are in use continuously. Unfortunately this form of space heating is only useful in cold weather during low-demand periods. It may be better utilised elsewhere (e.g. for space-heating the dining room or pre-heating water supplies). Often parts of the external casings of fridges and freezers are used to dissipate the heat extracted from the food stored therein. Consequently these surfaces are at above-ambient temperatures and so more heat than is necessary re-enters the inner cold environment compartment via the insulant. Often to overcome this, extra insulant is fitted, although it is more desirable to site the condenser (i.e. the heat sink) remotely from the appliance or cold-storage zone. The successful reclamation of heat emitted from the condensers and compressors of refrigeration equipment usually results in significant savings, especially in establishments that require a large refrigerated/frozen storage facility. Typically, pay-back periods for such heat-recovery systems are of the order of 2 years (Forwalter, 1979; Fretton, 1982). As well as achieving operational energy savings, the caterer can then expect the refrigeration equipment to function satisfactorily over a longer period.

Vending machines are being employed increasingly for dispensing hot and cold foods as well as confectionery and beverages. Those which issue hot drinks usually store water at temperatures of nearly 100°C, so that tea can be prepared properly. Unfortunately studies have revealed that many versions employ poorly designed water heating/storage systems, which have unnecessarily large capacities and are often under-insulated: for example, the cladding is often merely 5mm of expanded polystyrene. Because of these factors, the water in many vending machines is maintained at near-boiling temperatures during periods when there is no demand, so that a sufficient rate of hot water can be made available during subsequent (potentially peak demand) periods. In general, although more advanced microprocessor-controlled systems have been developed (including some which have integral microwave cooking facilities and forced-convection heaters to re-heat and brown rapidly the chilled pre-cooked food portions), many of the more common versions, which despatch hot beverages, have been designed without due regard to the effective use of energy. This appears to be a profligate oversight, because about 51% of the total liquid intake of humans in the UK is constituted by hot drinks (Anon., 1985). Such beverages consist mainly of water, which has a relatively specific-high heat capacity, and so a substantial heat input is required during their preparation. For example, an annual input of about 3PJ is required (to satisfy the total hot-liquid consumption of the adult population) assuming that:- (i) evaporative heat losses during preparation are ignored, (ii) the mean specific heat capacity of the liquids consumed is 4.1 kJ $kg^{-1}K^{-1}$, and (iii) the mean temperature rise during heating is 90°C. Thus it would be apposite for designers to attempt to improve the thermal efficiencies of catering appliances (such as vending machines, kettles and urns) which are used to satisfy a significant part of the UK's hot-drinks requirement.

Finally the kitchen design team should consider the relatively small energy consumptions of supplementary kitchen appliances (e.g. automated choppers, potato-chippers, meat saws, slicers and liquidisers). A dearth of reliable data exists concerning the efficiencies of these appliances, and so the following recommendations are suggested:-

* Ensure that integral capacitors are fitted to all large a.c motor-driven appliances if they have power factors of 0.8 or less, so that peak electrical demands can be reduced.

* Select enclosed well-insulated trolleys and urns, especially if they are electrically heated, in order to reduce rates of heat loss.

* Purchase low-emissivity, flat-based, robust, copper, or copper-bottomed stainless-steel pans with tightly-fitting thermally-insulated lids.

Recent evidence suggests that the use of utensils and pans made from aluminium alloys is ill-advised in health terms (Vogt, 1986; Anon., 1986(b); Hodgkinson, 1987). Traditionally, dietary intakes of aluminium have not been regarded as hazardous, although it has long been recognised that, for instance, cooking rhubarb in aluminium saucepans mobilizes significant amounts of aluminium presumably complexed by oxalate. Aluminium appears to be absorbed from the gastrointestinal tract and deposited in the brain and other tissues. If consumers' diets are sufficiently rich in aluminium, several ailments can result including senile dementia - already approximately 300,000 people in the UK suffer from such premature ageing, and hence this represents a tremendous loss of available effort. Zook and Lehman (1965) reported that total diets, comprising of foods bought from different supermarkets in the USA, provided an overall average daily intake of 24.6mg of aluminium per person, with a range of 3.8 to 51.6mg per person: the contribution to typical daily intakes from utensils has been estimated to be about 3.5mg of aluminium per person per day (Greger, 1985). However, when boiling artificially-flourinated water, as is supplied throughout many regions of the UK, excessive quantities of aluminium tend to be absorbed from cooking vessels (Hodgkinson, 1987). Furthermore, some foods contain significant amounts of this element (Coriat and Gillard, 1986): additives, spices and tea appear to be the major dietary contributors (e.g. see Table 18). Several simple precautions suggest themselves: for example, avoid (i) digestion tablets containing soluble aluminium compounds; (ii) vegetables grown in aluminium-rich, acidic, soils and (iii) cooking acidic foods (e.g. apples, rhubarb or cabbage) in aluminum saucepans (Anon., 1986). However, it is especially recommended that universities, hospitals and industrial facilities (which often prefer using cheap aluminium-alloy utensils for catering purposes), should in future limit their employment of aluminium-alloy cooking pots, pans and cutlery.

TABLE 18

Foods with relatively high aluminium contents (adapted from Greger, 1985).

Food	Average aluminium concentration, (mg/100g)
Baking powder	2300
Tea bag (dry)	128
Thyme	75
Oregano	60
Celery seed	46.5
Bay	43.6
Basil	30.8
Cheese, processed	29.7
Salt (with aluminium additives)	16.4
Cocoa	4.5
Pickles	3.92
Bran	1.28

CONCLUSIONS

An energy-thrift strategy should form a fundamental part of the operating policy for any catering organisation that wishes to give value for money and/or maximise its profit. Achieving large energy savings within the food-service industry can be attacked upon three fronts via (i) kitchen design, (ii) equipment design, and (iii) staff practices. Unfortunately, simple economies concerning energy-use, which are practised by individuals in their own homes are often forgotten when someone else is paying the fuel bill. Thus if the operational efficiencies of kitchens are to be maximised, those concerned with designing and operating food-service establishments must take responsibility for the effects that their various actions have on the overall annual energy-consumptions incurred.

A low annual energy bill can only be achieved if the kitchen is well designed. Inadequate thermal design of the building structure, poor lay-out of the catering equipment, stores and utensil-washing section, the fitting of incorrectly sized air-conditioning and boiler plant, the selection of poorly-insulated cooking appliances (with controls which have not been ergonomically designed) and inadequate maintenance of energy-consuming equipment within a kitchen, provide the recipe for inherently high annual energy bills. However, energy-thrift measures (e.g. insulating the building fabric, installing heat-recovery devices and fitting energy control systems), can be 'built in' to the kitchen most effectively if considered at the planning stage. Therefore thorough coherent design analyses are desirable if more energy-efficient catering facilities are to be introduced. In future, the effectiveness with which human effort is utilised by the catering industry will be improved substantially via the introduction of kitchen-design-analysis computer software. This should permit the optimisation (e.g. with respect to minimising the total human movement within the kitchen) of the locations of the work-centres and work zones. Furthermore, once the typical energy consumptions of catering appliances have been determined and published, it will be far easier for equipment-selection teams to choose the most appropriate devices.

Finally, the efforts to reduce operational energy costs made by the kitchen-design and equipment-selection teams must not be undermined by the kitchen management once the food-service facility is in operation. Unfortunately many existing catering managers negate their positive achievements (in terms of negotiating low food prices and maintaining high rates of production) by allowing operatives to mis-use energy supplies. Thus it is essential that the managers appointed to operate the establishment are well trained in strategies that will eradicate energy mis-use (Batty et al, 1987). Only then can the associated energy (and hence financial) savings be maximised, without lowering the quality of the food produced.

APPENDIX 1

ENERGY-THRIFT ANALYSIS OF A TYPICAL INDUSTRIAL CATERING-ESTABLISHMENT

Due to the crude designs of existing kitchen buildings, many problems are encountered when attempting to reduce expenditures on environmental conditioning. The real-life establishment discussed hereinafter highlights several of the characteristic disbenefits of industrial kitchens and canteens. Although current building regulations (Department of the Environment, 1985) would not permit a similar structure to be constructed now, this building (which is approximately 15 years old) was chosen for discussion because it epitomises the results of poor design on thermal performance and energy consumption.

The rear wall of the kitchen separated it from an adjoining factory, while the remaining walls were constructed of single-leaf brickwork and single-glazing. (The latter comprised 36% of the total area of the exposed vertical components of the building envelope). The roof was uninsulated: it was constructed of asphalt on boards over decking and the ceiling was approximately 4m above the floor (i.e. at least one metre higher than it needed to be). The two external porch doors associated with the canteen had been removed to improve access for the diners. Consequently the rates of ambient air infiltration into the building were considerable. Also the kitchen and canteen were not separated, and so regulation of the indoor environment was attempted for the whole building despite the varying demands of the thermally distinct zones contained therein.

In the kitchen, two large ventilation hoods (each extracting air at a constant rate of $\sim$ 1.5 $m^3 s^{-1}$) were situated above the catering appliances. A gas-fired hot-water boiler was used to heat the canteen via two heating coils, which were positioned in the fresh-air 'make-up' blower units. These were fixed just below the ceiling and introduced heated fresh air at a rate of approximately 3 $m^3 s^{-1}$ during periods of cold weather. Thus the total rate of air input to the canteen matched the total rate of extraction from the kitchen, i.e. a significant pressure gradient between the dining area and the kitchen did not exist. Because of this, steam was not discouraged from entering the canteen from the kitchen/servery and so, during cold weather, considerable amounts of condensation formed on the uninsulated domed sky-lights in the roof of the canteen. Unfortunately, during peak-demand periods, condensate then tended to drip down onto the diners. Remedial action had been taken: this involved employing (i) two 3kW electric 'fan-heaters' just beneath, and along opposite sides, of each sky-light which was located close to the servery; and (ii) one 3kW electric fan-heater under each of the remaining sky-lights, which were located further away from the servery. This ensured that water vapour did not condense on any of the skylights (instead it probably condensed on the windows) and eliminated complaints from diners associated with the previously occurring hazard. However the electricity bill for the establishment increased significantly!

Calculations revealed that to maintain an average air temperature of 19°C within the canteen, the average hourly heat losses due to ventilation were approximately 2.5 times greater than those conducted through the building fabric. Thus attempts to reduce the building's overall rate of heat loss by insulating its fabric would result in only slight savings in the annual heating bill. For example, if the transmittance of the roof was reduced to 0.6 $Wm^{-2} K^{-1}$, the annual expenditures on heating would fall by only 6%. The estimated simple pay-back period associated with this energy-saving measure would be 26.5 years!

Evidently the annual heating costs for this building were high primarily because (i) rates of ventilation could not be varied, and (ii) the canteen and kitchen were not separated and ventilated independently. Unless remedial measures are to be implemented, it is unwise to consider employing a waste-heat recovery system for the kitchen's ventilation hoods, because overall heating costs would still be unnecessarily high.

In conclusion, it was evident that the opportunities for improving the thermal performance of this building economically were limited. Unfortunately this situation is not uncommon within the food-service industry (Batty et al, 1987). A low initial construction cost is usually the main parameter considered during the design stage. If the facility needs to be partially or fully refurbished, capital cost appears to be the main criterion considered (vis-à-vis the aforementioned installations of electric heaters to obviate complaints from customers). Little attention appears to be given to the function of the building or the recurrent costs of environmental conditioning and maintenance. Thus it is vital that thermal performance and energy-thrift criteria are considered when initially determining the design of a new catering facility.

APPENDIX 2

ELECTRICITY USAGE FOR OPERATING VAPOUR-COMPRESSION REFRIGERATION EQUIPMENT

Excessive electricity expenditures incurred in refrigerating and freezing foods, will occur unless kitchen designers attempt to set desired targets for the peak-demand requirements of the compressors associated with cold-storage facilities.The amount of heat that needs to be extracted per unit time, when a frozen-food store is loaded with the estimated largest mass of warm food may be deduced as follows:-

Total rate of cooling requirement = [Rate of cooling requirement for food] + [Rates of heat gain via the building fabric, occupants, lights, internal air-moving equipment and opening of doors]

i.e. :-

$$\dot{Q}_c = \dot{Q}_F + (\dot{Q}_M + \dot{Q}_W) \qquad (1)$$

where

$$\dot{Q}_F = \sum_{i=1}^{i=z} \left[\frac{(m_F C_t (T_d - T_f) + m_F LH_F + m_F C_b (T_f - T_s))}{u} \right] \qquad (2)$$

$$\dot{Q} = \frac{N \rho V C_A (T_d - T_s)}{3600} + v\,(n\,a\,\varepsilon\,\sigma (T_r^4 - T_s^4) + \dot{L}) + \dot{M} \qquad (3)$$

The appropriate values for N may be estimated from Fig. 25.

$$\dot{Q}_W = \sum_{j=1}^{j=y} \left[\frac{A\,(T_\infty - T_s)}{(x/k + 1/h_{in} + 1/h_{out})} \right] \qquad (4)$$

or

$$\dot{Q}_W = \sum_{j=1}^{j=y} \left[A_j U_j (T_\infty - T_s) \right] \qquad (5)$$

The peak power required by the compressor(s) may be written as follows:-

$$P_E = \frac{\dot{Q}_c}{COP\,\eta_c'} \quad \text{(in watts)} \qquad (6)$$

or

$$P_V = \frac{\dot{Q}_c}{pf\;COP\,\eta_c'} \quad \text{(in volt-amperes)} \qquad (7)$$

where P_V is measured in volt-amperes.

The simplest way of minimising P_E is to ensure that the food loaded

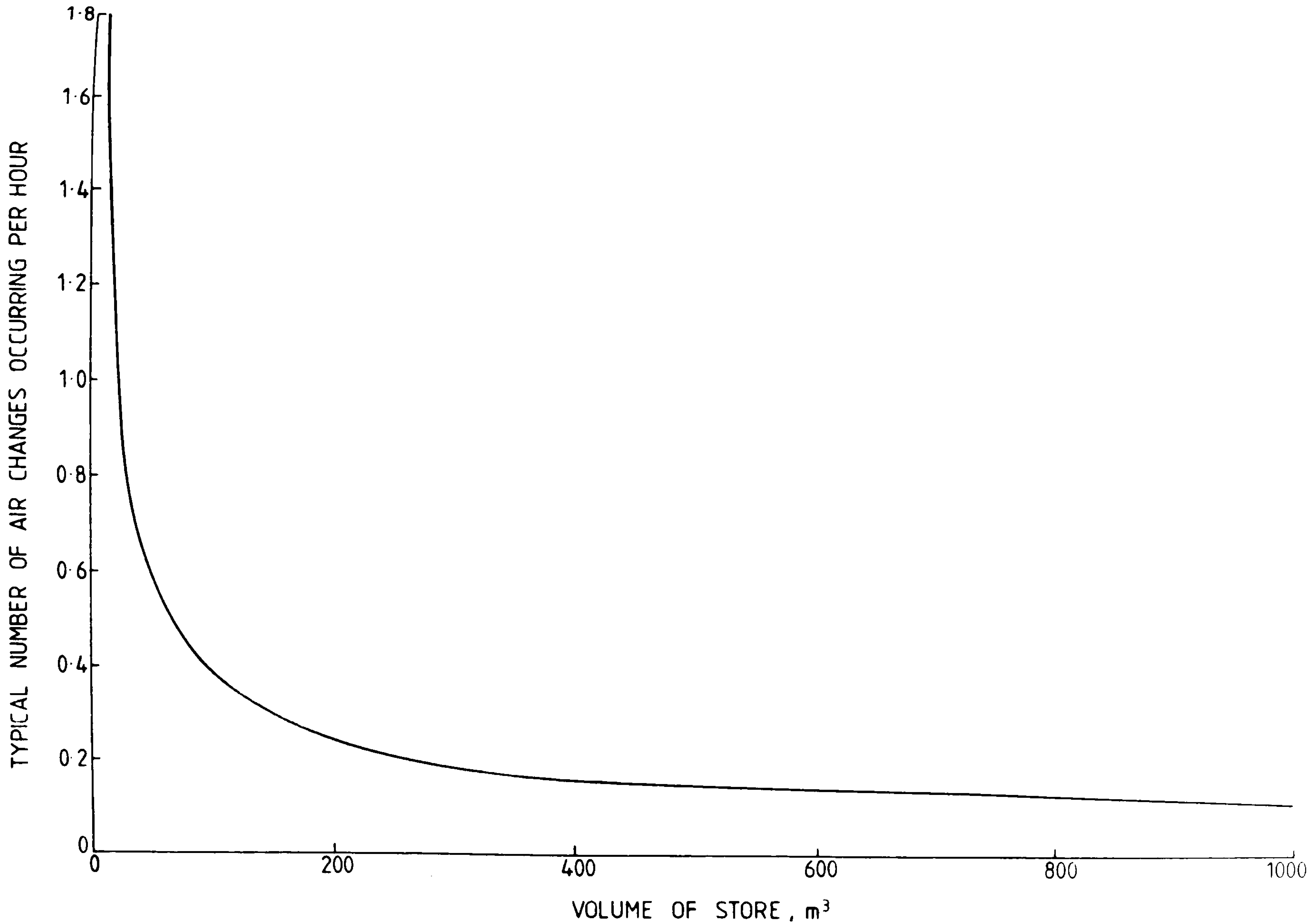


Fig. 25 The approximate relationship between the volume of a cold-store and the number of air changes it incurs when subjected to normal usage (adapted from ASHRAE, 1981).

into the cold-store is at approximately ambient temperature. However this may require that some foods be cooled for prolonged periods in the kitchen after they are cooked. Consequently these items may undergo dangerous or undesirable bacteriological, chemical and nutritional degradations, as well as limit the usable space in the kitchen. Therefore, when determining the peak electrical demand of the refrigeration equipment, $\dot{Q}_F$ should be fixed ; its value being calculated with a view to limiting T_d , m_F and perhaps T_5, and maximising u - see equation (2). However, the primary means of limiting P_E is to reduce $\dot{Q}_W$. This may be achieved in three ways:-

i) reduce the store's surface area-to-volume ratio;
ii) select a suitable thermal insulant, which has a low mean thermal conductivity over the range between the store's typical operating internal temperature and that of the kitchen environment; and
iii) increase the applied thickness of the chosen thermal insulant.

Practical target values for the thermal transmittances of cold stores (at $\sim -20^{\circ}C$), freezers (at $\sim -20^{\circ}C$) and fridges (at $\sim 3\ ^{\circ}C$) are <0.1, <0.15 and <0.3 $Wm^{-2}K^{-1}$ respectively. Attempts to reduce the heat losses via method (i) may be significant. For example, if a cold-store of $45m^3$ capacity is built, with dimensions 2.5m high by 3m wide by 6m long, it incurs heat gains which are approximately 3.2% higher than if it were built of identical height, but of equal width and length. Alternatively, if the storage of items above head-height is permitted, a reduction in heat gains of 6.3% could be achieved by constructing a cubical store of the same internal volume. More advanced designs may be devised to reduce heat gains further (e.g. a vertical cylindrical-shaped store of equal radius and height would incur heat gains which were 8.5% less than those incurred with the original design of cold store).

Finally, kitchen designers should ensure that the refrigeration equipment's C.O.P. is high (i.e. >1.75) and that the efficiency and power factor of the associated compressor approach 100% and unity respectively. It is essential that all options to achieve low values of P and P , are considered in terms of investment wisdom. For example, it may be more cost-effective to install capacitors to improve the power factors of the compressors for a kitchen with a large frozen-food facility (if the electrical demand will then be charged at a lower tarriff), than to add an extra layer of insulant to the structure of the store. A simple energy-analysis, i.e. the comparison of feasible energy-saving measures in terms of pay-back periods, offers one straight-forward means of choosing between alternative design strategies (Helcke, 1981). When planning new sites, kitchen designers should try to determine the optimal combination of energy-saving measures which together will most easily satisfy achieving the acceptable return on investment specified by the establishments' owners/investors.

APPENDIX 3

REFURBISHING AN INDUSTRIAL CATERING FACILITY IN ORDER TO IMPROVE ITS OPERATIONAL EFFICIENCY

Many factors add to the considerable inertia inhibiting the evolvement of energy-efficient food-service establishments in the UK. For example, consider an industrial catering facility which was due to be refurbished . The owners determined the capital and operational budgets that would be allocated for the development, but are unhappy with the rising running costs which have characterised the existing facility in recent years. Consequently the contract-caterers concerned with the project, study methods of increasing operational efficiency by reducing expenditures on labour, food and energy. Past experience has shown that reducing the size or quality of the work-force, opting strictly for the cheapest food supplier(s) or restricting menu-choice eventually results in dissatisfied customers (i.e the operational efficiency decreases). Therefore improving the design of the kitchen lay-out and the wise choice of equipment fitted therein are viewed as main priorities.

The paucity of reliable information concerning the energy consumptions of the equipment currently-available tends to make the case for installing allegedly better energy-efficient versions of standard appliances uncertain. Nevertheless a work-study of the existing operations and the purchase of some more-efficient appliances were proposed. Subsequently a time-and-motion study was instigated and most of its findings approved by the owners, although investment in more efficient catering equipment was rejected, because it would increase capital expenditures significantly. Consequently, the contract-catering company investigate the means of raising extra capital, so that the annual energy bill of the catering facility might be reduced further by installing more efficient kitchen appliances. Unfortunately information gleaned from the UK's Department of Energy reveals that no source of impartial information concerning the energy performances of food appliances exists and no assistance in the form of financial incentives are available for prospective purchasers of more energy efficient food-service equipment. (This scenario prevails, even though general remedial recommendations were proposed at the 1982 OECD/IUFoST Symposium and the 1984 Symposium on Catering Systems Design (Koivoistoinen et al, 1982; Glew, 1985)). Thus the contract-catering organisation found it difficult to justify a higher capital investment in the food-service facility, which would be required in order to purchase more efficient equipment. As a result the establishment's initial operational costs would be reduced only slightly, relative to those of the existing facility.

In the long-term, the owners will have to afford increasing operational expenditures (despite the efforts made by caterers to reduce operational costs) due primarily to rising unit-energy prices. Moreover many appliance manufacturers will continue to view the market for less energy consuming equipment as unprofitable, due to the apparent unwillingness of food-service operators to make the appropriate purchases. Consequently they are disinclined to develop better energy-efficient appliances for the catering industry. Thus it is evident that unless:-

i) an independent organisation is set up to establish (and then publish) the relative energy consumptions of catering equipment, and

ii) the Government provides financial inducements for caterers who select recommended energy efficient versions of kitchen appliances,

the fuel savings achieved by the food-service sector will probably be disappointing.

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CHAPTER FOUR

ENERGY-CONSCIOUS DESIGN IMPROVEMENTS

FOR ELECTRIC HOBS

ABSTRACT

Energy-efficient practices for users of cooking-tops are reviewed, and the opportunities available to appliance-designers for improving the thermal efficiencies of electric range-tops are discussed. Several prospective developments relative to existing designs have been analysed quantitatively. The main alterations suggested are:- (i) the introduction of thermally-insulated pan-caps in place of conventional lids; (ii) the optimisation of pans in terms of their thermal and geometric properties; (iii) the employment of intelligent control systems, which permit the rates of energy supply to cooking elements to be regulated automatically (i.e. without the cook's supervision) according to the temperature of the pan's contents; and (iv) the fitment of insulated reflectors beneath 'radiant-ring' cooking elements. In particular, the design of an advanced electric cooking system is described: by using it, energy savings of at least 40%, when compared with employing a conventional 'radiant-ring' cooking element of identical power dissipation, should be achieved.

NOMENCLATURE

- A Area via which heat is lost directly from a covered pan, (m^2).
- C Specific heat capacity, ($J\ kg^{-1}K^{-1}$).
- E Energy consumed by range-top to facilitate the cooking operation, (J).
- g The mean steady-state temperature difference between the external surface of the vertical unwetted area of a pan and the local environment, divided by that for the vertical wetted area, $0 < g < 1.0$.
- H Height of cylindrical pan, (m).
- h Heat transfer coefficient for the pan-base/water interface, ($Wm^{-2}K^{-1}$).
- I Mean electric current supplied to the cooking element, (A).
- K Arbitrary constant, which is a characteristic of the performance of the pan under test.
- k Thermal conductivity, ($Wm^{-1}K^{-1}$).
- m Mass, (kg).
- n Numerical index equivalent to the gradient of a log-log plot of the water-boiling efficiency, η, versus thermal capacity ratio, CR, for a pan.
- r Radius, (m).
- T Temperature, (^{o}C).
- t Period of energisation of the electric hob, (s).
- V Nominal voltage applied to the cooking element, (V).
- v Volume, (m^3).
- α Coefficient of thermal expansion, (K^{-1}).
- δ Pan-base thickness, (m).
- ε Emissivity, $0 < \varepsilon < 1.0$.
- η The water-boiling efficiency, i.e. the ratio of the energy required to raise the water placed in the pan to its boiling temperature, divided by that supplied to the cooking system for achieving this.
- λ Peak wavelength of radiation emitted by the cooking element, (m).
- ρ Mean density of water across the temperature range $12^{o}C$ to $100^{o}C$, (kgm^{-3}).
- ϕ Ratio of the wetted height to the unwetted height for a pan.

Subscripts

- B Of boiling water.
- C Predicted value.
- H Of the upper surface of the cooking element before energisation.
- i At the initial condition of the water.
- M Measured value.
- OPT Pertaining to the optimal condition.
- P Of the pan.
- PB Of the pan's base.
- SW Of the sidewall of the pan.
- u Of the unwetted region of the pan's sidewall.
- W Of water.
- w Of the wetted area of the pan's sidewall.

∞ Of the ambient kitchen environment.

Abbreviations

AR Aspect ratio, i.e. the ratio of the height of the pan to its radius.

CI Conductivity index, i.e. the effective thermal conductance of the pan's base divided by the mean heat-transfer coefficient associated with the pan-base/water interface.

CR Thermal capacity ratio, i.e. the ratio of the thermal capacity of the water contained in a pan to that of this water plus the pan.

DI Configuration index, i.e. the ratio of the radius of the pan to that of the heat source.

INTRODUCTION

In many catering and household kitchens, the hob or range-top is the item of equipment that is most used for heating water for cooking purposes. Indeed, in UK homes, hob operations account for up to 90% of the annual energy expenditures for cooking (Electricity Consumers' Council, 1982). Yet, despite the increasing need to reduce the energy intensity of food preparation, relatively little attention (Brundrett and Poultney, 1979; Enga, 1984; American Gas Association, 1984; Holck et al, 1986) has been given to the task of improving the energy efficiency of this ubiquitous cooking system.

Gas-fired hobs, which can be ignited automatically, are more efficient than electric ones in primary energy terms (Probert and Newborough, 1985). Also they are often preferred because of their more rapid thermal responses, when compared with traditional electrically-stimulated hot-plates or radiant-ring cooking elements. Although, induction and 'halogen' ceramic-hobs offer their users a degree of controllability, which is approximately similar to that achievable with gas burner-tops, these relatively energy-efficient electric appliances are not used widely because of their high initial costs. Thus conventional gas and electric designs still dominate both the commercial and residential markets for cooking-tops.

Smaller annual financial expenditures for cooking are usually incurred if burner-tops are employed, but because they tend to be less efficient in end-use terms, conventional designs liberate more waste heat into the kitchen per cooking operation than electric hobs. Consequently air-conditioning loads tend to increase: to some extent, this negates the cost advantages of gas-fired systems. Thus it is considered that efforts to improve the efficiencies of cooking processes performed with electric hobs are desirable. Indeed, appropriate developments of such appliances should be of international benefit, because the developed world is becoming increasingly dependent upon electrical energy for cooking.

Fundamentally, there are three factors, which influence the effectiveness of a range-top:-

i) the energy management capability of the individual using the cooking system;
ii) the design of the pans and their compatabilities with their respective cooking elements; and
iii) the design of the range top.

These will be discussed in relation to the common operations of heating liquid foods and 'boiling' vegetables.

ENERGY-EFFICIENCY PRACTICES

There are several simple energy-thrift procedures, via which cooks can reduce energy consumptions for cooking and air-conditioning without significantly sacrificing quality of product or environment, when using cooking-tops. Although largely dependent upon common sense, these are often neglected:-

* Always use lids on the pans : at simmering temperatures, energy savings of about 85%, and reductions in rates of evaporation of approximately 99%, can thereby be achieved (see Fig. 1).

* Ensure that the pan-base area exceeds that of the energised heat source, then position the pan centrally on the cooking element.

* 'Boil' foods at the minimum necessary power input. When operating above this minimum, the temperature of the cooking medium cannot be raised beyond the fluid's boiling point - more steam is generated and hence greater energy losses incurred. Whenever slightly longer cooking periods are acceptable, simmer foods and (if feasible) arrange for them to be stirred automatically (e.g. see Figs. 1 & 2).

* Do not position the pan so that it only partially covers the cooking element once the liquid is boiling. Similarly, do not partially remove the pan-lid to obviate 'boiling-over'. Never rely on rattling lids, the hissing noise of fluid boiling-over or the characteristic bubbling noise created by rapidly rising vapour columns within vigorously boiling liquids, to indicate that cooking is continuing satisfactorily. Instead reduce the power supply.

* Switch off the power supply just before the cooking operation is finished.

Usually cooks can proffer persuasive reasons as to why most of these recommendations are only rarely implemented. These include:- (i) the heating element does not facilitate adequate control of the cooking operation for the operative to avoid easily the characteristic symptoms of 'over-enthusiastic' boiling; (ii) the user cannot ascertain how near to boiling the contents of a covered pan are, and so is inclined not to attempt adjusting the power supply to determine the optimal minimum rate; (iii) the progress of cooking is more easily observed if a lid is not fitted to the pan; and (iv) such energy-thrift measures tend to complicate the operatives activities. Although the motivation of kitchen staff to achieve efficient practices is primarily the responsibility of the catering manager or head chef (Sutcliffe Catering Ltd., 1986), appliance designers can make pertinent contributions by developing energy-efficient versions of standard cooking systems, via which the typical user can achieve significant energy savings more easily (Newborough and Probert, 1987).

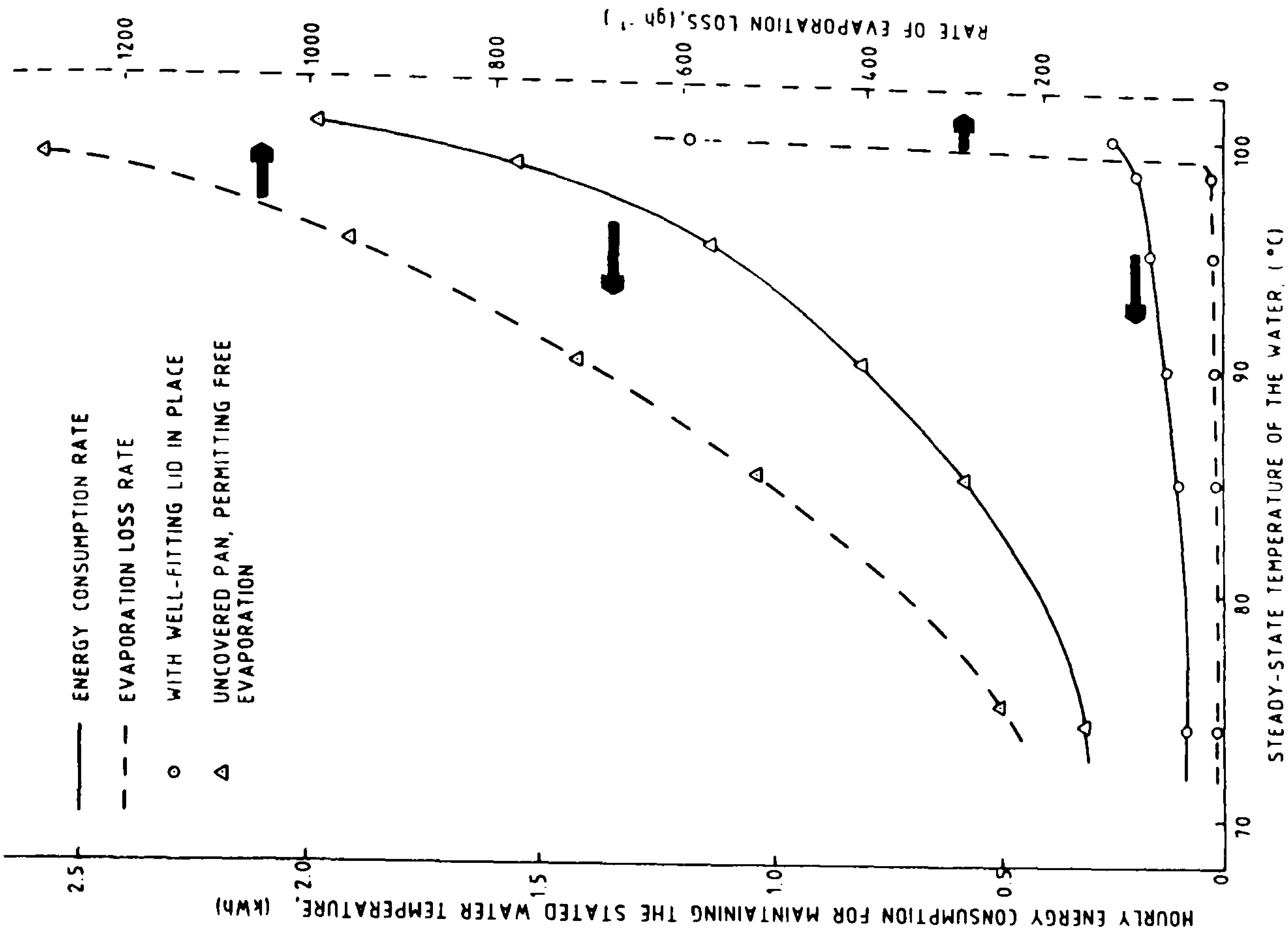

Fig. 1 Energy consumptions and evaporation losses for maintaining two litres of water in an aluminium-alloy pan of 0.25m diameter at elevated steady-state water temperatures for a period of one hour.

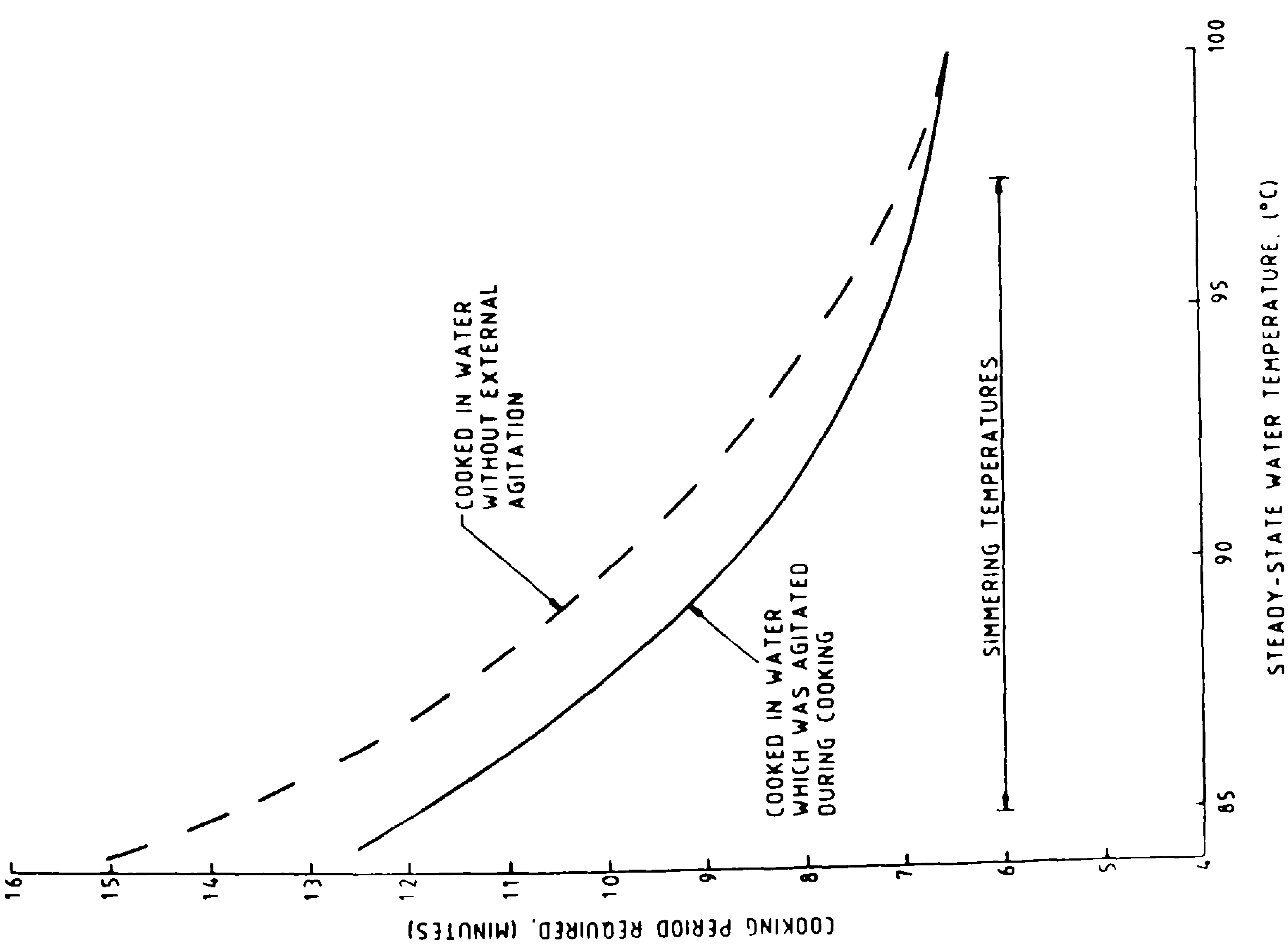

Fig. 2 Required cooking periods for 'boiling' standard cylinders of potato (adapted from Dunning, 1953). Each cylinder was approximately 76mm high by 12.7mm diameter.

THERMAL PERFORMANCES OF COOKING PANS

A multiplicity of pots and pans of various capacities, shapes and materials is available commercially. Cooking vessels tend to be sold according to cost, durability, cleanability and appearance criteria, but rarely on the basis of thermal efficiency. Unfortunately, few manufacturers of pans have collaborated with producers of associated catering appliances to develop coherent designs of 'pan-heating' cooking systems. In the meantime, some organisations only too readily attach labels proclaiming high efficiencies for their new designs, without providing sufficient data to support their claims. In general, caterers need to be wary of appliance manufacturers who allege energy-thrift improvements, which have not been substantiated in a scientifically rigorous manner (Unklesbay and Unklesbay, 1982). Indeed 'jumping on the energy-efficiency bandwagon' by manufacturers may occur increasingly, simply because the food-service industry is now demanding more efficient devices.

To assess the opportunities available to engineering designers for (i) improving the thermal efficiencies of pans, (ii) limiting wild heat losses to the kitchen during cooking, and (iii) reducing peak power demands, an experimental investigation was undertaken with an electric range-top.

Experimental Details

A standard electric 'radiant-ring' cooking element, of 2kW nominal power rating, was connected to a single-phase 240 V $\pm$1% a.c. supply via an autotransformer. The thermal performance of this heater, when under no-load conditions, is illustrated in Fig. 3: it had a thermal capacity of approximately 380 JK^{-1} and reached its maximum surface temperature within 130 s when in free-air. The mean electrical current flow, I, and period of energisation, t, were recorded so that the energy dissipation from the heater could be determined via:-

$$E = V\, I\, t \qquad (1)$$

For most cooking operations involving covered pans, the greatest energy input is required during the 'initial heating period' (i.e. to raise the cooking fluid's bulk temperature to its boiling point). Therefore a suitable means of comparing the thermal efficiencies of different pans can be achieved via the 'water-boiling' effectiveness parameter:-

$$\eta = \frac{\rho V_w C_w (T_B - T_i)}{E} \qquad (2)$$

where ρ, V_w, and C_w are the mean density, volume, and specific heat capacity respectively of the water during heating, i.e. from the initial temperature of the water, T_i, to its boiling-point temperature, T_B.

The following conditions applied during the tests :- $T_B = 99.8 \pm 0.3$ °C, $T_i = 12.0 \pm 1.5$ °C, the ambient temperature $T_\infty = 15.0 \pm 2.0$ °C, and the initial temperature, T_H, of the cooking element was such that $T_\infty \leqslant T_H \leqslant T_\infty + 5$ °C. The latter was measured using iron-constantan thermocouples : all other temperatures were obtained via copper-constantan thermocouples. Unless stated otherwise, cylindrical pans were used with their well-fitting lids in place during testing. Each pan was placed centrally on the radiant-ring at a fixed orientation, so that mean values of energy dissipations and heating periods could be determined accurately. The maximum capacity for a pan was defined as the volume of water which filled it to 3cm below the lip of its cylindrical sidewall. This definition was chosen because, when pans were filled beyond this height, most of the pan-lids under test failed to prevent excessive evaporative heat losses and water spillages (at water temperatures above about 90°C).

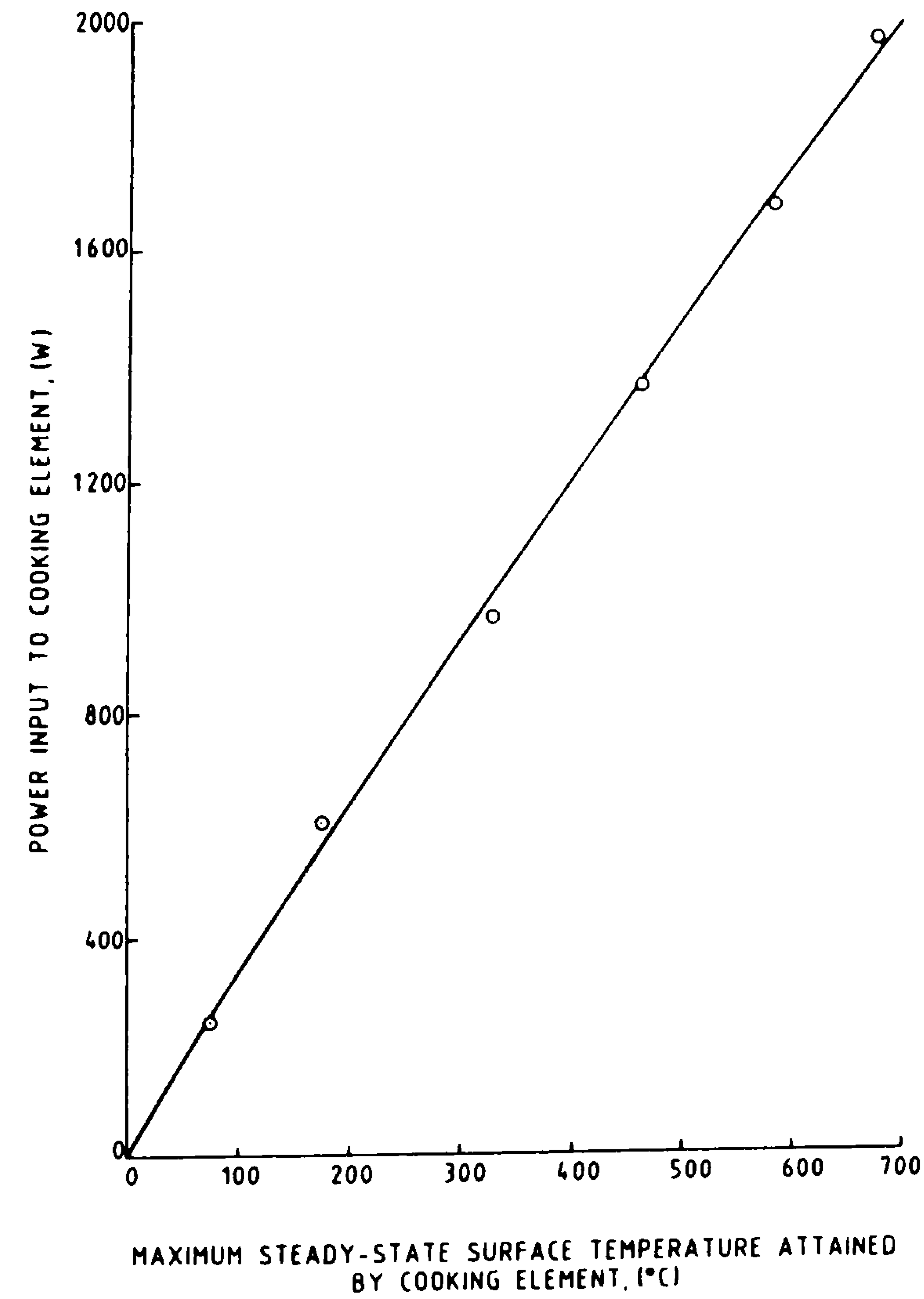

Fig. 3 The thermal response of the tested radiant-ring cooking element, when energised in the absence of a pan.

Pan Efficiency

Initial tests, with three different aluminium-alloy pans#, indicated that the efficiency increased with the used proportion of the pans' maximum capacities. Also a significant variation in efficiency existed between (otherwise similar) pans of different diameter (see Fig. 4), as reported by Angus (1930). So the efficiencies of families of aluminium-alloy, copper-bottomed stainless-steel, and enamelled cast-iron pans were analysed in terms of their geometries and thermal properties, as well as with respect to the thermal loads imposed upon them. It was considered that the water-boiling efficiency of a good-quality pan (i.e. one with a flat base, which did not bow appreciably during heating), could be described in terms of six parameters, provided that a well-fitting lid was employed to inhibit evaporative losses, i.e. :-

$$\eta = f\,(CR, CI, AR, DI, \varepsilon_{PB}, \varepsilon_{SW})$$

where the 'thermal capacity ratio', $CR = \left[\frac{m_w C_w}{m_p C_p + m_w C_w}\right]$

the 'conductivity index', $CI = \left[\frac{k}{\delta h}\right]$

the 'aspect ratio', $AR = \left[\frac{H}{r_p}\right]$

the 'configuration index', $DI = \left[\frac{r_p}{r_H}\right]$

and the emissivities of the pan's base and its other external sidewalls, are ε_{PB} and ε_{SW} respectively.

Footnote

A correlation between dementia and aluminium content of the brain has been established (Vogt, 1986). Thus it is prudent to reduce dietary intakes of aluminium. A contribution to reducing daily consumptions of this metal can be achieved by avoiding eating foods cooked in aluminium-alloy pans (Greger, 1985). Such abstinence may be particularly significant in regions subjected to 'acid rain' or where the water supply is artificially-fluorinated (Hodgkinson, 1987; Pearce, 1987).

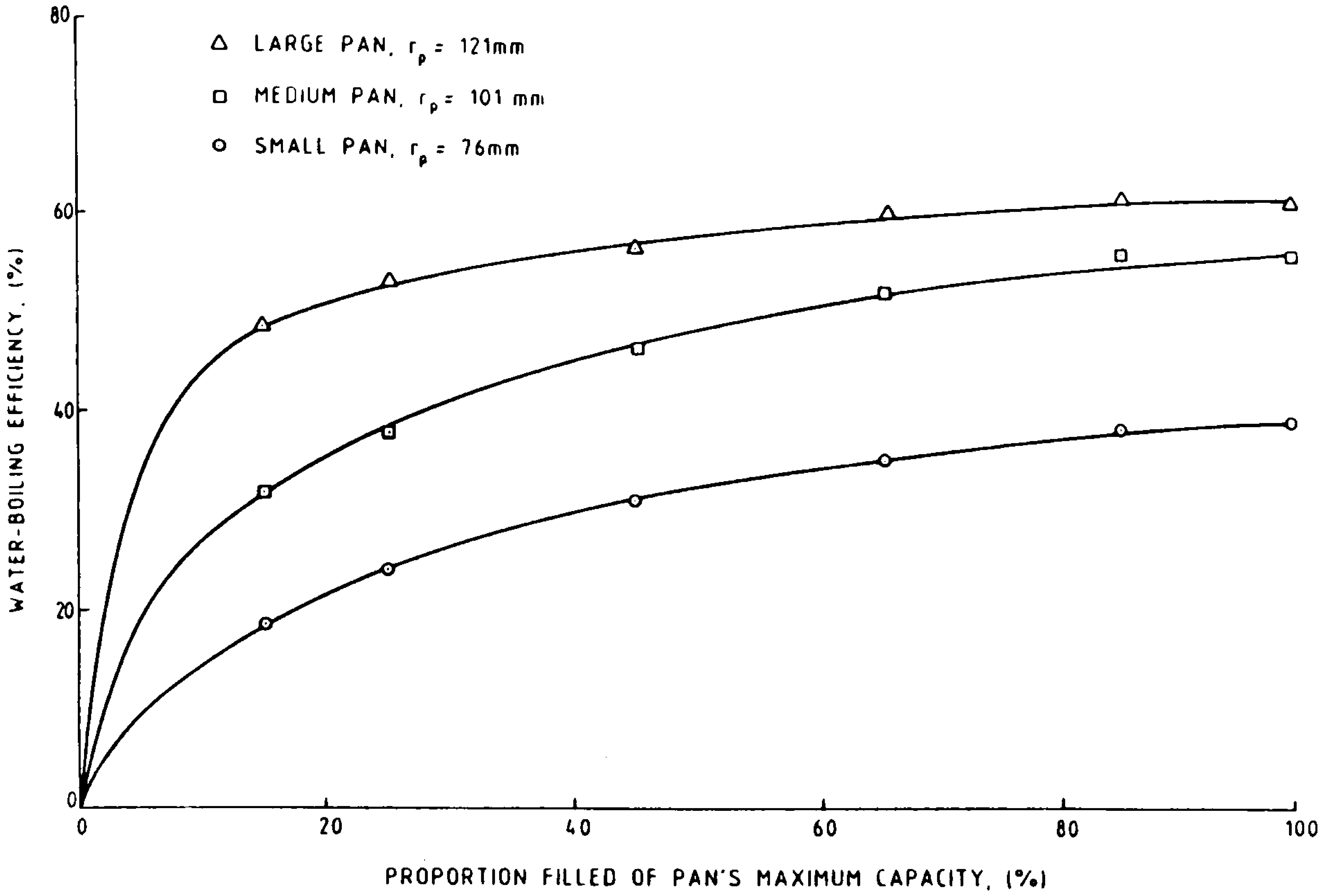

Fig. 4 The relationship between water-boiling efficiency and the proportion filled of the maximum capacity for three covered aluminium-alloy pans of identical aspect ratio.

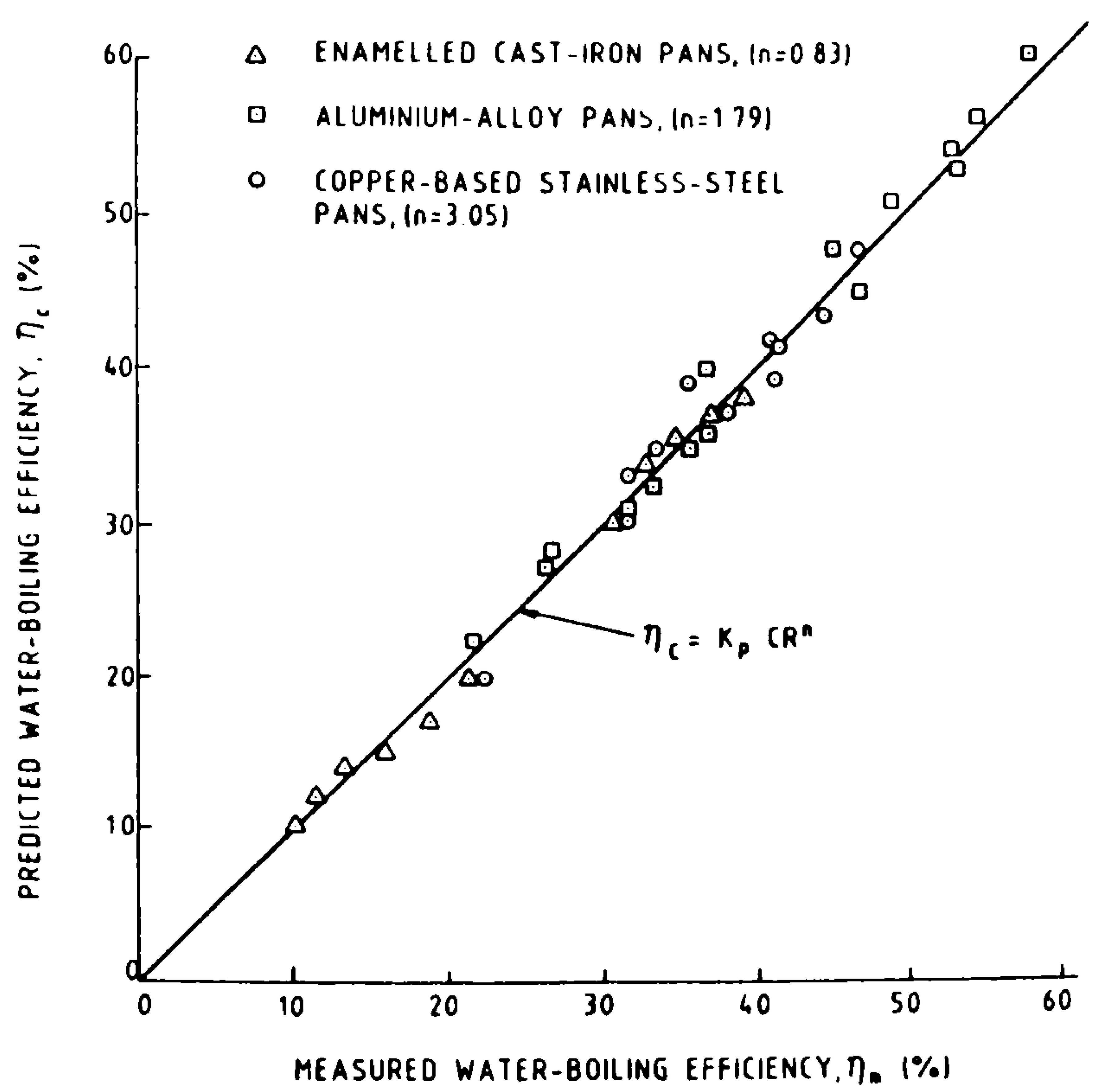

Fig. 5 Correlation between calculated and measured water-boiling efficiencies for the cooking system when it was subjected to different thermal loads (i.e. various pans filled with various amounts of water).

Ideally, if a relationship between these parameters and the water-boiling efficiency for pans of different geometry and composition could be established, efficiencies could be assessed by prospective buyers without having to undertake experimental tests. In this preliminary investigation, the thermal capacity ratio was found to correlate well with the water-boiling efficiency for a wide range of pans (see Fig. 5). The arbitrary constant, K_p, in the logarithmic correlation, is probably a function of the pan's conductivity and configuration indexes, because pans within each group had very similar aspect ratios and emissivities. However, the index, n, is a complex function of a combination of the characteristic dimensionless groups. Unfortunately, the extensive testing required for determining these relationships, and hence obtaining a generalised equation for the water-boiling efficiency, was beyond the scope of this study.

As expected the water-boiling efficiency increased as the thermal capacity ratio approached unity. This suggests that cooks should attempt to employ pans of low thermal mass (i.e. high thermal diffusivity - see Table 1), and only use them when they are well-filled. Also, efficiency tended to increase with the configuration index (i.e. vessels of large radius were more efficient than their nominally-identical counterparts - e.g. see Fig. 6). Within the typical range of pans suitable for use on the hob, there appeared to be no optimal configuration index.

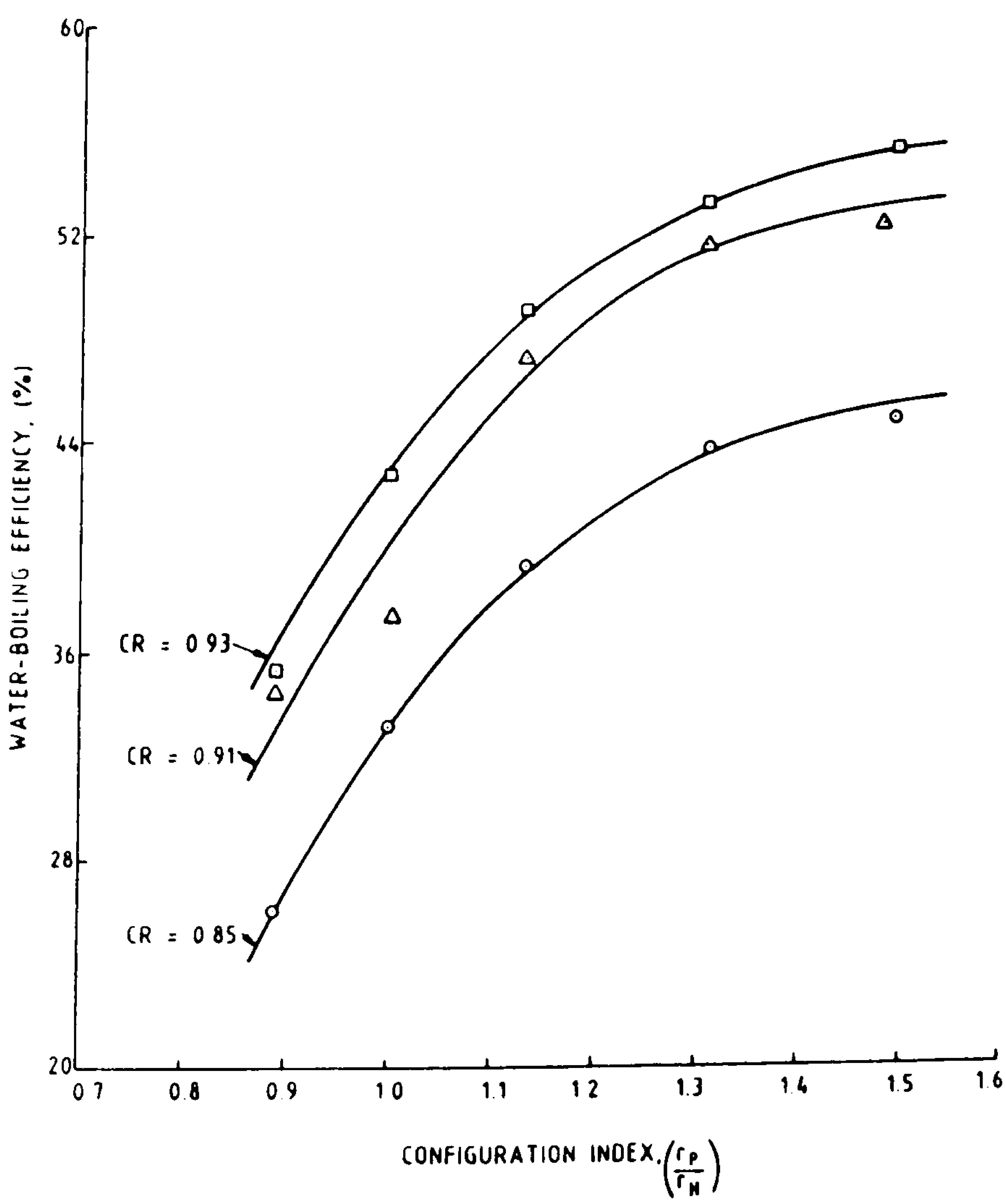

Fig. 6 The relationship between water-boiling efficiency and configuration index for some similar composition pans of identical aspect ratio but different thermal-capacity ratios.

TABLE 1

The thermal properties of various metals, from which cooking pans are often fabricated (Gubareff et al, 1960; Tennent, 1971; Kreith, 1973).

Material	Typical range of emissivity*	Estimated emissivity of used pan	Thermal conductivity ($Wm^{-1}K^{-1}$)	Density ($kg\ m^{-3}$)	Thermal diffusivity ($10^{-6} m^2 s^{-1}$)
Copper	0.04–0.87	0.55	385	8930	112
Aluminium-alloy (Duralumin)	0.04–0.4	0.2	180	2800	73
Stainless-steel (18/8)	0.15–0.85	0.4	150	7930	37
Cast iron**	0.06–0.96	0.7	75	7150	21

* The stated values are those corrresponding to the extremes encountered across the thermal radiation band $3.6\mu m < \lambda < 9.3\mu m$ (i.e. from about 40°C to 530°C) : those of low magnitude are for the material when it is highly polished, whereas the greatest emissivities are for oxidised, weathered or sand-blasted surfaces.

** The external surfaces of an enamelled cast-iron pan would usually achieve emissivities of about 0.9 at temperatures below about 100°C.

Theoretically, an optimal aspect ratio for a covered cylindrical pan, when under steady-state conditions, may be derived. The enclosed volume of such a pan may be expressed as:-

$$v_p = \pi r_p^2 H_u (\varnothing+1) \qquad (3)$$

where $$\varnothing = \frac{H_w}{H_u} \qquad (4)$$

If the pan is assumed to be fitted with a flat lid, the area via which heat is lost directly from the assembly is:-

$$A = 2\pi r_p H_w + g(2\pi r_p H_u + \pi r_p^2) \qquad (5)$$

By substituting from equation (4) into equation (5), the latter becomes:-

$$A = 2\pi r_p \varnothing H_u + g(2\pi r_p H_u + \pi r_p^2) \qquad (6)$$

Then by substituting from equation (3) into equation (6):-

$$A = \left[\frac{2v_p(\varnothing+g)}{r_p(\varnothing+1)}\right] + \pi g r_p^2 \qquad (7)$$

The least rate of heat loss per unit volume of the pan, occurs when this area is a minimum, i.e. where $dA/dr_p = 0$. Thus by differentiating equation (7) with respect to r, the optimal radius may be deduced as:-

$$r_{OPT} = \left[\frac{v_p(\varnothing+g)}{\pi g(\varnothing+1)}\right] \qquad (8)$$

By substituting from equation (8) into equation (3):-

$$H_{OPT} = \left[\frac{v_p(\varnothing+g)}{\pi g(\varnothing+1)}\right] \qquad (9)$$

Thus, $AR_{OPT} = 1$ (10)

Unfortunately, practical verification of this optimal aspect ratio was not feasible due to the non-availability of nominally-identical vessels of various heights. The experimentation necessary for substantiating this optimum needs to be undertaken via collaboration with a manufacturer of cookware. Also, attempts should be made to identify an optimal aspect ratio for the initial heating period, as well as for this steady-state (or simmering) period. From an energy-thrift perspective, experimental evaluation of the former parameter should take precedence.

Throughout testing only smooth flat-bottomed pans were superimposed on the relatively flexible radiant rings, and so good thermal contacts were made. However, the actual contact areas between such pans and their heaters are only sufficient to support the imposed loads. Usually, the area via which solid conduction heat transfers occur is only about 10^{-3} times that of the nominal contact area (Snaith et al, 1986). Thus, less than 0.1 cm^2 of a typical radiant ring (which provides a nominally-horizontal surface of area 98 cm^2 for supporting pans), would actually contact a similar diameter pan having a flat base area of 211 cm^2.

Essentially the temperature distribution across the base of a pan is not uniform, because (i) the area of the heat source with which it contacts is relatively small; and (ii) the base of the pan tends to bow (either towards or away from the cooking element) during heating. The directions in which contacting solids (at different temperatures) bow, depend largely upon their coefficients of thermal expansion, α, and conductivity, k (Veziroglu and Chandra, 1970). Scheidler (1985) reported peak base movements of 0.9mm towards and 1.8mm away from the heat source respectively, when enamelled stainless-steel pans were used to heat vegetable oil to 204°C via conventional or halogen ceramic-hobs. Good and poor quality pan-bases achieved respective peak separations from their supporting hobs of about 0.35mm (i.e. when cold) and 3.0mm (i.e. when hot).

Manufacturers often attempt to reduce variations in pan-base temperature by fabricating pans with relatively thick bases. However, although such pans are robust, they are too thick to facilitate efficient boiling operations. For example, cast-iron and glass pans, which had characteristically thick structures (i.e. δ >4mm), achieved significantly inferior water-boiling efficiencies, when compared with similar copper-bottomed stainless-steel and aluminium-alloy pans of base thicknesses 2 to 4mm. The former types were relatively inefficient and heavy. Indeed, the increasing popularity of enamelled cast-iron and glass pans in British kitchens, owes much to the success of the marketing campaigns (instigated by their manufacturers) which encouraged consumers to regard a pan's weight and visual appearance as a measure of its quality/efficiency. Yet efforts to identify optimal thicknesses for pan-bases of different composition are clearly desirable from energy-thrift and ergonomic perspectives.

Unfortunately, accurate measurement of the temperatures associated with a real pan/heater interface was impractical in the present preliminary series of tests, and so worthwhile indications of the thermal contact resistance could not be calculated. However, the contact resistance for a pan placed on an electric range-top may be reduced by increasing the applied load. In an attempt to achieve this, without significantly increasing the imposed thermal load, ceramic weights were placed on the low conductivity lid-handles of various pans. The best improvement in water-boiling efficiency was recorded for a copper-bottomed stainless-steel pan, which achieved a 9% energy saving when it exerted a total load on the heater of about seven times that imposed by the pan and the water alone. Further improvements to the effectiveness of conductive heating may be achieved by:- (i) increasing the number of heating coils per unit radius of the radiant-ring; (ii) fabricating the coils so that they have flatter upper surfaces; (iii) manufacturing the tripodal support for the heater from a mechanically-strong (in compression) low thermal-conductivity ceramic; (iv) shaping the outer face of the base of the pan so that when it is heated it achieves conformity with its supporting cooking element; and (v) reducing the thermal mass of the hob: Holck et al (1986) suggested that an energy saving of 15-20% could be achieved by reducing the heat capacity of the cooking element by half.

Fundamentally, because a pan is heated primarily by conduction via the metal-to-metal contacts and radiation across the interfacial gap, it is desirable to construct cooking elements and pan-bases so that they have high thermal conductivities and emissivities (e.g. see Table 1). In terms of achieving the most effective use of energy, Dunning (1946) demonstrated that, with burner-tops, a cylindrical pan which had a sidewall of low emissivity and a base of high emissivity, was preferable (especially for simmering operations). A large value for the product of thermal diffusivity and typical emissivity, indicates a good prospective material (e.g. tarnished copper) for a pan-base. However, concerns for durability and thermal distortion of the pan base during heating usually necessitate a greater base thickness for a copper-based pan than for, say, a stainless-steel one, (because the latter material has a greater stiffness per unit thickness), and so the positive attributes of copper-based pans are not as overwhelming as might be expected.

The development of bespoke pans, for radiant-ring cooking elements, with indented bases which fit over the coils of their associated heaters, should be worthwhile (e.g. see Fig. 7). Such pans would achieve greater nominal contact areas when placed on radiant-rings, as well as raise slightly the characteristic shape-factors for radiation between the emitting and receiving surfaces. In practice, energy savings will be achieved simply because the pan will always be located centrally on the cooking element : Enga (1984) found that if a centrally-positioned pan was displaced horizontally by 25% of its diameter, the thermal efficiency of the burner-top employed fell by 15 percentage points. Furthermore, the improved stability and fixed orientation of these modified pans when superimposed on radiant rings should help ensure safety, especially for many old, blind and handicapped people, who cook for themselves.

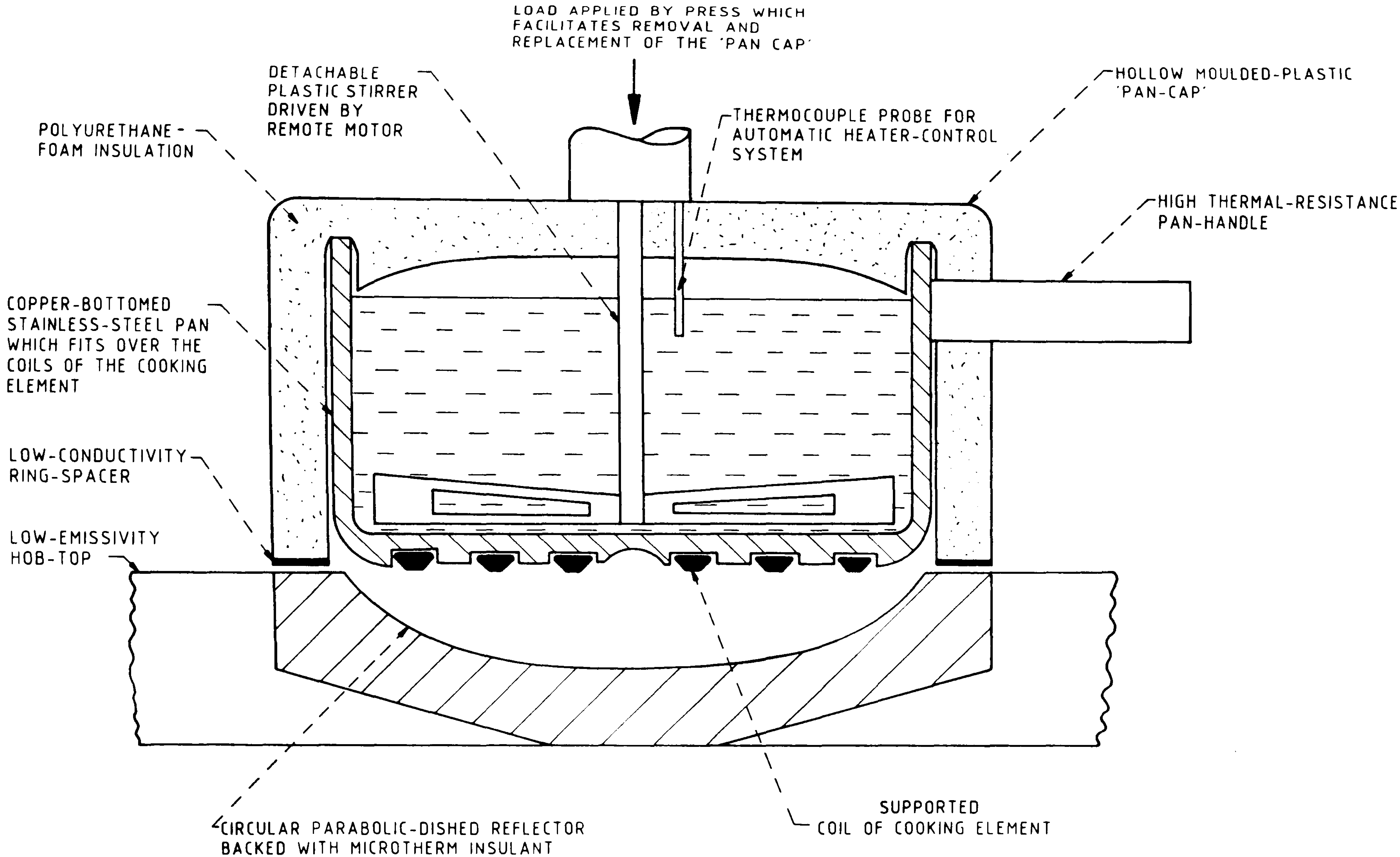

Fig. 7 Schematic sectional representation of a cooking system, which (i) controls automatically the power supply to the cooking element, via the measured temperature of the liquid contained in the pan; (ii) places and removes the insulated pan-cap, under the cook's supervision; (iii) applies additional loading to reduce the thermal contact resistance of the pan/heater interface; and (iv) provides the facility to stir appropriate foods via a motor-driven paddle.

Facilitating More Effective Control of Cooking Operations

Energy savings were disappointing when attempting to simmer small quantities automatically, because modest rates of energy input to the cooking element could not be facilitated by the control system. Unfortunately, energy-controllers associated with catering appliances are often poorly designed, e.g. when rotated continuously clockwise some dials adjust the power input from minimum to maximum and then to intermediate rates of supply (Sutcliffe Ltd., 1984). In many cases, it would be apposite for manufacturers to develop ergonomic designs of energy regulators to assist energy-conscious users of such cooking systems. When rotated in one direction, these controls should increase power inputs logarithmically, if efficient simmering/poaching operations are to be achieved.

Improvements in water-boiling efficiency ensued when the mean power input to the heater was reduced, although excessive reductions caused the efficiency to fall below that achievable at the maximum power setting, because then the rates of heat loss from the pan accounted for a large part of the power input. Unfortunately, attempts to raise the system's efficiency by reducing the mean power output of the heater, resulted in substantial extensions in boiling periods (e.g. the water-boiling efficiency of one pan rose from 48.3 to 50.7% when the power supply was reduced to about 60% of the maximum power output, but the overall period of heating was thereby prolonged by 59%). However, because the rates of radiative and convective heat loss from a pan increase rapidly with the bulk temperature of its contents, it is logical to reduce the power input to the pan only during the first part of the heating period. Significant energy savings were achieved when reduced rates of energy supply were provided only during the first 40 °C temperature rise of the water contained in a pan (e.g. see Table 2). Thus, for an advanced hob (e.g. see Fig. 7), it would seem expedient to design a control system, which gradually increases the mean power input as the temperature of the water in the pan rises. Supplementary to this, it may be necessary to increase the maximum power output of the cooking elements by 10-20%, in order to achieve a favourable compromise between prolonged boiling periods and reduced energy expenditures. Although the instantaneous peak power demands for a kitchen employing such range-tops may then be greater, the probability that they would demand maximum rates of energy supply simultaneously would be less, because the maximum power input to each cooking element would occur only during part of each heating period.

TABLE 2

Energy savings achievable by reducing the power input to the cooking element during the first part of the heating period. (One litre of water was boiled in a chrome-plated duralumin pan, which had an aspect ratio and configuration index of 0.99 and 1.22 respectively).

Power input to heater during the first 40°C temperature rise of the cooking water, expressed as a percentage of the heater's maximum power input	Approximate increase in the period required to raise the water to 100°C, (%)	Approximate overall energy-saving for boiling the water, (%)
100	0	0
75	12	5
62	18	8
47	41	10
32	68	11

FURTHER DEVELOPMENTS FOR RANGE-TOPS

Unfortunately the effectiveness of these cooking systems depends largely upon their users willingness to employ pan lids (fully in place) during cooking operations. Although some cooks may be persuaded to use lids properly, it is desirable to provide an automatic lid-placement/removal facility for a hob (e.g. see Fig. 7). This may be designed to apply an additional load on the pan in order to reduce the thermal contact resistance of the pan/heater interface. To permit preliminary analyses of such a system, a prototype double-skin steel 'pan cap' was constructed as a replacement lid for one of the aluminium pans employed during testing.

The cap cavity was insulated with 25mm of polyurethane foam in order to (i) maintain the surfaces of the pan, with which the user might touch during cooking, at temperatures below those maxima recommended for brief contact (Probert and Giani, 1976) - e.g. see Fig. 8; and (ii) reduce the rates of radiative heat loss to the kitchen. Energy dissipations to maintain water at useful cooking or food-holding temperatures (i.e. 75-100°C) decreased, on average, by 39%, during typical 30 minute simmering periods, without increasing substantially the pre-heat periods required initially for raising the temperature of the water to boiling point. This saving may be increased if a moulded-plastic cap (similar to that manufactured for electric jug-kettles) was employed, so that a more practical and cheaper cover of higher thermal resistance and lower surface emissivity could be achieved.

At boiling temperatures, steam escaped from the pan and condensed partly on the lower outer surfaces of the cap, thereby raising substantially its temperature. Usually when the bulk temperature of the water exceeded about 93 °C, the system possessed sufficient residual heat to ensure that boiling occurred subsequently, without further stimulation of the cooking element. However, when the heater was energised until the bulk temperature reached approximately 100 °C, boiling continued for several minutes. Because there is nothing to be gained from generating steam when undertaking conventional cooking operations on a range, it is highly desirable for the heating systems used in conjunction with such insulated pans to be controlled so that such energy-profligacy can be eliminated. For example, the cooking element should be switched off automatically (i) before the fluid boils (Holck et al, 1986), and (ii) when the pan (or pan-cap) is removed by the user (Enga, 1984).

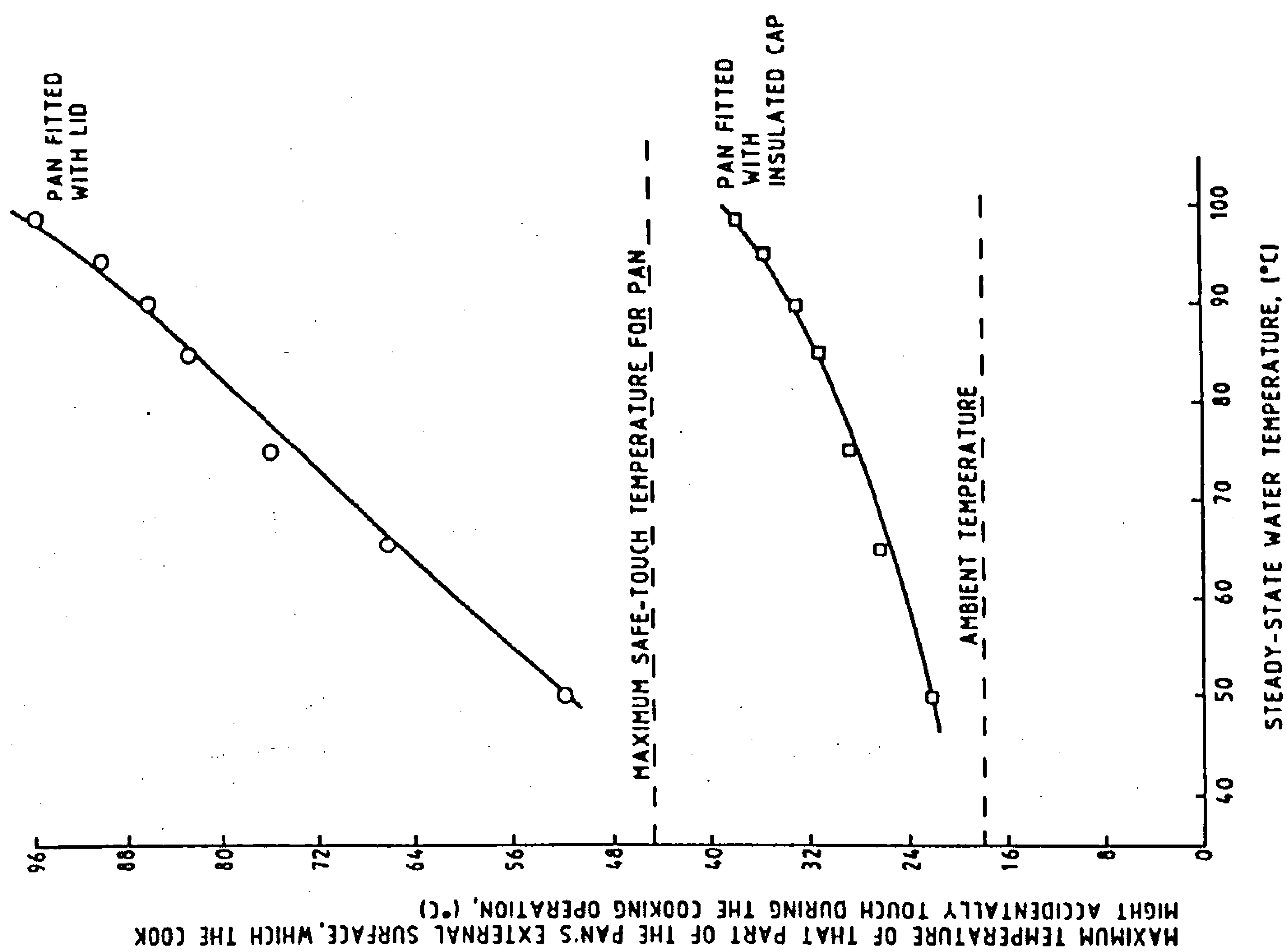

Fig. 8 Peak external surface temperatures for the conventional lid and insulated pan-cap of a 0.25m diameter aluminium-alloy pan, when it contained two litres of water at steady-state temperatures for periods of 30 minutes.

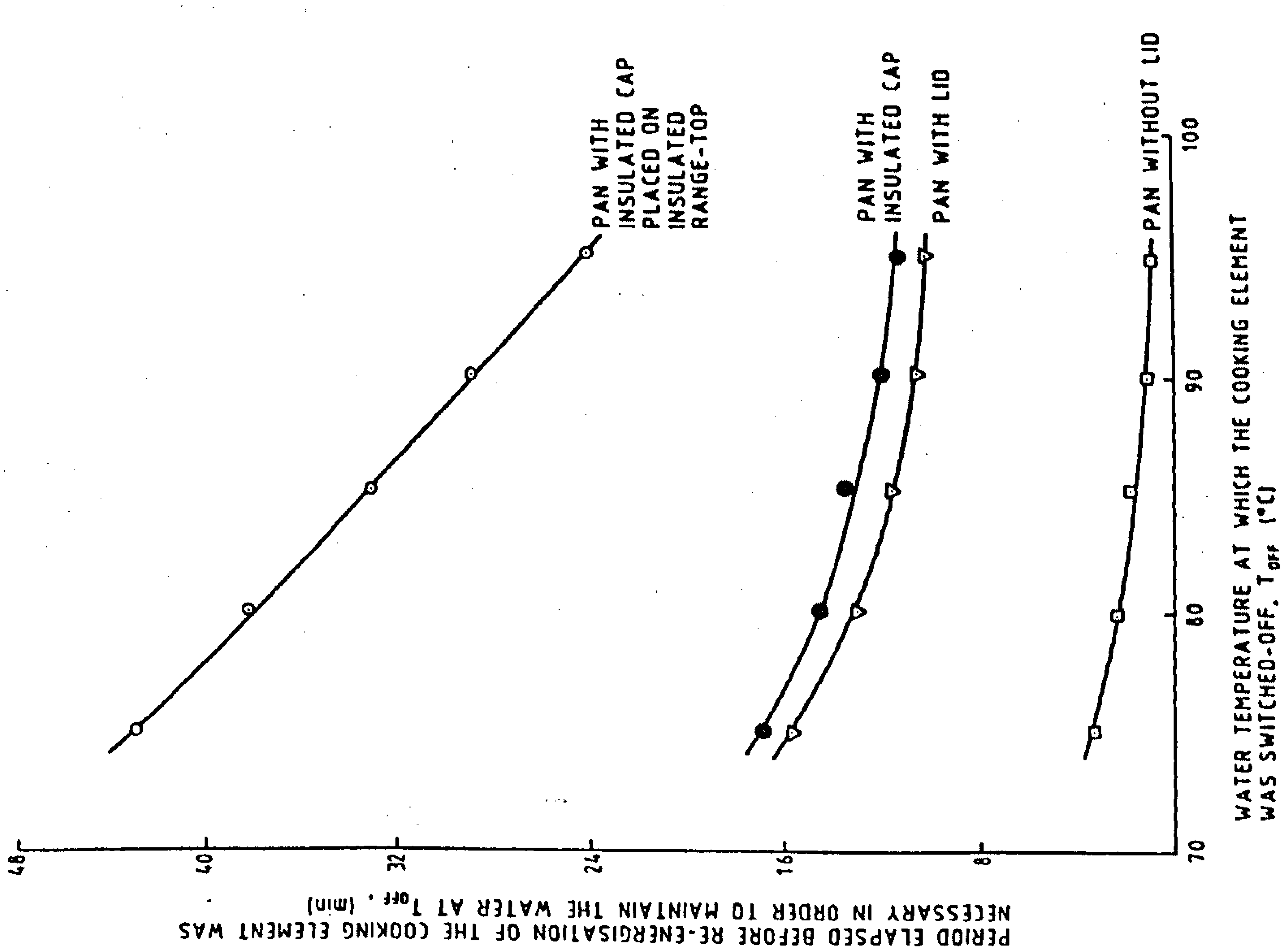

Fig. 9 Periods elapsed before further stimulation of the cooking element was necessary to maintain the useful cooking/food-holding temperatures at which the system was initially switched off, for a 0.25m diameter aluminium-alloy pan containing two litres of water.

It is recommended that the aforementioned cooking system (see Fig. 7) employs a probe containing a thermocouple or thermistor (which protrudes from the inside horizontal circular surface of the cap) so that the power supplied to the hob-heater may be regulated automatically according to the temperature of the pan's contents. Consequently, the water need not boil vigorously for prolonged periods, thereby producing large quantities of steam which increase the relative humidity of the local environment, as well as cause the temperatures of the external surfaces of the insulated cap to exceed those maxima recommended for brief contact. Also the temperature of the cooking medium could then be displayed for the cook's information. Enga (1984) reported that, of those energy-saving modifications identified for burner-tops, a 'pan-sensor' (which automatically terminated the gas supply when the pan was lifted off the hob) offered the greatest reductions in annual energy expenditures. Unfortunately, such devices may not achieve satisfactory useful lives, when employed in typical catering kitchens. However, this reliability problem may be rectified for the cooking system illustrated in Fig. 7, by automatically switching-off the power supply to the cooking element as the pan cap is raised to its standby position.

Previous investigations have indicated that significant reductions in cooking periods can be achieved by backing the heaters in food appliances with appropriate reflectors (Probert and Newborough, 1985; Newborough et al, 1987). Unfortunately, in practice, hob reflectors become soiled (i.e. less reflective) and so they need to be cleaned regularly. Furthermore if they are cleaned with scouring agents or abrasives, degradations in their thermal performances occur, because their emissivities increase permanently. However, if the cooking element is controlled automatically so that pans cannot 'boil-over', the rate of soiling of such reflectors should be reduced sufficiently to ensure that they achieve satisfactorily long useful lives (i.e. provided that they are cleaned carefully and regularly).

Energy-thrift may also be achieved by thermally insulating properly the cooking-top from its supporting structure or associated oven (e.g. see Fig. 9). During one series of tests, the underside of the tested system was insulated with a ceramic-fibre insulant, which was shielded from the cooking elements by flat stainless-steel reflectors, so that an effective thermal resistance of about 0.5 m^2KW^{-1} was encountered by downward heat fluxes. On average, this yielded a 10% reduction in initial heating periods and a 5% saving in energy consumptions for achieving and then maintaining useful cooking/holding temperatures for 30 minutes, when compared with using the conventional arrangement for heating the modified pan. However, as had been found with uninsulated circular dish-shaped hob -reflectors (Probert and Newborough, 1985), an increase in the surface temperature of the radiant ring occurred (i.e. by approximately 50°C for the insulated range-top). Because this leads to a reduced life expectancy for the heating elements, they would need to be derated. It is estimated that a radiant-ring hob would need to be derated by about 25% if fitted with insulated circular dish-shaped reflectors. Consequently the peak power demand and annual energy consumption of the appliance would be reduced by approximately 25% without incurring any deterioration in its thermal performance.

CONCLUSIONS

The identified energy-thrift measures, together with the typical steady-state (unless stated otherwise) energy savings achievable via their implementation (indicated in brackets), may be summarised as follows:-

1. Use well-fitting lids on pans (>20% for initial boiling).

2. Simmer foods at 90°C in a pan with a well-fitting lid in place, instead of with the pan uncovered, (~85%).

3. Attempt to use copper-based pans, which are well-filled and achieve a configuration index of say 1.25 instead of 1.0, (~10% for initial boiling).

4. Use thermally-insulated pan-caps, (~40%, for 25mm of polyurethane-foam insulation).

5. Employ close-fitting parabolic reflectors beneath radiant-ring cooking elements (<20% for initial boiling).

6. Increase the contact load between the pan and its heater by at least 500%, whilst ensuring that heat leaks to this extra load are inhibited (>5% for initial boiling).

7. Allow the water temperature to control the power input to the pan (> 5%).

8. Insulate the range-top so that a thermal resistance to downward heat fluxes of about 0.5 $m^2 K W^{-1}$ is provided, (~5%).

The first three of these findings can be implemented readily by energy-conscious cooks, whereas the others need to be designed into an appropriate cooking system to achieve energy-thrift (e.g. see Fig. 7). The energy savings achievable via use of the latter should exceed 40%, when compared with employing a conventional radiant-ring hob: it is estimated that theese savings may be increased to at least 60%, if cooks adopt energy-thrift procedures, e.g. recommendations (1)-(3), whenever feasible. Consequential reductions in annual expenditures for ventilating and cooling the kitchen should then be achieved.

It is plausible that further energy savings may be accrued via the utilisation of insulated pans with internal heating systems. Although highly-insulated vessels with conventional immersion elements can achieve high water-boiling efficiencies (>75%), this form of heating is usually incompatible with the preparation of high-quality food.

Therefore self-contained insulated systems with electric heaters (possibly incorporating high power-density thin-film heaters) may be developed. If caterers are prepared to re-direct capital investments from conventional 'pan-and-hob' to such 'pan-and-heater' cooking systems, large overall financial savings should be achievable. Furthermore, the market for insulated pans with integral heaters within the residential sector may be substantial. For example, from an energy-thrift perspective, it would be expedient for conventional energy-profligate electrically-heated ceramic hobs to be replaced by such pans, placed on attractive ceramic hob-tops (Newborough and Probert, 1987). Consequently, householders could reduce their annual expenditures for cooking, yet achieve the positive attributes (i.e. in terms of aesthetics and cleanability) of ceramic hobs.

Although manufacturing costs may tend to increase if energy-conscious design modifications are introduced to cooking systems, the prospective pay-back periods for such improvements should be acceptable. Within UK homes, a cooker achieves a high ratio of operational energy cost to capital cost over its useful life, when compared with other major energy-consuming artefacts employed by typical householders, i.e. individuals are required to pay disproportionately high energy bills for cooking (see Table 3). Thus scope exists for reducing the energy consumptions of household cooking-appliances in an economically-justifiable manner. Moreover, within catering kitchens, the introduction of more energy-efficient equipment appears even more desirable in terms of investment wisdom, due to the characteristically high rates of utilisation.

Unfortunately in the UK, the institution of comprehensive energy-thrift design programmes by manufacturers of catering equipment is inhibited by (i) traditional thinking within the industry; (ii) the lack of appropriate inducements from Government, for would-be clients of independent engineering research establishments which offer energy-conscious design facilities; (iii) the non-availability of tax incentives for prospective purchasers of more efficient versions of standard appliances; and (iv) the current complacency-inducing scenario of temporarily low unit oil prices. Nevertheless, considerable opportunities still exist for making advances, which reduce energy consumptions per cooking operation, while improving the safety and comfort for users of cooking appliances without adversely affecting the thermal performance, food-quality and hygiene requirements. Without doubt, in future, it will become increasingly important for the food-service industry to realise these objectives.

TABLE 3

Approximate costs (at 1987 prices) associated with various energy-consuming devices when used by a typical family of four in the UK.

Energy-consuming device used by a household	Approximate capital cost (£)	Typical energy cost, at 1987 prices, over a ten-year useful life*, (£)	Total energy cost divided by initial capital cost
Colour T.V.	325	108	0.33
Washing machine	280	187	0.67
Vacuum cleaner	85	68	0.80
Car (petrol-driven)	7000	6500	0.93
Electric refrigerator	130	228	1.75
Electric cooker	300	678	2.26

* Adapted from the Electricity Consumers' Council (1982).

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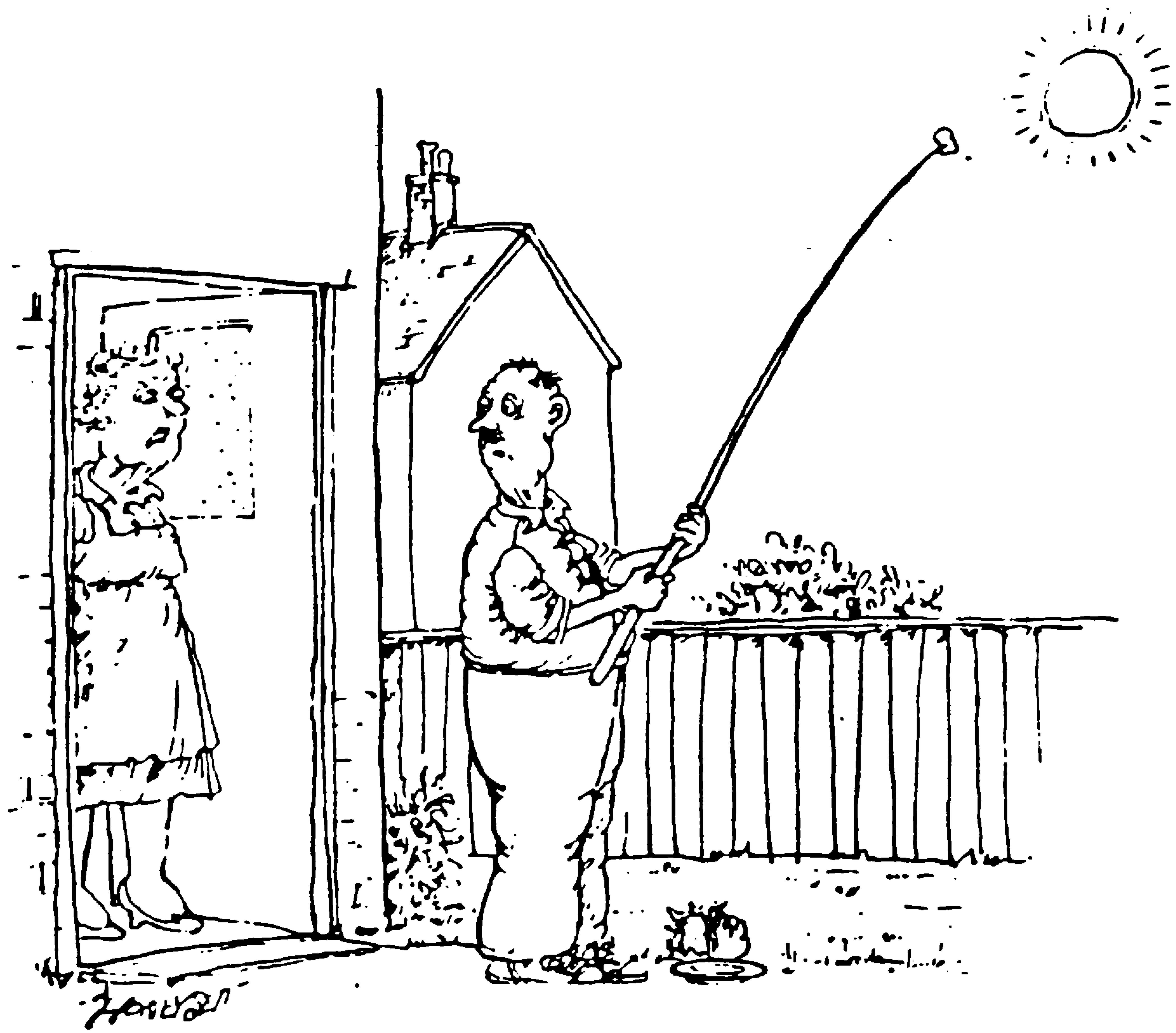
CHAPTER FIVE

DESIGN IMPROVEMENTS FOR THE

UBIQUITOUS ELECTRIC TOASTER



"How much longer are you going to be, making that toast?"

Design Improvements for the Ubiquitous Electric Toaster

SUMMARY

Previous studies concerning bread-toasting operations, as well as the designs and performances of currently available domestic toasters are reviewed. Methods for improving the quality of the toast produced by a typical double-slot toaster, together with modifications which will raise its thermal efficiency and make it safer to use, are discussed. A controller is described which can compensate automatically for the initial non-ambient environmental temperature of the toaster (which is caused usually by an immediately preceding toasting operation), so that batches of toast of similar quality can be produced consistently. The findings from a survey concerning the toast-eating habits of 250 adults are presented as an appendix.

NOMENCLATURE

a	Absorption coefficient for monochromatic radiation passing through the food (m^{-1}).
C	Specific heat capacity ($J\,kg^{-1}\,K^{-1}$).
k	Effective thermal conductivity ($W\,m^{-1}\,K^{-1}$).
m	Moisture content ratio (i.e. mass of water within the food divided by the food's total mass).
$\dot{q}$	Net radiative heat flux impinging on the surface of the food ($W\,m^{-2}$).
s, S	Scattering and extinction coefficients respectively for monochromatic radiation passing through the food (m^{-1}).
t	Thickness of heating tape (m).
T	Temperature (°C).
w	Width of heating tape (m).
x	Thickness of the food being irradiated (m).

α Thermal diffusivity ($m^2 s^{-1}$).
λ Wavelength of the thermal radiation (m).

Subscripts

a due to absorption.
b of crumb.
B of bread.
o entering the surface of the food.
s due to scattering.
t of crust.
W of water.
x at some depth x, into the food, from its irradiated surface.
1, 2 denoting different heat fluxes.

ABBREVIATIONS AND GLOSSARY

Bagel	A ring-shaped bread roll.
DSTR	Double-slot toaster rig, which has been used for test purposes.
End-use efficiency	For a cooking appliance, this is the amount of heat actually required to cook the food in the desired manner, divided by the corresponding amount of energy supplied to the cooking appliance for this purpose.
IC	Integrated circuit—a small single structure, including an assembly of electronic elements, which cannot be subdivided without destroying its intended purpose.
LED	Light-emitting diode.
Mutagen	A substance which, when produced within a food, increases the carcinogenicity of the food.
Nichrome	An alloy suitable for use as a high-temperature electrical-resistance heating element: it usually comprises 42·5% Fe, 37% Ni, 18% Cr, 2% Si and 0·5% Mn when used in domestic-appliance heating systems.
NTC	Negative temperature coefficient. When used as a prefix for describing a thermistor, it indicates that the thermistor has an electrical resistance which decreases as its temperature rises.
Oligopoly	A market which can be influenced by several producers, without any one of them having decisive control over it.

Organoleptic	This adjective describes any method of systematically testing or assessing the effects of a substance, on the human senses.
Overall efficiency	For a toaster, this represents the ratio of the actual amount of energy required to transform the bread into toast, to the total quantity of primary energy required by the appliance in undertaking this operation.
Primary energy	The energy contained in the fuel at the point of extraction.
RC network	Part of an electric circuit comprising a capacitance and resistance, in which the voltages developed across the resistance are passed through a blocking capacitor. This achieves a system response characterised by a time-constant (in seconds) which is equivalent to the product of the resistance and capacitance.
Triac	A bi-directional semiconductor switch, which can be operated directly from an a.c. power supply (i.e. triggered into being conductive via positive or negative signals).

BREAD AND TOAST

'The pleasure of eating is an enjoyment of which few people will consent to be deprived'-Rumford*

Unleavened bread-like products are thought to have been consumed originally about 4000 BC. Subsequently a wide variety of foods based on

* Count Rumford (Benjamin Thompson, 1753–1814), was a distinguished physicist with interests in proper nutrition and the efficient use of fuel. He organised the feeding of the poor in Munich, and the distribution of rations to the Bavarian army. He popularised potato eating, with such success that the potato became a staple food in Bavaria. His efforts devoted to helping the public are commemorated by the English Garden in Munich. He spent two months in Dublin, again working for the poor. Public kitchens were erected (at his instigation) in many major towns of England and Scotland: some 60 000 people per day were fed from these kitchens in London alone. This example was copied in France. The cooking of food and heating of houses were subjects which occupied much of Rumford's time—he claimed to have cured more than 500 smokey chimneys. In the late 1700s he proffered numerous practical suggestions concerning cookery, clothing and fuel-economy. He proposed the establishment of a society for bettering the conditions, and increasing the comfort, of the poor—a society which subsequently became the Royal Institution of London. He invented (i) a coal-burning, high heat-storage cooking range (which was the precursor of the 'Aga') in 1789, and (ii) a roasting oven and steam boiler for cooking which were installed at the Foundling Hospital, London. He developed the pressure cooker, and in his final essay of 1812, extolled the qualities of coffee and described a new coffee-maker–the 'percolator'.

bread have been produced: these are usually inexpensive, nutritious and enjoyable to eat. The exact date at which the consumption of toast became significant is uncertain, but it is alleged (Hatco Corporation, Milwaukee, Wisconsin, USA, 1986, private communication) that the first recipe book to stipulate a need for toasted bread was published in AD 1430. The toasting of bread-based foods probably began because man attempted to increase the edibility of such foods after they had become slightly stale. Clearly the psychological and sensory benefits for an individual when he ate a warm slice of toast were substantial, compared with eating a cold slice of stale bread.

In the UK, the total annual expenditure on baked products is about £3 × 10^9; £7·5 × 10^8 being spent on white bread alone.[1] On average, Britons eat about 10^7 loaves of bread per day and by doing so receive significant amounts of their intakes of nutrients (e.g. see Table 1). Bread has always been a major constituent of the typical British diet, and although its consumption fell significantly after the end of post-war rationing (see Fig. 1), as average real incomes in the UK rose, many individuals are now once again tending to eat more bread (especially of the wholemeal variety) because they realise it is such a cheap source of nutritious food.[2] Above-average consumptions of bread have been associated with those who earn below-average incomes (see Table 2). For example a family, of two adults and four

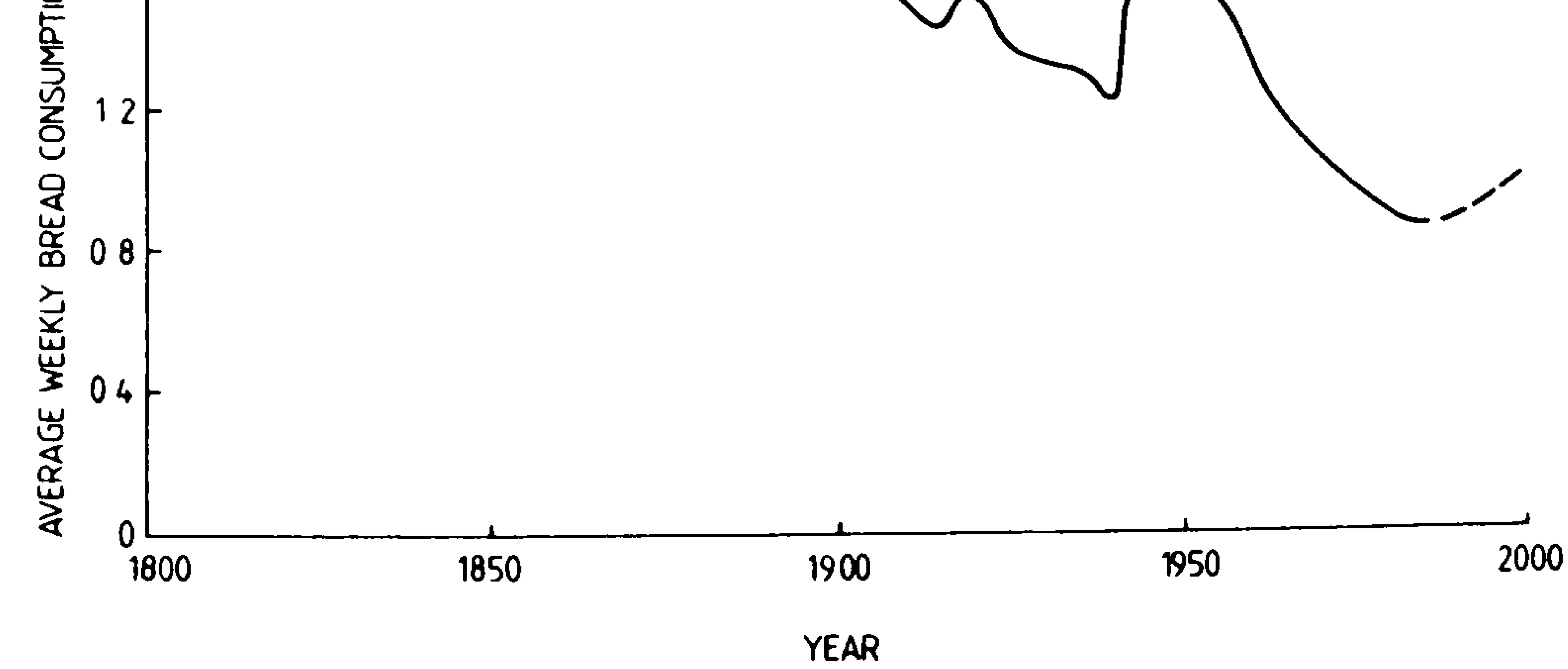


Fig. 1. Average rates of bread consumption within the UK during the period AD 1800-2000 (adapted from Refs 3, 4 and 2).

TABLE 1

Nutrients Provided by Bread, Expressed as Percentages of the Total Amounts of the Respective Nutrients Consumed by Human Occupants of Average UK Households During 1981[3]

Nutrient	*Percentage of total respective nutrient intake* (%)
Carbohydrate	23·9
Thiamin (vitamin B_1)	21·3
Iron	17·2
Protein	14·2
Energy	13.5
Calcium	12·4

children, whose head was an agricultural labourer in the early 1800s, typically spent approximately 65% of their total weekly income on buying bread.[5] (A corresponding family in 1986 usually spends less than 4% of its income on bread.) Relatively poor people not only eat more bread per annum, but also consume more toast (see the Appendix)—the latter being primarily because they can least afford to waste stale bread. Such individuals spend more both on buying and toasting bread. Thus improving the designs of specific-purpose bread toasters will help the least well-off financially.

An individual's preference for toast is dictated according to what he/she has become accustomed and involves considerations such as its taste,

TABLE 2

The Average Bread Consumption per Week in British Homes during 1983[4]

Income group[a]	*Mass of bread consumed per person per week* (*kg*)
A1	0·614
A2	0·661
B	0·826
C	0·932
D	0·976
E1	0·755
E2	0.965
OAP	0·941

[a]The mean gross weekly income for the head of the household in each income group during 1983 was as follows: A1, >£320; A2, £250–£320; B, £135–£250; C, £80–£130; D, <£80; E1, >£80; E2, <£80; OAP, at least, the value of the state retirement pension (≃£34 per week in 1983). *Note*: Income groups E1 and E2 designate those households without an earner, whereas all other groups (except OAP) apply to households with at least one person in financially rewarding employment.

texture, aroma and appearance. Toast forms a significant part of the typical Briton's daily consumption of bread because

(i) the flavour of the bread increases when toasted;
(ii) toast is more easily digested than bread, primarily because some of the otherwise trapped water is driven off and much of the contained carbohydrate is converted into dextrin; and
(iii) toasters provide one of the most rapid means available for an unskilled domestic cook to prepare a hot meal.

Although some consumers opt for burnt, brittle or cold toast, most prefer to eat warm toast (made from white bread) which has a near-uniform light-brown surface colour and is relatively dry on its outside surfaces yet moist within.

From a nutritional viewpoint, the consumption of fresh bread rather than toast is advisable, if bread comprises a large part of an individual's diet. The nutritional value of bread is least in its crust and relatively low in toasted bread.[6] According to Downs and Meckel,[7] thiamin losses on toasting the various bread types, that they tested to a desired surface colour, amounted to between 12·5 and 19·7% of the total thiamin contents, and depended upon the toasting period and the temperature distribution within the bread. Thiamin contents per unit mass of thin slices of toast are substantially lower than those for thick slices.[8] Moreover the destruction of most of the B-group vitamins within bread due to toasting, is frequently complete.[9]

It has been suggested[10] that the biological value of toast is so low that it cannot support the growth of a young rat. Reynolds[11] reported that the availability of the essential amino acid lysine decreased significantly (and irreversibly) as a result of non-enzymic browning, which occurs during toasting.[12] Experiments concerning the feeding of rats, carried out by Tsen and Reddy[13] and Knight *et al.*,[14] with toasted bread of various surface colours, indicated that the quantities of most amino acids within bread decrease substantially during toasting. The progressive reductions in protein quality that occurred for lightly, medium- and darkly toasted bread (when compared with that for untoasted bread) led Tsen and Reddy[13] to recommend that consumers should toast bread only lightly in order to limit the reduction in its nutritional value. Nevertheless, tests performed by Downey[15] indicated that the mean mass of dietary fibre per slice of bread increased significantly when the bread was toasted, due to temperature-induced interactions between endogenous carbohydrate and protein. Thus health-conscious consumers should not regard toast as an undesirable food, especially if it is eaten in typical amounts (see the Appendix).

When starchy foods are cooked, undesirable mutagenic compounds are produced. Spingarn *et al.*[8] reported that when toasting white and brown breads, mutagens were formed initially at similar rates, but after long periods of heating, brown bread exhibited significantly higher levels of mutagenicity. Efforts are being made to isolate and identify the mutagens produced during the thermal processing of foods such as bread, in order to determine their carcinogenicities.[17,18]

To date, few investigations concerning the energy efficiency of toasting have been carried out. Research, associated with the thermal processing of bread, has concentrated on dough-baking techniques and only rarely has the operation of toasting the end-product been considered in detail. Nevertheless toast forms a significant part of the daily diet of many individuals—whether it be prepared via an electric toaster, electric grill, gas grill, commercial gas-toaster or an open fire. Usually a toaster provides the most convenient, rapid and energy-efficient means available for toasting bread (e.g. a toaster will consume typically less than 30% of the energy used by a standard domestic electric grill for toasting two slices of bread): thus its use is recommended. However, the designs of common commercially available domestic electric-toasters leave considerable opportunities for improvement.

THE TOASTING PROCESS

Usually toast is prepared by positioning a slice of bread at between 10 and 50 mm in front of a high-temperature, predominantly radiant-heating, source, for periods typically ranging from 50 to 400 s. However direct-contact toasting (i.e. in which much more conductive heating of bread occurs in a manner similar to that achievable with 'sandwich' toasters) is relatively energy efficient. Nevertheless, domestic 'pop-up' toasters operating on this principle, would tend to be more expensive to manufacture than conventional electric pop-up toasters. Toast can also be produced satisfactorily via high-temperature convective heating, e.g. an experimental forced-convection toaster utilising air at an average temperature of 338°C prepared toast (with an acceptable moisture content) within 35 to 40 s.[19]

During toasting, heat flows towards the central region of a slice of bread by a combination of radiation, conduction, convection and 'heat-pipe' phenomena. The simultaneous evaporation of water from the bread and the chemical reactions involved at its surfaces, makes the toasting process complicated to analyse quantitatively. The intensity of thermal radiation diminishes with depth within the slice of bread. When a radiative flux of a certain wavelength impinges normally on a sample of bread, it is absorbed and scattered. The total rate of dissipation within a layer of the bread (of thickness dx at depth x from its surface) is equivalent to the sum of those absorbed and scattered, i.e.

$$d\dot{q} = d\dot{q}_a + d\dot{q}_s \qquad (1)$$

According to the Bouger–Lambert hypothesis,[16,20] the reduction in the intensity of the radiation as it passes through the food is directly proportional to the received intensity, $\dot{q}$. Thus the rates of dissipation due to absorption and scattering in the layer of food can be written as follows:

$$d\dot{q}_a = -a\dot{q}\,dx \tag{2}$$

and

$$d\dot{q}_s = -s\dot{q}\,dx \tag{3}$$

If a coefficient of proportionality S, the extinction coefficient ($= a + s$), is introduced, then eqn (1) becomes

$$d\dot{q} = -S\dot{q}\,dx \tag{4}$$

By integrating eqn (4) over the path length x:

$$\int_{\dot{q}_0}^{\dot{q}_x} \frac{d\dot{q}}{\dot{q}} = -S\int_0^x dx \tag{5}$$

Hence the radiation intensity, $\dot{q}_x$, at any depth x within the bread can be deduced, i.e.

$$\dot{q}_x = \dot{q}_0\,e^{-Sx} \tag{6}$$

where $\dot{q}_0$ is the radiation intensity entering the outside surface of the bread, i.e. at $x = 0$.

The magnitude of S depends upon the wavelength of the incident radiation and the properties of the food. To describe the absorptive effectiveness with respect to radiation, a 'penetration depth' is usually defined as the reciprocal of the extinction coefficient (i.e. the depth at which the radiative flux intensity has decreased to the reciprocal of the base of Napierian logarithms of its value at the food's surface). For radiations of wavelength 0·122 m (i.e. microwave), 2–4 μm (i.e. medium-wave infrared) and 1·25 μm (i.e. short-wave infrared) the penetration depths were deduced to be 9·8 mm, 0·5 mm and 1·25 mm respectively, when used to heat similar portions of lean meat.[21] Generally, for the wavelength range $0{\cdot}5\,\mu m < \lambda < 10\,\mu m$, the penetration depth increases as the wavelength decreases.

When a food is subjected to infrared heating, its bulk temperature distribution depends largely on its surface reflectivity and bulk transmissivity with respect to the wavelength of the radiation. For example, when the temperature of the heater (assumed to be a perfectly black body) was increased from 300°C to approximately 1900°C, the peak wavelength of the radiation it generated decreased by 80%, whilst the transmissivity of the irradiated bread increased by a factor of 17.[20] The reflectivities of 40 mm thick slices of bread crumb and crust, when subjected to radiations of

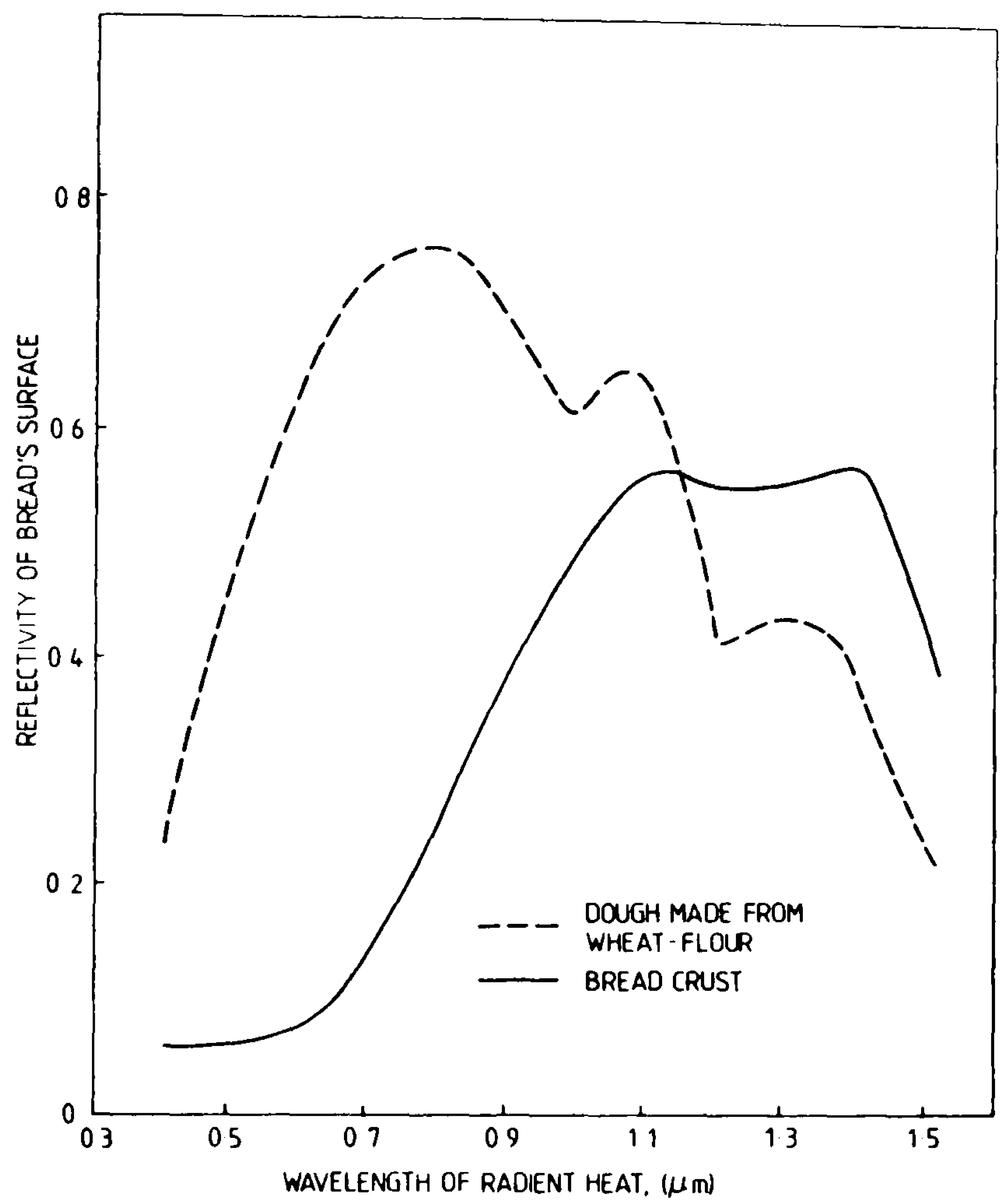


Fig. 2. Reflectivity spectra for dough and bread crust, when subjected to short-wave infrared radiation.[22]

$0{\cdot}4\,\mu m < \lambda < 1{\cdot}5\,\mu m$, are illustrated in Fig. 2. Marn[19] suggested that average reflectivity values of 0·065, 0·211, and 0·365 occur for darkly, medium- and lightly toasted white bread respectively when prepared in a conventional 'pop-up' electric toaster. For wavelengths exceeding approximately $1{\cdot}2\,\mu m$, both the reflectivity and transmissivity tend to decrease (see Figs 2 and 3) and the absorptivity increases. Therefore when toasting thin slices of food, heaters emitting radiation mainly within the range $1{\cdot}5\,\mu m < \lambda < 5\,\mu m$ are more desirable because the food's surfaces are then heated preferentially. When irradiated in the narrower wavelength band $2{\cdot}8\,\mu m < \lambda < 3{\cdot}4\,\mu m$, the rate of evaporation of water from the food's surface should be high.[23] Thus high-emissivity heaters which operate mainly in the wavelength range $2{\cdot}5\,\mu m < \lambda < 4{\cdot}5\,\mu m$ (i.e. approximately 600–1000°C) should be most appropriate for toasting operations.

Because bread has a complex heterogeneous structure (i.e. a solid matrix around various size pores), the amount of heat per unit surface area required

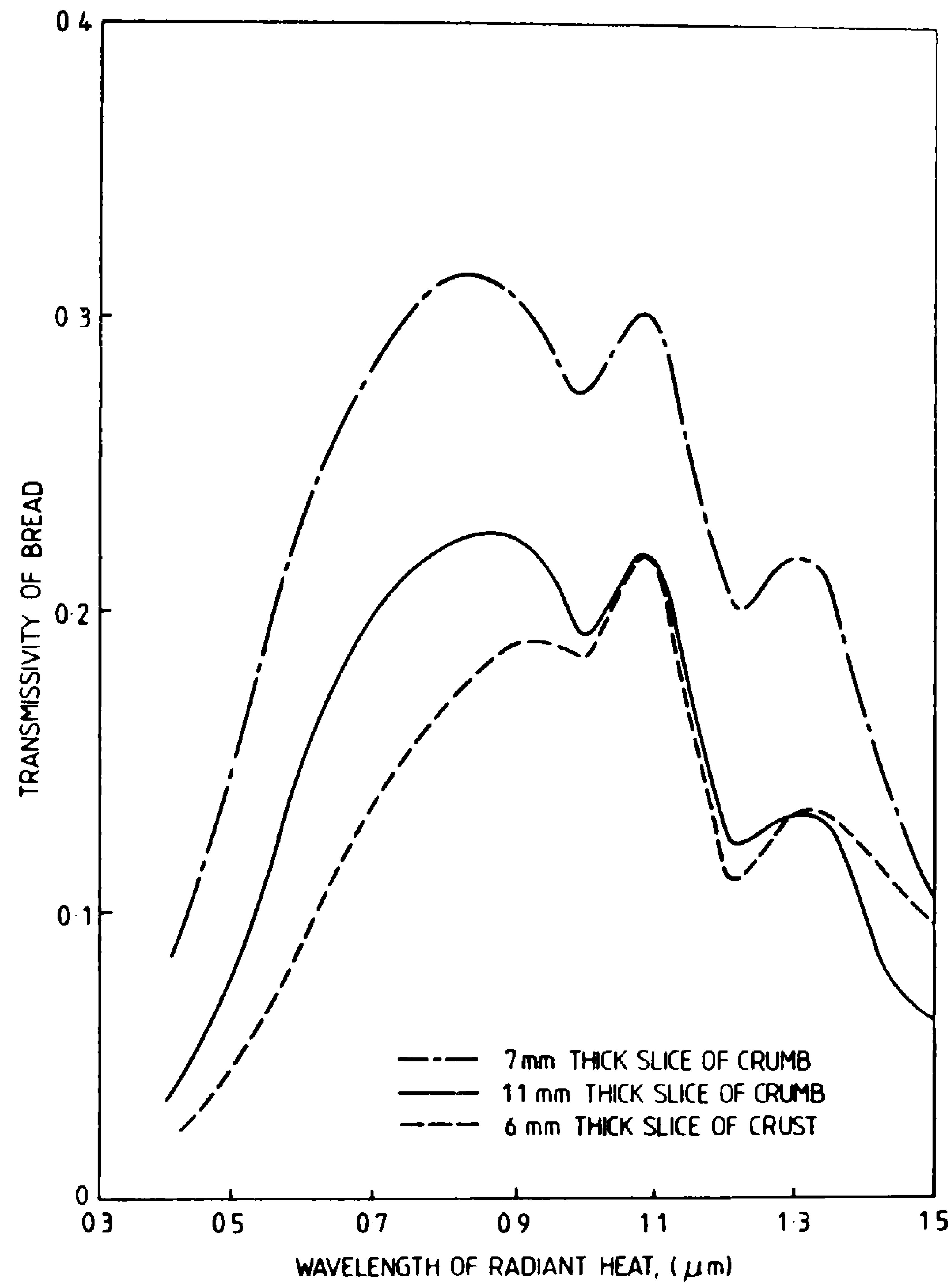


Fig. 3. Transmissivity spectra for various thicknesses of bread, when subjected to short-wave infrared radiation.[22]

to toast parts of its surface to the same colour varies. Furthermore the heat-transfer demands, when toasting thin slices of bread, differ from those associated with toasting other bread-based foods, such as muffins. The latter should be heated thoroughly before attaining a brown surface colour, whereas thin slices of bread should be browned rapidly on their surfaces to avoid excessive dehydration from within. Thus the multi-purpose requirement for a toaster (designed to toast a variety of bread-based foods, despite variations in their properties) tends to militate against attempts to optimise its thermal design.

The exact relationships between the emissivity and absorptivity of bread and its temperature are uncertain, because the combinations of spectral characteristics of the varying compounds and reactants present on the surface of bread during toasting are largely unknown. Nevertheless knowledge of such properties is desirable when designing a food-heating appliance, because if the process that it performs is to be optimised for a certain function, then an optimal range of heater temperatures needs to be determined. Unfortunately accurate deductions of wavelength-dependent extinction coefficients, penetration depths and bulk temperature distributions for bread-based foods are impeded by a lack of information concerning

(i) the thermal properties of bread, especially at temperatures above 20°C; and
(ii) the chemical complexities of the reactions that occur within bread during toasting.

However, the specific heat capacity and thermal conductivity of white bread have been measured. The mean specific heat capacity for white bread crumb of approximately 40% water content (i.e. $m = 0{\cdot}4$), as measured in the present series of tests was $2{\cdot}68\,\mathrm{kJ\,kg^{-1}\,K^{-1}}$. Tshubik and Maslow[24] and Nebelung[25] suggested values of $2{\cdot}7\,\mathrm{kJ\,kg^{-1}\,K^{-1}}$ and $2{\cdot}8\,\mathrm{kJ\,kg^{-1}\,K^{-1}}$ for bread crumb of 42% and 45% water contents (by mass), respectively. The following linear relationships were derived by Johnsson and Skjoldebrand[26] for calculating the specific heat capacities of bread crumb and crust during baking:

$$C_b = 1{\cdot}60(1 - m)T_B + mC_w + 1373(1 - m) \tag{7}$$

and

$$C_t = 2{\cdot}62(1 - m)T_B + mC_w + 1263(1 - m) \tag{8}$$

where $20°\mathrm{C} < T_B < 100°\mathrm{C}$. The former yields $2{\cdot}5\,\mathrm{kJ\,kg^{-1}\,K^{-1}} < C_b < 2{\cdot}6\,\mathrm{kJ\,kg^{-1}\,K^{-1}}$ for the aforementioned crumb which had a 40% water content. (The disagreement between the measured and calculated values is due partly to slight compositional differences between Swedish and British wheat bread, as well as to experimental errors.)

The measured mean values for the effective thermal conductivity of a typical sample of white bread, within the temperature range −20°C to 60°C, are illustrated in Fig. 4. The mean value of k recorded for frozen bread (at −20°C) was $0{\cdot}087\,\mathrm{W\,m^{-1}\,K^{-1}}$, which exceeded that of just-thawed bread. This was because the considerable amount of ice contained within the frozen bread transmitted heat more readily than liquid water. No similar measurements appear to have been made for bread, other than those of Unklesbay *et al.*[27] who suggested a thermal conductivity of $0{\cdot}068$ $(\pm 0{\cdot}004)\,\mathrm{W\,m^{-1}\,K^{-1}}$ for white bread measured whilst it was baking via convective heat. Johnsson and Skjoldebrand[26] proposed an average thermal diffusivity value of $4{\cdot}07 \times 10^{-7}\,\mathrm{m^2\,s^{-1}}$ if $30°\mathrm{C} < T_B < 60°\mathrm{C}$ for bread

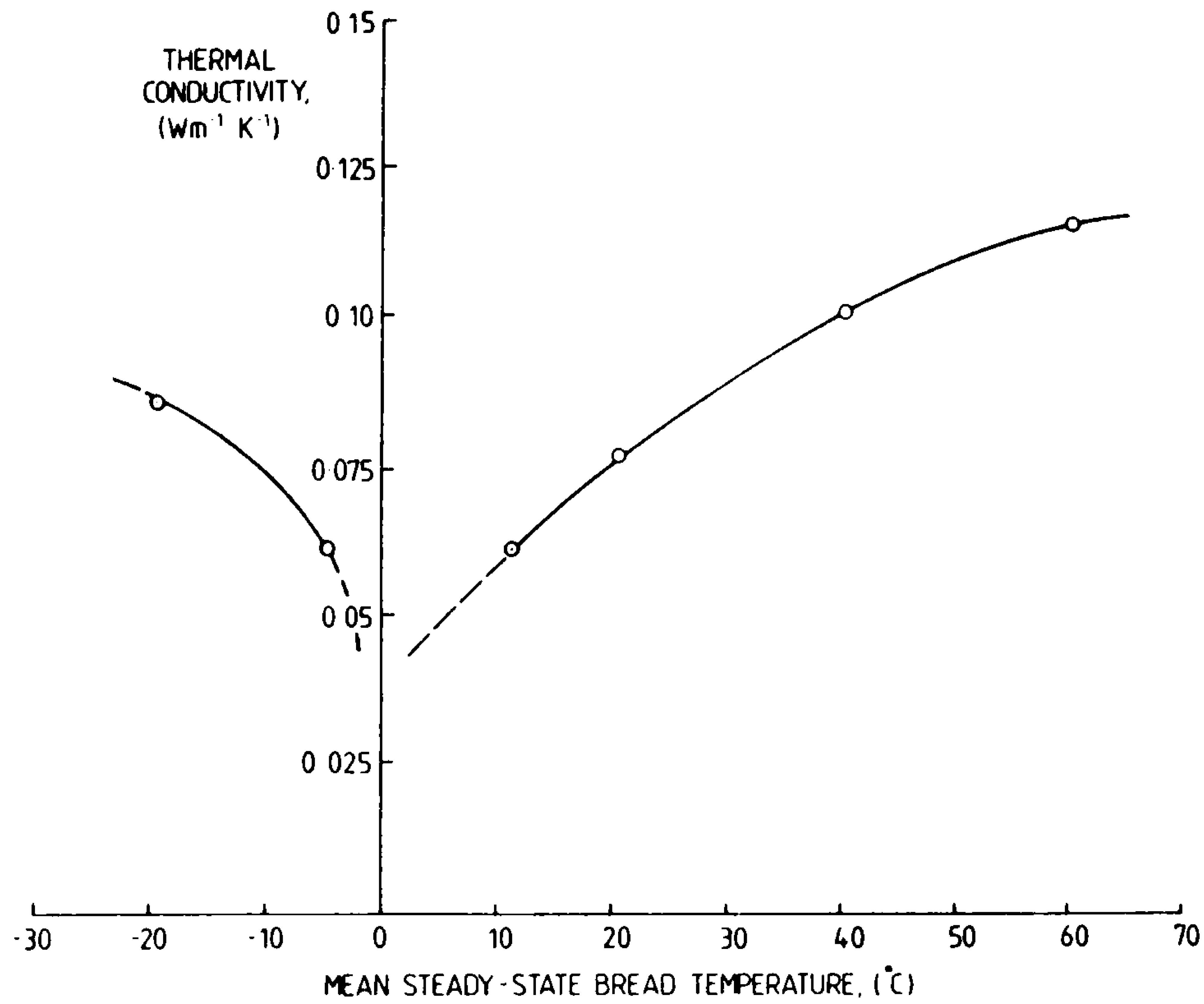


Fig. 4. A typical relationship between effective thermal conductivity and temperature for bread crumb from a standard loaf of white bread.

crumb, and a decaying exponential relationship for the diffusivity α of bread crust with temperature. Earlier measurements by Tichy[28] and Nebelung[25] indicated α values for bread crumb of $2{\cdot}2 \times 10^{-7} m^2 s^{-1}$ and $5{\cdot}6 \times 10^{-7} m^2 s^{-1}$, respectively. However, these apparent values depend partly on the methods used for measuring and calculating the diffusivity.[26,29] Thus in general, only approximate property values for bread are available for designers of food-heating appliances such as toasters (see Table 3).

Bread, like all carbohydrate-rich foods, undergoes several complicated chemical reactions when subjected to heat (e.g. temperature-dependent chemical changes in the contained starch granules cause the bread to warp). Maillard[12] described the general reactions which lead to non-enzymic browning and the formation of flavours and aromas, although knowledge concerning the 'browning process' (i.e. the 'Maillard reaction') remains incomplete.[30,11,31,32]

When bread is heated, multi-stage reactions occur between the free reducing sugars and the nitrogenous compounds (e.g. the amino groups in the amino acids or proteins). Subsequently brown-coloured polymers, and compounds with characteristic cooking odours and flavours, are produced at rates which tend to increase rapidly with the temperature of the bread. At high temperatures, caramelization reactions ensue (i.e. a brown substance of

TABLE 3
Properties of Bread (Unless Stated Otherwise)

Considered parameter	*Typical value(s)*
Bulk density[a]	175–350 kg m^{-3}
Porosity	0·75–0·86
Specific heat-capacity	2·5–2·8 kJ kg^{-1} K^{-1}
Thermal conductivity	0·06–0·13 W m^{-1} K^{-1}
Energy density of bread	0·95–1·05 MJ kg^{-1}
Energy density of toast	1·50–1·60 MJ kg^{-1}
pH value	5·5

[a] The bulk density of toast is equivalent approximately to that of bread, because weight losses as a result of toasting are similar, in percentage terms, to volumetric reductions.

characteristic aroma is produced due to the partial thermal breakdown of the carbohydrate). Also secondary degradative thermal reactions tend to occur.[33] Carbon dioxide as well as water vapour are evolved within the bread during toasting, and so some of the radiation emitted by a toaster's heater will be absorbed by these fluids, and subsequently convected away from the bread.

The process of browning appears to accelerate once the colour of the bread's surface begins to change. This occurs partly because the radiation of visible wavelengths is absorbed slightly more rapidly by the bread during this part of the toasting period.[34,35] As the rate of water migration from within the bread increases, the activation energy for the Maillard reaction decreases and so the browning rate increases.[36] Ginzburg[20] recorded the increases in the surface and centre temperatures of a sample of dough (in a surrounding environment of 90°C), as it was heated initially by microwave radiation to a centre temperature of about 98°C and subsequently by infrared radiation until toasted. Although the size and shape of the sample and the temperature conditions associated with this test were slightly different from those for normal bread-toasting operations, the resultant thermal response curves (see Fig. 5) indicated that the *surface* temperatures rose most rapidly towards the end of the toasting period. Tests confirmed this (see Fig. 6), although considerable practical difficulties were encountered when trying to measure accurately the surface temperatures of the slices of bread during toasting.

Toasting should be terminated once the item's surface temperature reaches between 155 and 190°C, depending on the surface colour desired by the consumer as well as the sugar content and texture of the bread-based food being toasted. If surface temperatures are allowed to increase above

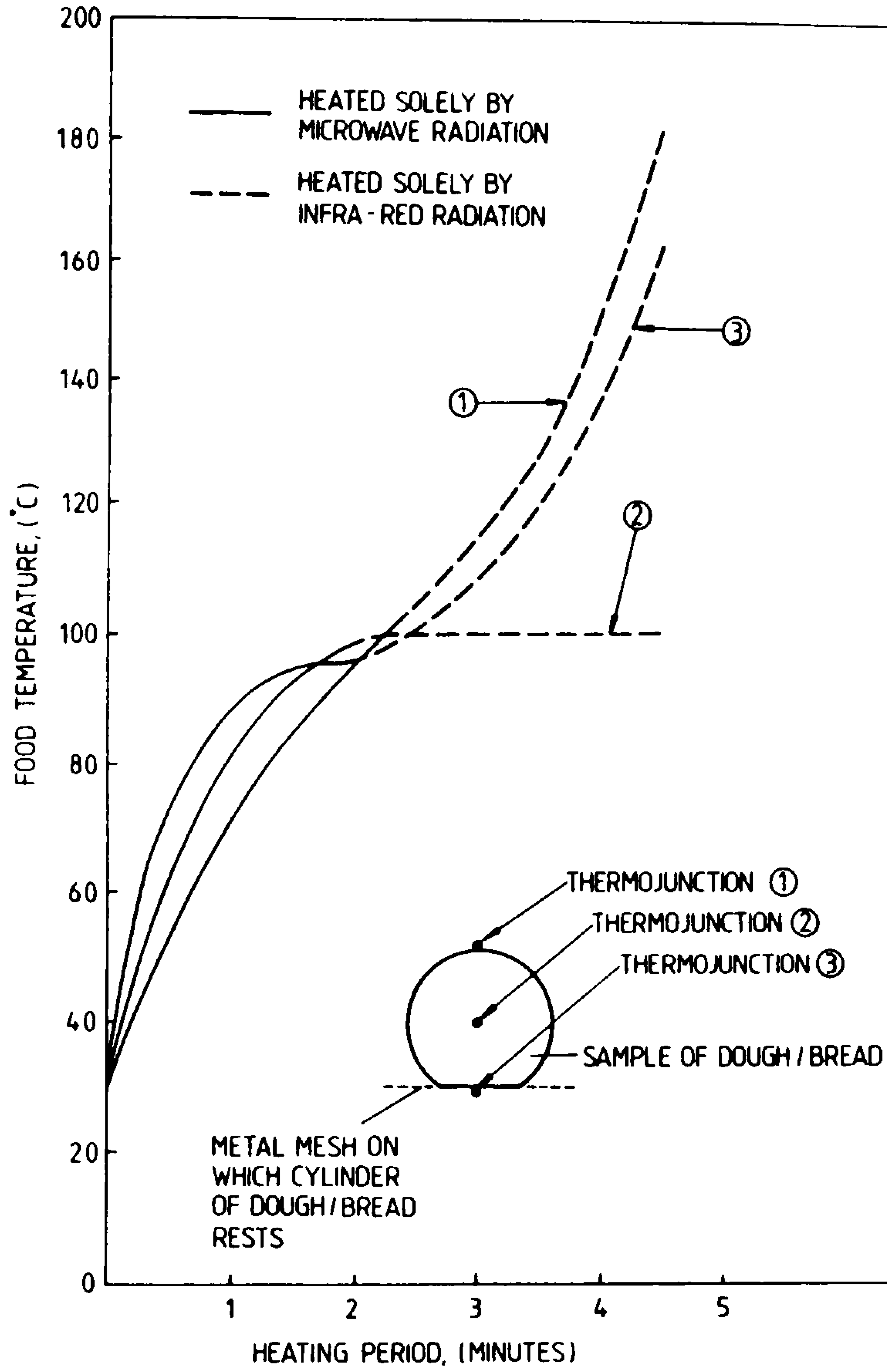


Fig. 5. The thermal response of a 0·1 kg sample of dough, when baked initially by microwave radiation and subsequently heated by infrared radiation until toasted.[20]

this range, the toast will exude temporarily the characteristic 'burnt toast' odour, which was identified as pyruvic aldehyde by Baker *et al.*,[37] until the toast's surface eventually ignites, when its temperature exceeds approximately 250°C.

Optimising the toasting process to achieve the required quality of toast for the least expenditure of energy is difficult. Accurate analyses of the heat and mass transfers that occur when moist porous foods (e.g. bread) are heated primarily by radiation, are often not feasible owing to the complexity of the mathematical abstractions involved and difficulties in specifying accurately the physical property values in the describing equations.[16,29] Thus a preliminary empirical approach with respect to improving the designs of toasters was undertaken.

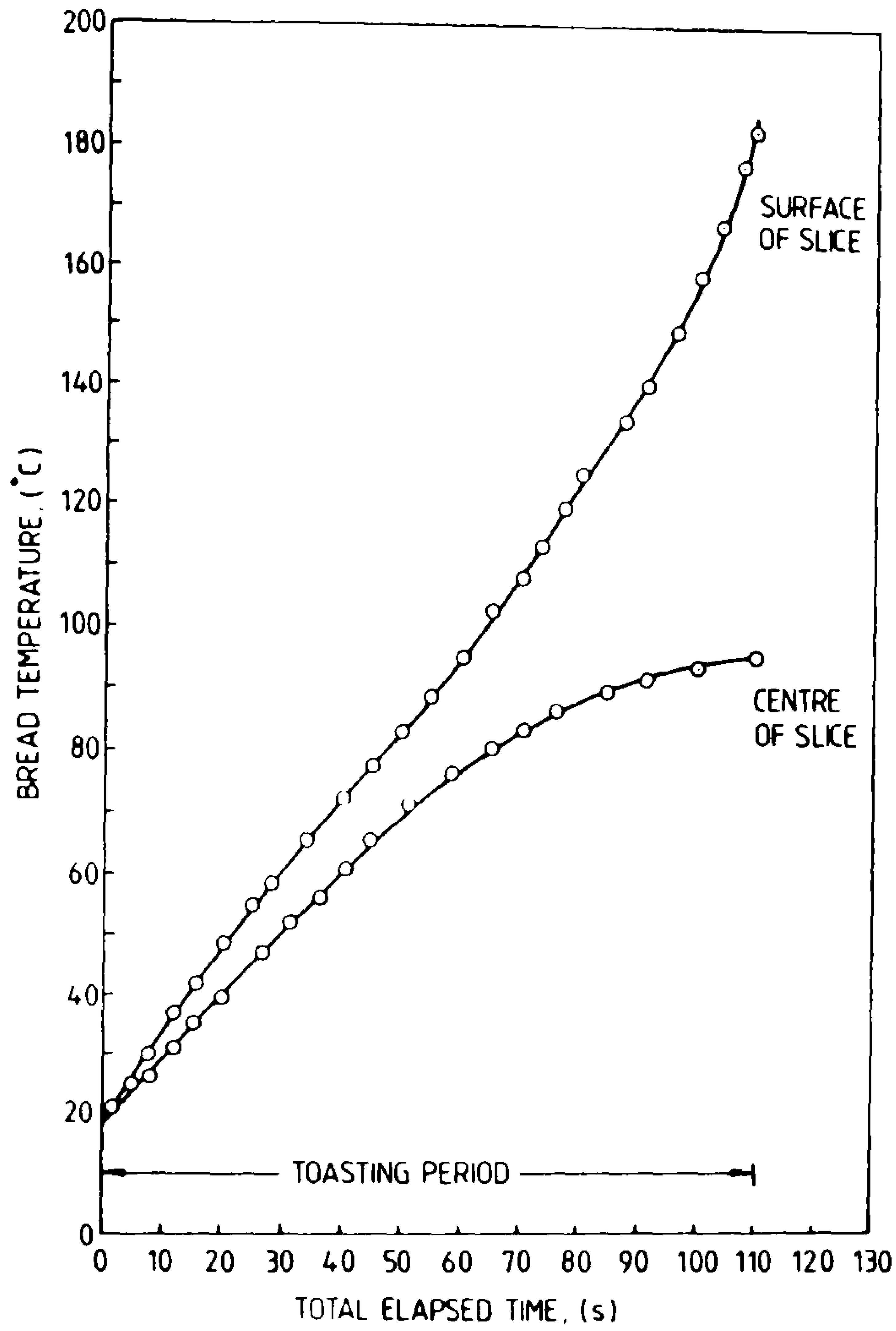


Fig. 6. The average thermal response of a slice of white bread, when heated in a conventional double-slot toaster.

TOASTER DESIGNS

Two main types of toaster are used currently in UK homes: (i) double-slot and (ii) single long-slot systems—both being 'pop-up' designs. They tend to employ alloy-tape heating elements, although some long-slot toasters use coiled elements, which are mounted on ceramic rods and are backed with reflectors (see Fig. 7).

Conventional double-slot pop-up toasters permit toasting periods to be controlled via either thermo-mechanical, bi-metallic strips or electronic timers. Usually after the user has loaded the toaster with the bread slice(s) by pressing down the carriage handle, a mechanical, magnetic or electromagnetic latch holds down the carriage while heating takes place. A control system, incorporating an electromagnetic latch can be designed to ensure that the heaters can be energised *only when slices of bread are present in the*

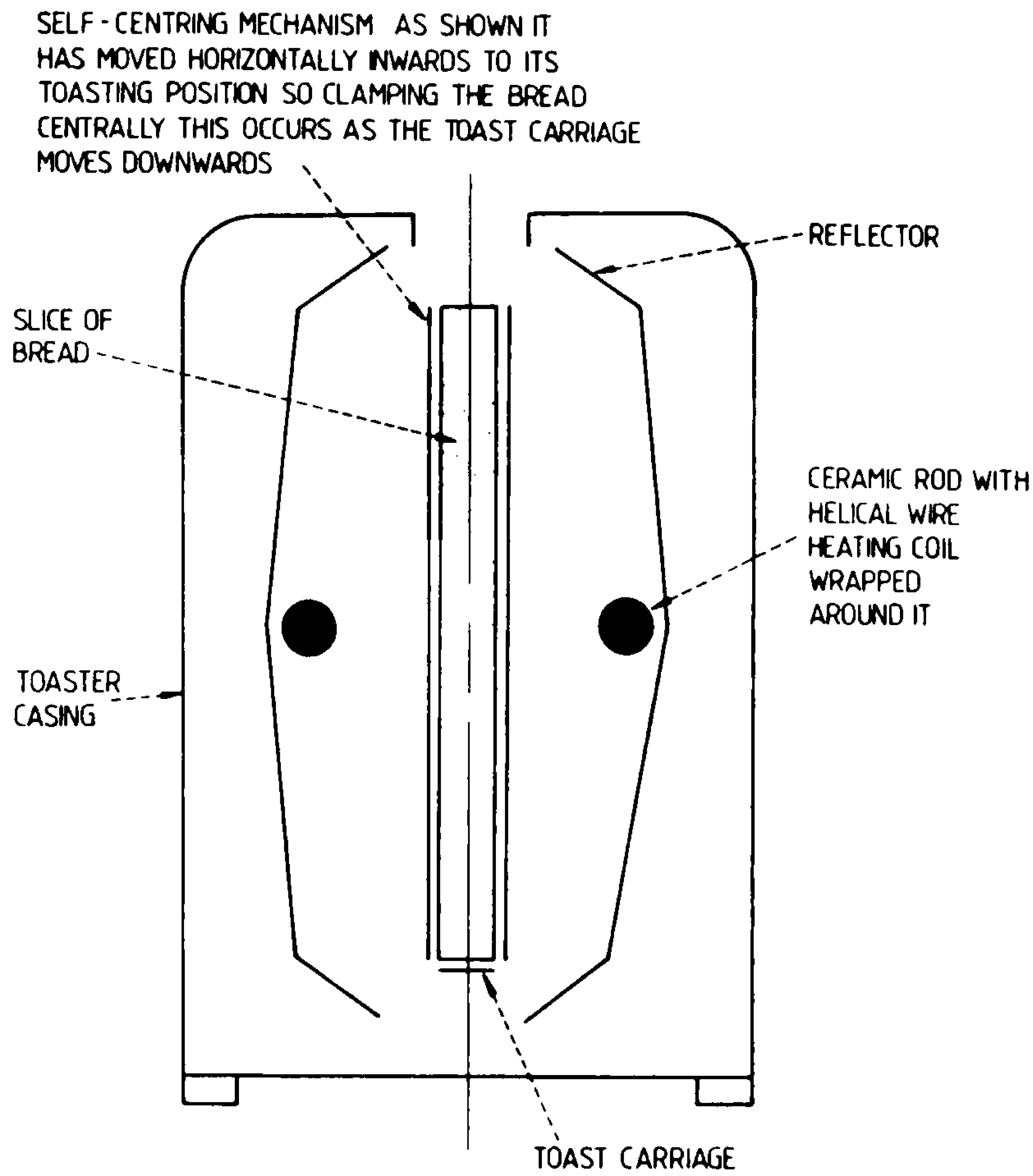


Fig. 7. A schematic cross-sectional view of a single, long slot electric 'pop-up' toaster.

toast slots (Russell Hobbs, Stoke, Staffs, 1985, private communication). The weight of the food augments the force generated electromagnetically, so permitting the toast carriage to be held down and the heating to ensue. The heating is terminated when the bi-metallic strip or electronic timer breaks the circuit supplying current to the heating elements. This allows a spring to raise the toast carriage, and so the toasted slices of bread pop-up, thereby indicating to the operator that they are ready to eat. The pop-up feature is well suited to domestic bread-toasting operations.

Long-slot and double long-slot pop-up toasters have been available in the UK since 1984 and 1985, respectively. Their advantages are that they can toast a greater variety of bread-based foods (e.g. muffins, buns, tea-cakes, scones and irregularly sized slices of bread). Control of the toasting period is achieved in a manner similar to that for the double-slot toaster.

Antiquated side-opening toasters (e.g. see Fig. 8) can toast two slices of bread simultaneously—one each side of the heater. They toast only one side of a slice at a time—the user has to turn each slice over in order to toast its second face, once the first has browned. The toasting operation is controlled by a clockwork timer, but the period required for each side varies because

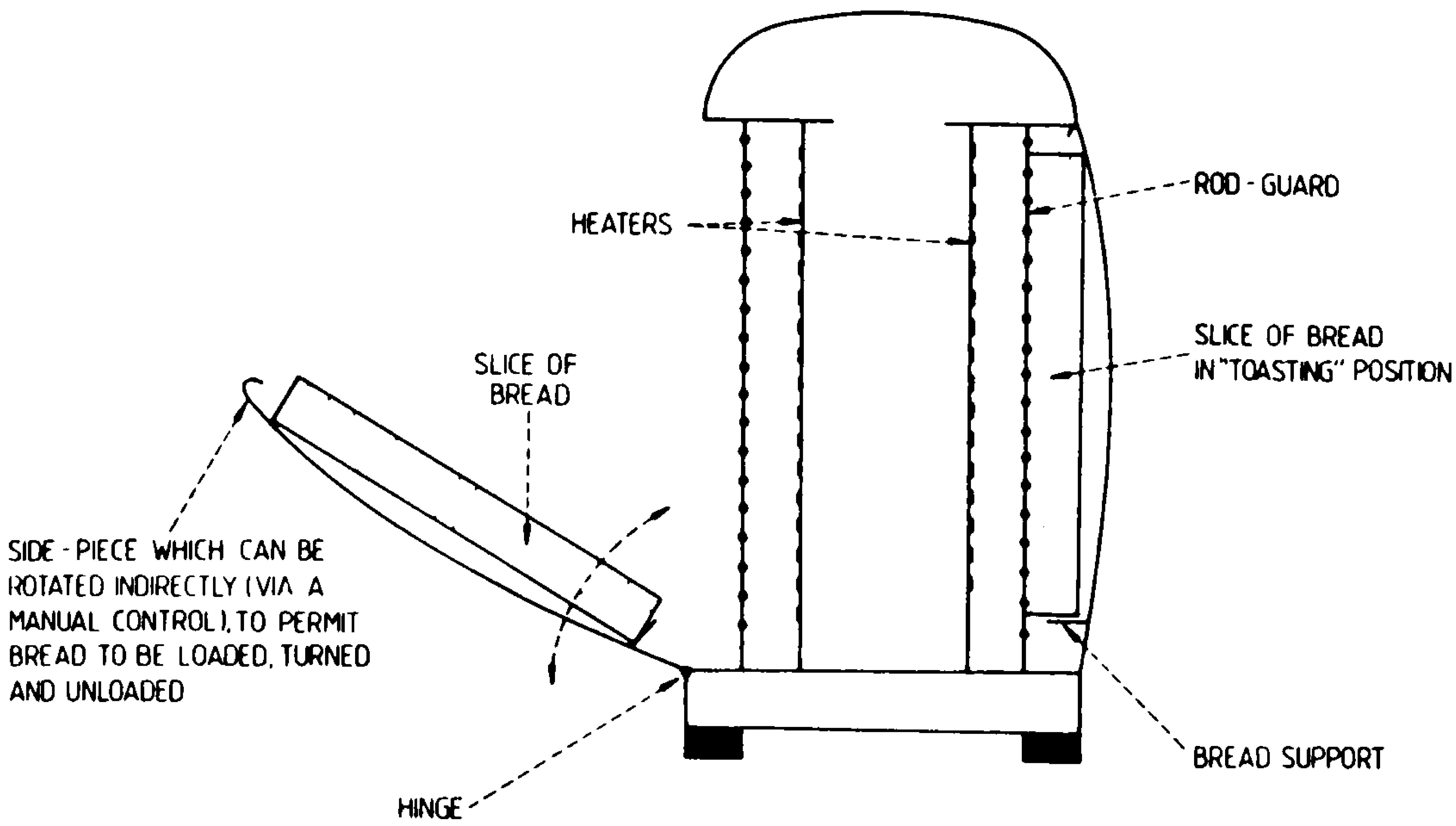


Fig. 8. A schematic cross-sectional view of a side-opening toaster, which requires the user to select the toasting period.

the temperatures of the toaster and the bread have increased significantly relative to the start of the operation by the time that toasting of the second side commences (e.g. see Table 4). Therefore the use of this type of toaster involves skill and careful supervision (especially when more than two slices of bread are required to be toasted for a single meal) if acceptable toast is to be produced.

In the UK, four-slot toasters are employed widely; they usually resemble two double-slot appliances joined end-to-end. Some four-slot toasters are manufactured so that the heating elements for each pair of slots can be

TABLE 4
Required Toasting Periods for a Side-opening Toaster (see Fig. 8), when Subjected to Successive Toasting Operations in Rapid Sequence

Batch number[a]	*Approximate period required (in seconds) for toasting*	
	Side 1 of slice A	*Side 2 of slice A*
1	105	61
2	48	38
3	39	33

[a] Batches of two slices (A and B) of bread were toasted, with intervals of 15 s between each toasting period for reloading the toaster with a new batch of bread slices.

controlled separately. This permits two different types of bread-based food to be toasted simultaneously (McGraw-Edison Co Ltd, Elgin, Illinois, USA, 1986, private communication). Built-in 'tilting' toasters, which reside in a kitchen wall, so that they do not occupy any of the kitchen's work-surface area, are becoming popular in US homes. If the user wishes to prepare toast, the toaster can be tilted outwards to facilitate loading and unloading operations, but when the appliance is not required it can be pushed backwards to fit flush with its supporting wall.

Expensive automatic toasters are available, some of which incorporate tubular quartz heating-elements,[38] and adjustable-width toast slots to facilitate the toasting of buns and waffles. Some electric grills have also been modified, so that they can toast both sides of a piece of bread simultaneously, e.g. by mounting heating elements at the rear of the grill compartment and high-reflectivity surfaces above and below the food.[39] If such systems are designed so that when the grill door is opened, the power supply to the heater is shut-off and the shelf supporting the toast automatically moves towards the user, then more efficient and less hazardous toasting operations should result.

Marn[19] investigated the possibilities of using gas-fired heating systems for toasting bread rapidly. Designs were proposed for non-portable conveyor and pop-up toasters utilising either radiant burners or hot-air generators. Appliances based on the latter technique produced acceptable slices of toast in about 30 to 40 s, but were expensive to manufacture primarily because in each a high-pressure blower and high-temperature heat

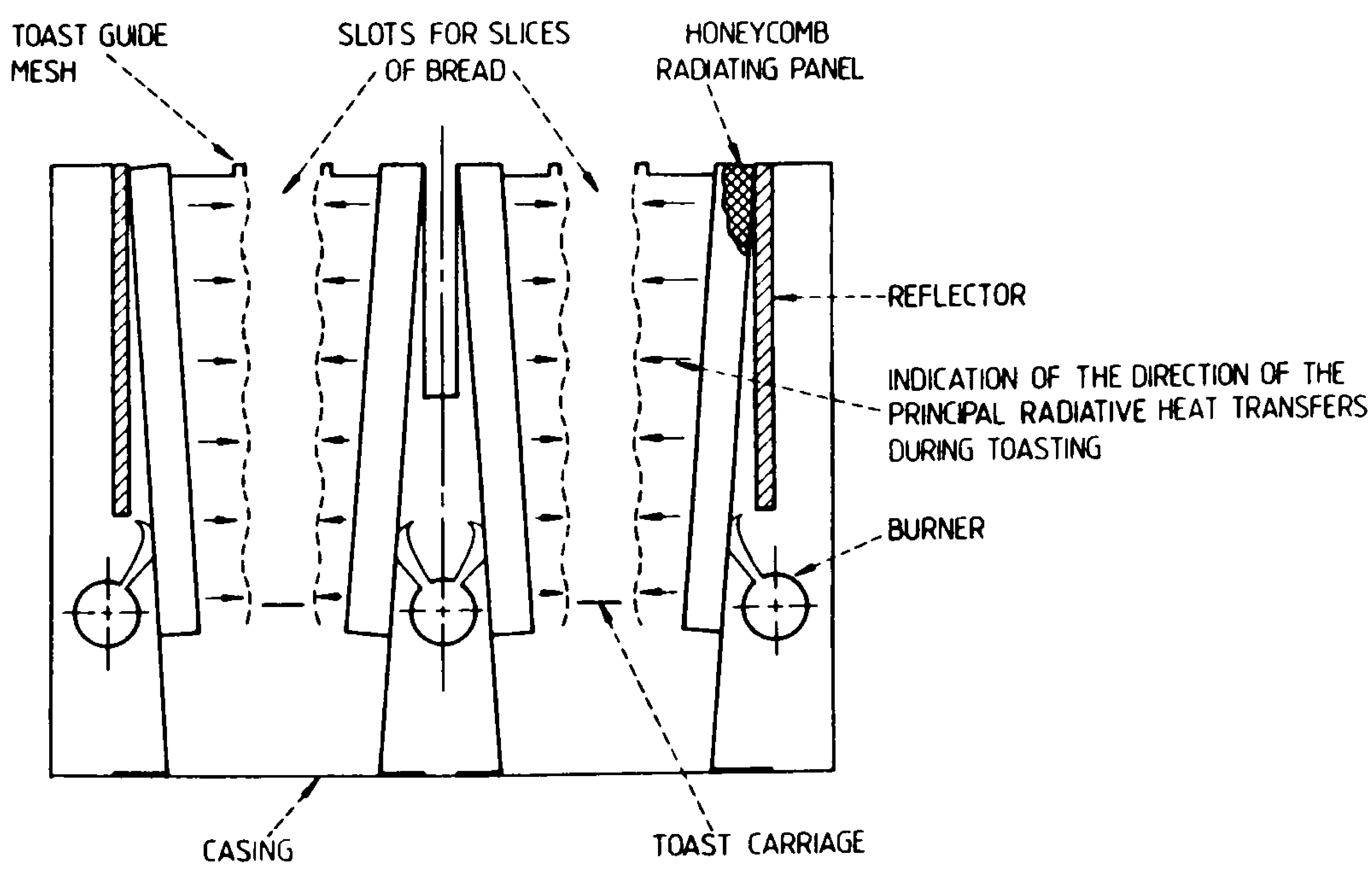


Fig. 9. A schematic view of the basic features of a prototype gas-fired 'pop-up' toaster.[19]

TABLE 5
Performance Data for a Prototype Gas-fired Pop-up Toaster (see Fig. 9) and a Conventional Electric Pop-up Toaster, when each was used to Toast Two Slices of White Bread[19]

Toaster	*Bread*	*Average reflectivity of the toast*	*Weight loss during toasting (%)*	*Toasting period (s)*[a]	*Approximate primary-energy usage (MJ)*[b]
Gas-fired	Lightly toasted	0·343	12·3	55	0·42
	Medium toasted	0·253	15·1	65	0·50
	Darkly toasted	0·075	20·3	75	0·58
Electric	Lightly toasted	0·365	15·5	70	0·68
	Medium toasted	0·211	16·3	86	0·83
	Darkly toasted	0·065	21·4	102	0·98

[a] The toasters were initially at the ambient environmental temperature.
[b] Assumes overall supply efficiencies of 92% and 28% for the gas and electricity supplies, respectively.

exchanger were employed. Similarly the pop-up toaster, utilising radiant burners (see Fig. 9), toasted bread more rapidly than a conventional electric pop-up toaster (see Table 5). Today in the UK, gas-fired toasters are employed within the catering industry, but high capital-costs inhibit prospective sales of gas toasters within the domestic market.

In a catering kitchen, some form of toasting appliance is desirable, especially during breakfast periods. From the perspective of a food-service establishment, the preparation of toasted foods offers significant benefits, when compared with most other food-cooking techniques, e.g.

—Toasting is a rapid process. It is feasible that the toasting should occur after the customer's order is received (i.e. toasted items can be made to order).
—Foods can be toasted directly from an initially frozen and/or partially stale state without affecting adversely their palatability.
—Toasted items can be prepared by relatively unskilled staff.
The end-products can be dressed (by the customer if he wishes) with a variety of toppings (e.g. marmalade, pâté, cheese, baked beans or sardines) so that several attractive and distinctive toast-based foods can be created.

Usually groups of electric (or natural-gas) toasters (each having 4 to 12 slots), or conveyor toasters (some of which are capable of toasting 1500 slices of bread per hour, once they have been pre-heated) are used to satisfy high rates of demand. Speciality toasting appliances (e.g. those designed for toasting rolls, bagels or waffles) may be employed, although the energy-profligate use of electric grills and ovens for such toasting purposes is not uncommon. However, at home, the typical consumer favours an inexpensive toaster of small base area. Consequently double-slot, four-slot and long-slot toasters dominate the UK domestic market.

FAILINGS OF EXISTING DOMESTIC TOASTERS

It is estimated that at least 10^7 toasters are employed currently in the UK, and that British consumers spend about £2 × 10^7 p.a. buying domestic electric-toasters. From the findings of a survey (see the Appendix) it has been concluded that the typical toast-eating Briton spends about £1·10 and £12 p.a. respectively on buying electricity and bread for toasting purposes. Users tend to purchase toasters mainly on the basis of least cost and attractive appearance. Subsequently any inadequacies in performance are tolerated, partly because there are seemingly few better automatic toast-making appliances available. Owing to market forces, manufacturers have tended to concentrate their efforts on minimising capital costs and improving the visual appeal of their domestic toasters. Yet the common commercially available appliances receive many criticisms from consumers, e.g.:

—The slices of bread toast too slowly, thereby causing the end-products to be brittle and too dry in their inner regions.
—Slices of bread cannot be toasted successively without necessitating re-adjustment of the 'browning' control.
The degree of browning varies for slices of bread toasted by the same appliance.
—Toast is produced which has a non-uniform surface colour and often the periphery of the slice is not toasted properly.
—The bread is liable to smoulder or even ignite, if the control system for the heating elements is either set incorrectly or suffers a breakdown.
—The external surface temperatures of the toaster's casing exceed recommended safe-touch temperatures[40] and are therefore particularly dangerous when used near young children.
—The toaster is difficult to clean properly.
—The appliance has an unacceptably short useful working-life.

COMPARATIVE PERFORMANCES

Several toasters, on sale in the UK during 1985 have been tested. In view of the conclusions of the consumer survey undertaken to determine British toast-eating habits (see the Appendix), pre-cut white bread was usually employed for the test specimens in these experiments, i.e. the findings refer to the toasting of this type of bread, unless stated otherwise.

Some of the observed erratic behaviours of toasters can be attributed to variations in the thickness and weight of the slices of bread taken from any given commercially pre-cut loaf (e.g. the weights of nominally identical successive slices, from the same loaf, varied by up to 17%). A similar problem was encountered when uncut bread was sliced carefully into slices of nominally similar dimensions. This occurred because the distribution of moisture within a loaf of bread varies significantly,[41,42] e.g. when fresh, the moisture contents of bread crumb and crust are about 45% and 3% respectively, but when stale both parts tend towards an equilibrium moisture content of about 14%.[10] Furthermore the ability of a vertical slice of bread to support its own weight affects the uniformity of browning achieved by a toaster. When loaded into the toast slot, a slice of fresh bread often does not stand quite erect; thus it will not be heated uniformly. To overcome this problem and the tendency for the slice of bread to move during toasting (such that it does not remain parallel with, and equidistant from, the heaters), some manufacturers have fitted self-centring guides to their toasters (Tefal (UK) Ltd., Slough, Berkshire, UK, 1985, private communication; Rowenta Ltd., Ashtead, Surrey, 1985, private communication). When the carriage handle is pushed downwards, these guides lightly clamp the bread and position it centrally, so that it always remains parallel with, and equidistant from, the heaters. Consequently the bread is heated relatively uniformly, but unfortunately the guides tend to obscure strips of the bread's surface from the incident thermal radiation: this results in the production of striped toast.

For these reasons, only qualitative decisions concerning the similarities and efficiencies of medium-toasted samples of bread produced by different toasters were made. Specific criticisms of a manufacturers' products are not proffered, although the findings tended to corroborate those of concurrent studies.[43-45] The exact method for comparing the uniformities of browning achieved by various toasters as suggested by BS 3999,[46] and extensive organoleptic testing, were inappropriate owing to the wide ranges of variables not under the control of the authors.

It is estimated that the end-use and overall efficiencies of operation for a typical domestic electric-toaster (when used to its full capacity) are approximately 24% and 6%, respectively. Table 6 illustrates the energy consumptions per slice of toast prepared, the approximate maximum heater temperatures attained during toasting and the representative toasting periods required to produce similar pieces of toast by the long-slot and double-slot toasters tested. The necessary heating periods were least for the long-slot toasters that employed wire-wound cylindrical heaters backed

TABLE 6

Typical Maximum Heating-element Temperatures, Toasting Periods and Primary Energy Consumptions for the Seven Toasters Tested (Initially at ~ 15°C) when used with One or Two Slices of Bread (also Initially at Approximately 15°C)

Make and type of toaster	*Approximate indication of the maximum temperature of the heaters (°C)*[a]	*Typical toasting-period (s)*[b]		*Approximate primary-energy usage (MJ)*	
		for 2 slices	*for 1 slice*	*for 2 slices*	*for 1 slice*
Tefal[c] (long-slot)	795	156	128	0·67	0·55
Rowenta[c] (long-slot)	780	123	117	0·42	0·39
Philips (long-slot)	705	295	211	0·68	0·49
Russell Hobbs (double-slot)	625	172	169	0·59	0·58
Philips (double-slot)	580	291	212	0·73	0·53
Indesit (double-slot)	565	176	162	0·63	0·58
Morphy Richards (four-slot)	560	253	219	1·30	1·13

[a] These temperatures, all obtained in an identical manner, were slightly lower than the true temperatures of the heaters, because the thermocouples employed for measuring purposes tended to affect the temperatures of the areas of the heaters to which they were attached.
[b] Toasting periods may vary by up to 10 s because only subjective decisions (as to whether the item of toast produced by each toaster, was similar to the end-product from the reference toaster) were made.
[c] Toaster employed wire-wound cylindrical heaters, backed with aluminium-alloy reflectors.

with reflectors. However, the *effective* radiating areas of the heaters were usually smaller than the receiving areas of the slices of bread inserted in the toaster. Consequently the bread tended to be relatively undercooked along its uppermost edges. Therefore, although toast was usually produced at a lower energy cost, its aesthetic quality suffered.

Those appliances requiring more than about 170 s to toast two slices of bread simultaneously, tended to produce toast that was often considered to be too dry in its inner regions. On average, slices of bread lost about 15% of their mass when toasted from their 'deep-freezer' state (i.e. from an initial temperature of about −20°C), and 17% when toasted from a near-ambient temperature of about 15°C. These losses (i) were mainly due to the evaporation of water from the bread during toasting and (ii) increased from

9 to 22% with the degree of toasting (i.e. the 'browning' of the toast's surface).

The moisture content of a typical slice of bread is 30 to 45%, although usually bakers are concerned only with satisfying requirements which stipulate a maximum moisture content for bread. Wolfrom and Rooney[47] suggested that the maximum rate of browning occurred in heated foods when they contained about 30% moisture (by mass). Thus a toaster's effectiveness may increase if high evaporative losses from bread during toasting are inhibited. This may be achieved by modifying the design of the toaster's heaters and toast compartment. Marn[19] found that bread lost only 10% of its moisture content when toasted in 15 s by positioning it 25 mm away from a gas-fired heater radiating at approximately 816°C. However, the end-product was considered too moist and so an average moisture loss due to toasting of about 15% was recommended. Nevertheless it is considered that, because many people in the UK use pre-cut bread (see the Appendix), slices of which are sometimes only about 7 mm thick, a moisture loss of about 12% may be the optimum. Clearly, the amount of water driven off per unit mass of bread during toasting, is critical to the quality and acceptability of the toast produced.

Maximum temperatures of the sides and end-pieces of various toasters are shown in Table 7. Brookes[48] measured the outside surface temperatures of a toaster when subjected to successive toasting operations. He reported that these hot surfaces were exceedingly dangerous (see Fig. 10) especially to young children, and illustrated the benefits of insulating the toaster's casing. Nowadays, most toasters are sold with product information which states that the appliance's casing is liable to become dangerously hot. However such advice is of little value to an individual who inadvertently (i) touches the toaster when it is operating or (ii) allows the polythene wrapping of a typical loaf of pre-cut bread to contact the toaster's casing, thereby leaving an unsightly mark (which is particularly difficult to remove) on a domestic appliance that has been partly selected because it is visually attractive. Nevertheless, some manufacturers are becoming concerned with the need to reduce the temperatures of outer surfaces, which are likely to come into contact with human skin.[45] To avoid this problem, it is recommended that an easily cleaned plastic casing, which encloses internal radiation reflectors, is used and if necessary air is encouraged to flow over the inside surface of the casing to ensure its temperature does not become excessive (see Fig. 11). Also because the temperature gradients within a toaster are very high, it is desirable to eliminate any thermal shorts via which heat may be transferred easily from the internal components to the external surfaces with which the user is liable to come into contact. Recently, the judicious employment of plastic, aluminium alloy and ceramic components by some manufacturers in

TABLE 7
Typical Maximum Operating Temperatures of the Outer Surfaces of 12 Domestic Toasters as Purchased 'Off the Shelf' from Retailers in Britain[44]

Make and type of toaster	*Typical maximum temperature attained by toaster's*	
	Vertical side panel (°C) (i.e. approximately parallel with the slice of toast)	*Vertical end panel (°C)*
Russell Hobbs (four-slot)	155	65
Black & Decker (four-slot)	137	55
Salton (four-slot)	136	55
Pifco (four-slot)	125	35
Swan (double-slot)	108	28
Sunbeam (double-slot)	107	42
Kenwood (double-slot)	100	51
Swan (four-slot)	94	36
Morphy Richards (four-slot)	88	38
Tefal (long-slot)	79	27
Philips (double-slot)	60	33
Rowenta (long-slot)	26	26

place of mild-steel ones has reduced the thermal mass of toasters. Thereby their thermal efficiencies have improved slightly.

All the toasters tested tended to perform inconsistently when more than a single batch of toast was prepared in quick succession. The final temperatures (i.e. those at the ends of the toasting periods) of the toast compartments increased after each successive toasting operation, and so the periods (and hence the energy inputs) required for achieving satisfactory toasting fell progressively to minimum values which were usually about 70% of those for the initial toasting operations. Such minima were attained after 8 or 10 slices of toast had been prepared, in pairs, by typical double-slot toasters. Normally the browning control had to be adjusted for each batch in order to ensure that the same colour toast was obtained. Without

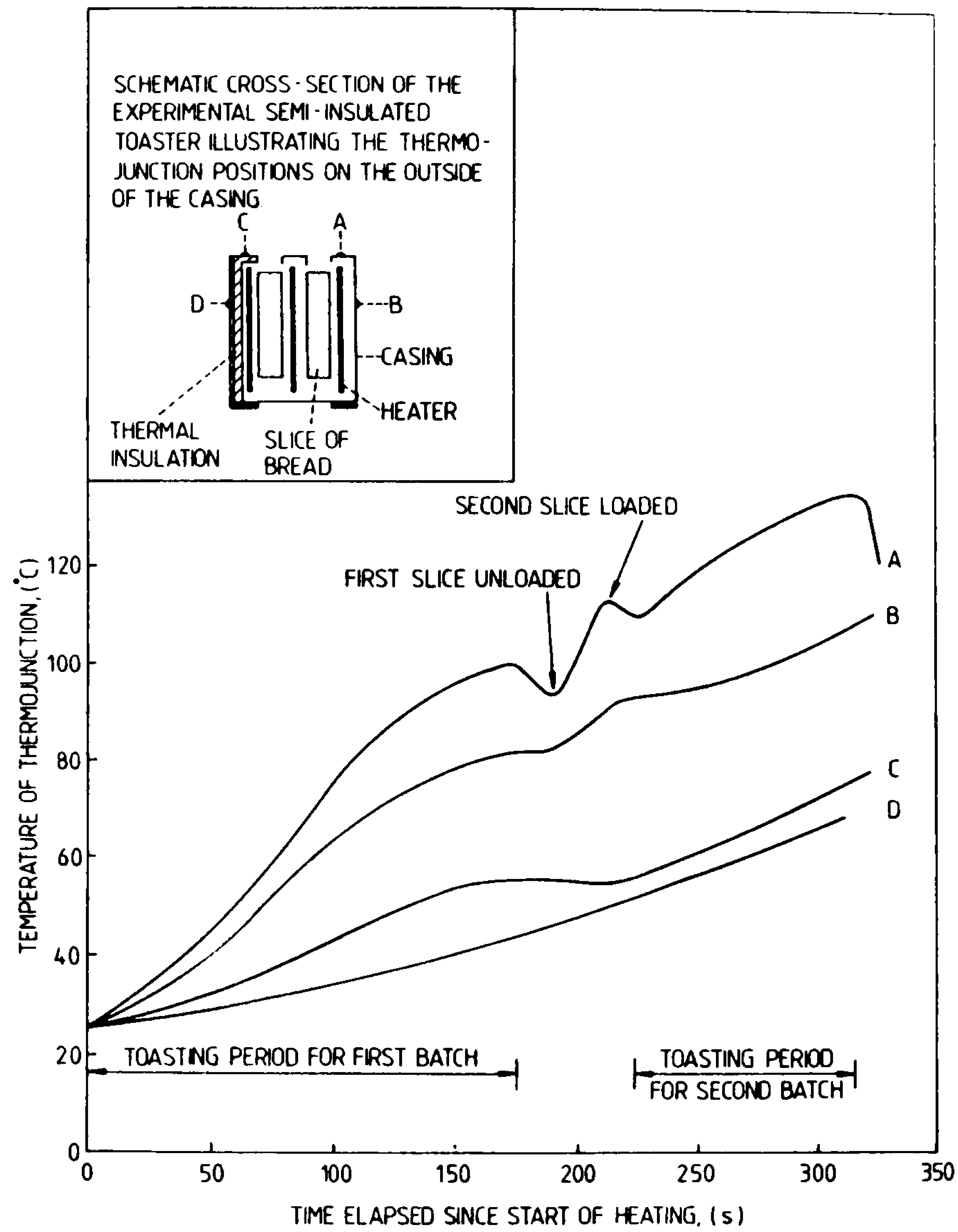


Fig. 10. The temperatures at various locations on the outer casing of a double-slot toaster, when used to prepare four slices of toast (adapted from Ref. 48).

experience, appropriate re-adjustment of the browning control is difficult to achieve and so food, energy and time may be wasted. Usually successive batches of acceptable toast can be produced only when the user is able to supervise the operations (i.e. to release the toasted items before they become overcooked or re-insert them for extra heating if they have been ejected undercooked). (Because this negates the automatic feature of pop-up toasters, some toasters have been fitted with control systems which attempt to re-adjust the heating period automatically when the toaster is subjected to a high rate of use.)

During testing, non-uniform browning of a slice of bread occurred frequently. The problem was made worse if a double-slot toaster was used to

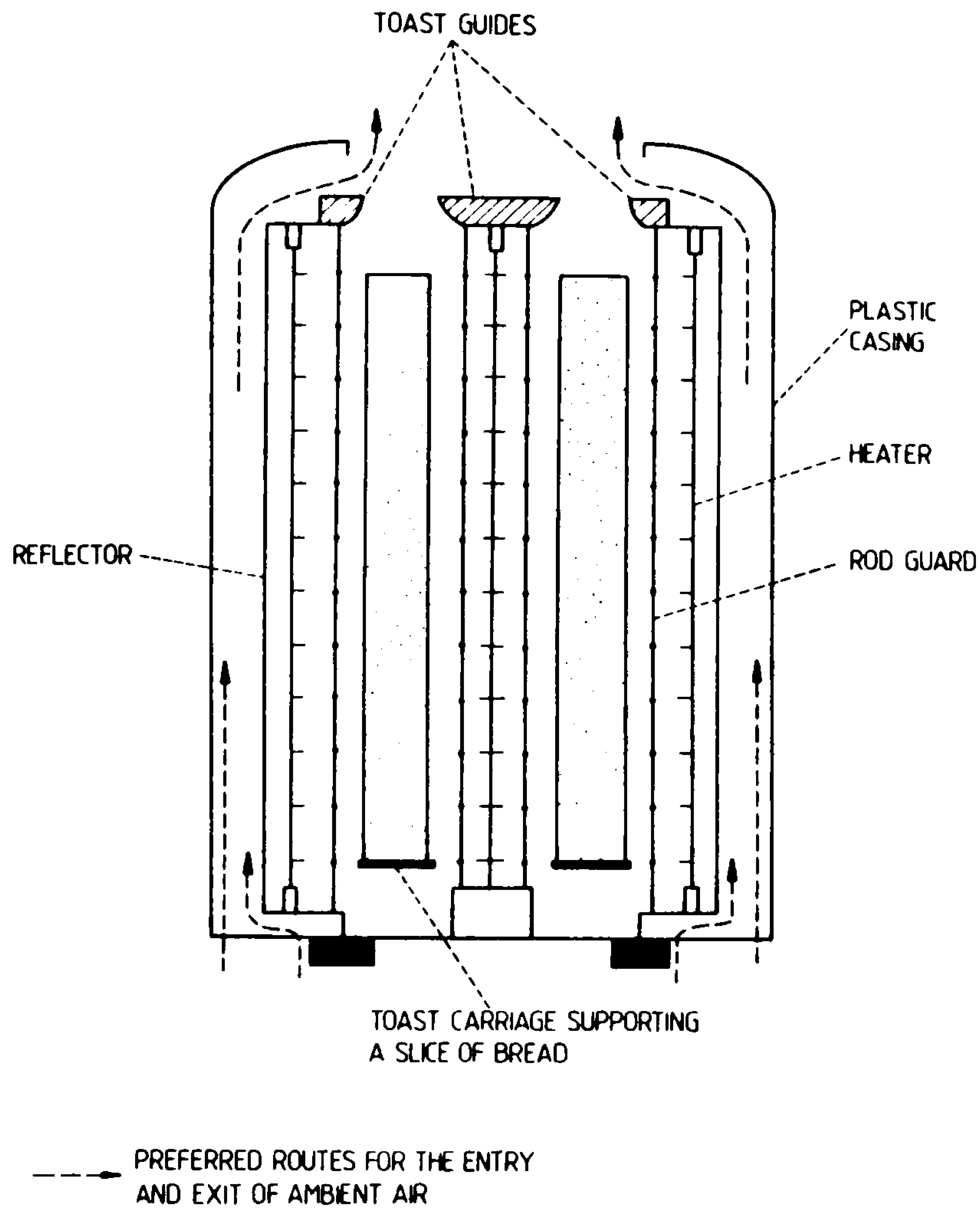


Fig. 11. A cross-sectional end-view of a double-slot toaster, designed to operate with safe outside surface temperatures.

toast only one slice of bread at a time. (Some four-slice toasters are fitted with a facility to switch on only the immediately adjacent heating elements when toasting just two slices of bread, but double-slot toasters do not offer this facility to users who wish to toast one slice only.) By the end of the toasting period, one side of the slice reaches a higher temperature than the other, thereby causing it to have a darker surface colour.

In order to ensure that both sides of a slice of bread are toasted equally, a toaster should be designed so that the heat fluxes incident upon each side are identical. This heat balance cannot be achieved when toasting only one slice in a double-slot toaster, because the central heater is designed to toast adjacent sides of two slices of bread simultaneously. Ideally a toaster should be designed so that each toast compartment can prepare toast satisfactorily and independently. However the provision of the means to achieve this optimum may be prohibitively expensive, despite the savings accrued

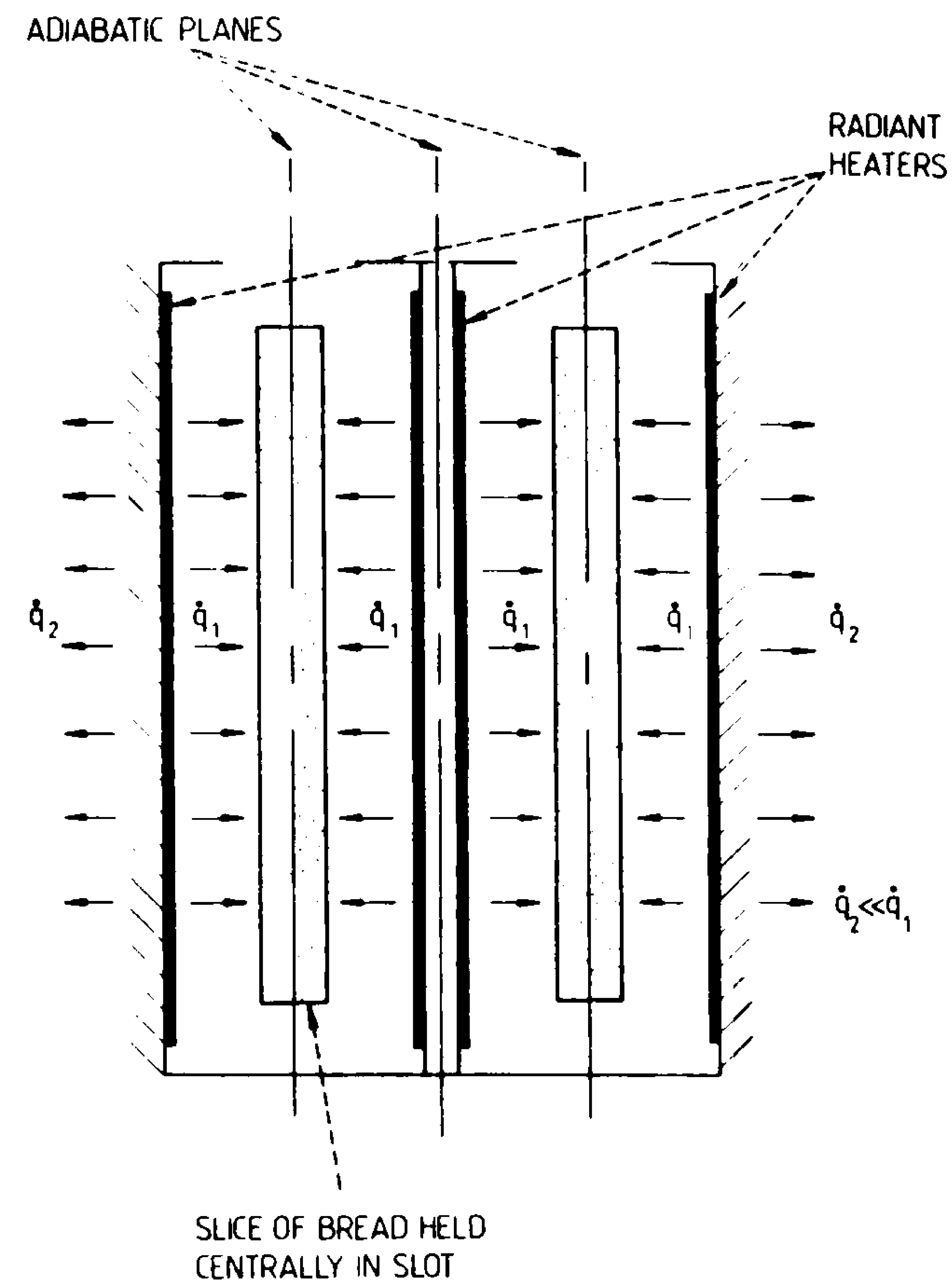


Fig. 12. A schematic cross-sectional end-view of a double-slot toaster, indicating the ideal heat transfers which should prevail for all toasting operations.

subsequently by users when toasting only one or three slices of bread in double- or four-slot toasters, respectively. Nevertheless attempts should be made to achieve a cost-effective design based on that shown schematically in Fig. 12. The main objectives should be (i) to bias the power outputs of the central and outer pairs of heaters, so that a lateral heat balance prevails for all operating conditions; (ii) to permit the heaters for a toast compartment to be energised only when required; and (iii) to ensure the bread is held centrally within each toast compartment throughout the operation.

One of the double-slot toasters tested experimentally, failed to toast bread rapidly despite operating with elements which attained above-average surface temperatures. This indicated that the power densities of its Nichrome-tape heating elements were inadequate. Clearly some manufacturers have chosen to reduce costs by minimising the length of heating tape employed. This practice necessitates the use of high resistivity, low cross-sectional area heating tapes to ensure rapid responses and high surface temperatures. Unfortunately some overcompensation may have occurred (i.e. the heaters may have been designed with too large a ratio of resistivity to cross-sectional area) and so insufficient power is dissipated per unit area of the heating tape. Therefore it is essential that the objective of ensuring that the heater is constructed with an acceptable radiating area and power dissipation, is considered alongside that of reducing heating-system costs.

Two of the toasters examined suffered from a basic design fault, which seems inexcusable. If a slice of bread became jammed in the toast-slots so that the 'pop-up' mechanism could not eject it, the power supply to the heaters was not terminated automatically. Consequently the toast began to smoulder and eventually caught fire. Simple toast guides and self-centring mechanisms should overcome any tendency for slices of toast to wedge in their slots (e.g. see Fig. 11). Furthermore it was noted that most toasters had an unnecessarily wide range of toasting periods: usually when the control was set to the 'lightly toasted' mark, untoasted bread was produced and when the 'well-toasted' setting was chosen, charred black toast was prepared. Recent attempts to provide multi-purpose domestic toasters, which are capable of toasting various breads, buns and muffins may be partly responsible for the extremes of the browning controls available. However, some toasters are unable to toast such a variety of foods because they are incompatible dimensionally, yet unnecessarily wide ranges of toasting periods are still provided! For example, one of the toasters tested offered toasting settings ranging between 16 and 185 s, but bread only became browned when heated by this appliance for periods of 140 to 185 s. Evidently a toaster's heating and control systems must be designed coherently to ensure that good-quality toast is produced efficiently, consistently and safely.

Other basic design faults associated with domestic toasters revealed during testing, include:

(i) stiff carriage handles—one actually jammed after being used only seven times from 'new';
(ii) sharp edges on external surfaces, especially on components which could come into contact with a hand when unloading the toast; and
(iii) external surfaces which gradually discolour, owing to the high temperatures experienced by the appliances' casings: one toaster, which mainly had painted external surfaces, exhibited the tendency to lose flakes of paint, especially from the vicinity of its top surface *surrounding the toasting slots*.

For a long-slot toaster, the facility to vary the intensity of radiation incident on opposite sides of certain foods (e.g. buns and tea-cakes) is desirable, because the crust surfaces of such items should be warmed rather than toasted. Such a control was not available on any of the toasters that were tested.

Specific criticisms of long-slot toasters mainly concern the dimensions of their slots. These are often (i) not deep enough to accommodate standard size slices of bread; (ii) insufficiently long to allow two slices to reside adjacently; and (iii) incapable of lifting small toasted items (e.g. muffins) to a height that facilitates their safe removal from the main heating zone. As a result of the latter, users may be inclined to employ knives or other kitchen implements for removing non-ejected toast (in order to avoid suffering skin burns). This crude, yet common, practice could be eliminated by good design, thereby preventing accidental damage to the toaster's heating elements or the operator receiving an electric shock. Some manufacturers may have calculated the lengths and depths of the slots, based on information concerning slices taken from loaves of continental bread, because these tend to have smaller cross-sectional areas (orthogonal to their lengths) than loaves of British bread. Nevertheless, bearing in mind that the aforementioned faults counteract the most frequently claimed advantages of long-slot toasters, it seems that consumers need to be particularly wary when buying such appliances. Generally it is recommended that toast slots designed to contain only one slice of bread are constructed with the minimum dimensions of 140 mm length, 25 mm width and 125 mm depth; and toast slots intended for long-slot multi-purpose toasters should exceed 290 mm in length, 30 mm in width and 135 mm in depth.

The thermal efficiency of a toaster is reduced if bread crumbs are allowed to accumulate on its heating elements. Unfortunately, providing a facility for users to clean their toasters, presents difficulties to appliance designers. There are three main options:

(i) fit a crumb tray to the base of the toaster, which can be removed to dispose of the collected crumbs after, say, every 50 toasting operations;
(ii) allow toast crumbs to fall through the toaster unimpeded, so that they can be wiped off the supporting surface after toasting; or
(iii) instruct users to invert the toaster and shake it (in order to remove debris) whenever they feel it is necessary.

The latter operation, though crude, is effective if performed frequently (e.g. once every five toasting operations). Nevertheless the adverse effects on the useful life of the toaster must be considered if it is to be subjected to this type of mechanical treatment regularly.

A toaster which allows toast crumbs to fall straight through onto the supporting surface is preferred by some consumers. However from a heat-transfer viewpoint, this type of construction provides a direct route for ambient air to enter and then flow vertically upwards over the bread, whilst it is being toasted. Consequently the thermal efficiency of the appliance would be significantly lower and the toasting periods prolonged.

Toasters, incorporating crumb trays, tend to be criticised severely by their owners. Often, to remove the crumb tray, screws or plastic fasteners need to be undone, or the component has to be unclipped. Unless accomplished carefully, spillages occur, the cleaning operation is prolonged and so the user *often* prefers to postpone or avoid such activities. The consequent inaction results in the generation of smoke during toasting and can eventually cause the toaster to malfunction—in some cases, vermin are responsible for the damage, having been attracted to the crumbs left in the uncleaned toaster. Thus it is particularly desirable for appliance designers to develop superior crumb trays for domestic toasters.

Finally, although comparative testing of toasters is uncommon, recent consumer surveys have reported several design faults. For example, 6 out of 19 toasters did not survive tests intended to simulate five-years of typical domestic usage,[43] and one toaster out of 18 tested began to behave erratically after only two weeks of use.[45]

HEATING SYSTEMS

An electric heating system for a toaster should

(i) emit thermal radiation mainly in the wavelength range $2{\cdot}5\,\mu m < \lambda < 4{\cdot}5\,\mu m$;
(ii) operate with a near-uniform surface temperature;
(iii) have a low thermal mass;
(iv) be sized such that its effective radiating area exceeds slightly that of the food intended to be placed in the toast slot;
(v) be able to tolerate repeated mechanical and thermal shocks without significant performance deterioration or failure;
(vi) have elements possessing a low coefficient of resistivity across their operating temperature range;
(vii) be designed such that it lends itself to mass-production techniques; and
(viii) be inexpensive.

Unfortunately there are no heaters available that will simultaneously satisfy all these criteria. Polymer graphitic area-heaters are excellent for emitting heat uniformly and safely, but permissible operating temperatures are usually below 150 C,[49,50] i.e. too low for toasting (e.g. see Fig. 13). High capital cost militates against the use of infrared quartz heaters, as employed in some commercial ovens, grills and toasters for rapid cooking operations.

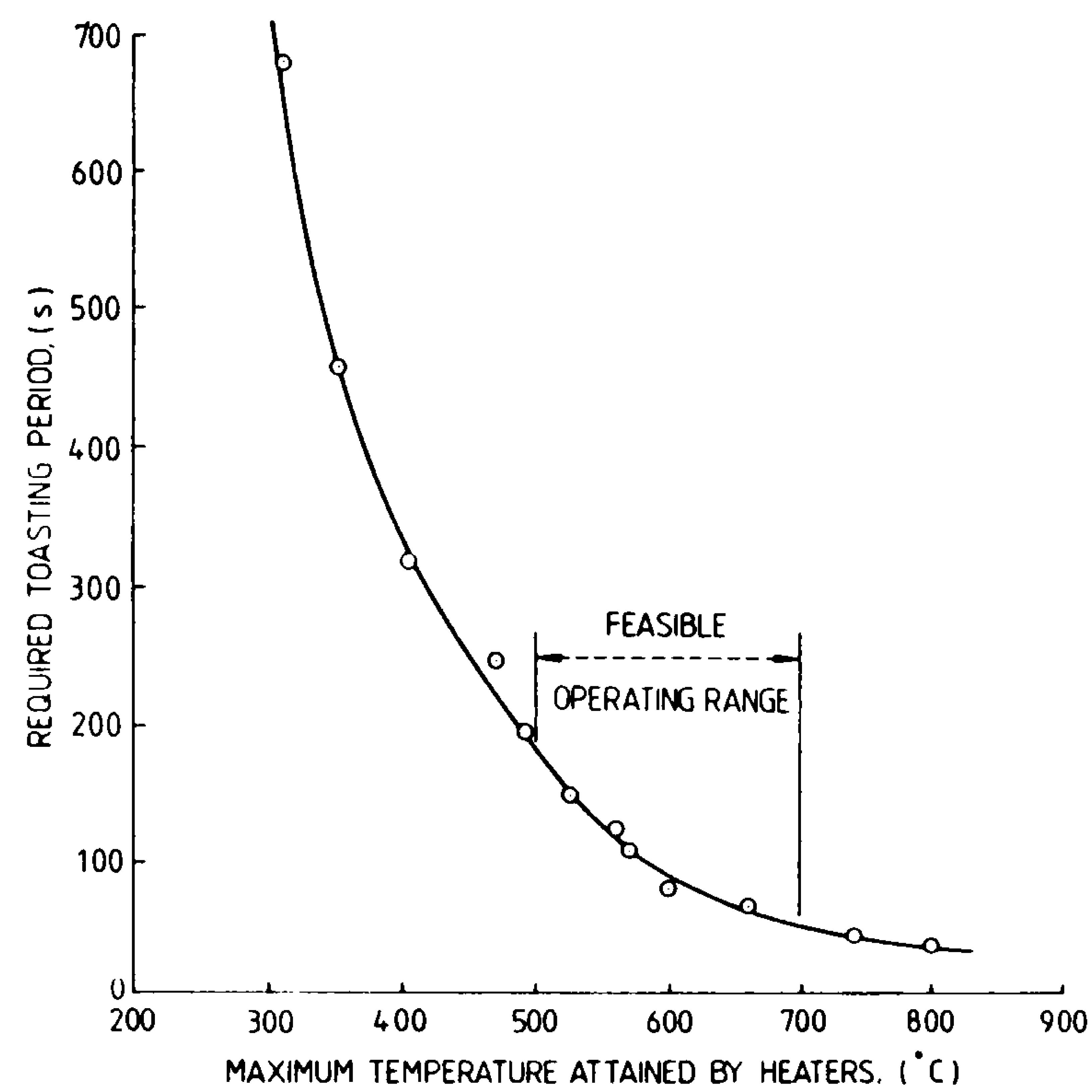


Fig. 13. The relationship between the maximum temperature attained by the heaters of the DSTR and the corresponding toasting period required for the simultaneous toasting of two slices of white bread. The initial (i.e. at ambient temperature) heater-to-bread separation was approximately 10 mm.

Also at present, the use of rapid-response porous heating elements is not feasible because they are not available as flat emitters (Fogarty, plc, Boston, Lincolnshire, UK, 1986, private communication). Etched-foil elements,[51] supported by ceramic insulating materials, provide uniform heating and are suitable for toasting appliances. Although these heaters are fitted into some commercially used toasters (McGraw-Edison Ltd, Elgin, Illinois, USA, 1986, private communication), no similar domestic toasters are available currently in the UK, probably because etched-foil heaters are more expensive than conventional alloy-tape heating elements. Therefore, at present, conventional nickel-based resistance heating alloys (e.g. Nichrome), in the form of metal tapes or wire coils mounted on substrates, which offer high thermal and electrical resistances, provide the most cost-effective and practicable means for satisfying the requirements of a domestic toaster's heating system.

Tests with Nichrome-tape heating elements

The choice of an alloy for the heating elements of toasters is largely dictated by cost. The properties of the most widely used alloy are shown in Table 8.

TABLE 8

Typical Values for the Characteristic Properties of the Nichrome Alloy Employed for Fabricating the Tested Toaster Heaters[52]

Maximum operating temperature	1050°C
Resistivity at 20°C	$1{\cdot}05 \times 10^{-6}\,\Omega\,m$
Mean temperature coefficient of resistance over the temperature range 20–100°C	$2{\cdot}4 \times 10^{-4}\,K^{-1}$
Density	$7950\,kg\,m^{-3}$
Specific heat capacity	$460\,J\,kg^{-1}\,K^{-1}$
Thermal conductivity at 100°C	$13\,W\,m^{-1}\,K^{-1}$
Melting point	1390°C
Mean coefficient of linear expansion over the temperature range 20–1 000°C	$1{\cdot}9 \times 10^{-5}\,K^{-1}$
Tensile strength	$6{\cdot}5 \times 10^{8}\,N\,m^{-2}$

Most of the preliminary testing in the experimental project associated with this investigation was carried out using the alloy mounted on mica substrates (typically 130 × 130 × 1 mm) which were slotted into a standard uncased double-slot toaster rig (hereafter referred to as the DSTR). Nickel–chromium/constantan thermojunctions were welded to the heaters employed.

Bread was browned satisfactorily when placed in close proximity to (i.e. <20 mm from) a heat source radiating at a temperature of 350°C or more. However if acceptable toasting periods (i.e. <250 s) were to be achieved for a typical initial heater-to-bread separation of 10 mm in the DSTR, then the heater had to reach at least 450°C by the end of the toasting operation. (Similar tests carried out by Marn[19] indicated that, when slices of bread were positioned at the same distance from two gas burner systems, radiating at about 816°C and 343°C, respectively, use of the latter burner arrangement incurred unacceptably long toasting periods.) Despite their enhanced visual appeal, slices of toast prepared in the DSTR, with heaters reaching a maximum temperature of about 450°C, were considered to be too dry in their inner regions. Thus a lower limit for the maximum heater temperature of about 500°C existed, below which optimal quality toast could not be prepared.

If the maximum heater temperature exceeded approximately 700°C, toasting periods with the DSTR were very short (e.g. <50 s), the bread tended to become scorched on its surfaces and remained too moist internally, and the process was extremely difficult to control accurately. Therefore a maximum heater temperature of about 700°C existed for the DSTR, above which acceptable toast could not be produced.

When the base of the DSTR was sealed completely, reductions in toasting periods of up to 10% were achieved. In addition, radiation reflectors were fitted behind the rear sides of the heater substrates: this resulted in an average reduction in toasting periods of 16%. Clearly convective and radiative heat losses can reduce significantly the thermal efficiencies of toasters. Thus substantial reductions in toasting periods and energy consumptions should be achievable if toasters are designed properly (see Figs 11 and 12). Also it should be remembered that these tests were carried out for slices of pre-cut bread of similar thickness, and so the bread-to-heater separations were approximately identical in each case. Because convective heat transfers can play a significant role in the toasting process, the heater-to-bread separation is critical to the toaster's efficiency. If an optimal value for this parameter exists, the use of self-centring guides and heaters which automatically move laterally (in accordance with the thickness of the food placed in the toast compartment) may be necessary, in order to minimise convective heat losses during toasting.

The typical thermal responses of five Nichrome elements (of constant resistivity), when used for toasting two slices of bread in the DSTR, are illustrated in Fig. 14. The ratio of the actual radiating areas of the heaters to their effective radiating areas fell by approximately 44%, for a 50% reduction in toasting periods. Thus it is important to maximise the actual radiating area of the toaster's heaters. In addition, the ratio of the actual radiating areas of the heating elements to their masses should be maximised, so that the rates of heat transfer are high and the effects of thermal inertia when they are energised initially are low. If changes to the heater's overall resistance for a tape of known resistivity are not permitted, the ratio of the length of the element to its cross-sectional area must remain constant (i.e. if a longer length is used, in order to increase the actual radiating area, then the product of tape width and thickness must be increased in proportion). However, attempts to increase the actual radiation areas of a toaster's heaters may lead to a substantial decrease in the appliance's useful life if very thin heating tape is employed. Furthermore if the tape width-to-thickness ratio (w/t) is too high, then the thermal expansions of the heating elements, when in operation, become excessive, and so greater bread-to-heater separations are necessary. This would reduce the toaster's thermal efficiency. Therefore a value of tape width-to-thickness ratio within the range $10 < w/t < 16$ is recommended for toasters of conventional double-slot configuration.

Some consumers may feel that they are forced to eat 'cold' toast due to their hectic schedule during breakfast periods. Thus the feasibility of leaving slices of toast in the toaster for a short period after toasting (i.e. with the heater switched off) so that they may cool down less rapidly than when

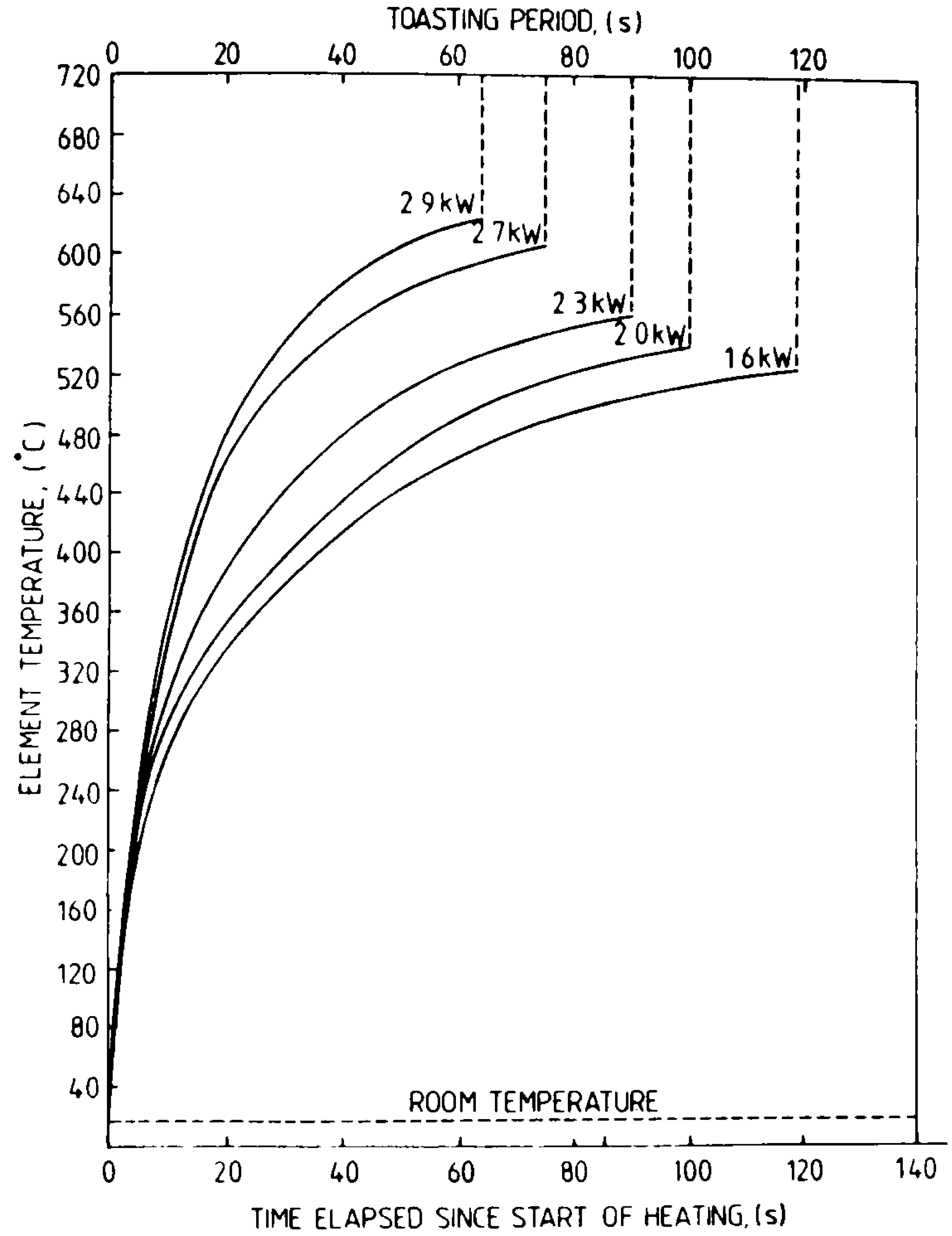


Fig. 14. Typical thermal responses during toasting for five different Nichrome heater elements (of constant resistivity) when fitted to the DSTR. In each case, two slices of white bread were toasted simultaneously: the initial heater-to-bread separation being about 10 mm.

placed on a plate, was investigated. The DSTR (fitted with a 2·0 kW heating system) was used for this. Mean weight losses (relative to the untoasted slices of bread employed) for toast on immediate removal, after two minutes on a plate, and after two minutes in the toaster were 11·5, 13·6 and 14·9%, respectively. The surface temperatures of the slices remaining in the toaster were typically only about 6°C higher than those placed on a plate. Thus the use of an unstimulated toaster as a type of 'hot cupboard' for keeping toasted items warm seems inappropriate. Design strategies to increase the thermal mass of the toaster so that slices of toast residing in the toast compartments cool down more slowly, tend to oppose achieving the main objective of the appliance, i.e. to prepare toast rapidly for the least energy expenditure. However, if toasters were sold with covers for their toast slots, the rate of cooling of foods after toasting would be inhibited, because convective losses would then be reduced. Unfortunately such 'slot-covers' may attain high temperatures and thus need to be removed carefully by users. This is an irksome practice, which may be disliked by consumers. If a means for removing the slot covers indirectly was manufactured as an integral part of the toaster, then use of the covers throughout the toasting operation would be desirable. A substantial improvement in efficiency may then be achieved because convective losses from the toast compartments would be inhibited. Nevertheless the quality of the toast so prepared may be impaired because the bread would be heated in a more humid environment. Furthermore manufacturing costs may increase significantly, because (i) materials would have to be selected for the slot covers, which were able to withstand the hostile chemical and thermal environment thereby enclosed; and (ii) employment of a conventional pop-up type mechanism would not be feasible.

Evidently, if warm toast is preferred, it should be eaten immediately after preparation.

CONTROL SYSTEMS

Most domestic toasters are fitted with two manually operated controls—a spring-loaded carriage handle and a browning control. All carriage handles of the units tested were of almost similar design, but browning controls tend to be either mechanical sliders or variable resistors (depending upon the design of the automatic controller employed for regulating toasting periods). When the heaters are energised, one can usually override the automatic control for the toasting period by (i) lifting the carriage handle; (ii) pushing down the carriage handle to initiate its automatic release; or (iii) disconnecting the power supply (e.g. by pressing the 'cancel button'), for toasters fitted with a solenoid for holding down the carriage handle.

Designs of automatic controller for toasters vary considerably, some being far more accurate and reliable than others. The choices available are as follows:

- (i) by a manual control (e.g. a clockwork timing mechanism);
- (ii) with a bi-metallic strip;
- (iii) via an electronic timing circuit;
- (iv) as (iii) but the circuit provides the facility to compensate automatically for changes in the environmental temperature of the toaster;
- (v) by sensing the temperature of the bread;
- (vi) by sensing the humidity of the air leaving the toast compartment; or
- (vii) by measuring the amount of radiation reflected by the bread.

Nowadays, clockwork timers are not employed by domestic-toaster manufacturers, because other controllers of similar cost are available which enable toasters to be more automated. Bi-metallic strip controllers have tended to be the most widely used means for regulating toasting periods. Usually the strip was fitted with a small tape heater, and sited remotely from the toast compartment (so that it was cooled by air at near-ambient temperatures, and shielded from the radiative fluxes emanating from the heating elements). When the toasting operation commenced, the temperature of the strip was raised, by its integral heater, until a predetermined temperature (effectively set by the user via the browning control) was attained. Once the strip had cooled down to a lower reference (i.e. near-ambient) temperature, a switch was activated and the main heating elements were switched off. Thus this type of mechanism attempted to compensate for different toast-compartment temperatures and so produce consistent results upon successive toasting. Unfortunately, toasting periods tended to fluctuate owing to the wide tolerances (e.g. about $\pm 10^{\circ}$C) associated with the bi-metallic controller. Also toaster manufacturers disliked this type of control, because each one had a slightly different operating characteristic and so production times were extended as a result of the precise mechanical adjustments of the strip and its contacting components that were necessary during assembly. Nevertheless, robust domestic toasters, fitted with bi-metallic strip controllers, often operated successfully without breakdown for more than 12 years when subjected to daily usage, because the lengths of their useful lives depended mainly on the designs and constructions of their pop-up mechanisms and heaters, respectively. Conversely most modern toasters have design lives which equate to only five years of typical domestic usage by a family of four.

The use of electronic timers for controlling toasting periods began with the employment of *RC* networks similar to the one shown in Fig. 15. A capacitor was charged from a rectified a.c. source, via a tapping from the toaster's heating elements, to a known voltage (which was sufficient to activate a triggering device) at a rate determined by the time-constant of the circuit. Consequently a thyristor energised a solenoid, which then switched off the power supplied to the heating elements and so ended the toasting operation. The circuit normally included one of the following features:

(1) a fixed value resistor, which maintained a constant toasting period;
(2) a variable resistor, which enabled the user to alter the toasting period;
(3) feature (2), plus a NTC thermistor, which attempted to control toasting periods according to the temperature of some zone within the toaster;
(4) feature (3), plus a discharge circuit (connected across the aforementioned capacitor) which was designed so that the discharge-time curve for the capacitor was substantially similar to the cooling curve of a chosen zone within the toaster (e.g. see Fig. 15).

KEY

1. HEATER
2. TOAST COMPARTMENT'S TEMPERATURE SENSOR
A NEGATIVE TEMPERATURE - COEFFICIENT THERMISTOR
3. 'BROWNING' CONTROL (I.E. A VARIABLE RESISTOR)
4. DISCHARGE NETWORK FOR CAPACITOR y
5. SOLENOID FOR SWITCHING-OFF HEATERS BY OPENING SWITCH A, THEREBY RAISING INDIRECTLY THE TOAST CARRIAGE AND SWITCHING ON THE DISCHARGE NETWORK BY CLOSING SWITCH B

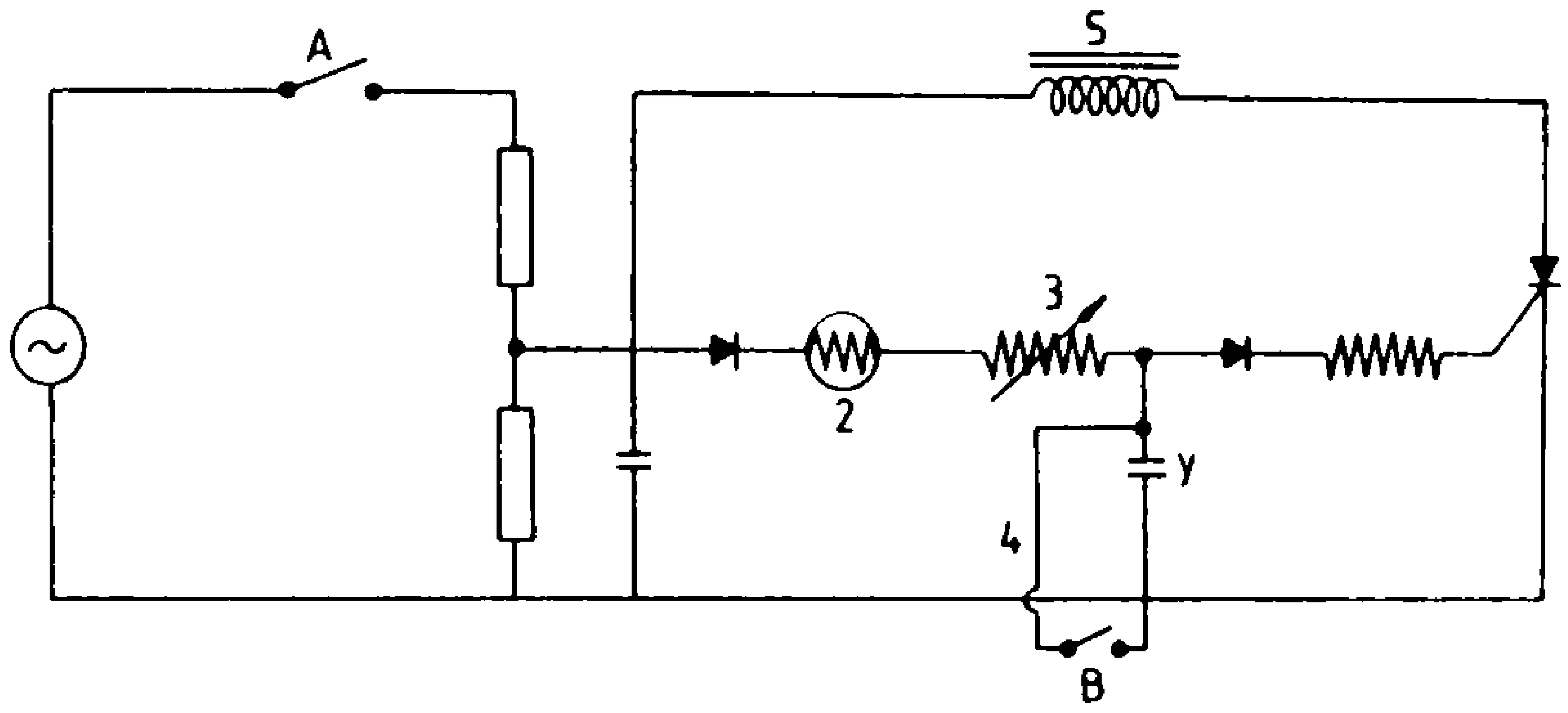


Fig. 15. A simple electronic control circuit for an electric toaster, which was designed so that toasting periods were adjusted automatically according to the temperature of a pre-selected zone within the toaster.[53]

Features (1) and (2) facilitated the automatic toasting of bread, but neither attempted to ensure automatically that overcooked slices of toast were not produced when the toaster was subjected to successive operations. However, features (3) and (4) are widely employed, because they attempt to achieve optimal regulation of the toasting period. Today in the UK, electronically controlled toasters tend to be based on these designs and some manufacturers are now making use of ICs in order to improve the reliability, cost-effectiveness and marketing appeal of their toasters.

One of the toasters tested incorporated an IC controller (see Fig. 16), which functioned on the general principle of feature (3), and performed almost consistently when subjected to successive toasting operations. However control systems which attempt to model (thermo-mechanically or electronically) the process involved, may be better achieved if the temperature of the bread (or the amount of heat it absorbs or reflects) during toasting, is monitored. Originally, double-slot toasters operating on this principle incorporated two bi-metallic strips. One was placed in the immediate vicinity of the bread to sense its approximate temperature and thereby to facilitate thermo-mechanical control of the duration of toasting, whilst the other compensated for variations in the starting temperature of the toaster. Usually in order to simplify assembly and calibration, these two bi-metallic strips were built into a single unit.[48] Apart from the previously mentioned problems associated with bi-metallic controllers, when used for

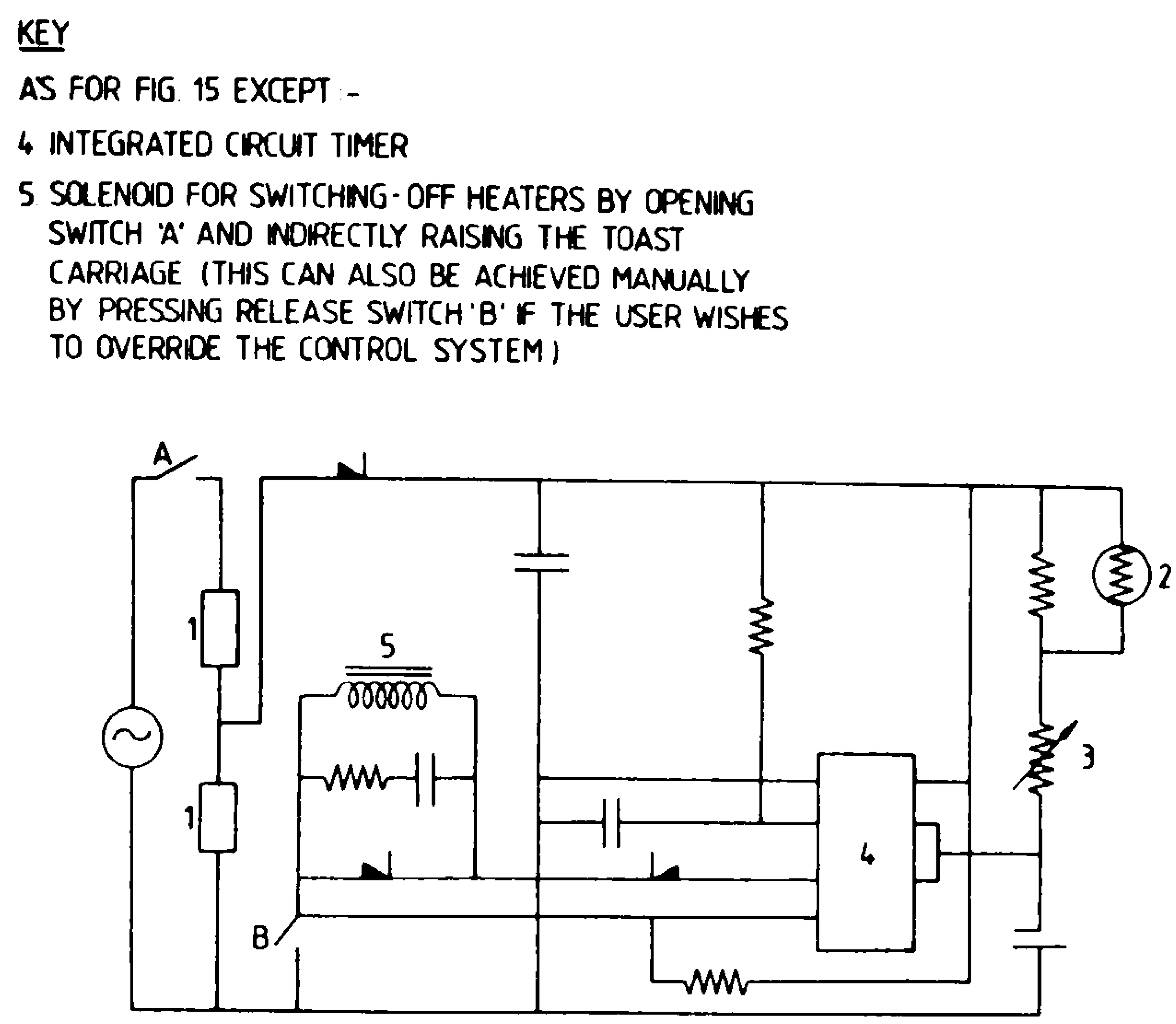


Fig. 16. A circuit, including an IC timer, for an electronic controller of an electric toaster (Russell Hobbs, Stoke, Staffs, 1985, private communication).

regulating toasting periods, the difficulties encountered with bread-temperature sensing designs mainly concerned the positioning of the sensor. The provision of sufficient space to fit this device between the bread and its heaters determined the bread-to-heater separation and thus the power requirement and thermal efficiency of the toaster.

Regulation of toasting periods may be achieved by measuring the humidity of the air leaving the toast compartment. The humidity of the air in close proximity to a heated food, tends to increase rapidly just prior to completion of the cooking process.[54] This change can be detected by using a material, which exhibits a marked change in resistivity with humidity (e.g. a compound of $MgCr_2O_4$ and TiO_2). However, although this technique is commonly employed for controlling cooking periods in microwave ovens, it may be too expensive to be adopted for domestic toaster applications.

Other means employed for sensing the bread's temperature during toasting are electronic, and utilise thermocouples or thermistors. Their successful operation depends upon the consistency of thermal contact between the temperature sensor and the bread being toasted. Therefore accurate and reliable performances may not be attainable when the appliance is subjected to typical usage. Essentially these disadvantages exist because it is difficult to ensure that the temperature sensor

(i) is isolated thermally, so that it does not receive any radiative fluxes directly from the heat source;

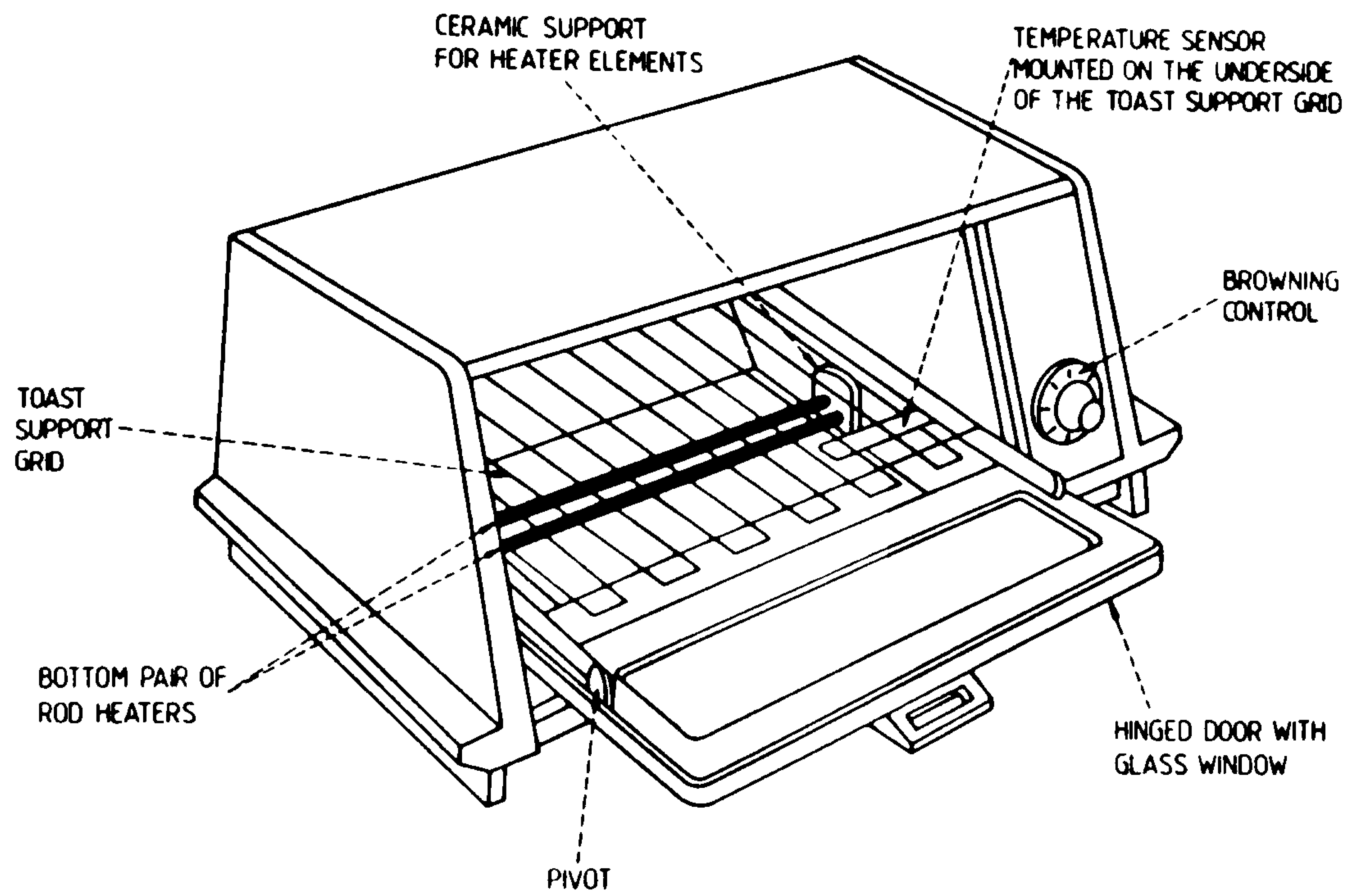


Fig. 17. A four-slice toaster, incorporating a control circuit (see Fig. 18), which attempts to regulate the toasting period by monitoring the surface temperature of one slice of bread, whilst it is being toasted.[55]

(ii) mechanically contacts the bread-based foods, which have widely different properties, consistently (especially because they warp and shrink when toasted);
(iii) does not impede loading/unloading operations;
(iv) withstands the long-term thermal and chemical effects of the hostile environment which characterises a toast compartment;
(v) does not obscure from irradiation an unacceptably large area of bread during toasting;
(vi) does not increase any of the hazards incumbent upon using the toaster (e.g. the probability of short-circuits); and
(vii) will not be damaged during bread loading and toast unloading operations.

Often the sensor is mounted on the metal grid, which prevents the bread from touching the heater (e.g. see Fig. 17). In conventional domestic pop-up toasters this is not practicable because a poor contact exists between the bread and guard, although it may be acceptable for toasters which have self-centring mechanisms. Nevertheless, because the thermal properties of the guard are substantially different from those of the bread, their temperatures and thermal responses vary and so the temperature measured by the sensor only approximates to that of the bread.

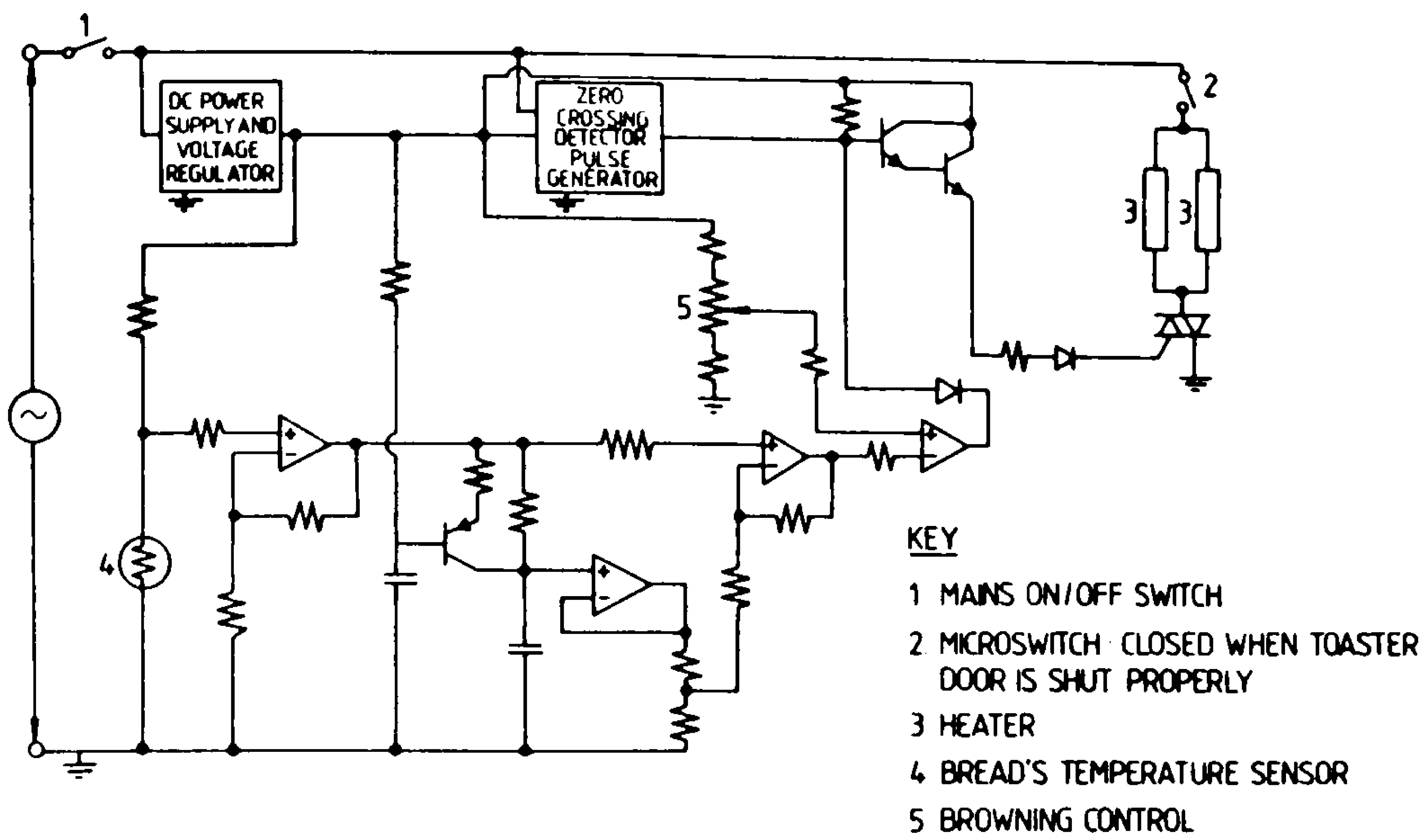


Fig. 18. A control circuit involving a temperature-sensing probe, which touches the slice of bread in an electric toaster.[55]

Figure 18 shows the circuit for an electronic temperature-sensing controller that is alleged[55] to ensure that a consistent toast colour is attained, regardless of the temperature of the toast compartment, the properties of the bread and the number of slices being toasted. The control system's operating principle involves the generation of three distinct transient voltages, which are functions of (a) the temperature of the item being toasted, (b) the ambient environment's temperature in the vicinity of the toast, and (c) the difference between these two temperatures, respectively. A comparator circuit is employed for comparing voltage (c) with a reference voltage (which corresponds to the desired toast colour and is set by the user via the browning control). When the voltages are equal, the heating elements are switched off and the toast is presumed ready for consumption.

Because of the aforementioned problems associated with this type of controller, especially when fitted to domestic pop-up toasters, efforts were made to design a similar system which would not require a a mechanical contact to be made between the sensor and the item being toasted.

Non-contacting temperature-sensing automatic electronic toaster controllers

Two systems for regulating toasting periods were developed as alternative designs of commonly employed controllers. Both use opto-electronic sensors to generate voltages which are functions of the surface characteristics of the bread (e.g. its reflectivity or temperature).

The first prototype attempted to sense the colour of the bread during toasting: this concept was discussed by Marn [19] and Borley.[56] Three LEDs directed predominantly green light at the surface of the bread, whilst a photodiode measured the amount of light reflected. The signal generated by the photodiode (which is proportional to the amount of light reflected by the bread) depended upon the reflectivity of the bread. By designing a circuit to compare the voltages generated by the light reflected from the surface of the bread during toasting, with a reference voltage corresponding to that generated by a slice of toasted bread, a means for controlling toasting periods regardless of the toaster's initial temperature may be achieved. However, although preliminary tests (e.g. see Table 9), indicated that this technique could be made sufficiently sensitive to colour changes to facilitate satisfactory control of the toast's colour, it was considered susceptible to the influences of stray light (particularly red light emanating from the heating elements). This may preclude accurate and reliable control for all sizes of bread likely to be heated in a toaster.

To supersede this design, an infrared photodiode was employed, so that the heat reflected by the bread during toasting could be measured.(Jones[57] suggested a system which operated on a similar principle. This attempted to

TABLE 9

Indications of How the Signal Generated by a Photodiode Varied with the Type of Irradiated Material that it Viewed (A Small Area, i.e. ~25 mm², of the Test Material was Illuminated by a Constant Intensity Light Source of 405 mW. The Peak Wavelength of the Light Emitted was 565 nm and the Photodiode, which was Positioned so that it Received some of the Light Reflected by the Material, had a Peak Spectral Response at 560 nm)

Material[a]	*Voltage measured (mV)*
Aluminium foil	15·3
Aluminium-alloy sheet	10·6
White polystyrene	6·4
White paper	5·8
White bread	5·8
Balsa wood	4·4
Bread crust	3·0–4·2
Brown paper (matt)	2·7
Toast	2·0–4·5
Red paint	1·4
Dark room	0·3

[a] The surface temperature of each material approximated to the ambient temperature (i.e. ~15°C).

control the duration of toasting by using a thermistor to measure the temperature of the radiation reflected by the bread via a horizontal ceramic tube). A controller incorporating this photodiode, as used for test purposes, is shown in Fig. 19. The infrared sensor generates a voltage which is used to charge a capacitor at a rate depending upon the time-constant of the network as set initially by the user via a variable resistor (i.e. the browning control). When the voltage at the negative input of the amplifier is sufficient to cause an output signal at pin 6 of the IC, the triac is triggered. This switches off the heating elements when the a.c. waveform next crosses the zero-voltage axis. Generation of excessive radio interference is thereby avoided.

The infrared detector was mounted behind one of the outer heaters of the DSTR: it viewed a central region of the slice of bread via a 3 mm diameter hole in the heater's reflector and substrate. The controller adjusted the toasting period automatically as the toaster's temperature increased during successive toasting operations (see Table 10). Consequently toast of near-identical surface colour and moisture content could be produced, even when the DSTR was subjected to very high rates of throughput.

Tests indicated that although partially stale bread toasted more quickly than fresh bread, the controller compensated adequately for changes in toaster temperature. However when frozen bread (initially at −20°C) was toasted, some re-adjustment of the browning control was necessary in order

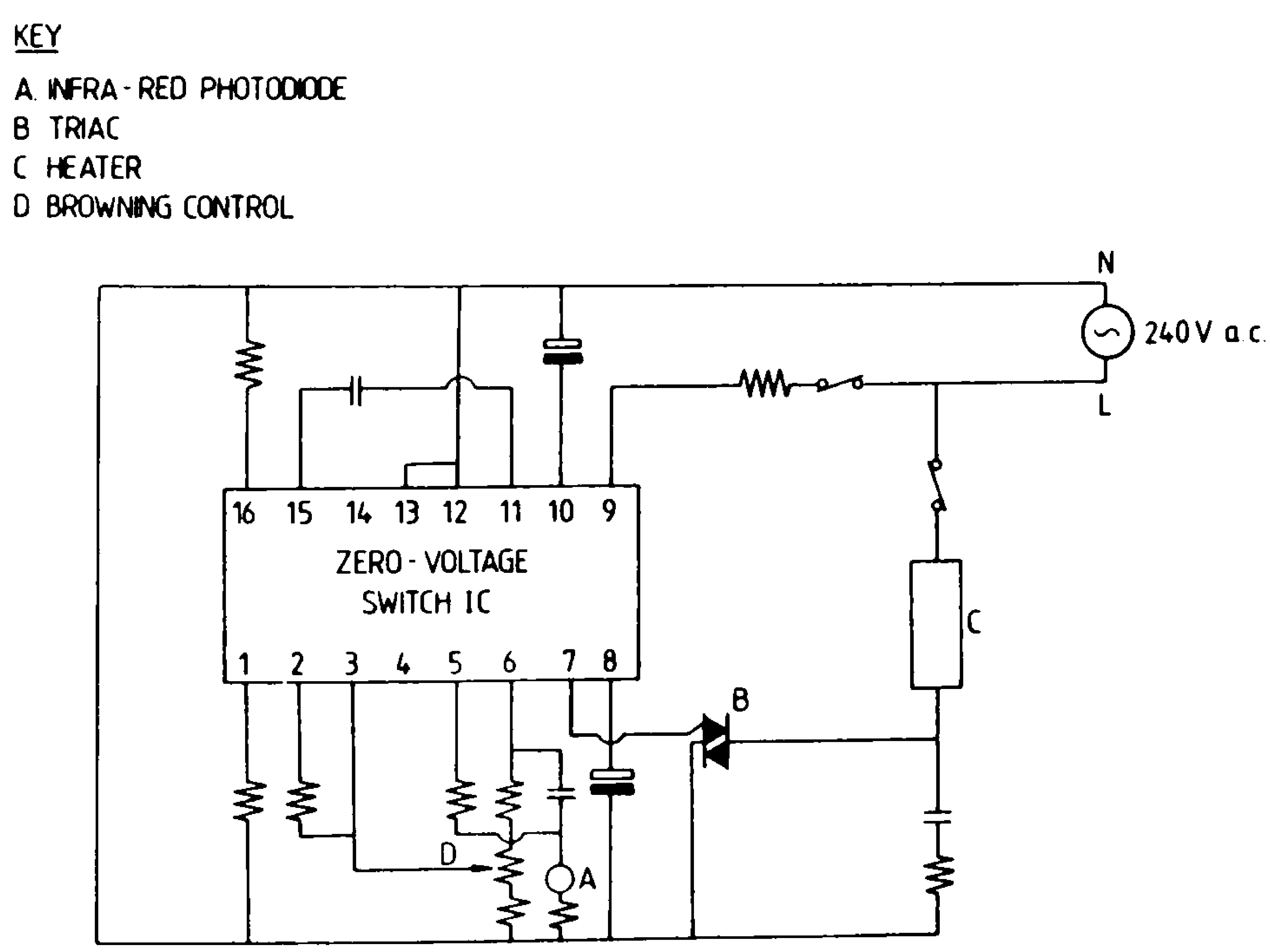


Fig. 19. The control circuit involving a non-contacting temperature sensor for detecting and responding to the temperature of a slice of bread as used in this investigation.

TABLE 10
Toasting Periods for the DSTR when it was Used to Toast *Succesive* Batches of Two Slices of Various Breads, as Controlled Automatically by the Circuit Shown in Fig. 19

Batch number	*Typical toasting period (s)*[a]				
	Brown loaves		*White loaves*		
	Pre-cut	*Cut*	*Pre-cut*	*Cut (stale)*	*Pre-cut (frozen)*
1	87	84	83	64	119
2	70	67	65	52	97
3	64	63	61	49	89
4	62	61	60	48	85
5	61	60	59	47	83
Typical bulk density (in $kg\,m^{-3}$) before toasting	334	274	314	228	345
Approximate thickness of slice before toasting (mm)	8	18	12	14	12

[a] Slices were taken from the same loaf and successive operations proceeded with 15 s intervals.[46] The DSTR was equipped with heaters consuming 2·18 kW and reaching maximum temperatures of about 540°C.

to ensure acceptable toast was prepared. This requirement existed because (i) initially the bread contained a considerable amount of ice which reflected some heat away from its surface, (ii) the latent heat of fusion for water had to be supplied before thawing ensued, and (iii) the overall change in the surface temperature of the bread was greater (i.e. by approximately 35°C) owing to its lower initial temperature. Because of these factors, the heating elements were switched off about 10 s before the thawed slices would have been fully toasted and about 25 s before any browning took place. Nevertheless, once adjusted, the controller performed consistently for successive toastings of frozen bread (e.g. see Table 10). Toasting initially frozen bread increased the electricity consumption of the DSTR by, on average, 44% when compared with toasting bread which was initially at about 15°C. Thus toasting frozen bread is relatively energy-profligate. Furthermore it is alleged that the subsequent application of high-viscosity butter or margarine tends to tear and crack the surfaces of slices of toast made from frozen bread more easily, than those made from bread initially at a near-ambient temperature (Hatco Corporation, Milwaukee, Wisconsin, USA, 1986, private communication). However, some consumers prefer to prepare toast from frozen bread

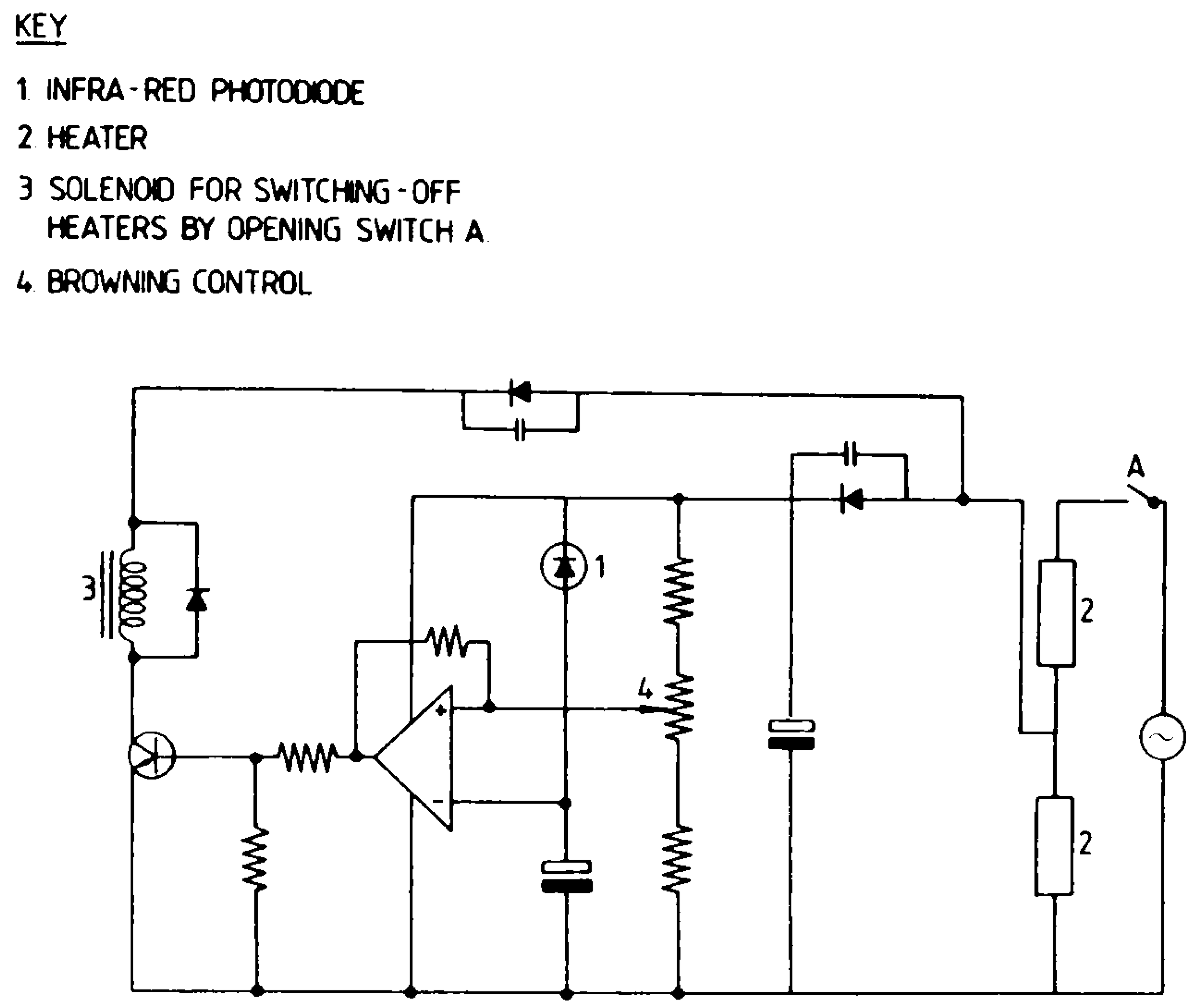


Fig. 20. A control system operating on the principle of the circuit shown in Fig. 19, but designed to suit the size and cost constraints of commercially produced toasters.

because (i) the storage life of the bread they use specifically for toasting is prolonged, and (ii) the moisture content trapped within the toast so prepared is greater.

The circuit used for test purposes (see Fig. 19) was developed into a design which operated on a similar principle, but was better suited to production toasters (see Fig. 20). From experimental studies with the DSTR, it is considered that further control improvements may be achievable if a system is designed which

(i) permits the toaster's heaters to reach about 750°C for an initial part of the toasting period, in order to increase the rates of evaporative loss from the superficial layers of the bread; and
(ii) reduces the temperature of the toaster's heaters to say 450°C for the remaining duration of the toasting operation, so that the outer surface of the bread may be browned more uniformly.

Because a toaster's temperature distributions vary dramatically during successive toasting operations, the infrared detector should be employed to regulate the first (i.e. the variable) part of the toasting period, and then a simple timer used for providing a second 'browning' period of fixed duration. Manufacturing costs for such a proposed system might be acceptable if production quantities are high (e.g. $>10\,000$ p.a.), so that considerable financial benefits can be attained by employing purpose-built IC controllers.

The reliability of a toaster partly depends upon the design of the appliance's pop-up mechanism and the manner in which users operate the carriage handle. To lower the carriage handle of a conventional toaster by approximately 60 mm, a force of about 5 N needs to be exerted by the user. However this action could be achieved automatically by employing a solenoid which lowers the carriage via a mechanical linkage. If the carriage handle is replaced by this form of electromagnetic pop-down mechanism, the toaster's useful life should be increased and its appearance improved. Consumers may, for example, initiate toasting operations merely by pressing momentarily a touch-sensitive button, so that the solenoid is energised. Consequently the toast-carriage would be lowered (against the force exerted by the pop-up spring) until it became latched in a position in which the slices of bread faced their respective heaters.

CONCLUSIONS

Toast forms a substantial part (i.e. $\sim 46\%$) of the bread consumption of the UK population. Although electric toasters have undergone significant developments since their introduction about 60 years ago, current designs of automatic specific-purpose domestic toasters, like several other types of food appliance, tend to (i) use energy inefficiently; (ii) be thermally hazardous to employ; and (iii) proffer end-products which are frequently of inferior, and/or of inconsistent, quality.

If white bread is toasted with a typical domestic toaster, the overall primary energy requirement increases by about 26%, when compared with eating it untoasted (e.g. see Fig. 21). Energy consumptions involved in toasting are small but significant, and reductions in annual expenditures of about 20% (i.e. amounting to at least £3×10^6 in the domestic sector) could be accrued if toasters are better designed. Within the *catering industry* large energy savings are achievable already, because a few appliance manufacturers, having recognised the increasing need within the food-service sector to reduce utility bills as energy costs per meal prepared increase, are attempting to improve the efficiencies of their toasters (Hatco Corporation, Milwaukee, Wisconsin, USA; Hobart Corporation, Troy, Ohio, USA; McGraw-Edison Co. Ltd., Elgin, Illinois, USA; Roundup, Addison, Illinois, USA; Wisco Industries, Oregon, Wisconsin, USA; 1986, private communications). In future, design improvements which set precedents in terms of performance may tend to be instigated mainly by manufacturers of commercial food-service equipment, because their products usually have

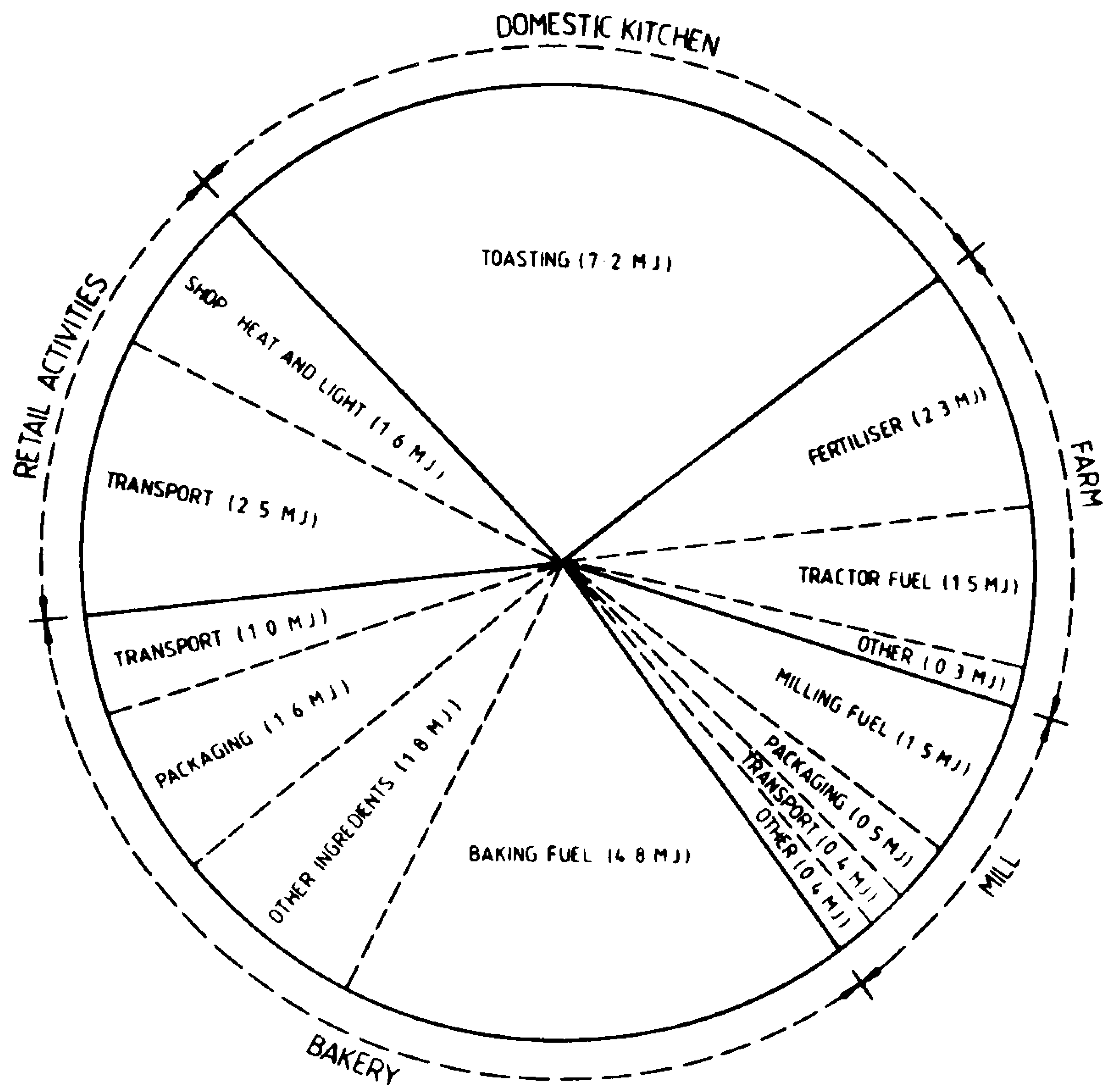


Fig. 21. The primary energy inputs required to produce (and subsequently toast when sliced) one standard loaf of white bread in the UK. The total primary-energy consumption per loaf of toasted bread is approximately 27 MJ (adapted from Ref. 58).

relatively high capital costs. Thus the additional expense incurred by introducing such improvements should be more easily justified.

The numerous inadequacies of a typical *domestic toaster* may have resulted from the adoption of a non-integrated design approach when optimising separately only one or two of the heating, control, safety and cost factors. By overemphasising cosmetic attractiveness and low capital cost, some manufacturers have neglected their customers' desires to use appliances which perform adequately and consistently. In recent years, sales have been increased by introducing fashion concepts to the consumer: these imply that it is desirable to own, for example, a toaster, a kettle and a cooker which match each other aesthetically. The need for improved performance (i.e. relating to the quality of the food prepared, and the reliability, energy efficiency and safety of the appliance employed) has tended to receive a relatively low priority by manufacturers. This may be due to the ease with which they have been able to convince prospective customers that the appearances of their kitchens are more important than the functions performed therein! However, such attempts to dictate the criteria of choice eventually result in high levels of consumer dissatisfaction, thereby increasing demand for high-quality artefacts which have been designed coherently. Unfortunately, few British manufacturers seem to be changing their strategies with respect to domestic appliances such as toasters: instead, most prefer to operate within the existing oligopolistic market. Evidently, a technical revolution in the UK's domestic appliance and food-service manufacturing sectors is now overdue if consumers are to obtain better 'all-round' devices.[59]

Properly designed energy-efficient toasters should offer consumers (i) facilities to prepare toast of consistent quality regardless of the demand they place on the equipment, (ii) better protection from burns as a result of touching the toaster's outer casing, and (iii) reductions in energy consumptions relative to the present generation of toasters. To achieve these objectives, further research and development are needed (e.g. to optimise the bread-to-heater separation and the convective flows within the toast compartment). As consumers increasingly choose to toast a wider variety of bread-based foods, the need to construct toasters with competent control systems (e.g. ones which attempt to monitor the thermal characteristics of the surfaces of the items being toasted) increases. Also, because the multi-purpose long-slot toaster is likely to attain an increasing percentage of new sales in the domestic market, the optimisation of its design would be worthwhile. Long-slot toasters employing coiled heaters, mounted on ceramic rods which are backed with reflectors, deserve attention, because they tend to use energy more effectively than toasters fitted with conventional tape heaters. The development of novel reflecting surface configurations to assure uniform heating of the bread positioned in the toast slot would be particularly valuable. Furthermore, the effects of using (i) direct-contact toasters (which permit slices of bread to be toasted via conductive heating) and (ii) integral slot-covers during toasting, on reducing the energy requirement for toasting, improving the quality of the toast prepared and the manufacturing costs incurred should be investigated. Mathematical modelling of the simultaneous heat and mass transfers involved in the toasting process, should be attempted once the appropriate heat-transfer coefficients have been determined, for instance, by Mach–Zehnder interferometry. Then worthwhile theoretical predictions of optimal designs should be achievable.

APPENDIX

A survey of 250 adults (50% of which were male) was undertaken. Results exhibited approximately Gaussian distributions with respect to the magnitudes indicated in the replies and revealed that, on average, 13·3 slices of toast were eaten per person per week. This represented 45·9% of the typical person's total consumption of bread per week.

Attempts were made to correlate an individual's toast consumption with the financial income of the head of his/her household (see Table 11). The assessment suggested that the rate of toast consumption was proportional to a function of the reciprocal of financial income. Some other interesting results were recorded (see Table 12) which are not claimed to be wholly representative of the UK population. However most of the individuals questioned during this survey toasted pre-cut *white* bread with specific-purpose electric toasters. It was alleged that the taste of toasted white bread was preferable to those of the brown and wholemeal varieties.

TABLE 11

The Average Weekly Rate of Toast Consumption for a Random Sample of 250 Adults, Questioned in the UK During 1986, According to the Gross Annual Income of the Heads of their Households

Definition of income group into which the head of the household can be categorised[a]	*Slices of toast eaten per week*	*Toast consumed, expressed as a percentage of the total amount of bread eaten per week by that individual*
Earns a gross annual income of >£13 000	8·8	44·5
Earns a gross annual income of <£13 000	13·6	44·7
Is an old-age pensioner	14·2	45·1
Is either unemployed or a student	16·2	48·6

[a] Each income group was mutually exclusive and consisted of at least 34 people.

TABLE 12
The Bread-toasting Preferences of 231 Individuals who Ate Toast, from a Total Sample of 250 Adults

Consumer activity	*Percentage of people interviewed*
Variety of bread used for toasting:	
(i) white bread	33
(ii) brown bread	18
(iii) wholemeal bread	14
(iv) a combination of (i), (ii) and (iii)	30
(v) neither (i), (ii), (iii) or (iv)	5
Form of bread used for toasting:	
(i) pre-cut bread	69
(ii) bread initially from uncut loaves	20
(iii) varying use of (i) and (ii)	11
System employed for toasting:	
(i) electric toaster	62
(ii) electric grill	16
(iii) gas grill	14
(iv) varying the use of (i) and (ii)	8

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CHAPTER SIX

ENHANCING THE HEAT-TRANSFER PERFORMANCES OF CONVENTIONAL OPEN-TOPPED CLOSED-SIDED TOASTERS

SUMMARY

The steady-state heat transfers occurring within a test rig designed to simulate the thermal behaviour of a conventionally-heated electric toaster have been measured. An initial (i.e. at ambient temperature) heater-to-bread separation of about 10mm was deduced to be the optimal arrangement, if an acceptable degree of uniformity of temperature across the main surfaces of the bread, as well as a favourable thermal efficiency, were to ensue. The introduction of improved heaters, so that small (i.e. < 10mm) heater-to-bread separations can be achieved without affecting adversely the uniformity with which slices of bread placed in the toaster are heated, was identified as a basic requirement for a 'low energy' toaster. Also it was demonstrated that, in practice, substantial improvements in thermal efficiency should be achievable by fitting covers over the bread slots of conventional toasters.

NOMENCLATURE

a	Height of the slice of bread placed in the toaster, m.
C	Numerical constant in equation (4).
D	Characteristic dimension of the thermal system, m.
Gr	Grashof number (i.e. the ratio of buoyancy to viscous forces within the air).
g	Acceleration due to gravity ($\backsim 9.81$ m s^{-2}).
H	Height of the cavity, m.
h	Heat transfer coefficient, $Wm^{-2}K^{-1}$.
L	Length of the cavity (see Fig. 1), m.
l	Length of the slice of bread placed in the toaster (see Fig. 1), m.
m	Numerical index in equation (4).
n	Refractive index of air.
Nu	Nusselt number (i.e. the ratio of the steady-state rates of heat transfer through the air by combined convection and conduction, to that had conduction alone occurred).
Pr	Prandtl number (i.e. the kinematic viscosity of the air divided by its thermal diffusivity).
p	Partial pressure, N m^{-2}.
Ra	Rayleigh number (= Gr Pr).
T	Temperature, K
T_c	Surface temperature of the bread-simulator, K.
T_H	Heater temperature, K.
T_{W1}, T_{W2}	Surface temperatures of the vertical sidewalls facing one another across the cavity, K.
$\bar{T}_W$	Average temperature of the cavity's vertical sidewalls, K.
T_∞	Ambient temperature, K.
t	Thickness of the considered slice of bread in the toaster, m.
W	Heater-spacing (see Fig. 1), m.
x, y	Cartesian co-ordinates of a position within the cavity (where the heated surface defines y=0), m.
α	Thermal diffusivity of air, $m^2 s^{-1}$.
β	Coefficient of thermal expansion of the air, i.e. approximately the reciprocal of the mean temperature of the air within the cavity between the heater and the main surface of the slice of bread, K^{-1}.
δ	Heater-to-bread separation, m.
ΔT_c	The characteristic temperature difference of the thermal system, K.
ν	Kinematic viscosity of air, $m^2 s^{-1}$.

Subscripts

cc	Via combined steady-state convective/conductive heat transfer.
CD	Of carbon dioxide.
cl	Of the thermal conduction layer.
DA	Of dry air.
l	Of the laminar boundary layer.
r	Pertaining to steady-state heat transfer by radiation.
t	Of the turbulent boundary layer.
WV	Of water vapour.

Abbreviations

MZI Mach-Zehnder interferometer.

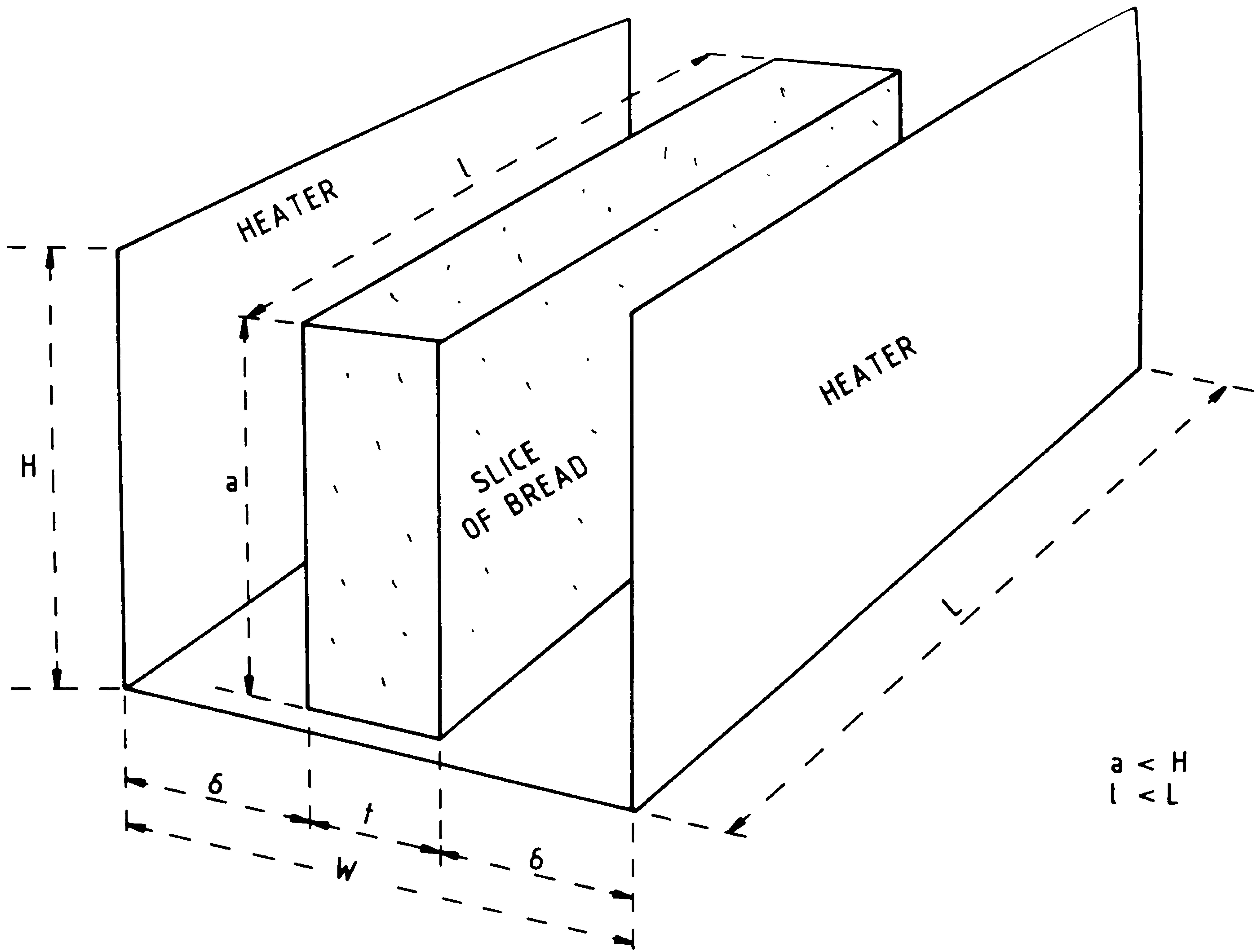

Fig. 1 Schematic representation of the basic geometry of a typical toaster.

INTRODUCTION

Many popular kitchen appliances are characterised by low end-use energy efficiencies. Yet, improvements in their performances are often achievable by relatively simple measures (e.g. by thermally insulating the cooking system from the kitchen environment or by fitting appropriately-designed reflectors to heaters). However, a quantitative appreciation of the rates of heat transfer occurring within a food-heating appliance is desirable if an optimal thermal design is to be devised.

Previous studies concerning the ubiquitous electric toaster (Newborough et al, 1987a) revealed that significant prospective improvements in its thermal efficiency are achievable. Thus an experimental investigation was undertaken to examine quantitatively the heat transfers occurring within this type of cooking system. The test rig was constructed to simulate (as far as was feasible) the conditions that ensue in a real toaster. The steady-state temperature distributions associated with the bread/heater air space were observed (via optically-flat glass plates, which were sealed to each end of the cavity) by employing a laser-stimulated 18cm field-of-view Mach Zehnder interferometer (MZI). This has the advantage of mapping, instantaneously, the whole field-of-view without the presence of any disturbing thermometry. The interferometer was adjusted so that a single fringe filled the whole field of view, when the heat transfer system was at ambient temperature. The interference lines, which formed at elevated temperatures, then represented isotherms - this is referred to as the infinite fringe-spacing method. Subsequently, local Nusselt numbers were calculated from local temperature gradients evaluated from the interferograms.

Two design improvements were identified as being needed in order to increase the energy efficiency of a conventional toaster: (i) optimising the heater-to-bread separation, δ , and (ii) suppressing convective heat losses. The latter could be achieved by fitting the toaster with covers for its bread slots (Newborough et al, 1987a).

Theory

Within a toaster, buoyancy forces created by heating the air cause it to flow through the toast compartment. At high temperatures, the absorption of radiation by carbon dioxide and water vapour within the air augments the flow, but this process is of less influence on the toasting process than the primary radiative and convective heat transfers occurring within the appliance. Numerous theoretical and experimental studies concerning heat exchanges within systems of approximately similar geometry to that of a toaster have been undertaken (see, for example, Elenbaas, 1942; Carlson, 1956; Bodoia and Osterle, 1962; Engel, 1965; Aung et al, 1972, Carpenter et al, 1976). Usually, the characteristic temperature-difference employed when calculating convective/conductive heat transfer parameters for an open vertical cavity is:-

$$\Delta T_c = \overline{T}_w - T_\infty \qquad (1)$$

The Rayleigh number for the cavity is defined by:-

$$Ra = (Gr\ Pr) = \frac{g\beta \Delta T_c D^3}{\nu\alpha} \qquad (2)$$

where D (the characteristic dimension of the system) is the gap width, and the fluid properties are calculated at $0.5(\overline{T}_w + T_\infty)$, except at large ΔT_c when they should be calculated at $\overline{T}_w$ (Raithby and Hollands, 1985).

However for a fully-enclosed vertical cavity, the characteristic temperature difference is:-

$$\Delta T_c = T_{w1} - T_{w2} \qquad (3)$$

where the fluid properties are calculated at $\overline{T}_w$.

For vertical air-filled slots, it can be shown by dimensional analysis (Raithby and Hollands, 1985) that the Nusselt number is a function of the Rayleigh number and the vertical aspect ratio for the cavity, H/D , provided that the horizontal aspect ratio is large (i.e. L/D >5). Consequently, it is conventional to correlate average Nusselt numbers found experimentally with the dimensionless group Ra(D/H). For example, it has been found that, in the steady-state, for vertical cavities which are open top and bottom:-

$$Nu = \left[\left(\frac{Ra}{24}\right)^m \left(\frac{D}{H}\right)^m + C^m\ Ra^{m/4} \left(\frac{D}{H}\right)^{m/4}\right]^{1/m} \qquad (4)$$

where $0.62 < C < 0.68$ (Elenbaas, 1942; Bodoia and Osterle, 1962) and $m = -1.9$, for $Ra < 10^5$ (Aung, 1972).

Correlations for certain semi-enclosed configurations, such as vertical fins have also been determined. For instance, Jambunathan et al (1984) deduced the following relationship for the steady-state heat transfer performance of vertical rectangular isothermal fins protruding upwards from a horizontal base:-

$$Nu = 0.0173 \left(Ra\ \frac{D}{H}\right)^{0.566} \qquad (5)$$

where $90 < Ra(D/H) < 2x10^4$.

For air flows in fully-enclosed cavities, the relationship between average Nusselt numbers, Rayleigh numbers and vertical aspect ratios is complicated (El Sherbiny et al, 1982). When H/D > 5 and L/D > 5, three regimes are encountered as the Rayleigh number increases, firstly an almost wholly conduction regime (i.e. a layer of near-stationary air : Nu being at or close to unity), then a laminar boundary-layer and finally a turbulent boundary-layer regime. Respective correlations for these phenomena have been proffered by El Sherbiny et al (1982):-

$$Nu_{c\ell} = \left[1 + \left(\frac{0.104Ra^{0.293}}{1 + (6310/Ra)^{1.36}}\right)^{3}\right]^{1/3} \tag{6}$$

$$Nu_{\ell} = 0.242\left(\frac{Ra\ D}{H}\right)^{0.273} \tag{7}$$

$$Nu_{t} = 0.0605Ra^{1/3} \tag{8}$$

where the magnitude of Nu, for a particular condition, is the maximum of those calculated via these three equations. The maximum value of Ra for which this correlation has been validated is approximately $2x10^5$, for 5< H/D <40. (In this experimental study, the vertical aspect ratio remained within the range 8< H/D <22).

Unfortunately, no general formulae for the steady-state heat-transfer behaviour of the geometry of a conventional toaster (see Fig. 2) have been located in the literature. Equation (4) for closed-sided open cavities tends to over-estimate Nusselt numbers, because it applies to a system which is completely open at the base as well as at the top of the cavity. Similarly, correlations for vertical fins mounted on a horizontal plate are inappropriate for a toaster, because (i) air is completely precluded from entering the cavities via the base of the fins, (ii) the formulated equations have only been validated for fin-base temperatures below 150°C; and (iii) the fins and base are usually almost isothermal. Also, the relationships between Nusselt numbers, Rayleigh numbers and vertical aspect-ratios for fully-enclosed vertical cavities - see equations (6),(7), and (8) - are for air-tight enclosures, and as such are not appropriate to practical designs of toasters. (A fully-enclosed toaster may influence adversely (i) the quality of the toast thereby prepared; and (ii) the reliability of the appliance, because increased amounts of water vapour/condensate would be held within its structure).

Thus this investigation aimed at identifing thermal performance correlations for a 'partially-enclosed' toaster, as well as for a standard 'open' design (see Fig. 2). The partially enclosed design was considered to provide a compromise between fully-enclosed (i.e. air-tight) and open (i.e. conventional) designs, and hence offered a practical alternative option.

Fig. 2 Sectional end-views of three prospective designs for a vertical, conventionally-heated, electric toaster.

THE EXPERIMENTAL RIG

This consisted of a conventional toaster-heater (i.e. Nichrome tape mounted on one side of a plane mica former) backed by a flat aluminium-alloy reflector. The latter was supported via a tripodal screw arrangement, which permitted the heater-to-bread separation, δ, to be adjusted (see Fig. 3). The heater was connected to a stabilised, variable-DC power supply. Because bread would rapidly begin to smoulder and burn during this series of steady-state experiments, a substance for simulating a slice of bread (of similar height and breadth to the heater) was then mounted so that it faced the heater (see Fig. 3). Unfortunately a suitable test specimen for imitating accurately the thermal behaviour of bread during toasting was not available. The employment of bentonite-clay to model foods undergoing infra-red heating is often chosen (Unklesbay et al, 1980), but its use for this study was not feasible, because the moisture content of the sample would decrease substantially as the rig attained steady-state conditions before being placed in the test section of the MZI. Also evaporation from the bread-simulator would disturb the observed interference fringe patterns, because the refractive index of moist air is slightly less than that for dry air (Kaye and Laby, 1973). Although it is possible to calculate accurately a refractive index for moist air via :-

$$n = 1 + 7.5\times10^{-9}\left[\frac{103.49\ p_{DA}}{T} + \frac{177.4\ p_{CD}}{T} + \frac{86.26}{T}\left(\frac{1 + 574.8}{T}\right) p_{wv}\right] \quad (9)$$

there would be significant moisture variations (and hence corresponding changes in refractive index) across the air gap between the bread-simulator and the heater. Measuring these variations, so that heat-transfer coefficients could be calculated accurately from interferograms, would be difficult. Therefore a dry bread-simulator was employed for this initial interferometric investigation of the thermal behaviours of conventional toasting appliances : a ceramic-fibre insulant (Fiberfrax), with no organic constituents, was chosen.

A Nickel-chrome/constantan thermocouple was welded to the tape heater to provide an indication of its temperature, and copper/constantan thermocouples were employed to measure temperatures along the vertical centre plane (parallel to the heated surface) of the bread-simulator. The system was fitted with a wooden base, which was constructed so that air could enter the cavity from below in an approximately similar manner to that entering a real toaster. Then optically-flat glass plates were fixed and sealed to the two ends of this test cell. An appropriately fabricated lid for the assembly was available so that the system could be enclosed when desired (see Fig. 3).

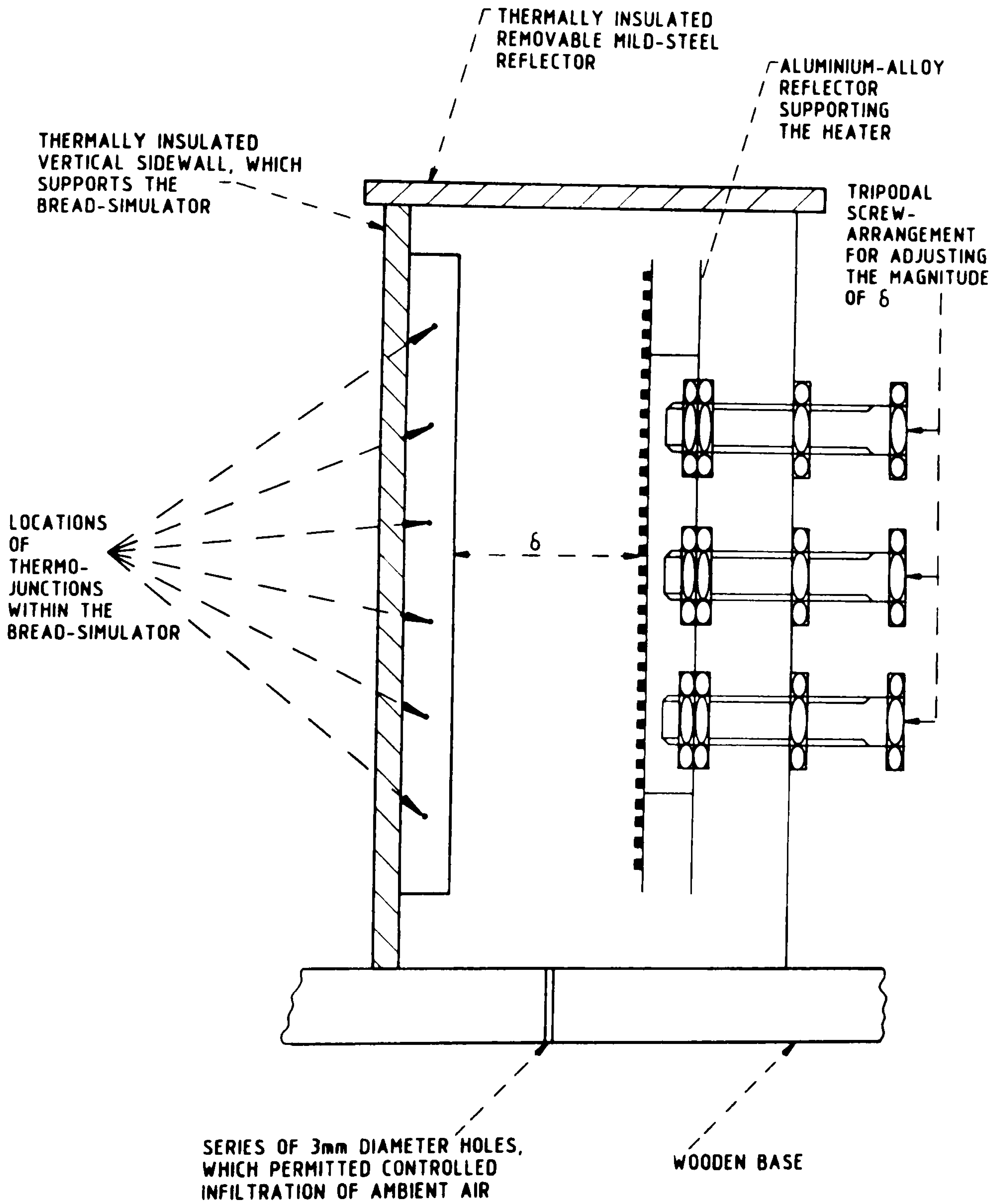

Fig. 3 A cross-sectional end view of the experimental rig.

EXPERIMENTAL PROCEDURE

Two series of tests were undertaken :- (i) with the cavity open to the ambient environment, and (ii) with this cavity enclosed by a lid. In order to simulate the operation of a typical toaster the following ranges of variables were chosen:-

$$50°C < T_H < 650°C, \quad 0.007m < \delta < 0.017m, \quad \text{where } t \approx 0.02m$$

Although at high temperatures, for large values of δ, the flow becomes unstable, interferograms were recorded across the aforementioned temperature range, so that the limiting (in terms of interpretation accuracy) temperature difference for the computer-based photogrametric system (developed in parallel with this investigation — see Newborough et al, 1987b), could be identified.

The test rig was mounted on a movable cantilever framework which facilitated its introduction to the test section of the interferometer. Before each set of readings was taken, the orientation of the rig was adjusted so that the plane of the heater was parallel with the laser beam passing through the test section. Then the interferometer was adjusted to the infinite-fringe setting with the rig in position. The power input to the heater was set to the required value, and the test cell was left to attain a steady-state condition. Once this had been established, the interference fringe-pattern was photographed and the thermocouple readings were recorded.

After each series of tests, matt A4-size photographs of the fringe patterns were developed. (When neccesary, these were enlarged so that individual fringes could be observed by the naked eye). Then the digital photogrammetric system was employed to determine the distances between fringe-centres and the reference plane (i.e. the heated surface) : the associated software was used to calculate local and average property values for the conditions represented by the interferograms.

EXPERIMENTAL ERRORS

The employment of a MZI for heat-transfer studies is subject to a number of possible sources of error due to:-

i) refraction;
ii) end effects;
iii) vibration;
iv) evaluation mistakes; and
v) uncertainties in measuring the reference temperature.

Refraction Errors

The relationship between fringe shift and temperature difference assumes that the light beam travels horizontally through the test section (Newborough et al, 1987b). However, due to the refraction of the light by the density gradients within the test cell, individual rays actually traverse curved paths. Consequently the fringe shift is modified slightly: this can result in distortion of the fringe pattern near the hot wall. Refraction errors can be reduced by focussing the camera on a vertical cross-sectional plane well within the test cell (Hauf and Grigull, 1970). According to Mehta and Black (1977), this plane should be one-third of the length of the test cell away from the optical plate nearer the camera. This recommendation was adopted in this study.

End Effects

Although the camera was focussed on the aforementioned plane, the fringe pattern formed by the interferometer resulted from integrating the temperature field along the total optical path. Thus the results include to some extent the end effects of the test cell, and any other disturbances along the path of the light rays. In practice, a thermal boundary layer forms along each end-plate, and hence relatively high temperature gradients occur there. Hauf and Grigull (1970) investigated the resulting errors : they recommended that test cells should be at least 0.5m long in order to render such end effects negligible. The test rig constructed for the present investigation complied with this requirement.

Vibration

The MZI is sensitive to vibration, and so to attenuate its influence, the instrument is mounted on partially-inflated tyred wheels, the actual inflation pressure depending upon the frequency band which needs to be suppressed. Perturbations of the fringe pattern could result from vibrations of the transformers in the power supply employed for the test rig. Thus the power-supply was insulated acoustically so that the interference fringes were perceived to remain unaffected by its operation. Because the rates of heat transfer of vibrated systems are greater than those of static ones, the movable cantilever framework housing the test cell also had anti-vibration mounts between it and the floor.

Evaluation Errors

Usually the largest single source of error in the evaluation of interferograms arises as a result of the subjective mistakes and poor judgement of the investigator. Although, the computer-based system used for analysing the fringe patterns generated in this study, provided a consistent level of accuracy, further attempts to improve the precision with which it reads an interferogram are required before it can be recommended in preference to the conventional technique of employing a travelling microscope (Newborough et al, 1987b). It was found that the computer-based system could not be used to interpret interferograms for the test rig when the heater temperature exceeded approximately 300°C, whereas it was possible to obtain temperature distributions from interferograms, photographed when the heater was at nearly 400°C, by using a travelling microscope capable of reading to an accuracy of 0.02mm.

Errors of Temperature Measurement

The thermocouple attached to the heater acted as a heat leak. Consequently the recorded value of T_H was always lower than that of the true value for the heated surface. This inaccuracy was evaluated by comparing the thermocouple reading with that produced by an optical pyrometer when focussed on the heating element. Consequently it was estimated that errors in measuring this temperature of up to 6% occurred during testing.

DISCUSSION and RESULTS

Convective air-flows through the cavity of the test cell increased with the heater-to-bread separation. A typical interferogram for δ >10 mm comprised two distinct regions (see Fig. 4). In the boundary layers which formed on the opposing hot and cold surfaces, the isotherms were closely packed, but in the central region of the cavity the horizontal temperature gradient was small, because the convective flow near the vertical walls counteracted the effect of conduction straight across the cavity. Typical temperature distributions across the air cavity are shown in Fig. 5. At high temperatures (i.e. T_H > 150°C) the temperature of the surface of the bread-simulator exceeded significantly that of the air in the central region of the cavity. This was because radiation rapidly became the dominant mode of heat transfer as T_H was increased. However for small heater-to-bread separations (e.g. δ=7mm) the local temperature profile tended more towards a conduction (i.e. linear) profile, so indicating that convection was then more suppressed within the cavity.

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Fig. 4 Typical steady-state interferograms for the experimental toaster-rig, when the initial heater-to-bread separation and heater temperature were approximately 12mm and 435°C respectively. In case (a) the rig was open at the top, whereas for case (b) the cavity was enclosed with an insulated lid. For both configurations, restricted infiltration of ambient air from the base of the cavity was permitted, as would occur in practice.

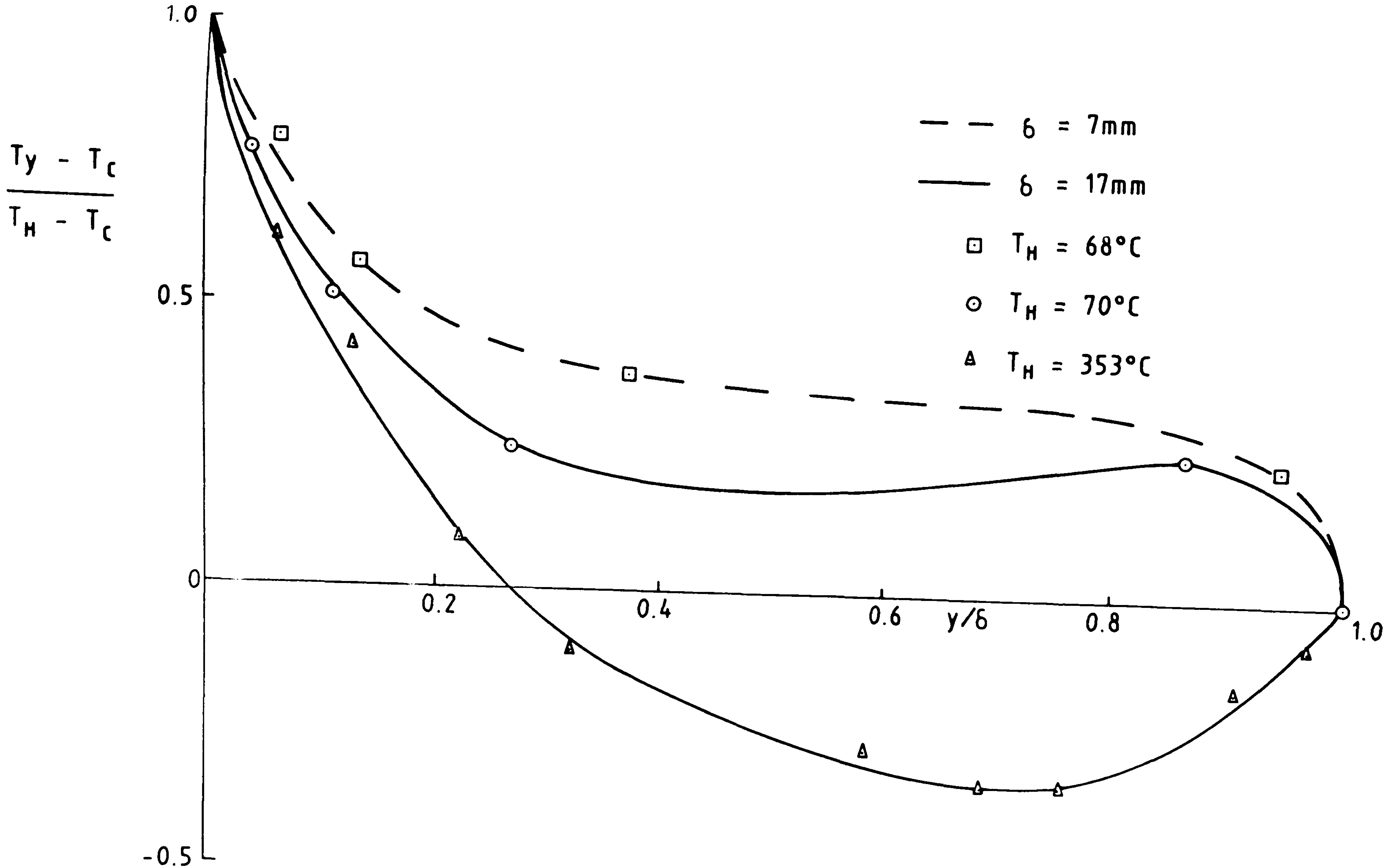

Fig. 5 Typical steady-state temperature profiles for the open-topped bread/heater air cavity.

Substantial improvements in thermal efficiency (i.e. by reducing the steady-state power input required to achieve a certain mean centre temperature of the bread-simulator) were obtained when the heater-to-bread separation was reduced and a lid was placed over the cavity (see Figs. 6 and 7). However, as expected, significant temperature differences then occurred between the lower and upper regions of the air cavity (see Table 1 and Fig. 4). Also temperature differences along the vertical centre plane, parallel to the heated surface, of the bread simulator were largest for small values of (see Fig. 8). These factors indicate that attempts to improve the thermal efficiency of a conventional toaster by (i) reducing the heater-to-bread separation, and (ii) suppressing convective air-flows, would tend to reduce the probability of achieving uniform browning of the bread's surface.

It is feasible that the heater may be inclined (i.e. so that at the top is greater than at the bottom) in order to achieve a more uniform surface temperature across the slice of bread. An optimal inclination angle (from the vertical plane, parallel to the bread) at which the heater should be positioned undoubtedly exists. However, because radiative heat transfers predominate (i.e. $h_r > 7h_{cc}$ for $T_H >$ 150 °C in this steady-state investigation), attention to the construction of the actual heaters should be more pertinent in terms of achieving uniformly browned toast (e.g. the actual radiating area of the heating element should increase towards the bottom of the heater).

From the interferograms taken with the cavity (i) open at its top, and (ii) enclosed, local Nusselt numbers and heat-transfer coeffficients were calculated. For both cases, attempts were made to correlate average Nusselt numbers with the dimensionless parameter $Ra(\delta/H)$. The experimental data recorded in this interferometric investigation, are shown in Fig. 9. The 'best-fit' straight-lines for the two geometries were deduced to be:-

Conventional toaster configuration : $$Nu = 0.134\left(\frac{Ra\,\delta}{H}\right)^{0.493} \qquad (10)$$

Enclosed toaster configuration : $$Nu = 0.313\left(\frac{Ra\,\delta}{H}\right)^{0.262} \qquad (11)$$

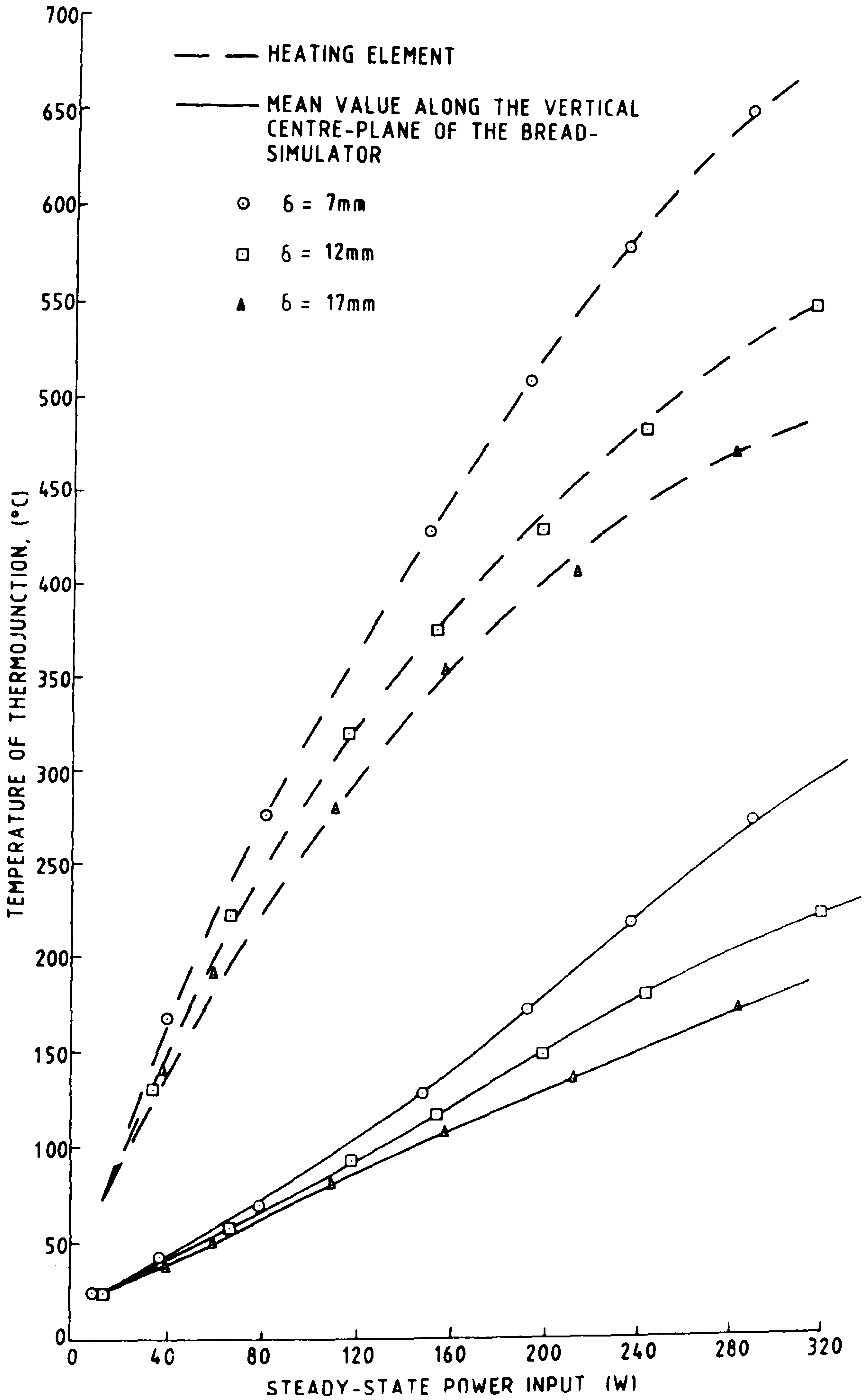

Fig. 6 Steady-state temperatures attained by the heater and bread-simulator in the open-topped cavity, for different heater-to-bread separations.

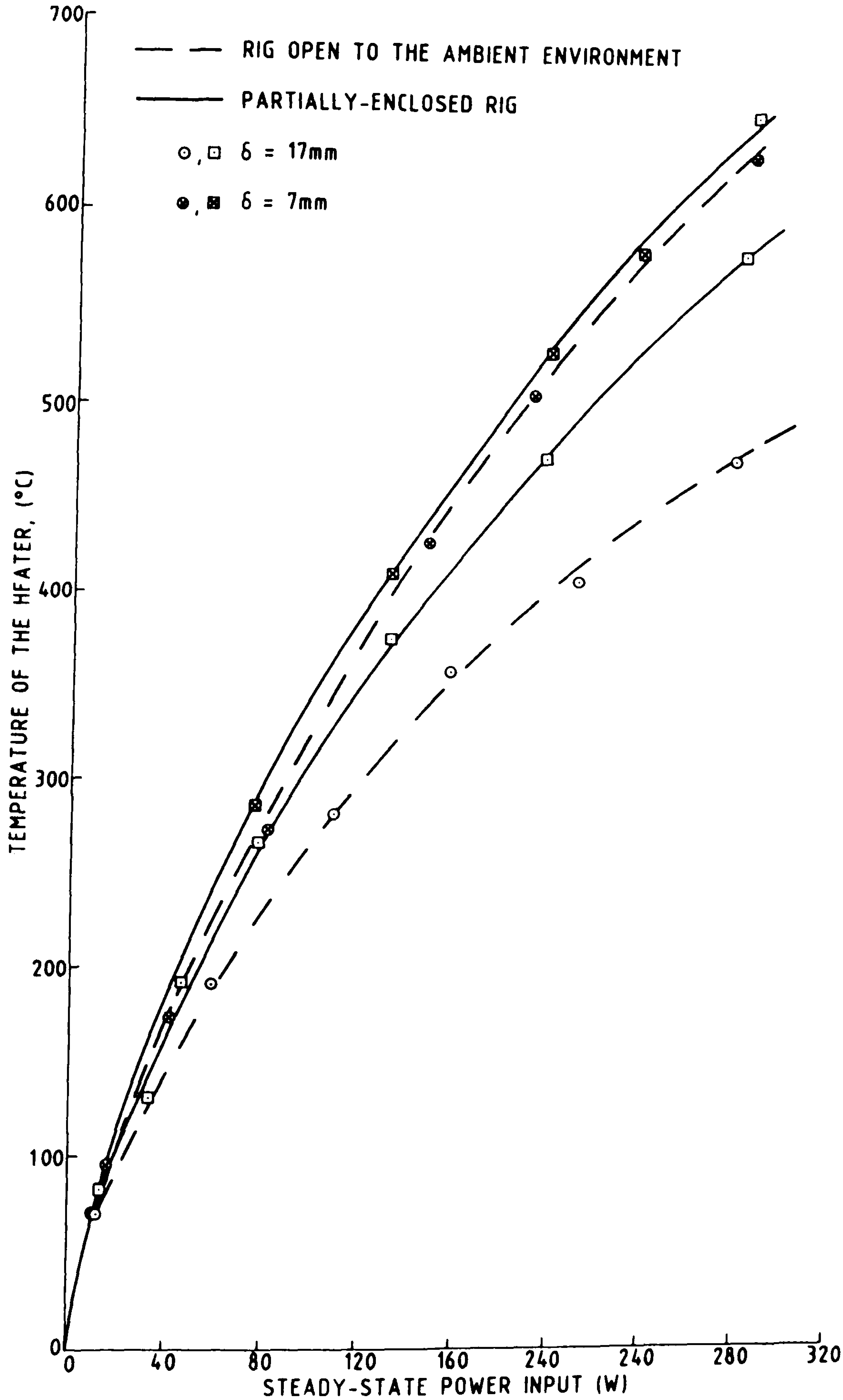

Fig. 7 Steady-state temperatures attained by the heater in the open-topped and partially-enclosed cavities for large and small heater-to-bread separations.

TABLE 1

Steady-state power inputs and resultant temperatures, when a pre-selected heater temperature was maintained for large or small heater-to-bread separations, with the rig open or partially enclosed.

Rig configuration	Heater-to-bread separation (mm)	Power input required to maintain the heater at $400 \pm 15^{\circ}C$ (W)	Temperature difference across the horizontal mid-plane of the cavity (orthogonal to the heater), (°C)	Temperature difference along the vertical mid-plane of the cavity (parallel with the heater), (°C)	Mean temperature of the vertical centre plane of the bread-simulator (parallel with the heater), (°C)
Without lid	7	142	30	136	127
With lid	7	133	28	183	141
Without lid	17	202	124	42	134
With lid	17	136	75	109	119

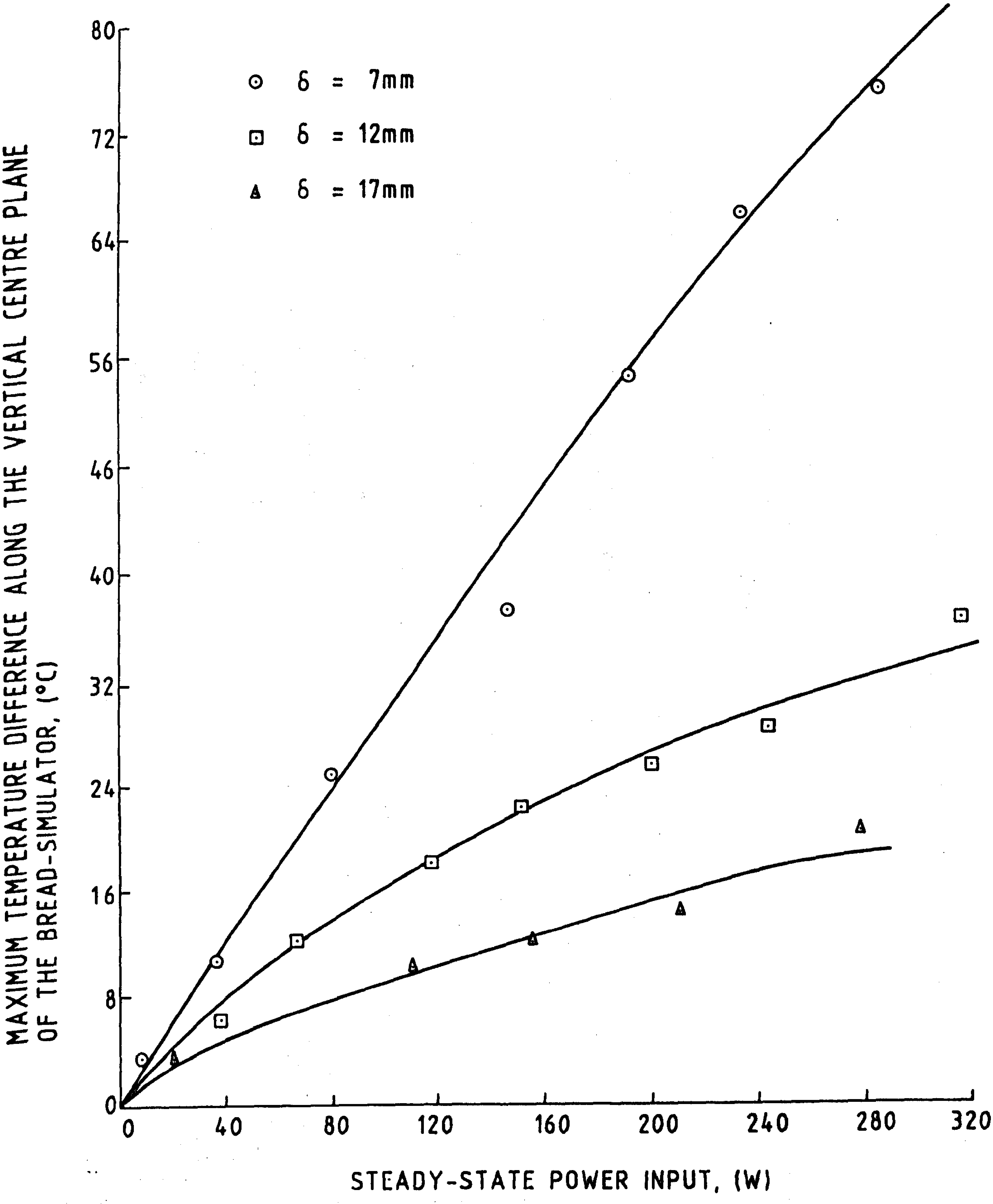

Fig. 8 Maximum temperature difference along the vertical centre plane (parallel with the heater) of the bread-simulator, for different heater-to-bread separations when the cavity was partially-enclosed.

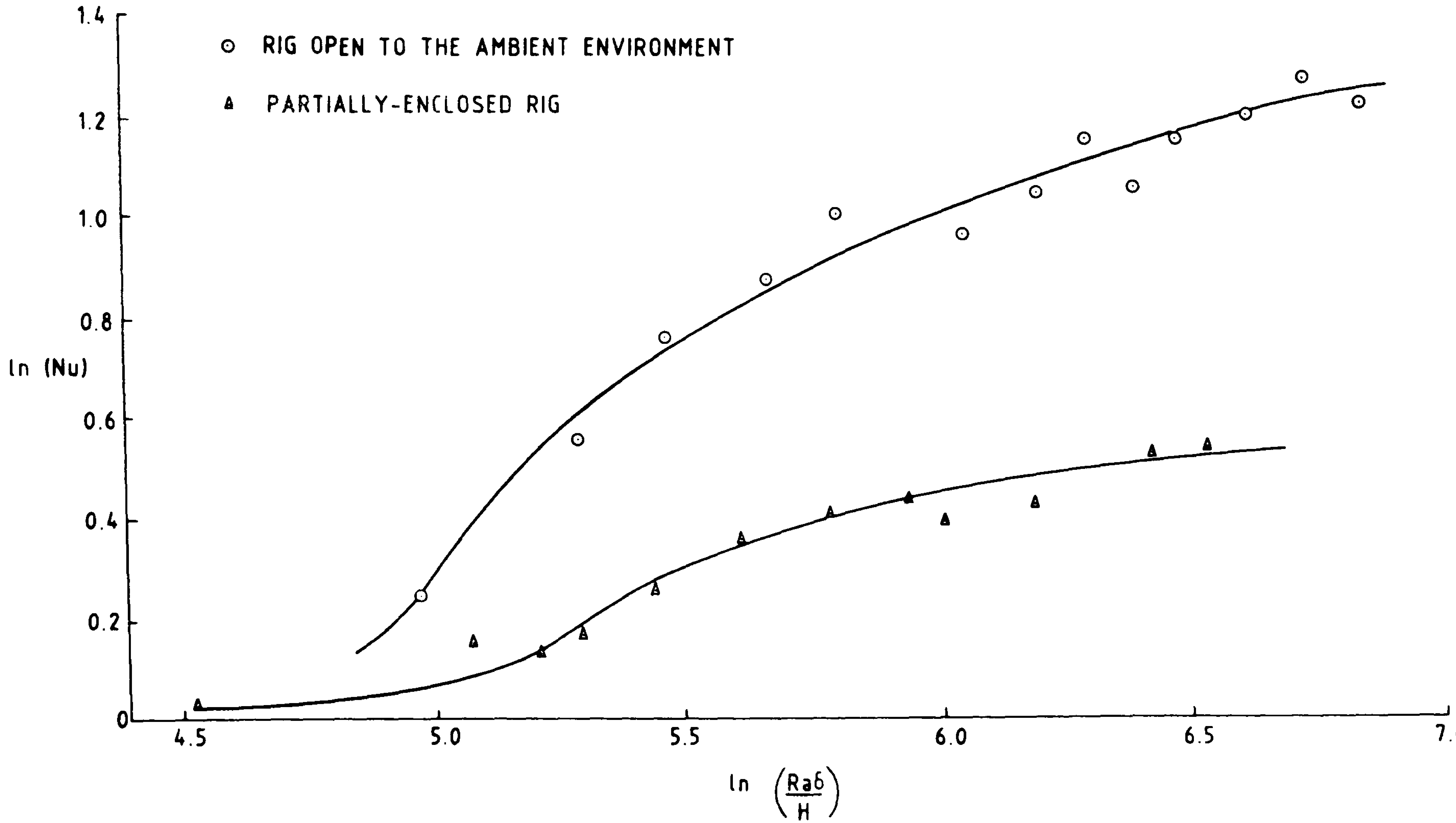

Fig. 9 Log-log plots of average Nusselt numbers versus the dimensionless group Ra(δ/H) for the open-topped and partially-enclosed cavity configurations.

CONCLUSIONS and RECOMMENDATIONS

The heating effectiveness of the experimental toaster-rig under study improved significantly when the heater-to-bread separation was reduced. It is considered that the practical minimum for the initial (i.e. at ambient conditions) heater-to-bread separation is about 7mm for toasters employing tape-heaters. However as this limit is approached, the uniformity of heating achieved (and hence the eveness with which a slice of bread would be toasted in practice) tends to diminish. Thus the optimal initial heater-to-bread separation for a toaster employing such heaters in practice would be about 10mm.

A conventional alloy-tape heating system is unsuitable for a 'low-energy' toaster, mainly because the heating surface, (i) has a radiating area which is usually too small; and (ii) experiences considerable distortions (due to thermal expansion) as the necessarily high temperatures (i.e. >500°C) are reached during the toasting process. The use of flatter, thin-film heaters (as employed in some commercial toasters) should enable small (i.e. <10mm) heater-to-bread separations to be achieved and so improve the toaster's thermal efficiency, without affecting adversely the quality of the toast thereby prepared. If high efficiencies are to be achieved regardless of the thickness of the slice of bread placed in the toaster, the heater-to-bread separation should be maintained at its optimal value for the particular design of toaster. Thus the facility to move opposing heaters in a horizontal direction automatically to achieve this optimum, as the bread is lowered into the toast compartment, is a basic design requirement. However, it is unlikely that such a heating system will be designed into an average domestic toaster, due to the extra production costs incurred. Even if the concept of a pay-back period (e.g. the capital cost of such a toaster, divided by the annual financial saving which results from employing it) is introduced to prospective purchasers of more efficient versions of household appliances, the commercial prospects for a 'low-energy' toaster would be poor, because the typical domestic toast-consumer spends only about £1.1 p.a. on electricity for toasting purposes, and the average useful life of a domestic toaster is only about 6 years (Newborough et al, 1987a).

Substantial improvements in the thermal efficiency of toasters should be achieved by fitting integral slot-covers to their bread slots. Tests indicated that a simple well-fitting lid on a toaster yielded energy savings (relative to the standard design), which were nearly as great as those achieved when infiltration of cold ambient air was prevented entirely (see Fig. 10). These slot covers need not increase manufacturing costs substantially, although if the traditional 'pop-up' feature of domestic toasters is to be retained, the associated mechanism would become more complicated (i.e. the slot covers would need to be removed automatically once the food was prepared so that it could be elevated from the toast compartment).

It is recommended that further experimental studies be undertaken

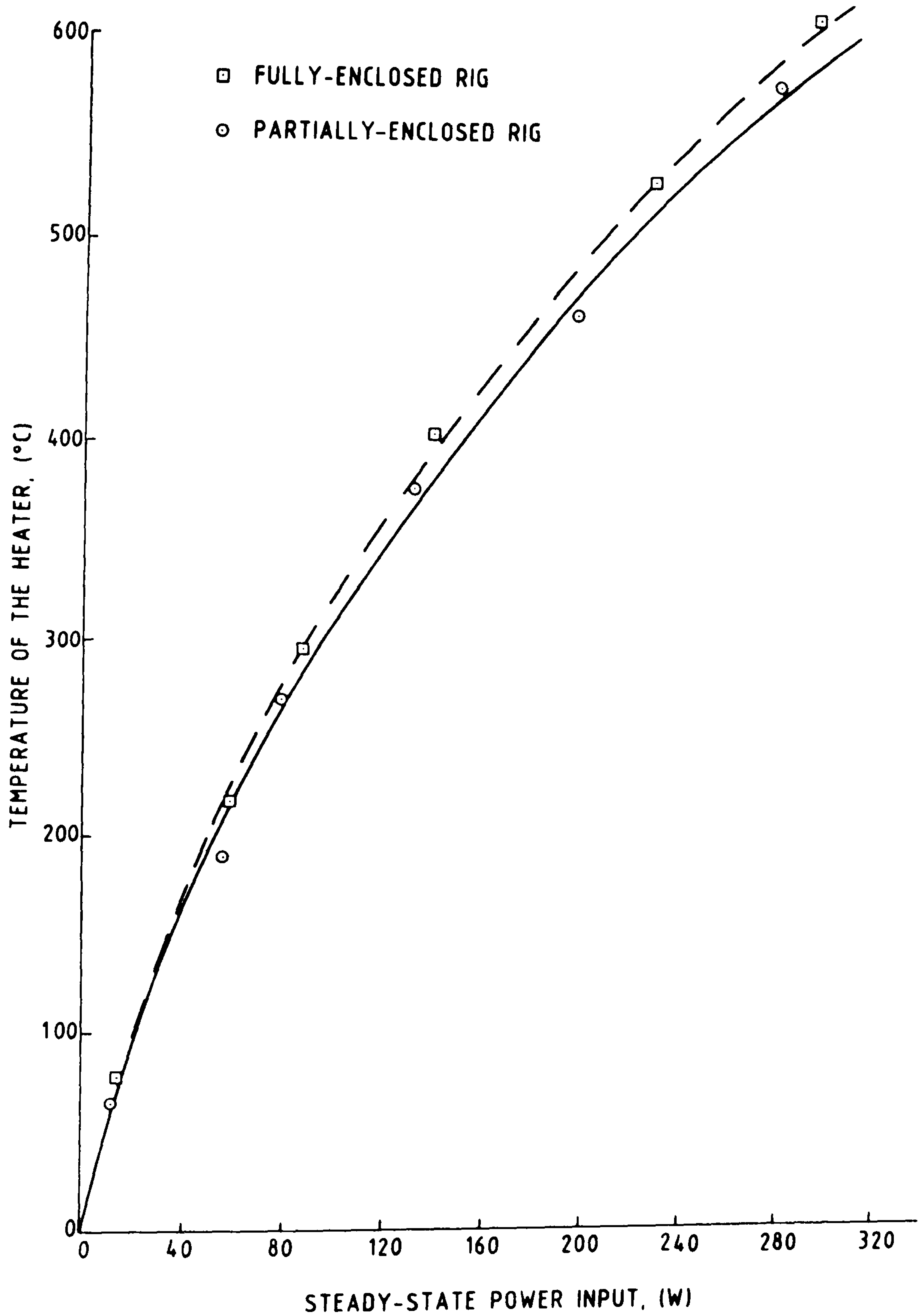

Fig. 10 An indication of the improvements in thermal efficiency achieved, when attempts were made to enclose fully (i.e. seal) the cavity from the ambient environment, compared with the partially-enclosed rig configuration.

with a prototype toaster, which utilises (i) covers for its bread-slots; and (ii) heaters of greater surface area (positioned to achieve relatively small heater-to-bread separations). Organoleptic and 'browning-uniformity' tests (BS 3999, 1972) should be carried out to compare the quality of toast prepared by the modified toaster with that produced by a standard toaster. If satisfactory toast can be produced via this prototype, then it would be logical to design an improved electric toaster (in terms of improved reliability, better control and shorter toasting-period as well as high efficiency criteria) based on the findings of this study and the precursory investigation (Newborough et al, 1987a). The appliance thereby developed would not necessarily be commercially-unattractive, despite its higher manufacturing cost, because British consumer-interest in superior designs of domestic appliances is not inconsiderable (viz the commercial success of certain high-performance 'food-processors', microwave ovens and washing machines which cost nearly twice as much as their conventional counterparts). Thus it is recommended that further attention be given to optimising the general design of what is currently a commonly-employed, yet widely-criticised, appliance, so that consumers may have the opportunity to employ better 'all-round' toasters.

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CHAPTER SEVEN

AN AUTOMATICALLY-CONTROLLED ISOGRAM-ANALYSIS SYSTEM

FOR INTERFEROMETRIC STUDIES

SUMMARY

A simple low-cost digital photogrammetric system for interpreting Mach-Zehnder interferograms is described. The associated software permits heat transfers occurring within test cells of linear geometries to be deduced. Interferograms may be analysed much more rapidly and with less supervision via this facility, than by the laborious conventional technique of using a travelling microscope. Furthermore a consistent high level of accuracy can be achieved, even though the users (e.g. post-graduate engineering students) may have little experience of interpreting interferograms.

NOMENCLATURE and ABBREVIATIONS

G	Gladstone-Dale constant, $m^3 kg^{-1}$.
h, $\bar{h}$	Local and average heat-transfer coefficients respectively, $Wm^{-2}K^{-1}$
(I_i/I_t)	Opacity, i.e. the ratio of the incident luminous flux to that transmitted by the considered transparent medium.
K	Constant in equation (14), K.
k	Thermal conductivity of air, $Wm^{-1}K^{-1}$.
L	Path length, i.e. length of the test cell in the direction of the laser beam, m.
L	Optical path length, m.
l	Real dimension in the x-direction of the scanned area, m.
N	Number of wavelengths of light along a given path length.
n	Refractive index of the air within the test cell.
Nu, $\overline{Nu}$	Local and average Nusselt numbers respectively. (The Nusselt number is defined as the actual steady-state rate of heat transfer by combined convection and conduction through the fluid, divided by the heat transfer rate had conduction alone occurred).
$\dot{q}$	Steady-state rate of heat transfer, W.
T	Temperature, K.
x,y	Cartesian co-ordinates of a point within the cavity, m.
Δ	Difference between two values of the parameter.
δ	Characteristic dimension for the geometry of the test cell under test, m.
λ	Wavelength (=632.8 nm) of light emitted by the 3mW He-Ne laser.
ρ	Density of air, kg m^{-3}.

Subscripts

C	Of the cold surface.
CA	Of the lowest air temperature across the fin space.
CD	Pertaining to the temperature difference associated with the characteristic geometry of the system under test.
H	Of the hot surface.
0,1,2	Conditions of state for the gas.

Abbreviations

CPS	Microcomputer-based photogrammetric system.
MZI	Mach-Zehnder interferometer.
PRS	Photoelectric 'reflective scanner', containing a light-emitting-diode and a phototransistor. Light produced by the diode is reflected by the photograph of the interference fringe pattern and converted into an electrical signal by the receiver (i.e. the phototransistor). When the scanner is mounted in close proximity to a 'black-and-white interferogram' sufficient differences in the generated electrical signal occur, as the scanner views successively black and white areas, to facilitate the exact location of these regions.
VDU	Visual display unit.

INTRODUCTION

Traditional methods for interpreting optical interference phenomena rely on manually-controlled measuring devices (such as travelling microscopes) to determine the separations between interference fringes. Although such methods can be performed accurately, they become tedious when having to be repeated frequently during extensive experimental investigations and hence become increasingly prone to human error. Therefore alternative means of assessing interference fringe patterns were investigated. The primary motive for this study was to develop a system which would enable those involved in interferometric investigations to achieve a more effective use of their time.

Fundamentally, a system for interferometric analysis should measure accurately and rapidly the number of fringes and the separations between adjacent fringes. There are two principal methods available for achieving this:-

1) digitise a photograph of the fringe pattern; or
2) 'store' the fringe pattern directly.

The latter method may be facilitated by employing a computer-controlled video camera, in place of the standard camera (see Fig. 1), to record fringe patterns in digital form via video tape and floppy disc. The data thereby stored may be utilised by appropriate software, so that analyses of the heat transfers occurring within the test cell under investigation, can be performed. The main advantage of this type of system is that the fringe pattern can be recorded directly (i.e. relatively few opportunities occur for human mistakes to prolong analyses and/or cause errors in the ensuant calculations). Images may be scanned and reproduced on paper in periods of only a few seconds (ARS Microsystems, 1987; Agema Infrared Systems Ltd., 1987). Also, analyses of transient heat transfers (by employing short time intervals between each scan) should be feasible.

However, it may be difficult to avoid collecting large quantities of irrelevant data when filming test cells, which contain cavities of large (e.g. >5) or small (e.g. <0.2) height-to-airspace (or diameter-to-airspace) ratios. The inadequate resolution of the fringes displayed on the VDU may prevent accurate analyses being performed, especially when large temperature-differences exist between the opposing sides of the cavity, i.e. when a large number of isotherms need to be reproduced per unit width of the VDU screen. (To some extent, this problem can be rectified by employing a photogrammetric technique, because the interferogram can be enlarged photographically until the 'critical magnification' is reached beyond which individual fringes become too poorly defined for analysis purposes). Alternatively, a 'phase shifting' method (Cheng and Wyant, 1985) may be employed with a heterodyne interferometer, to achieve very high accuracy by analysing the phase, rather than the intensity, of an interferogram (Lavan et al, 1975; Massie et al, 1980; Dandliker and Thalman, 1985). It can be shown (Reid, 1986) that the current generated by a photoelectric detector, which measures the intensity of light at a given position within the interference field, is a function of the phase value of the fringe pattern at that position. By shifting the phase of the interferogram by appropriate amounts, a series of fringe patterns can be generated from which the phase value of each monitored position (or pixel) within the interference field can be derived. Consequently, an enhanced (i.e. relatively error-free) image can be constructed by computer for subsequent analysis (Cheng and Wyant, 1985). The accuracy to which a typical interferogram can be interpretted is thereby improved by two to three orders of magnitude, when compared with the conventional manual means of interferogram-analysis (Reid, 1986). Nevertheless, because this technique would (i) necessitate modification of the Mach Zehnder interferometer, and (ii) require considerable financial investments in appropriate digital image-processing equipment and computer hardware, a less expensive photogrammetric technique, based on method (1), was preferred for development.

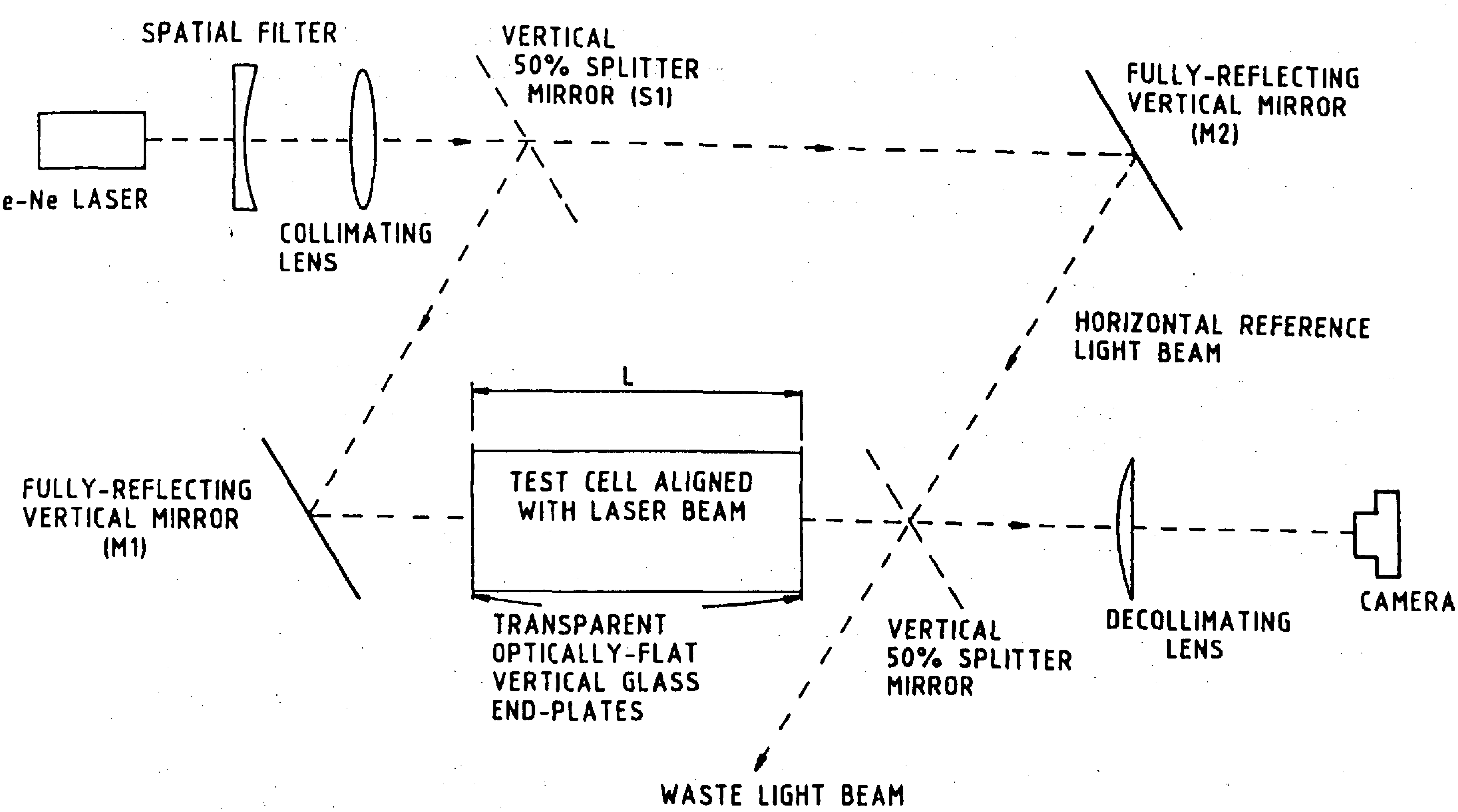

Fig.1 Schematic plan view of the 18cm field-of-view Mach-Zehnder interferometer in operation.

ISOGRAM-ANALYSIS SYSTEM

The prototype microcomputer-controlled isogram-analysis system (CPS), using a photoelectric reflective scanner (PRS) to examine the interferograms, is illustrated in Fig. 2. The scanner was mounted on a carriage, which was driven by servo motors via a pulley system, so that the PRS could be moved (accurately parallel to the supporting table) in steps of 0.25 and 0.125 mm in the x and y planes respectively. Control software written for the system's computer (i.e. a 128kRAM BBC Master microcomputer) permitted duplicate high-resolution representations of interferograms positioned on the table to be constructed on the VDU, and then (if necessary) stored on a floppy disc. Also the facility to enlarge such images was provided, to aid visual understanding (e.g. see Fig. 3). The height at which the PRS was positioned above the photograph was critical to the consistency of the screen image obtained. Therefore the detector was held accurately in a fixed position and a vacuum table constructed to hold the photograph flat (see Fig. 2). Furthermore provision was made for the user to adjust finely the threshold signal generated by the PRS via a potentiometer, so that a high-quality image could always be obtained, even when the contrast level of interferograms under examination varied slightly.

In order to simplify subsequent calculations, each interferogram must be placed on the vacuum table so that it will be scanned from the line describing the hot surface to the one representing the opposing (usually colder) surface. For linear geometries, the PRS scans the y-plane (see Fig. 3) in strips, across an area of the photograph designated by the user, with the line representing the hot surface as y=0. Consequently the dimensions associated with the centre-lines of the fringes on an interferogram can be determined and related to those of the test cell, so that temperature distributions and instantaneous rates of heat transfer occurring therein may be quantified.

The software was developed specifically for studies with the 18cm field-of-view Mach Zehnder interferometer (MZI) available at Cranfield, which was employed in the 'infinite fringe-spacing' mode. This technique is relatively simple to utilise : for isobaric fluids it yields interference fringes which represent isotherms. Initially, when the temperatures of the reference and test sections of the MZI are equal, the interferometer is adjusted (via mirror M2 - see Fig. 1) so that a single fringe covers the entire field-of-view (i.e. the nominally infinite fringe-spacing). The subsequent introduction of temperature gradients within the test cell initiates changes in density (and hence refractive index) across the air gap under study. Due to the ensuant changes in optical path length of the test beam, L_o , relative to that of the reference beam, the infinite-fringe pattern (where the two beams meet) is disturbed and interference fringes form. Dark lines occur when the reference and test beams are out of phase by an odd number of half-wavelengths; bright lines ensue where the beams are out of phase by an even number of half-wavelengths. Thus a movement of the fringes equal to the fringe spacing corresponds to a change in optical path length of the test beam of one wavelength (i.e. 632.8nm), where the optical path length is defined as:-

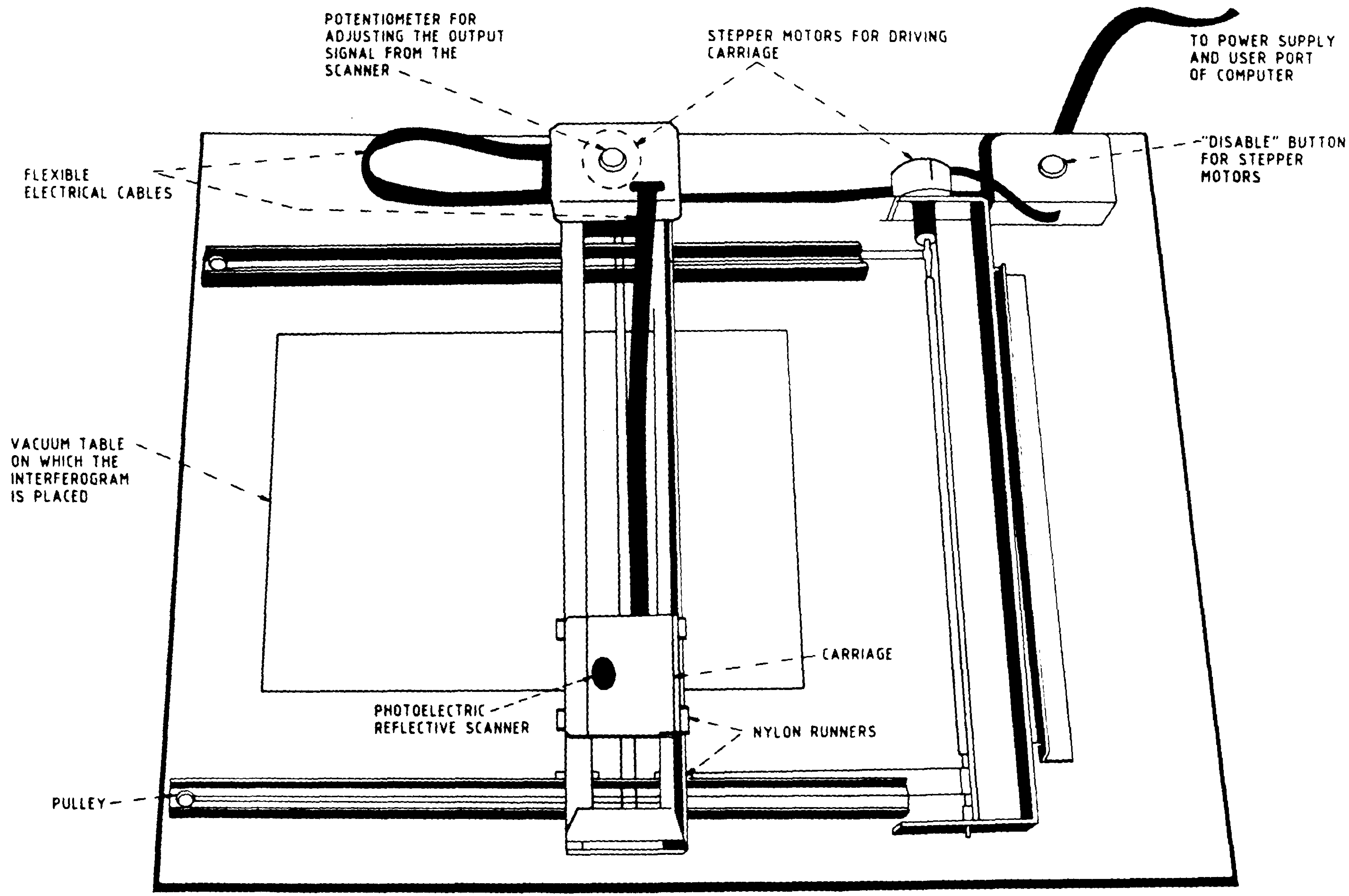

Fig.2 The prototype microcomputer-based photogrammetric system employed for analysing interferograms.

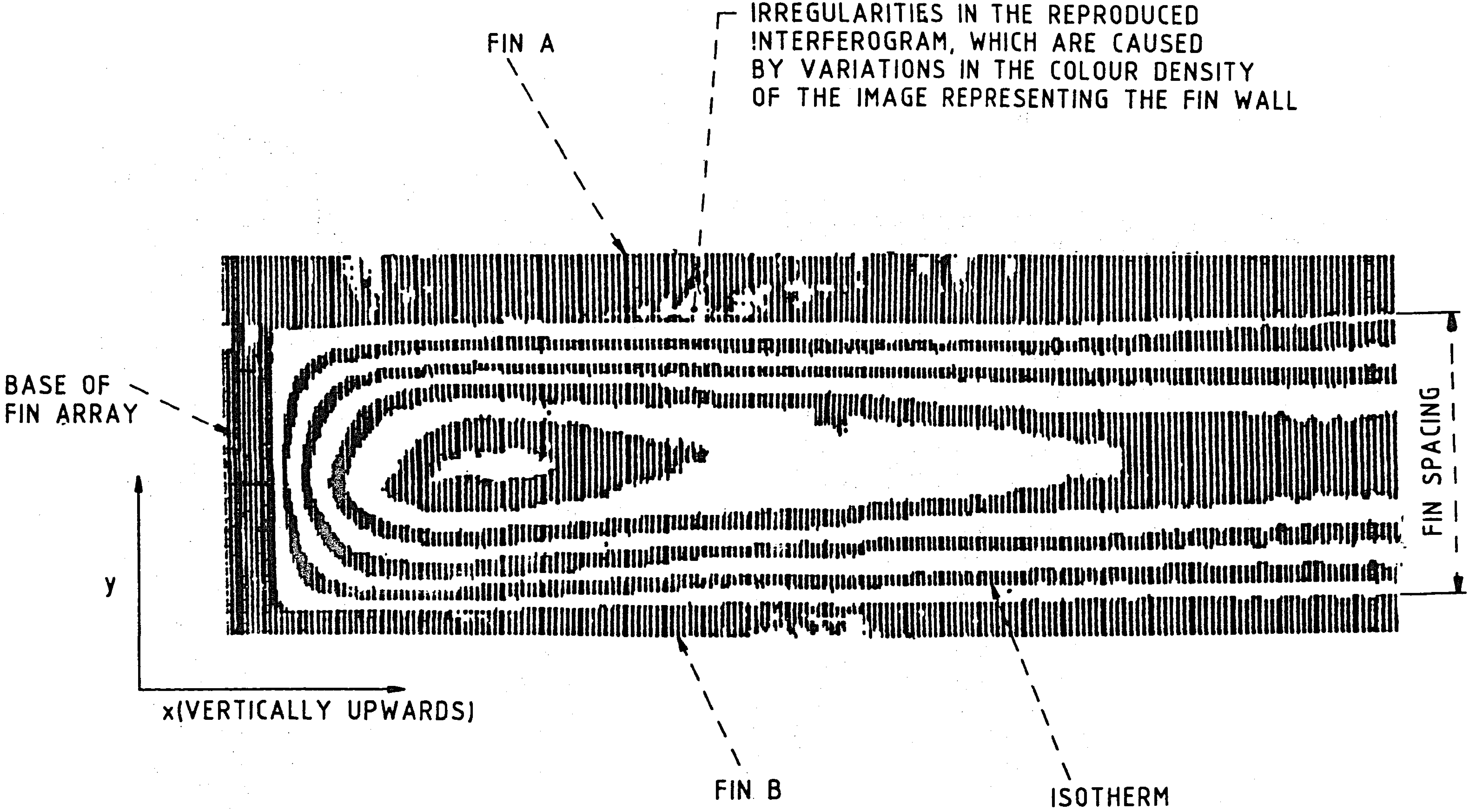

Fig.3 Typical representation of the image displayed on the VDU of an interferogram, as printed by a standard dot-matrix printer. In this case, the isothermal contour map is that for the air cavity between two aluminium-alloy fins of height 90mm, spaced uniformly 12.7mm apart with a base temperature of 40°C. (The irregularities indicated on the diagram will yield inaccurate results, which should not be included in the calculation of average heat-transfer parameters).

$$L_0 = \int n \, dL \quad (1)$$

Because all density changes are integrated by the interferometer along the length of the test cell, it is desirable to limit the air's density variations to those occurring in planes which are orthogonal to the light path, i.e. the MZI measures two-dimensional temperature distributions. The density gradient may be determined from the Lorenz-Lorentz relationship (Kennard, 1932; Hauf and Grigull, 1970):-

$$\left(\frac{n^2 - 1}{n^2 + 2}\right) = G\rho \quad (2)$$

For a gas, $(n+1)/(n^2 +2)$ is nearly constant (i.e. $\sim\frac{2}{3}$) and so equation (2) may be approximated by

$$n - 1 = G\rho \quad (3)$$

where G is the Gladstone-Dale constant, and $G\rho$ is the optical density (i.e. log $[I_i/I_t]$). Thus, for a change in refractive index from n_1 to n_2:-

$$n_1 - n_2 = G\ (\rho_1 - \rho_2) \quad (4)$$

The number of wavelengths of light, N, along the path length, L, through the test section is given by:-

$$N = \frac{L}{(\lambda_0/n)} \quad (5)$$

Combining equations (4) and (5) yields:-

$$\Delta N = \frac{L\ G\ (\rho_1 - \rho_2)}{\lambda_0} \quad (6)$$

Substituting for the Gladstone-Dale constant from equation (3), equation (6) becomes:-

$$\Delta N = \frac{L\ (n_1 - 1)(\rho_1 - \rho_2)}{\lambda_0 \rho_1} \quad (7)$$

If the air is assumed to be a perfect gas at constant pressure:-

$$\rho_1 T_1 = \rho_2 T_2 \quad (8)$$

and so equation (7) becomes:-

$$\Delta N = \frac{L\ (n_1 - 1)\Delta T}{\lambda_0 (\Delta T + T_1)} \quad (9)$$

where $\Delta T = (T_2 - T_1)$

Re-arranging equation (9) gives:-

$$\Delta T = \frac{T_1 \Delta N \lambda_o}{(n_1-1)L - \Delta N \lambda_o} \qquad (10)$$

Now from equations (3) and (4):-

$$n_o - n_1 = (n_o-1)\left[1-\frac{\rho_1}{\rho_o}\right] \qquad (11)$$

and from equation (8), equation (11) may be written as

$$n_1 - 1 = (n_o-1)\left(\frac{T_o}{T_1}\right) \qquad (12)$$

Taking the hot surface as at the reference temperature, T_H, and by substituting from equation (12) into equation (10), the latter becomes:-

$$\Delta T = \frac{T_H}{(K/T_H \Delta N) - 1} \qquad (13)$$

where

$$K = \frac{L\ (n_o-1)\ T_o}{\lambda_o} \qquad (14)$$

Thus the temperature associated with each isotherm may be determined.

The rate of heat flow from the hot surface (i.e. at y=0) may be written as:-

$$\dot{q} = h\Delta T_{CD} \quad \text{or} \quad \dot{q} = k\left[\frac{dT}{dy}\right]_{y=0} \qquad (15)$$

where ΔT_{CD} is the characteristic temperature-difference associated with the system under test, e.g. for an enclosed vertical air cavity and vertical fin, ΔT_{CD} is equivalent respectively to $T_H - T_C$ and $T_H - T_{CA}$.

$$\text{Thus,}\quad h = \frac{k}{\Delta T_{CD}}\left[\frac{dT}{dy}\right]_{y=0} \qquad (16)$$

$$\text{Now,}\quad Nu = \frac{h\delta}{k} \qquad (17)$$

where δ is a characteristic dimension of the system (e.g. for an enclosed vertical cavity, the separation between the hot and cold surfaces is normally used).

By substituting from equation (16) into equation (17), the latter becomes:-

$$Nu = \frac{\delta}{\Delta T_{CD}} \left[\frac{dT}{dy}\right]_{y=0} \tag{18}$$

Therefore in order to evaluate the local Nusselt numbers and heat-transfer coefficients, the temperature gradient at each location along the hot surface (i.e. at y=0) must be determined. To achieve this, the temperature distribution across the air-gap is calculated from equation (13) and the measured distances between the centre-lines of successive isotherms (see Fig. 3). Because the definition of ΔT_{CD} varies with the geometry of the test cell, appropriate allowances need to be made by the computer when calculating the temperature distributions. For example, in a vertical channel subjected to asymmetric heating, the temperature of the air in the boundary layer adjacent to the cold surface may exceed the temperature of the air in the central region of the cavity. Thus, in this case, the location of the lowest air temperature in the cavity may need to be identified.

The facility to display on the VDU a graph of temperature versus distance, y, across the air-gap may be employed so that a suitable regression analysis for determining the temperature gradient close to the x-axis can be instigated. (Because errors are potentially greater when exponential or polynomial curves are fitted, a linear regression analysis was incorporated). By viewing the graph displayed on the VDU, the operator may choose the number of points to be employed for determining $(dT/dy)_{y=0}$ for the interferogram under study. Usually a three-point straight line achieves an acceptable level of accuracy (Shilston, 1982).

From the local heat-transfer coefficients, average property values can be determined (for the linear system under test) as follows:-

$$\bar{h} = \frac{1}{\ell} \int h \, dx \tag{19}$$

The conventional procedure adopted when determining the average Nusselt number from an interferogram, is to calculate the mean of several local values (e.g. 4 or 5). However, the CPS provides the facility to calculate such properties from up to several hundred local values, because the interval between successive traverses of an interferogram is only 0.25mm. Thus investigators can employ the system to evaluate governing parameters from effective areas of the interferogram rather than single-line traverses. Consequently assessments of how the heat transfer parameters vary along the x-plane can be made. In order to avoid including spurious readings when determining average values, the user may choose to 'smooth out' the results automatically as the averages are calculated. The requirement for this facility is less when the photograph of the fringe pattern is of high quality, the respective surfaces are separated by a fixed distance and the hot surface is isothermal. However in an interferometric study concerning the thermal designs of electric toasters, which prompted development of the CPS, the considered surfaces (i.e. of the bread-simulator and the heater) were not perfectly flat, for this would have contradicted the real-life situation. Therefore the program was designed to make certain allowances for such conditions, (e.g. average values of δ were calculated to evaluate average Nusselt numbers). Nevertheless further development of the software is needed so that temperature distributions and Nusselt numbers can be derived from an enhanced fringe pattern, which is generated by applying regression analyses to the identified co-ordinates of the fringe centres.

DISCUSSION

Interferograms, associated with a concurrent heat-transfer study, were analysed in a similar manner using (i) the developed microcomputer-based photogrammetric system, and (ii) a travelling microscope capable of measuring to an accuracy of 0.02mm. Discrepancies between the results obtained via these methods were less than 12%. Furthermore the fringe pattern illustrated in Fig. 3 was examined at various points along the fin spacing. Differences in the calculated values of $(dT/dy)_{y=0}$ obtained via the traditional and digital photogrammetric methods for this interferogram typically ranged between 2% and 8% (e.g. see Table 1).

TABLE 1

Discrepancies in $(dT/dy)_{y=0}$ between the traditional and computer-based methods of interpretting interferograms, when each was employed to assess a certain range in the x-direction (equivalent to 4mm on the photograph) for the interferogram associated with Fig. 3. (In both cases, the temperature gradients were calculated by fitting a straight-line to the three isotherms closest to the reference wall).

Position along the x-plane on the interferogram	Temperature gradient (Km^{-1}) at the fin wall, obtained via the:- Computer-based photogrammetric system (I)	Travelling microscope (II)	Discrepancy between I and II
0.00	1323	1393	5.0
0.25	1287		7.6
0.50	1491		7.0
0.75	1357		2.5
1.00	1422	1382	2.9
1.25	1357		1.8
1.50	1897*		37.3
1.75	1897*		37.3
2.00	1323	1411	6.2
2.25	1323		6.2
2.50	1491		5.7
2.75	1357		3.8
3.00	1323	1437	7.9
3.25	1357		5.6
3.50	1357		5.6
3.75	1491		3.8
Average Discrepancy**			5.1

* Spurious results, (see Fig. 3).
** Not including spurious results.

These variations can be attributed to three main factors. Firstly, the conventional technique relies upon the investigators ability to estimate the position of the centre-line of each isotherm, when viewing it through the microscope. Shilston (1982) stated that, under good conditions (i.e. when the investigator is fully alert), a maximum error of ±2.5% in Nu would ensue when evaluating interferograms. Secondly, the accuracy of the CPS depends significantly upon the clarity of the fringe (displayed on the photograph) adjacent to the hot wall. If this isotherm cannot be identified by the PRS, the value of $(dT/dy)_{y=o}$ calculated by the program deviates appreciably from the true value. Thus, it is essential that high-quality photographs of the fringe patterns are recorded so that interferograms with markedly contrasting black-and-white regions are reproduced. Furthermore, it is recommended that the software is developed to calculate fringe-centres from the values of the current generated by the PRS as it scans an interferogram, instead of via the simple above-threshold/below-threshold method utilised by the existing system. Thirdly, at present, the PRS scans the interferogram along the y-plane in minimum increments of 0.125mm. This facilitates obtaining accurate analyses for interferograms exhibiting 3-4 isotherms per cm of the photograph (in the y-direction). However at high temperature differences (e.g. $\Delta T_{c0} > 30\ ^{\circ}C$), the isotherm nearest the hot surface tends to be unintelligible for the computer-based system described herein, even when the photograph is enlarged to its critical magnification. Therefore it is recommended that the prototype system designed in this project, is developed further to use a minimum stepping distance, in the y-direction, of 0.05mm (or less). Feasibly, the CPS could be improved to achieve a similar accuracy to that provided by a typical commercially-available film-digitiser, which moves the photoelectric detector (via a stepper motor and lead screw arrangement) in minimum steps of 0.0125mm (Hills, 1986). Alternatively the prototype system may be modified to scan projected images of film-negatives of the fringe patterns instead of photographs. This technique would facilitate much greater magnifications of the interferograms and so permit analyses of thermal systems characterised by large values of ΔT_{c0}. Also the errors which are intrinsic to the photographic process of developing enlarged pictorial reproductions of such systems would thereby be avoided (Carlson, 1956; Dew, 1964).

The operation of analysing say 50 or 100 interferograms within the timescale of a single investigation becomes tedious and frustrating, when performed with a travelling microscope. Hence the results thereby extracted are susceptible to random as well as systematic human error. Although advanced photogrammetric systems are available, which facilitate very rapid analyses of interferograms (Zanoni, 1978; Augustyn, 1979), the CPS offers a far less costly means of examining fringe patterns. Also, the prototype facility described herein provides a permanent record of the results on floppy disc and/or paper : this is a distinct bonus for investigators who would otherwise have had to use the aforementioned traditional method of analysis. Nevertheless, if it is to be superior in terms of accuracy and general usefulness for investigations employing the MZI, the CPS needs to be developed further, so that (i) the scanner can traverse the y-plane in smaller increments, and (ii) interferograms associated with annular or regular non-linear cavities can be analysed automatically.

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