1989

ELECTRICITY USE IN THE FARM DAIRY

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http://hdl.handle.net/10026.1/2679

http://dx.doi.org/10.24382/4128

University of Plymouth

ELECTRICITY USE IN THE FARM DAIRY

by Robert Christopher Bowes

A thesis submitted to the Council for National Academic Awards in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

The work reported herein was carried out at Plymouth Polytechnic and Seale-Hayne College, with the collaboration of the Electricity Council, the South Western Electricity Board and the Ministry of Agriculture, Fisheries and Food (A.D.A.S.).

March, 1989.

DECLARATION

I hereby declare that this work has not been accepted for any degree, and is not being concurrently submitted for any degree other than the degree of Doctor of Philosophy of the Council for National Academic Awards.

I also declare that all the work reported herein is my own work, except where acknowledged, and that none of this work has been previously published except as listed.

Signature of candidate...R. C. Bowes...

R.C.Bowes.

DEDICATION

To Matthew and Christian

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ACKNOWLEDGEMENTS

The work described in this thesis was carried out with the support of the Science and Engineering Research Council, for whose award of a C.A.S.E. Post-graduate studentship I am indebted.

I would also like to acknowledge the support, financial and otherwise of the following organisations:

- The Electricity Council, and especially Dr. Dan Mitchell, head of the Farm Electric Centre.
- The South Western Electricity Board, and especially Mr. Mike Grabham, Agricultural Adviser for the Devon area.
- The Ministry of Agriculture, Fisheries and Food, (A.D.A.S.), and especially Mr. Eddie Bromwell, Dairy Husbandry Advisory Officer.
- The National Institute for Research in Dairying, and especially Mr. John Belcher.
- The Agricultural Research Council.

The work for this thesis has been carried out largely at Seale-Hayne College, Newton Abbot, Devon and Plymouth Polytechnic. I would like to record my gratitude to both these institutes for making available the academic, technical and administrative facilities to undertake this work.

My thanks are especially due to my supervisors, Mr David Short of the Department of Mechanical Engineering at Plymouth Polytechnic and Dr. Adrian

Vranch of Seale-Hayne College. Without their guidance, support and patience this project would never have come to fruition.

I must also record my thanks to Mr. John Carpenter of Seale-Hayne College, who was largely responsible for the instigation of the project and Dr. Tony Vallis, formerly of the Department of Mechanical Engineering at Plymouth Polytechnic for advice on aspects of thermodynamics.

I am also indebted to Alice Norman who was working on a parallel project at the same time, for her assistance with data collection in the field and in the laboratory together with many in-depth discussions on the two projects.

I am also grateful for the technical assistance provided by Brian Selley and Ron Yandell of the thermodynamics laboratory at Plymouth Polytechnic who coped admirably with the intrusion of a bulk milk tank, its instrumentation and the provision of a tonne of warm water.

One of the most enjoyable aspects of the project was to visit the surveyed farms each week to collect data. I am indebted to all the farmers who participated and allowed me into their farms, and grateful to them for the many discussions of the practical aspects of dairy farming.

A number of other people have provided advice or help on a number of topics. Included among these are Barry Undy of Plymouth Polytechnic, for advice on statistical methods, Dr. John Kirk of Seale-Hayne College for discussions of calving patterns and lactation curves, Mr Mark Ridley for advice on programming matters and Mr. Ian Robertson of South Devon Microcentre for translation of the bulk tank program into 'C'.

I must also thank my employers, South Devon Microcentre and lately South Devon College of Arts and Technology for allowing me the use of computer equipment to complete the work and prepare this thesis.

Finally, I cannot overlook members of my family whose patience during the completion of this work and the preparation of the thesis, must surely qualify them for Beatification. I include my wives and especially my sons, to whom this work is dedicated and who gave, of their time with me, more than I had a right to expect.

ELECTRICITY USE IN THE FARM DAIRY

Robert Christopher Bowes

ABSTRACT

Dairy farmers suffered substantially increased energy bills during the 1970's, at a time of herd expansion and modernisation of equipment to allow bulk milk refrigeration and storage on the farm. Little was known of the levels of electricity use in the dairy farming sector, but extrapolations had suggested a figure of 300 to over 400 kWh/cow/annum. Farmers were requesting quantitative estimates for the potential of conservation equipment, particularly plate heat exchangers and heat recovery units.

An energy audit of dairy farms in South Devon is described. Over a period of two years, data were collected relating to energy use by each of the major components of a milking parlour and dairy, for a range of parlour sizes, levels of production and the ambient conditions. Analysis revealed the factors most influencing variations in energy use. An equation was developed to describe the energy use by a bulk milk tank, given the level of production and the ambient temperature. The bulk tank accounted for some 40% of the total energy used.

The bulk tank has been studied in detail. The stages of heat transfer from the milk to the chilled water and the resulting effects upon the ice bank have been modelled. Laboratory investigations were carried out to determine some parameters empirically. The model's limits, sensitivity and validation are reported.

Typical levels and ranges of energy use are suggested. A mean of approximately 250 kWh/cow/annum resulted from the audit, but 200 kWh/cow/annum was achieved by the most economical of farms without resort to conservation equipment, and this level is proposed as a target for the conscientious farmer. The factors affecting energy use in the farm dairy are identified as political, environmental, technical and managerial and these are discussed. The farmer's influence has to be directed mainly at the last of these categories. Investment in energy conservation equipment should not be considered until consumption is down to the proposed target level.

1.INTRODUCTION

1.1 The Energy Crisis and Agriculture.

The sharp rise in energy prices following the Arab oil embargo of 1973 focused attention on the finite nature and political vulnerability of fossil fuel resources. Dependence upon fossil fuels was reported by Pollock (1977) who estimated world energy demand at $8*10^{12}$W, 97% of which is derived from fossil fuels. Estimates of the remaining life of fossil fuels vary with projected rates of growth in demand and discoveries of new fields, but are generally placed at 30-50 years for oil and 200-300 years for coal. The fall in oil prices during 1985 and 1986 has not, at the time of writing, been reflected in a significant fall in the price of energy to the end-user. Furthermore it may be argued that falling prices will result in a more profligate use of energy thus shortening the remaining life of fossil fuel reserves. As a result, further price rises seem inevitable in the long term. The Department of Energy (1978) suggested that "the average level for energy prices must be expected to rise, perhaps doubling by the year 2000, in real terms."

The United Kingdom grows a little more than one half of its food, and Agriculture uses 4% of national energy to make this unprocessed food available at the farm gate (White, 1977). Lewis and Tatchell (1979) estimated the input to U.K. Agriculture as $410*10^6$GJ per year. There is a further significant energy input in transport and processing so that to feed the population of the United Kingdom involves the expenditure of about 16% of the nation's total energy use

(White, 1977). White (1979) has also observed that Agriculture in the United Kingdom is becoming more dependant on energy inputs to replace labour. Between 1950 and 1970 energy use on the farm of direct fuels and electricity increased by a factor of 1.7 while the labour force was halved.

1.2 The U.K.Dairy Farming Industry.

Agriculture is a major industry in the U.K., contributing 2.1% of the Gross Domestic Product (Ministry of Agriculture, Fisheries and Food (M.A.F.F.), 1982). Total sales in 1981 amounted to over £9,000 million (Central Statistical Office, 1980). Within the industry, dairy farming is the largest enterprise, producing milk and milk products to the value of nearly £2,000 million.

In recent years, dairy farmers have come under severe economic pressures as a result of surplus production of milk products in the European Economic Community (E.E.C.). Previous attempts to limit production by means of the Dairy Cow Slaughtering Scheme and the Co-responsibility levy have not succeeded and in 1984 a production quota on individual farms was imposed.

Dairy farming in the U.K. has been regarded as relatively efficient within the E.E.C. The U.K. has the highest average herd size (Castle and Watkins, 1977) and the second highest average milk yield in the E.E.C. (Milk Marketing Board (M.M.B.), 1980). Despite this the economic pressures have been particularly severe in the U.K. During the decade 1970-79, U.K. milk producers experienced the second most severe squeeze between input prices and output prices in the Community (National Economic Development Office, 1981). Nevertheless the high average herd size and milk yield has resulted in a high output per farm which has enabled U.K. producers to obtain relatively better levels of overall net personal earnings from milk.

1.3 Trends in Milk Production.

For a number of years there has been an increase in average herd size (Table 1.3(a)).

	1970	1975	1979
No. of registered milk producers	80625	60279	46972
Average herd size	33	46	56
% of all cows in herds >49	44.3*	62.4**	73.1

Table 1.3 (a) Changes in composition of dairy herds in England and Wales (M.M.B., 1980).

** 1969 figure ** 1974 figure*

During this period the total number of dairy cows remained relatively constant at approximately 2.7 million. The Milk Marketing Board expect this trend to continue with some 16,000 fewer milk producers in England and Wales by 1990, resulting in an average herd size of approximately 110.

During the same period, labour requirements for milking, cleaning and feeding are expected to fall from 40 hours per cow per year at present to less than 30 hours per cow per year (Anon, 1981).

These changes have been accompanied by a change in the type of milking installation (Table 1.3(b)). Cowshed systems have shown a decline, while herringbone parlours have increased by almost 50%.

Milking System	1973	1978
Abreast Parlours	13571	12673
Herringbone Parlours	8676	12617
Cowsheds	43871	22764
Others	2638	1563
Totals	68756	49617

Table 1.3(b). Numbers of milking systems in England and Wales (M.M.B., 1980)

1.4 Equipment currently in use.

1.4.1 Milking and the Transfer of Milk.

The generalised layout of a milking parlour and dairy is shown in Figure 1.4.

Since the very earliest development of machines for milking cows, the basic principle has been one of extraction of milk under vacuum. Today, vacuum power is also used to transfer the milk to its storage vessel. The vacuum pump is usually a vane-pump, belt-driven from a motor with a power rating of 1-4kW depending on the size of the installation. Air is admitted to the system through the teat cups and claw-piece during application to and removal from the udder, and through a weight-operated regulator valve which is present in the system to remove violent fluctuations in vacuum level. Most systems operate at 51kPa. Greater levels of vacuum would increase milking rate (Dodd & Clough, 1955) but have been shown to be associated with increases in teat damage (Kingwill et al., 1979). Vacuum supply to the inner chamber of the teat cup is continuous,

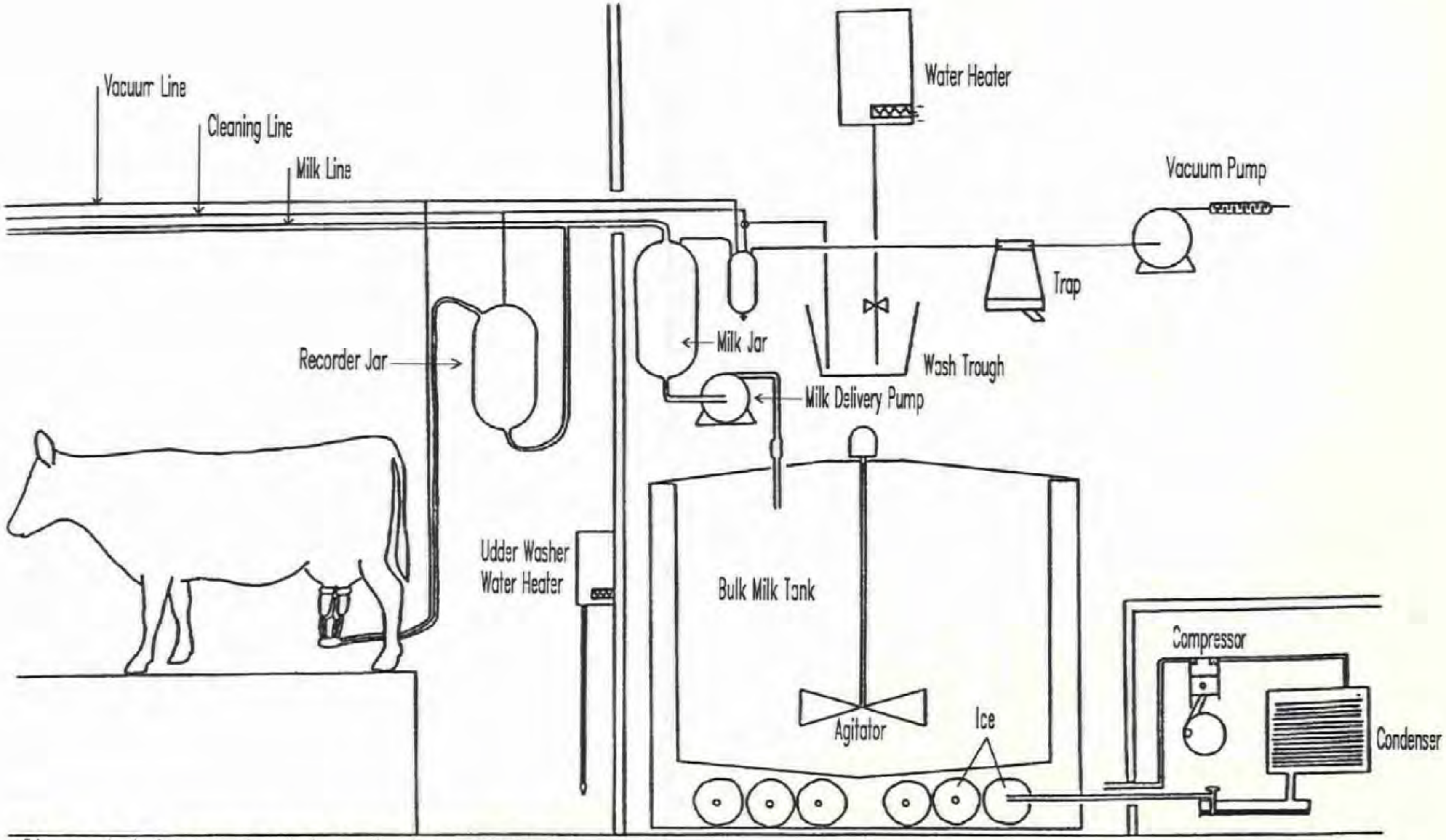


Figure 1.4 Generalised layout of a milking parlour and dairy

but to the outer chamber is pulsed at the rate of 45-70 cycles per minute, to allow regular relief to the teat and to allow the teat cistern to refill with milk.

As a means of improving labour efficiency, a recent development has been that of automatic cluster removal. A sensor in the milk line from the cluster detects the reduction in flowrate of milk associated with the termination of milking, and shuts off vacuum to that cluster, which then falls off the udder and is prevented from soiling on the floor by a retaining cord.

Other equipment within the system under vacuum includes recorder jars at each milking point, although these may be replaced by milk meters, and a receiver jar or balance tank which receives the milk before delivery to the bulk milk storage tank.

Final delivery of milk into the bulk tank is usually achieved by a small (c. 0.5 kW) electrical pump. Activation of the pump is by volume or mass in the milk receiver jar above it.

1.4.2 Cooling and Storage of milk.

All farm dairies now store milk in a bulk milk tank for collection by tanker once per day. There are specific requirements in terms of construction and performance of a bulk milk tank, the most important of which is a requirement on a producer to cool milk rapidly after production and to maintain a low temperature (Milk and Dairies Regulations, 1959). This is most often achieved by use of a refrigerated bulk milk tank. The refrigeration system may be direct or indirect.

The indirect system is based on the use of chilled water as the cooling medium. The low temperature of the chilled water is maintained by the presence of an ice-bank which may be built up slowly by a small condensing unit operating for most of the day. A 680-litre bulk milk tank for example would require a unit of just over half a kilowatt. With direct expansion tanks, refrigerant is evaporated in a corrugated plate or tubes fitted against the outside wall of the milk vessel itself. Therefore the cooling effect only occurs when the refrigerant is being evaporated, i.e. when the condenser unit is running. The requirements for rapid cooling therefore necessitate a relatively large condensing unit. The 680-litre tank would require a 2.25kW unit for direct expansion. In practice larger installations would probably require a three-phase supply and as a consequence are not very common. Producers of very large volumes of milk may prefer to use an insulated, non-refrigerated tank, reducing the temperature to an acceptable level before entry to the tank, by means of a pre-cooler.

1.4.3 Cleaning the equipment.

Many farms now have an automated cleaning system for the bulk tank. This consists of a small pump which delivers water to the milk vessel, and meters the addition of a suitable sterilant. The operation is started manually by the tanker driver after emptying the tank, and continues under the control of a timeswitch. After draining out of the tank, a second rinse of clear water is then metered into the tank and allowed to drain.

There also needs to be provision for cleaning all other milk contact surfaces after each milking. This is achieved by a combination of hot water and/or chemical disinfection.

Hot water is most often provided by an electrical water heater of suitable capacity with a minimum 3kW immersion heater.

Two methods of plant cleaning are currently in use. The first of these is the Acidified Boiling Water system (A.B.W.). This system is a once-through process with water close to boiling point being drawn through the system under vacuum and discharged to waste. The second system involves the recirculation, under vacuum, of a cleaning solution containing detergent and disinfectant, at a slightly lower temperature.

Until recently, general recommendations have been that hot cleaning should take place after every milking. However a number of dairy farmers, seeking to reduce their electricity costs, have successfully replaced the evening hot wash by a cold wash containing sodium hypochlorite as the disinfectant.

1.4.4 Cleaning Udders.

Dirty teats and udders need to be washed prior to milking. Modern installations are equipped with hoses with spray nozzles, piping warmed (40°C) water from a small water heater. Purpose-made heaters have a low capacity and continue heating the water by means of an immersion heater, typically of 3kW, during the extraction period. In older installations udders are often washed by means of a bucket and cloth, taking water from the main water heater. There is no general requirement for the water to be warmed and some farmers wash udders with cold water, at least during the summer months.

1.4.5 Miscellaneous equipment.

All parlours will require some level of artificial lighting for at least part of the year.

Cows are fed at least part of their concentrate ration during milking. Many systems involve an arrangement of pull cords and levers to deliver a metered volume of feed to the individual cow. Recent developments have utilised vacuum power and a central electronic controller working at low voltage.

The parlour should have provision for cleaning down the walls and floor after milking, with a plentiful supply of water. Some farmers fit a small pump to pressurise this supply.

Finally it is desirable to have sufficient standby capabilities to allow continuity of routine in the event of a power failure. This may take the form of a simple drive-shaft allowing the vacuum pump to be driven directly from the p.t.o. shaft of a tractor. Alternatively the tractor shaft may drive a 25kVA alternator capable of supplying all the parlour circuits at mains voltage through a change-over switch.

1.5 Literature Review of Related Work

The rise in energy prices referred to in Section 1.1, associated with the economic pressures on dairy farmers referred to in Section 1.2, along with the trends noted in Section 1.3, has caused farmers to express concern about the cost and level of energy needed to run their fixed equipment. There has been a response to this within the equipment supply industry to produce energy conserving equipment, notably Heat Recovery Units and Plate Coolers. These items represent significant investments for dairy farmers who are wondering what the level of savings will be. Some farmers are sceptical of the claims being made by the manufacturers of such equipment and are seeking reliable and scientifically-based assessments of the potential of such equipment.

In order to assess the potential for energy-saving or the reduction in cost of the energy, it is necessary to know how much energy is expended by a typical farm dairy before the installation of any conservation equipment. Very few dairy farmers are able to assess this level of energy use, as farm dairies are not usually metered separately from the rest of the farm supply. Furthermore, where a high level of energy use is suspected, it is difficult to establish whether this use is atypically high in the absence of recommended levels of use for efficient operating conditions.

This work has therefore commenced with an examination of the existing literature to investigate the basis on which the advisory services might assist farmers to make this appraisal.

Most of the work in the field of energy use has tended to investigate only single items of equipment, frequently the bulk milk tank. This review of the literature has first looked at work of estimating or monitoring complete dairy installations and then at the various components of the system.

1.5.1 The Total Dairy and Parlour electricity.

Little comprehensive work has been carried out to determine the energy demands of dairy farming. Bayetto et al. (1974) estimated that for milk production in 1972-73 929 GWh of electricity were used, with an estimated connected load of 540 MW on 30th September, 1972. Assuming a dairy herd population of 2.7 million cows, this estimate would suggest an annual consumption of approximately 344 kWh per cow. There was no error range suggested for this estimate, nor was there any comment on the seasonal or daily fluctuations in demand.

Monitoring of complete dairy installations in the United Kingdom has only been carried out by the Shropshire Farm Institute, the Ministry of Agriculture and the Electricity Council.

The earliest work which attempted to quantify and analyse the total electricity use in the farm dairy was carried out by Shropshire Farm Institute. (1967). In this work electricity and water meters were fitted to all circuits in the farm dairy and monitoring was carried out for a period of 28 weeks during the winter. The results are summarised in Table 1.5.1.

The main limitation of this work is that the monitoring was not carried out for a representative period of a whole year. The costs of cooling milk may be expected to rise during the summer, while the costs of water heating fall a little. Proportions of total use would therefore be different. Extrapolation of these data to an annual basis suggested an energy use of 406 kWh/cow, which would cost over £20 per cow at todays prices. However the method by which the annual figure was extrapolated is questionable. The Shropshire workers computed their annual costs by dividing their 28-week consumption by the average number of cows at each milking and then applying a factor of 52/28 to give the annual figure. Annual costs will have been incurred by the whole herd, assuming that all the cows in the herd have been in-milk at some stage in the year. Use of the mean number of cows in-milk fails to recognise that a greater

Electricity Use			
	percentage of total consumption	per cow per year kWh	per m^3 of milk kWh
Bulk Milk Tank	19	79	16.1
Water Heater	38	155	31.5
Udder Washing	19	78	16.1
Vacuum Pump	12	50	10.3
Other	12	44	8.8
Totals	100	406	82.8

Table 1.5.1 Electricity consumption in the parlour and dairy at Shropshire Farm Institute, October 1966 - April 1967.

number of cows have in fact been through a lactation cycle during the year. Common practice involves a 305-day lactation with 60 days dry. If this was the case at Shropshire, then the number of cows actually responsible for electricity use was the mean number of cows in-milk increased by a factor of 365/305. Alternatively the electricity use per cow was really the quoted figure multiplied by 305/365. The resulting figure falls quite close to that of Bayetto et al. (1974).

These data are also quoted as kWh per unit volume of milk. Choice of this parameter is considerably more sound for any period other than a full year. By removing the compounding influence of varying milk yields per cow, this also allows comparison between farms, both of electricity use by similar components and of total electricity use.

Electricity used for milk cooling is a function of the mass of milk to be cooled and completely unrelated to the number of cows which have produced it. It seems reasonable to assume that vacuum pump electricity is more closely related to the volume of milk extracted than to the number of cows milked. Electricity used by the plant cleaning water should be related to the size of the plant, not the number of cows using it.

The dangers of extrapolation have been mentioned but there is a further reason to question the applicability of these results. The Shropshire Farm Institute, being a teaching College, was known to maintain an exceptionally high standard of hygiene in the parlour and this is probably reflected in the high cost of heated water, which will also increase the total cost.

The Ministry of Agriculture, Fisheries and Food monitored the total electricity use on four experimental husbandry farms for two years from 1974 to 1976 (M.A.F.F., 1976). The electricity use for the whole dairy system included offices and collecting yards. The results showed a very wide range from 309 kWh/cow/annum at one farm to 533 kWh/cow/annum at another. The reasons for this wide range were not explored. The latter farm in fact recorded 468 kWh/cow for the first year and 638 kWh/cow for the second year, suggesting that some fairly dramatic but unspecified change had occurred. There was no attempt to break down the electricity use by component. A similar criticism to the Shropshire work must apply here also, in that the monitored farms were experimental husbandry farms rather than purely commercial milk producing farms.

The Electricity Council (1975) started monitoring electricity use by individual items in the farm dairy at the National Agricultural Centre. As at the Shropshire Farm Institute, the water heater was the heaviest user of energy, requiring 34.2 kWh/m^3, more than twice the energy use of the bulk tank. At both Shropshire and the National Agriculture Centre the plant was cleaned by the A.B.W. method which is known to have a higher temperature and volume requirement than circulation cleaning, per wash. The figures reported from N.A.C. were for a few weeks only and to date there is still no published work of monitoring all parlour items for a full annual cycle in this country.

Rennie (1979) reported monitoring of each piece of equipment at a single farm in New Zealand for the 1977/78 season. A "season" in New Zealand is frequently less than a whole year, it being common practice to dry off all the herd at once and cease milking for a few weeks, usually in mid-winter. Tariff arrangements in New Zealand are somewhat different to those in this country and ranking of equipment by electricity consumption will produce a different result to ranking by cost. For these reasons the results are not very applicable to this country, but it is interesting to note that the biggest electricity user, both by quantity and cost, was the water heater. The bulk tank used the second highest amount of electricity but the vacuum pump had the highest cost.

Some recommendations to farmers are available via the Electricity Council (1978) who suggest that approximate figures expected for a herd of 89 cows milked through a parlour with pipeline to a bulk tank, would be 26,600 kWh/annum if circulation cleaning is used and 31,750 kWh/annum if A.B.W. cleaning is used. In the latter case the water heater will be the highest user at 31% of the total. In the case of circulation cleaning the water heater electricity cost will be halved, leaving the bulk tank as the largest user. The apparent saving from using circulation cleaning would be £129 at 1978 prices. In either case the total electricity use would be considerably less than that suggested by the Shropshire work.

The figures available to farmers are therefore either estimates or the results of monitoring which is either incomplete or of questionable applicability. The estimates of Bayetto et al. (1974) and the corrected measurements from Shropshire Farm Institute at 344 and 339 kWh/cow/year respectively are fairly similar. The Ministry of Agriculture's figures are considerably higher but probably not truly comparable as the electricity use by collecting yards and offices was included. The Electricity Council's handbook suggests 299-357 kWh/cow/year depending on the cleaning method. There is very little indication as to whether these figures would be typical for commercial dairy farms or indeed if they represent typical figures for the operation of milking equipment in efficient operating conditions. It may be the case that one or more components of the system is using excessive amounts of energy while another is using less than it should. To expand upon this point, there is no indication that the water for plant cleaning was being heated to the recommended temperature or that the milk was being adequately cooled. Failure on one count might be compensated for by poor setting on the controls of the other, resulting in inefficiencies which cancel out when the total energy figures are examined.

These doubts therefore led to a further examination of the literature in respect of the individual components of the system.

1.5.2 The Bulk Milk Tank.

Despite the indications above that the water heater will have the largest demand, it is the bulk tank which has been reported in most detail. This is possibly due to the relatively recent innovation of refrigerated milk cooling and the obvious potential for energy reclamation offered by the cooling process.

The literature contains some suggestions of the likely energy expenditure for cooling milk together with some reports of laboratory work on milk cooling costs. The published work of on-farm investigation of milk cooling costs is limited.

Hoyle and Belcher (1971) suggested a typical cooling cost of 10 gallons (45l) of milk cooled per kWh of electricity used, with a variation of ±10%. The same figure is quoted by Bayetto et al. (1974) in their estimates previously referred to. This figure is equivalent to 22.22 kWh/m^3.

Exactly the same figure of 22.22 kWh/m^3 is quoted by Fleming and O'Keefe (1982) for an ice bank tank. They also gave a figure of 14.29 kWh/m^3 for a direct expansion tank, noting that this tank would require a condensing unit about twice the size of that for a comparably sized indirect refrigeration tank. Hoyle and Belcher (1971) had suggested that the direct expansion tank would require a condensing unit of four times the size compared with an indirect refrigeration unit.

As a prelude to investigating water heating with heat energy from the refrigeration cycle, Cromarty (1968) investigated the performance of a 125 gallon (568l) prototype refrigerated direct expansion tank following the M.M.B.

Specification BC 56 (DE10). A morning filling of 75 gallons (341l) was cooled at three different ambient temperatures and a full milk load, simulating an evening and a morning milking, was cooled at 70°F (21°C). The electricity used for cooling was recorded, and the heat removed was calculated. The Coefficient of Performance (C.O.P), being the ratio of thermal energy removed to electrical energy used, was calculated. The results are presented in Table 1.5.2. It should be noted that this work was carried out using a new tank in laboratory conditions. The information may not therefore relate directly to cooling costs incurred by typical farm equipment in typical farm conditions. However the work does illustrate very clearly the susceptibility of refrigeration performance to variation in ambient temperatures. Direct expansion tanks such as that used in this work are relatively uncommon in this country, having been limited to the smaller sizes of bulk tank until recently.

Milk Cooled (l)	341	341	341	568
Ambient Temperature (^{0}C)	32	21	10	21
Heat Removed (kWh/m^3)	17.4	15.0	13.5	17.2
C.O.P.	2.06	2.37	2.63	2.06

Table 1.5.2 Performance of a 568l refrigerated bulk milk tank under laboratory conditions, adapted from Cromarty (1968).

More recently, Shepherd (1981) monitored the electricity used by an indirect refrigeration tank in Scotland, over a series of recording periods around the year. Variations at different times of year were noted. The average performance was 23.8 kWh/m^3 with a figure of 16.95 kWh/m^3 being recorded in mid-winter.

A lower figure of 20.5 ± 2.36 kWh/m^3 was the mean performance of 19 ice-bank tanks on 8 farms throughout the country, monitored by M.A.F.F., Agricultural Development and Advisory Service (A.D.A.S., 1981). Ambient temperature recordings were made and a direct correlation between the cost of milk cooling and ambient temperature was suggested and given by the regression equation:

$$y = 15.8 + 0.53x$$

where y is the milk cooling cost (kWh/m^3)

x is the ambient temperature (°C)

The standard error for the intercept term was 0.79 and for the x-coefficient 0.07. The seasonal variations were remarkably similar to Shepherd's figures quoted above. The average of all sites had a minimum of 16.7 kWh/m^3 in January and a maximum of 24.7 kWh/m^3 in July. The lowest monthly figure for any site was 11.5 kWh/m^3 in January and the highest was 38.9 kWh/m^3 in July. The fillage rate showed no significant effect on electricity consumption. The between-farms variation in average cooling cost (25.4 — 16.8 kWh/m^3) was not correlated to difference in ambient temperatures between sites and A.D.A.S. concluded that standard of installations, mode of use, and level of maintenance must account for a substantial proportion of the variation.

1.5.3 Energy requirements for heating water.

There has been a considerable amount of published work relating to cleaning of milking equipment. However very little of this work refers to electricity use by the water heater. There is considerable dispute as to the temperature, volume and frequency of hot washing necessary to maintain the plant in a clean condition. This has resulted in a number of different recommendations being made to farmers (e.g Electricity Council (1978), A.D.A.S. (1977), BS 5226:1975). The differences have been reported by Norman et al. (1981).

Production and use of hot water in the farm dairy is the subject of another study being carried out at Seale-Hayne College. Production of warmed water for udder washing is also part of this study, but it should again be noted that recommendations to farmers are very unclear. There is a requirement in the Milk and Dairies (General) Regulations (1959) that visible dirt be removed from the udder, tail and flanks of the cow before milking. The extent of washing will result from the herdsman's subjective assessment of cleanliness. The work carried out at Shropshire Farm Institute and the N.A.C. have been the only attempts in this country to quantify the electricity use until the present study.

1.5.4 The Vacuum System

Much of the published work relating to the vacuum system is in connection with rates of milking and effects upon the udder (e.g. Dodd and Clough, 1955 and Kingwill et al. 1979). Again, only the works already cited refer to the electricity use.

1.5.5 Energy Conservation In the Farm Dairy.

The rising price of purchased energy has led to work in recent years to attempt to reduce the electricity costs in the farm dairy. Much of this work has centred around the significant level of low-grade heat which has to be removed from the milk. A cubic metre of milk has to give up approximately 125 MJ during cooling from 35°C to 4°C. Removal of this heat requires a further input of energy through the refrigeration system. This energy is normally all rejected to the atmosphere by the air-cooled condenser.

Most workers have taken one of two approaches. The first approach is to reduce the electrical cost of cooling the milk by reducing the thermal energy to be removed by the refrigeration system. This is achieved by pre-cooling the milk in a milk-to-water plate heat exchanger. The second approach is to recapture some of the heat from the high pressure side of the refrigeration cycle by inserting a water cooled condenser between the compressor and the air-cooled condenser. This is known as a heat recovery unit (HRU).

1.5.5.1 Pre-cooling.

A.D.A.S (1981) have recently carried out monitoring work involving single and two-stage plate heat exchangers in conjunction with ice-bank tanks. The single stage is a simple milk-to-water plate cooler. Twelve tanks on seven farms using the single stage method used an average of 1.8 cubic metres of water for each cubic metre of milk pre-cooled. Refrigeration costs for the remaining cooling stage averaged 11.2 kWh/m^3. The relationship between electricity consumption and water temperature was found to be given by:

$$y = 3.37 + 0.68x$$

where y = electricity consumed (kWh/m^3)

x = water temperature (°C)

However, water temperature was also found to follow closely the ambient temperature so the regression equation could be re-written as:

$$y = 6.81 + 0.41x$$

where x = Ambient Temperature (°C)

The two-stage plate exchanger removes all the heat necessary to reduce the milk to its target temperature before storage in an insulated, non-refrigerated tank. The two stages are firstly running water as for the simple plate cooler and secondly a refrigerated medium, usually glycol. Eight farms using this type of cooler used an average of 2.5 cubic metres of water per cubic metre of milk cooled and refrigeration costs were 9.7 kWh/m^3. The regression equation derived from these results was:

$$y = 1.54 + 0.55x$$

where y = Electricity consumed (kWh/m^3)

x = Water temperature (°C)

With both the single and two-stage pre-cooling there was no significant correlation between the Water/Milk ratio and the electricity used. Reference was made earlier to the part of this work which investigated the refrigerated tanks without pre-cooling, which had an average electricity use of 20.5 kWh/m^3. A.D.A.S. concluded that a correctly installed and operated water assisted system requires approximately half the electricity used by ice-bank refrigerated tanks. They also recognised and commented that the cost and/or re-use of the cooling water is vital to the economics of such systems. Where water has to be purchased, a high proportion must be re-used to justify the system in economic terms.

Ubbels et al. (1975) were able to save 6.6 kWh/m^3, or about one third of the cost of using a direct expansion tank, by pre-cooling. Later, Ubbels and Bouman (1978) reported that 50% of the thermal energy would be removed by pre-cooling.

Currier (1976) pointed out that, with water at 18°C, 72 MJ/m^3 were easily withdrawn from the milk. As a result of measurements made on a number of farms over a few years, Fleming and O'Keefe (1982) were able to produce typical annual cooling costs for farms in Ireland (Table 1.5.5).

Annual Output (litres)	Herd size	Direct Expansion		Ice-bank	
		No PC	PC	No PC	PC
80000	20	57.2	28.6	88.8	44.4
160000	40	114.4	57.2	177.6	88.8
240000	60	171.6	85.8	266.4	133.2
320000	80	228.8	114.4	355.2	177.6
400000	100	286.0	143.0	440.0	220.0
600000	150	428.0	214.5	660.0	330.0
800000	200	572.0	286.0	880.0	440.0

Table 1.5.5 Typical annual milk cooling costs (£) for different herd sizes, both with and without pre-cooling (PC), to 18^{0}C (after Fleming and O'Keefe, 1982).

Earlier, Fleming and O'Keefe (1977) stated that for effective operation of a pre-cooler an unfailing water supply at less than 18°C is essential. Then the water emerges at an ideal temperature for udder washing. In fact the volume of water produced by a plate cooler is likely to be considerably in excess of that required for udder washing.

A number of farmers with plate coolers offer this warmed water to cows as drinking water, arguing that the water would have to be purchased from the mains whether pre-heated or not. Benefits have been claimed for supplying cows with drinking water of up to 21°C (Kidd, 1979). A.D.A.S. (1981) commented that a cow drinking 40 litres of water at 4°C requires nearly 6 MJ of energy to raise this water to body temperature. Additionally it has been suggested that intake of water may be restricted if the temperature of the supply is low; this could have a detrimental effect on milk production. These claims have not been substantiated.

None of the workers refer to possible cost benefits resulting from reduced maintenance and longer life of the refrigeration equipment as a consequence of shorter running time. However, Fleming and O'Keefe (1977) pointed out that a possible reduction in milk tank compressor size by up to 50%, which pre-cooling makes possible, may substantially offset the plate cooler installation cost. Ubbels et al. (1975) also refer to a possible 50% reduction in compressor motor size.

1.5.5.2 Heat Recovery Units.

A prime requirement of a heat recovery unit must be that cooling performance is not affected. Belcher (1978) investigated a 180l HRU installed with a 1140l ice-bank tank in laboratory conditions following M.M.B. Spec. BC56 and found that cooling performance was not impaired. Hot water was produced at 45-60°C, worth £70-100 p.a. compared with the electrical cost of heating the same volume of water.

The potential for energy recapture has been recognised by several workers. Fleming and O'Keefe reported that for each litre of milk cooled from 35°C to 4°C a total of 40 kCals (0.17 MJ) is available from the milk and compressor if a direct system is used. With an indirect system this becomes 46 kCals (0.19 MJ). Dorfinger (1978) suggested that the use of HRUs could save Austria almost 10 million kWh per year. Sinclair (1979) claims a reduction in electricity consumption of 2500-4000 kWh per year can be made with a 135l HRU and a 900l bulk tank.

Despite this, economic benefits are uncertain when installation costs are considered. White (1979) reported that heat from the milk of 60 cows in an 1100l tank is sufficient to heat 130l of water to 43-60°C twice daily. The installation cost would have been £250 and the saving £70 p.a. The payback time suggested by White's figures (3.7 years on a simple ratio basis) must be viewed in the light of alternative investment possibilities to the farmer. Ubbels (1977) concluded that in many cases the use of a heat pump (strictly, a heat recovery unit) is still not justified.

Finally, Prosser (1977) summarised experiences with an HRU at the National Agricultural Centre and concluded that the evidence was still insufficient to say whether it was justified or not. Energy cost savings might be possible in other ways for very little cost.

1.6 Conclusions from the Literature Review.

Agriculture uses 4% of national energy to contribute 2.1% of Gross Domestic Product. Although this comparison is not strictly valid because of the different units involved, the energy input to Agriculture is substantial by any standards. Agriculture has traditionally been a labour-intensive industry, but in recent decades there has been a trend towards replacing labour by high energy input systems. In the light of this and other trends, referred to earlier, farmers' concern is understandable.

Energy use by the dairy farming sector has not been well researched or reported. The electrical energy use per cow would seem to fall in the range of approximately 300-350 kWh/cow/year but there is no published report of recording for a full annual cycle in this country. In the light of increasing yields per cow, farmers also need to know the energy costs per unit of milk produced, particularly in respect of marginal units produced. The seasonal variation of this total electricity demand has not been reported, neither has the variation within the daily cycle, points which are of interest to the Electricity Supply Industry.

Reports of work on the use of electricity by the bulk tank have indicated the susceptibility of cooling performance to temperature variation. It is suggested that cooling costs in winter are about one-third lower than the annual average. It seems reasonable to assume that if seasonal variation of ambient temperatures can cause such variation in the cooling efficiency, then the same should be true of the daily cycle, but none of the reports makes this point. It also seems reasonable to conclude that siting of the refrigeration unit, in respect of ambient conditions might be an important factor. Again, this point has not been clarified by the literature.

There is very little literature relating to the energy use by other components of the milking parlour and dairy.

Energy conservation equipment does seem to have considerable potential. However, there seems to be some doubt among the workers reported, about the extent of this potential and whether it is sufficient to justify the capital involved. The management of the equipment may be a crucial factor to the success of the investment.

The literature, then, leaves unanswered many of the questions which are pertinent to a consideration of energy conservation in the farm dairy. The suggested figures for total electricity consumption per cow need confirmation. The electricity use by the components of the system need to be determined and confirmed. The causes of variation need to be identified and quantified. Until this basic information is established, claims for the effect of conservation equipment will be spurious and lack credibility.

1.7 Methodology.

Having recognised that there is concern about the level and cost of energy use in farm dairies, the purpose of the current work is to establish reliable information upon which to base recommendations to farmers, their advisers, the Electricity Supply Industry and future workers in this field.

Farms will vary considerably in respect of the major factors which will affect the level of energy used. An energy audit of a number of farms was selected as a suitable method of identifying the factors involved. This was supplemented by the development of computer based models constructed from theoretical considerations which have been used to evaluate the factors which cause variation in the level of energy use. The quantitative data from the audit have been used for model validation. Sensitivity and limits to the model's applicability have been established.

This approach to the problem has permitted the answering of a number of questions posed by the literature review. A two-year energy audit was carried out to allow full and thorough examination of the seasonal variations. The audit has examined a number of commercial dairy farms, with variations in herd size, seasonality of production and type of equipment installed. Detailed observations have been carried out in respect of the bulk milk tank, this item appearing, from the literature, to have the highest within-farm variation of all the components of the system. For this reason, a major emphasis has been placed on the bulk milk tank in the modelling aspects of this work.

The audit has also allowed quantitative assessment of electricity use by other components of the system.

Development of the model has enabled a closer examination of the factors involved in variation of energy use. The object of this part of the work was to identify which of these factors would most readily repay managerial attention or design re-appraisal. The intention was to develop the criteria for optimisation of energy use before any equipment specifically designed for conservation is applied. Establishment of the optimum use of typical equipment in farm conditions can then be used as a baseline against which to measure the effects of conservation measures.

The work concludes with recommendations in respect of energy use in the farm dairy.

2. THE ENERGY AUDIT

2.1 Auditing Methods

2.1.1 Description of the Audited Farms

Thirteen dairy farms were selected for auditing, which commenced in the early spring of 1980 and lasted approximately two years. Selection was carried out from a pool of farms suggested by A.D.A.S., to provide a variation in herd size and equipment installed. All of the farms involved expected to make few or no major changes to their farming policy or equipment during the life of the audit. In practice there were a number of changes, detailed later.

Twelve of the farms were purely commercial dairy farms. Eleven of these were in the South Hams area of South Devon, the other being near Crediton, to the North-East of Dartmoor. The thirteenth farm was the Seale-Hayne College farm which was selected for monitoring in greater detail.

The farms were grouped according to herd size; small herds (up to 70 cows), medium sized herds (80-120 cows), and large herds (more than 120 cows). Farms were then labelled A to M following nominal herd size. The Seale-Hayne farm was designated farm X.

All the farms have herringbone milking parlours and Friesian dairy herds, except D which has a Jersey herd. Table 2.1 summarises the farms and their major equipment and herd size.

Farm	Nominal Herd Size	Parlour Size	Cleaning System	Cooling System	Conservation Equipment
A	60	5/10	CC	SS	
B	60	5/10	CC	J	
C	65	5/10	ABW	J	
D	70	5/10	CC	SS	
E	110	5/10	CC	SS(2)	Plate Cooler &2 HRUs
F	100	12/12	CC	SS	HRU
G	90	10/10	ABW	SS	
H	110	8/16	CC	J	
J	140	8/16	CC	J	
K	150	10/10	ABW	SS	2 HRUs
L	170	12/12	ABW	J(2)	
M	210	10/20	CC	J(2)	
X	90	6/12	CC	SS(2)	

KEY: ABW Acidified Boiling Water Cleaning
CC Circulation Cleaning
SS Sump and Spray bulk milk tank
J Jacketed bulk milk tank

Table 2.1 Summary of herd size and equipment on the audited farms

There were equipment changes on some of the farms following commencement of the audit. Farms E and K altered their parlours to a 12/12

(September 1980) and 16/16 (July 1981) respectively. A number of changes of cleaning system or routine took place. Farms C (September 1980) and H (June 1981) changed to larger milk tanks, farm H adding a plate cooler at the same time. Farm L ceased milk production in June 1981. Farm M reduced its herd size from 210 to 70 cows (Autumn 1981).

Farms D, J and X are under institutional ownership; all the other farms are under the ownership of an individual, family or partnership. In the case of farms B, C and F, the owners undertake a major proportion of the milking work. All other farms employ one or more herdsmen for most of the milkings. Farms D, J, K, L and X also employ a manager. All the farms practise twice a day milking.

Ten of the farms are mainly winter milk producers. Farms A and G aim for all year round production, while farm C is a mainly summer milk producer.

Farms B and F have new, purpose-built, prefabricated buildings which allow good penetration of natural light. Farms A, D, K, L and X have older purpose built buildings constructed of traditional materials. The remaining farms have old, converted buildings which are typically very dark.

2.1.2 Recording of Electricity Use.

Electricity meters were installed by engineers from the South Western Electricity Board (S.W.E.B.). On the twelve farms A to M, electricity meters were fitted to the circuits controlling the five major energy users in each farm dairy. These circuits were:

- The Bulk Milk Tank including compressor motor, condenser fan, milk and chilled water agitators.

- The Vacuum Pump Motor.
- The Hot Water Heater.
- The Udder Washer Heater.
- The Lights.

In addition, a further meter was fitted to the main supply to the dairy to meter the total electricity consumption. By subtraction of the sum of the five major components from the total, the energy use by minor components such as tank rinsing units and pressure washers could be found. Where circuits were taken off the main supply for non-dairy uses, e.g. calf-feeding water heaters, these were also metered to enable subtraction from the total. Where present, stand-by generators were also metered.

In the Seale-Hayne farm dairy (Farm X) additional meters were installed so that every circuit was individually metered. The additional meters covered the following circuits:

- Agitators and Chilled Water Spray Pumps (2)
- Automatic Tank Rinsers
- Pulsator
- Power Hose Pump
- Milk lift Pump
- Feeders

2.1.3 Recording of Water Use

The Seale-Hayne Farm was equipped with inferential water meters to measure the water used by each of the tank rinser units and by the power hose. This was done to give some indication of the relationship between the electricity used by these items and the mass of water handled.

2.1.4 Recording of Ambient Temperatures

Bimetallic thermographs were installed at each site to record ambient temperatures in the dairies. Charts were changed when the other meters were read. The charts were analysed by measuring the area under the trace with a planimeter. A simple model then converted this area into a mean ambient temperature for the period recorded.

2.1.5 Monitoring of Herd Parameters and unusual events.

Data on milk production, changes in herd size and numbers of cows in-milk were collected at regular intervals by accessing farm records. An Event Record notebook was left in each farm dairy and farmers were asked to record any unusual events, such as power cuts, which could affect the electricity consumption.

2.1.6 Frequency and Duration of Monitoring.

Monitoring commenced as soon as the metering was installed, which was on various dates during the winter and spring of 1980. Initially all meter reading was on a weekly basis. By the beginning of March 1980, all farms, except Farm G, were fully metered and had had a short "running in" period. During March 1981, foot and mouth disease precautions prevented meter reading by the author for a period of 4 weeks, commencing 24th March 1981. Farmers were asked to read the meters and send in the data by post for this period. This request was only partially successful, resulting in 4-week gaps in the data for some of the farms. The data were complete, however, for all the farms, except for Farm G, for the full year up to 17th March, 1981.

Having fulfilled the objective of obtaining a complete annual cycle of data, based on weekly meter readings, the decision was taken to continue the audit for a second year in order to obtain confirmatory data, but to collect the data on a monthly basis instead of weekly. The 30th of June, 1981 was a convenient date for the changeover in recording regime, this occurring on a weekly recording day and also being the end of the month. The audit continued on this basis until the end of April 1982 when readings were terminated. There was thus a complete second year of auditing from April 1981, when readings resumed after disease precautions were lifted, until April 1982.

2.2 Instrumentation and Calibration

2.2.1 Electricity Meters

These were calibrated by S.W.E.B. before installation, to comply with their standard accuracy range of -2% to +1%.

2.2.2 Water Meters

A simple test-rig was constructed for the purpose of calibrating water meters. This consisted of a header tank, refilled through a ball-valve from the mains supply, and feeding a down-supply in which the water meter was located followed by a gate-valve. Below the down supply was placed a vessel to catch the water passing through the meter. The meters were then calibrated against the mass of water passing through them.

The meters were Kent inferential meters of size 15mm and 22mm connections and were all found to be within the manufacturer's specifications. Errors were between -1% and +1%.

2.2.3 Temperature Measuring Instruments.

Thermographs were calibrated over their working range against a mercury-in-glass thermometer of known accuracy. At regular intervals the thermographs were checked on the farms against a hand-held digital thermometer, and adjustments were made as necessary.

The digital thermometer was calibrated in the laboratory against a mercury-in-glass thermometer of known accuracy. The error was found to be -1.5°C at 0°C and -0.75°C at 90°C. Intermediate errors were linear.

2.3 Analytical Techniques.

Recording sheets for weekly meter reading were designed to enable the week's consumption to be calculated and compared with the previous week's consumption while still on site. This method allowed inconsistent levels of consumption to be checked for validity while still on the farm. The data were then filed on the Prime mainframe computer at Plymouth Polytechnic and analysis was carried out using the statistical package 'Minitab'.

Data for each farm were initially filed as separate files. The data items for each farm were:

Week number	Week 1 for all farms was the week ending 3rd January 1980, irrespective of the date of commencement of recording.
Farm number	Farms were coded numerically for subsequent clarity after merging files.
Total Electricity Consumption . .	In kWh.
Bulk Milk Tank Electricity . . .	In kWh.
Vacuum Pump Electricity . . .	In kWh.
Water Heater Electricity	In kWh.
Udder Washer Electricity	In kWh.
Lighting Electricity	In kWh.
Ambient Temperature	Mean temperature in °C for the week or month.
Herd size	Total number of cows in herd.
Cows in milk	Number of cows being milked.

Milk Production . . . . .Litres.

Gaps in the data were given the numerical value -9, this being a value which never occurred naturally. An instruction was issued to ignore all occurrences of this value in the statistical analyses.

For each record, a record being a set of the above data items for a single week, the following calculations were made:

- The milk production was converted to cubic metres.
- The sum of the electricity-using components was subtracted from the total electricity to give the unmetered electricity.
- The total electricity, bulk tank electricity, vacuum pump electricity, lighting electricity and unmetered electricity were each divided by the volume of milk to give the respective consumptions per unit volume of milk.
- The percentage fill of the bulk tank was calculated.

The mean and standard deviation was calculated for all the basic data items, except week and farm numbers. The mean and standard deviation were also calculated for each of the electricity consumptions per cubic metre of milk produced.

Sample correlation coefficients were calculated for all combinations of pairs of the following:

- Total Electricity Consumption

- Bulk Tank Electricity Consumption
- Vacuum Pump Electricity Consumption
- Water Heater Electricity Consumption
- Udder Washer Electricity Consumption
- Lighting Electricity Consumption
- Unmetered Electricity Consumption
- Herd Size
- Number of Cows in–milk
- Milk Production Volume
- Ambient Temperature

Sample correlation coefficients were also calculated for all combinations of pairs of the following:

- Total Electricity per cubic metre of milk
- Bulk Tank Electricity per cubic metre of milk
- Vacuum Pump Electricity per cubic metre of milk
- Udder Washer Electricity per cubic metre of milk
- Lighting Electricity per cubic metre of milk

- Unmetered Electricity per cubic metre of milk
- Milk Production volume
- Ambient Temperature
- Herd Size
- Number of Cows in–milk

Regression analysis was carried out on all combinations of data items where the sample correlation coefficient suggested the relationship between variables might be worth exploring further. With a simple linear regression using a single predictor the regression equation was calculated, with the standard deviations of the coefficients. The Coefficient of Determination (R^2) was also calculated.

The following linear regressions were calculated:

- Bulk Tank Electricity on Milk Volume
- Bulk Tank Electricity on Ambient Temperature
- Bulk Tank Electricity on Percentage Fill of the tank
- Bulk Tank Electricity per cubic metre of milk on Milk Volume
- Bulk Tank Electricity per cubic metre of milk on Ambient Temperature
- Bulk Tank Electricity per cubic metre of milk on Percentage Fill
- Vacuum Pump Electricity on Number of Cows in–milk

- Vacuum Pump Electricity on Milk Produced
- Vacuum Pump Electricity on Ambient Temperature
- Vacuum Pump Electricity per cubic metre of milk on Milk Produced.
- Vacuum Pump Electricity per cubic metre of milk on Ambient Temperature
- Vacuum Pump Electricity per cubic metre of milk on Number of Cows in-milk
- Total Electricity on Number of Cows in-milk
- Total Electricity on Milk Produced
- Total Electricity on Ambient Temperature
- Total Electricity per cubic metre of milk on Number of Cows in–milk
- Total Electricity per cubic metre of milk on Milk Produced
- Total Electricity per cubic metre of milk on Ambient Temperature

Multiple Regression analysis was carried out on a number of combinations of data items:

- Bulk Tank Electricity on Ambient Temperature and Volume of Milk produced
- Bulk Tank Electricity per cubic metre of milk on Ambient Temperature and Volume of Milk Produced

- Bulk Tank Electricity on Ambient Temperature, Volume of Milk produced and Percentage fill
- Bulk Tank Electricity per cubic metre of milk on Ambient Temperature, Volume of Milk Produced and Percentage fill
- Vacuum Pump Electricity on Ambient Temperature and Number of Cows in-milk
- Vacuum Pump Electricity per cubic metre of milk on Ambient Temperature and Number of Cows in–milk
- Vacuum Pump Electricity on Number of Cows in–milk and Volume of Milk Produced
- Vacuum Pump Electricity per cubic metre of milk on Number of Cows in-milk and Volume of Milk Produced
- Vacuum Pump Electricity on Ambient Temperature and Volume of Milk produced
- Vacuum Pump Electricity per cubic metre of milk on Ambient Temperature and Volume of Milk Produced
- Vacuum Pump Electricity on Ambient Temperature, Number of Cows in–milk and Volume of Milk Produced
- Vacuum Pump Electricity per cubic metre of milk on Ambient Temperature, Number of Cows in-milk and Volume of Milk Produced

- Total Electricity on Number of Cows in-milk and Volume of Milk produced
- Total Electricity per cubic metre of milk on Number of Cows in-milk and Volume of Milk Produced
- Total Electricity on Number of Cows in-milk and Ambient Temperature
- Total Electricity per cubic metre of milk on Number of Cows in-milk and Ambient Temperature
- Total Electricity on Ambient Temperature and Volume of Milk produced
- Total Electricity per cubic metre of milk on Ambient Temperature and Volume of Milk Produced
- Total Electricity on Ambient Temperature, Volume of Milk Produced and Number of Cows in-milk
- Total Electricity per cubic metre of milk on Ambient Temperature, Volume of Milk Produced and Number of Cows in-milk

2.4 Results from the Audit.

2.4.1 The Total Electrical Energy Input.

The total electrical energy input is defined as all the electrical energy used within the dairy and parlour for the purposes of milking, cooling the milk, cleaning the equipment and lighting the area. Excluded are such items as additional water heaters for calf feeding and external lighting. Space heaters within the parlour are included where present.

Table 2.4.1 (a) shows the total electricity use for 11 farms for a period of exactly one year, March 1980 to March 1981. Farm G has been excluded because the data are incomplete due to metering difficulties. Farm E has also been excluded because this farm underwent a major change of equipment during the year. In particular there was a period of approximately three months during the alteration work when the herd was milked through temporary accommodation which was very difficult to meter accurately. The farms in the table have been arranged in ascending order of electricity use per unit volume of milk produced. Rankings by electricity use per cow are given in parentheses in the penultimate column.

The average electricity use was 46.9 kWh per m^3 of milk, but there was a range wherein the heaviest user, farm D, used slightly more than twice the electricity per unit volume of milk than the most economical, Farm F. The two most economical farms, F and K, both have heat recovery units installed to recapture heat from the bulk milk tank for pre-heating water. However these farms were only slightly more economical than Farms A and B, which are small family farms where the owner does the milking. Farms H, J, L and M are all fairly close to the mean. These are all farms where an employed herdsman is responsible for milking and operating the equipment. Farms X and C were both some 20% or more worse than the mean. Farm X is the Seale-Hayne College farm and Farm C uses the A.B.W. method of plant cleaning, which may have been a contributory factor to the high cost. Farm D appears to have a particularly high electricity usage per unit volume of milk. This farm has a Jersey herd and this

Farm		Mean No cows	Total milk produced	Milk yield /cow	Electricity used	Electricity Use per cow		Electricity /unit volume of milk
			m^3	l	kWh	kWh		kWh/m^3
1	F	114	630.1	5527	23446	206	(2)	37.2
2	K	143	777.5	5437	30836	215	(3)	39.7
3	B	54	276.5	5120	11003	204	(1)	39.8
4	A	61	339.7	5569	13875	227	(4)	40.8
5	H	120	709.9	5916	31027	258	(7)	43.7
6	L	151	885.8	5866	41661	276	(9)	47.0
7	M	202	987.1	4887	46559	231	(5)	47.2
8	J	128	654.1	5110	31969	249	(6)	48.9
9	X	90	518.1	5757	28868	322	(10)	55.7
10	C	60	356.9	5948	21245	357	(11)	59.5
11	D	70	245.4	3506	18630	266	(8)	75.9
Totals		1193	6381.1		299119			
Means				5349		251		46.9

Table 2.4.1 (a). Electricity use by 11 farm dairies in 1980-81, related to herd size and milk production, ranked in ascending order of electricity use per unit volume of milk, with rankings for electricity use per cow in parentheses.

breed produces a lower average milk yield than the Friesian breed. The lower volume of milk handled is likely to be a major factor here.

Examination of the data as electricity use per cow in the herd shows some similarities in the ranking. The leading four farms by electricity use per cubic metre of milk are also the leading farms by electricity use per cow. There is some rearrangement of these four and farm B becomes the most economical. In the mid-range, farms M and J appear to have an improved relative position, while

Farm		Mean No cows	Total milk produced	Av milk yield /cow	Electricity used	Electricity use per cow		Electricity /unit volume of milk
			m^3	l	kWh	kWh		kWh/m^3
1	F	110	572.3	5202	23133	210	(2)	40.4
2	B	54	275.7	5106	11522	214	(3)	41.9
3	A	67	310.8	4639	13288	200	(1)	42.8
4	H	129	750.2	5815	32100	249	(6)	42.8
5	K	183	1007.2	5503	47205	258	(7)	46.9
6	C	75	410.8	5477	20037	267	(9)	48.8
7	J	116	497.4	4288	26173	226	(5)	52.6
8	M	123	460.9	3747	27323	222	(4)	59.3
9	D	70	235.7	3367	18596	266	(8)	78.9
Totals		927	4521.0		219377			
Means				4877		237		48.5

Table 2.4.1(b). Electricity use by 9 farm dairies in 1981-82, related to herd size and milk production, ranked in ascending order of electricity use per unit volume of milk, with rankings for electricity use per cow in parentheses.

farms L and H appear to have a worsened relative position. Particularly noticeable is farm D which is only about 6% below the mean by this method of calculation, confirming previous suggestions that the low yield of the Jersey breed is an important factor when costs per unit volume of milk are considered.

Data from the second year of the audit are presented in Table 2.4.1(b). Farm E has again been excluded because the alterations overlapped with the beginning of the second year of recording. Farm L has been excluded because the farm ceased milk production during the course of the year and Farm X has also been excluded due to incomplete data. The similarities in the rankings and data are clear. On average the farms were slightly more expensive in terms of electricity used per unit volume of milk and a little more economical in terms of electricity used per cow. Particularly significant is the fall in average milk yield per cow from the first year to the second. Only farm K increased the average yield and in some cases there were falls of several hundred litres per cow. Following this it could have been expected that the average electricity cost per unit volume of milk would have increased rather more than 1.6 kWh/m^3 and the exclusion of farms X and L has almost certainly been responsible for the small size of this increase. Only farms C and H increased their efficiency of use of electricity during the period. Farm C altered the cleaning practice to provide a more economical cleaning routine and this reduced the amount of electricity used while the herd was expanded by 25%. Farm H achieved a marginal improvement by increasing the total milk production with a relatively small increase in electricity use. Farm K showed a deterioration in performance. On this farm there was a large increase in herd size and a corresponding increase in the size of the equipment. The result was an increase in electricity use of over 50% with an increase in milk production of less than 30%.

At the more economical farms, there was a remarkable consistency of performance between the first and second years. Farm A increased the herd by approximately 10% reducing the cost per cow by a similar proportion. At this farm a dramatic fall in milk yield was accompanied by an increase in cost per unit volume of milk. Farms F and B produced data which were very similar to the first year's.

At the bottom of the table, Farm D was relatively consistent but farms J and M both suffered from reductions in herd size and average yield. Farm M reduced the herd size during the second year from over 200 cows to 70.

The relationship between total electricity used and volume of milk produced was examined for each farm, using the monthly data for the 24-month period. The analysis was carried out for the twelve farms, L and X being included despite having incomplete records. For this relationship all farms had a correlation coefficient in excess of 0.6 and farms A, B, J and M had correlation coefficients in excess of 0.9. Linear regression analysis was carried out on these data and the results are shown in Table 2.4.1(c). In this analysis, all the coefficients were significant ($P>0.95$) except the intercept terms for farms L and K. The Coefficient of Determination (R^2) is the proportion of variation in the total electricity consumption (y) attributable to variation in the volume of milk produced (x). The indication from Table 2.4.1 (c) is that variation in milk production is an important predictor of variation in total electricity consumption. On some farms, notably B and M, the figure is very high; but there seems to be wide variation between farms suggesting that a more sophisticated model is needed.

The relationship between total electricity used and number of cows in-milk was then examined. The results did not suggest that the number of cows in-milk was a good predictor of total electricity use. There was wide variation in Coefficients of Determination from zero (farm J) to over 90% (farm L). Regression analysis was carried out as before, but the intercept term coefficients at five farms were not significant ($P>0.95$) and the gradient coefficients were not significant ($P>0.95$) at three farms.

Farm	Months	Regression Equation	R^2(%)
A	24	$y = 320 + 29.9x$	86.2
B	24	$y = 245 + 31.1x$	91.3
C	24	$y = 934 + 24.6x$	33.7
D	24	$y = 1104 + 22.3x$	66.1
E	21	$y = 983 + 16.1x$	52.5
F	24	$y = 884 + 21.1x$	61.1
H	24	$y = 1849 + 12.8x$	72.3
J	24	$y = 1165 + 26.2x$	85.0
K	24	$y = 723 + 34.0x$	58.5
L	17	$y = 577 + 37.4x$	81.1
M	24	$y = 1185 + 31.4x$	94.5
X	12	$y = 1385 + 23.9x$	35.6

Table 2.4.1(c). Regression of Total Electricity Consumption (y (kWh)) on Volume of Milk Produced (x (m^3))

Ambient temperature data were then examined in conjunction with the total electricity data. The results were very variable. Only two farms showed a coefficient of determination in excess of 50%. The regression line had a negative gradient on eight farms and a positive gradient on four farms. It seems likely therefore that any ambient effects on total electricity use were swamped by other, more significant effects.

Multiple regression analysis was carried out to determine whether the factors already considered in isolation could improve the predictability of total electricity when considered in combination.

When numbers of cows in-milk and volume of milk produced were considered as predictors in combination, the Coefficient of Determination improved on six farms compared with the figure produced when using milk production as a sole predictor. On farm E this improved from 52.5% to 76.8%, on farm L from 81.1% to 92.3% and on farm X from 35.6% to 49.6%. The other three increases were marginal and the remaining six farms showed slight reductions, in each case less than 1%.

Further analysis was carried out using the number of cows in-milk and ambient temperature in combination and using the volume of milk produced and ambient temperature in combination as predictors of total electricity use. The first of these analyses produced Coefficients of Determination only marginally different from those produced using milk volume alone as a predictor. The second analysis improved the predictability at farm C to 49.5% and at farm L to 96.1%.

All three factors were then combined in a multiple regression analysis, the results of which are given in Table 2.4.1 (d)

Farms K and X have been excluded because none of the coefficients were significant ($P>0.95$). All the intercept terms, except that for farm L, were significant ($P>0.95$). The x_1 term coefficients were only significant ($P>0.95$) at farms A, C and L. The x_2 term coefficient was only significant ($P>0.95$) at farm L. The x_3 term coefficients were all significant ($P>0.95$) except for farm C.

The analysis carried out up to this point has shown that the volume of milk produced is a better single predictor of total electricity use than either the number of cows in-milk or the ambient temperature. This was the case at all farms, except farm L. The number of cows in-milk produced very variable

Farm	No. of Months	Regression Equation	R^2(%)
A	24	$y = 192 + 6.88x_1 + 3.53x_2 + 25.3x_3$	88.3
B	24	$y = 284 + 1.11x_1 + 3.55x_2 + 36.1x_3$	90.2
C	24	$y = 771 + 26.30x_1 + 3.76x_2 + 15.4x_3$	47.4
D	24	$y = 1027 - 2.97x_1 + 4.22x_2 + 14.7x_3$	66.8
B	21	$y = 2509 - 22.10x_1 - 18.50x_2 + 27.3x_3$	77.0
F	16	$y = 979 - 0.55x_1 - 2.03x_2 + 23.0x_3$	62.1
H	24	$y = 1494 + 16.90x_1 - 0.61x_2 + 16.8x_3$	70.9
J	23	$y = 1297 + 9.34x_1 - 1.70x_2 + 25.0x_3$	85.5
L	17	$y = 92 + 61.80x_1 + 13.80x_2 + 11.5x_3$	97.5
M	18	$y = 1191 + 1.10x_1 - 5.45x_2 + 40.5x_3$	96.1

Table 2.4.1(d). Regression of Total Electricity (y (kWh)) on Ambient Temperature (x_1 (°C)), Number of cows in-milk (x_2) and Volume of Milk produced (x_3 (l)).

analyses and the ambient temperature was very disappointing as a predictor. Use of the factors in pairs as combined predictors generally produced only marginally more encouraging analyses in some cases, and use of all three factors in combination improved predictability at all but two farms, but again most of the improvements were marginal.

A high proportion (35.6 to 94.5% from Table 2.4.1(c)) of the variation in total electricity use could therefore be accounted for by variation in volume of milk produced, and addition of the other factors added little to this accountability. However the wide range between farms suggested that variation in the equipment installed or the management of that equipment should be taken into consideration and a more deterministic approach is needed.

Farm	Bulk Tank		Vacuum Pump		Water Heater		Udder Washer	
A	7902	(57.0)	2408	(17.4)	1940	(14.0)	1304	(9.4)
B	5331	(48.5)	1961	(17.4)	2326	(21.1)	1091	(9.9)
C	6980	(32.9)	2288	(10.8)	10773	(50.7)	588	(2.8)
D	6163	(33.1)	4006	(21.5)	6456	(34.7)	1042	(5.6)
F	12296	(52.4)	6014	(25.7)	812	(3.5)	2986	(12.7)
H	13888	(44.8)	5348	(17.2)	8853	(28.5)	1948	(6.3)
J	13317	(41.7)	6015	(18.8)	9914	(31.0)	2241	(7.0)
L	16425	(39.4)	5049	(12.1)	16816	(40.4)	1942	(4.7)
M	20089	(43.1)	7291	(15.7)	9471	(20.3)	7947	(17.1)
X	12446	(43.1)	3018	(10.5)	9644	(33.4)	1518	(5.3)
Totals	114837	(42.8)	43398	(16.2)	77005	(28.7)	22607	(8.4)

Table 2.4.1(e). Electricity (kWh) used by the four major components of the system in 10 farm dairies in 1980-81, with percentages in parentheses.

Further analysis was therefore carried out using the data for individual electricity-using components of the total system. The electricity use by the four major components of the system is given in Table 2.4.1(e). These four components accounted for over 96% of the total electricity used by the farms during the first year of monitoring.

An examination of the data for the individual components was carried out to investigate the possibility of a relationship between any component and the total electricity use. The degree of correlation between each of the four major components and the total electricity use was examined. This is expressed in Table 2.4.1(f) in the form of the Coefficients of Determination. The values indicated by asterisks are derived from negative correlation coefficients. The bulk milk tank and vacuum pump data are both suggestive of an association

Farm	Bulk Milk Tank	Vacuum Pump	Water Heater	Udder Washer
A	92.0	40.3	11.0*	1.3*
B	78.9	88.2	83.2	46.9
C	48.9	3.3	51.7	0.2*
D	29.6	90.2	44.1	41.0
B	40.4	70.9	24.4	3.9
F	37.2	49.8	0.4	38.3
H	83.4	81.5	47.1	67.6
J	81.2	73.3	2.8	0.0
K	63.0	76.2	37.2	19.1*
L	87.8	91.8	90.8	59.3
M	96.6	95.6	61.8	87.6
X	27.5	59.0	72.8	51.4

* Derived from negative correlation coefficients.

Table 2.4.1(f). Coefficients of Determination (R^2) produced from Correlation Analysis between the total electricity use and each of the four major components of the system in 12 farm dairies in 1980-81.

with the total electricity, the mean values of R^2 being 63.9% and 68.3% respectively. In some cases there are very close associations. This is most noticeable for farms B, H, L and M, and to a lesser extent J and K in respect of both the bulk milk tank and vacuum pump, and at farm A there was a high association between only the bulk milk tank and the total electricity. The water heater showed much less convincing evidence of an association with the total electricity, only farms B and L having a high value of R^2 and three farms showing hardly any measure of association. The mean R^2 value for the water heater and the total electricity was 43.9%. The udder washer was even less convincing of an association. The mean R^2 was 34.7% and only farm M seemed to have evidence of an association.

The results of the analysis at this stage demonstrate the importance of the bulk milk tank as the major component of the system in terms of electricity use. The bulk tank used approximately 43% of all the electricity used on all the farms. Furthermore it has been shown that almost two-thirds of the variation in total electricity use may be associated with variation in the bulk tank electricity use. The water heater was the second highest consumer of electricity (approx 29% of the total) but the association between its electricity consumption and the total is much less clear. A better association was seen between the vacuum pump electricity use and the total, but the vacuum pump accounted for only about 16% of all the electricity used.

It must be noted at this point that indications of statistical association do not themselves provide proof of causality; this would normally be sought from other evidence. However, the total electricity use can clearly be described by an additive model in respect of the components of the system. Given that this is so, it seems reasonable to conclude that a better understanding of the causes of variation in the components of the system will contribute to a more accurate method of estimating the total electricity consumption for a specific set of circumstances.

Further analysis was therefore carried out on each of the components of the system.

2.4.2 The Bulk Milk Tank.

Electricity is used by the bulk milk tank for the running of the compressor, the condenser fan, the milk agitator and either the chilled water spray pump for sump and spray tanks or the air pump for jacketed tanks. Of these constituents, the compressor motor invariably uses the most electricity

The audit data have already revealed that the bulk milk tank is generally the heaviest single user of electricity within the farm dairy (Table 2.4.1(e)). Table 2.4.2(a) ranks the farms in order of mean cooling cost per unit volume of milk.

Only at farms C, D and L was the bulk tank not the highest single user of electricity, and at these three farms the water heater was the heaviest user. However, the margin was slight (less than two percentage points) at farms D and L.

Percentages of the total may be slightly misleading as the total electricity use may fluctuate widely for reasons not connected with the bulk tank. In general, though, the bulk milk tank seems to account for 40% or more of the total electricity used.

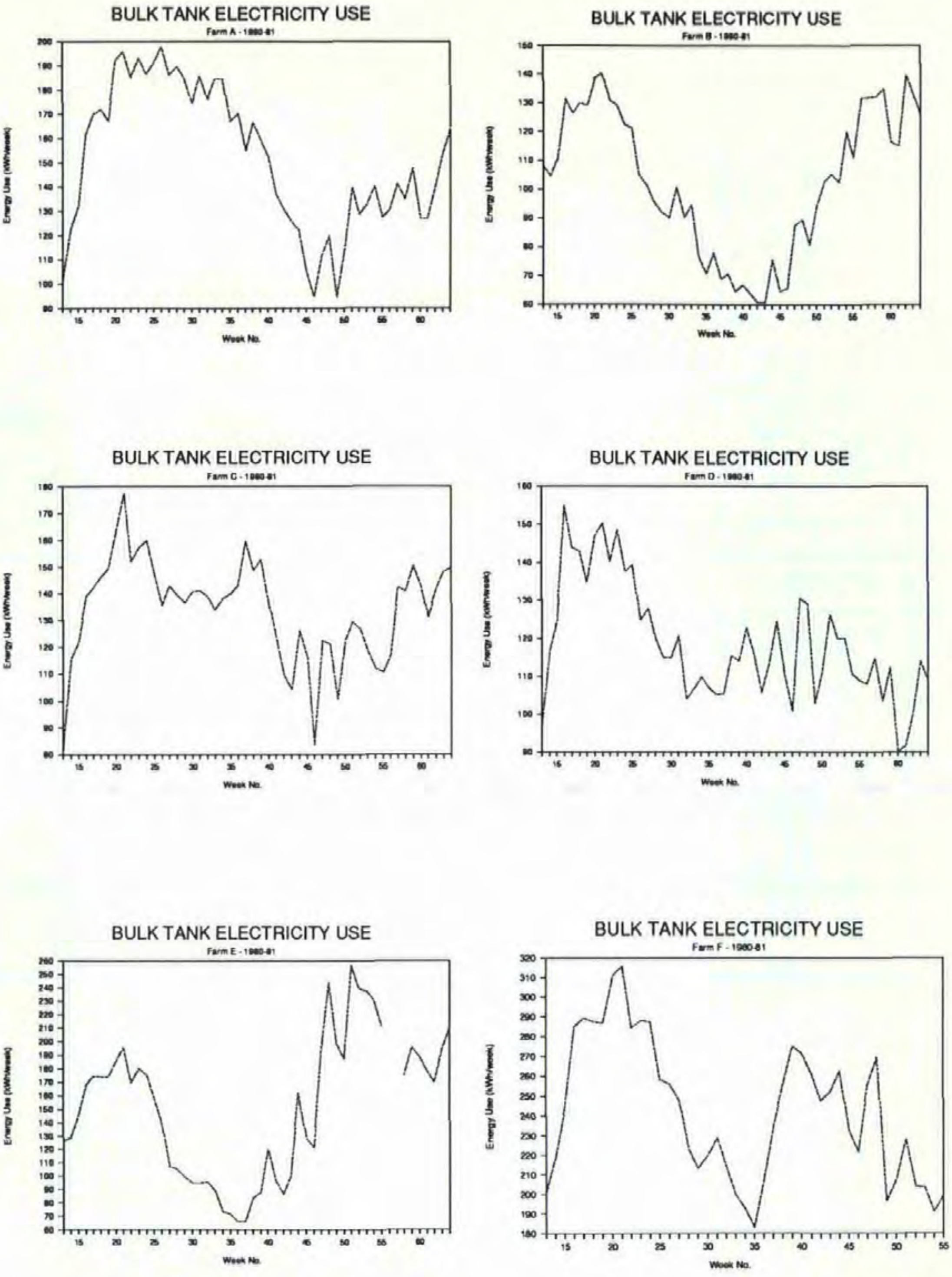
The bulk tank also shows the most noticeable seasonal variation in electricity use. Figures 2.4.2(a) to 2.4.2(l) show the weekly electricity use by the bulk tank during the first year of the audit for each of the farms. There are some similarities. All the farms showed a rise in the bulk tank electricity use in the first few weeks after commencement of the audit in week 13. This rise was followed by a peak occurring generally before week 23. There was then a decline

Farm	Milk Produced	Bulk Tank Electricity	% of Total Electricity	B.T.Electricity per unit of milk
	m^3	kWh		kWh/m^3
L	885.1	16425	39.4	18.56
F	630.1	12296	52.4	19.51
C	356.9	6980	32.9	19.56
H	709.9	13888	44.8	19.56
B	269.7	5331	48.5	19.77
M	987.1	20089	43.1	20.35
J	654.1	13317	41.7	20.36
K	777.5	17577	57.0	22.61
A	339.7	7902	57.0	22.61
X	51.1	12446	43.1	24.02
D	245.4	6163	33.1	25.11
Totals	6376.6	132414		
Means			44.3	20.78

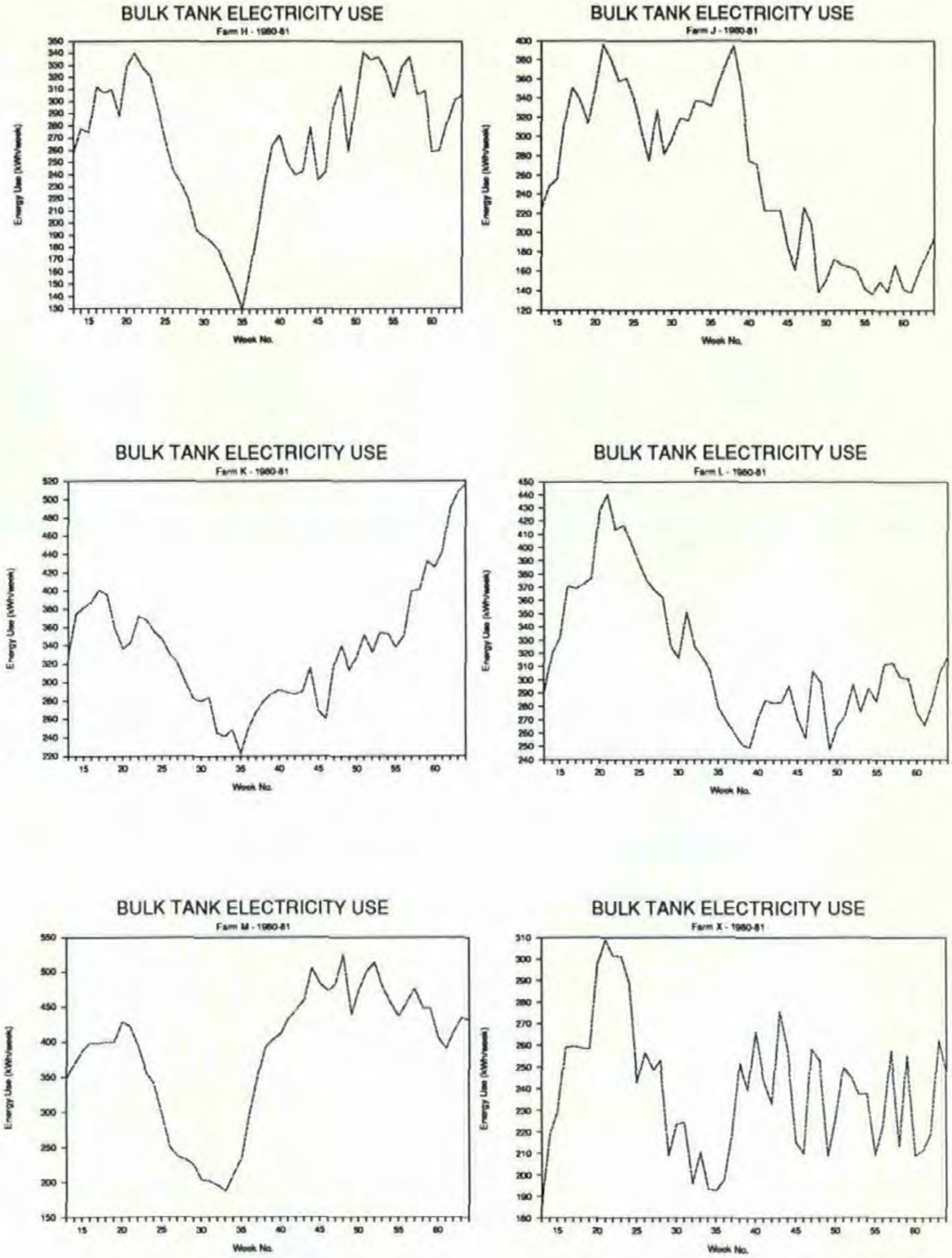
Table 2.4.2(a). Milk production and bulk tank electricity use in 11 farm dairies in 1980-81, ranked in order of mean cooling cost of milk.

until the trough was reached at some stage during the autumn, when the electricity use started to rise again. In some cases there was a second peak.

The best explanation of this pattern is provided by a consideration of the annual milk production cycle and its effect on daily volumes of milk to be cooled. Many of the farms claimed to be winter milk producers, that is to say the main bulk of calving will occur during the autumn. As more cows calve and approach their peak of lactation some six weeks later, the total volume of milk produced will increase considerably during the early winter. As the majority of the herd



Figures 2.4.2(a) to 2.4.2(f). Weekly electricity use by the bulk milk tank during the first year of the audit for six of the surveyed farms.



Figures 2.4.2 (g) to (l) Weekly electricity use by the bulk tank at farms H,J,K,L M and X respectively during 1980-81.

pass their peak as winter progresses, the onset of grass growth in the spring will provide something of a boost in the declining lactation curve, helping to produce greater volumes of milk in late spring or early summer (weeks 15 to 25). Reduction in grass quality as the summer progresses, together with the deliberate drying off of cows prior to calving, will combine to produce the lowest milk volumes in the early autumn before the main calving season restarts.

This explanation is satisfactory in explaining the pattern for most of the farms. Farm A aims for a flatter production pattern by spreading calving all round the year and this is shown by a broader peak extending throughout the summer weeks with a trough in mid-winter. Farm X has two main seasons of calving in the spring and autumn and this has also produced a flatter pattern. Farm C aims for more summer milk production by concentrating calving in early spring. The expansion in herd size at farm K towards the end of the year is clearly seen in the bulk tank electricity use.

The conclusion to be drawn at this stage is that the volume of milk to be cooled has a major influence on the bulk tank electricity use. Regression analysis was therefore carried out to examine the relationship between electricity use by the bulk tank and the volume of milk. Table 2.4.2(b) shows the regression equations and the Coefficients of Determination from this analysis, for twelve farms.

Farm X is the only farm where the coefficient of the gradient term is not significant ($P>0.95$). The R^2 value of 16.1% at this farm suggests that this equation would not be very reliable as a means of predicting the bulk tank electricity use. An explanation may be provided by the pattern of use of the cooling facility. At farm X there are two bulk milk tanks, each of 1365 litres capacity. Bulk milk tanks

Farm	Regression Equation	R^2(%)
A	y = -245 + 0.0322x	80.9
B	y = 118 + 0.0150x	75.4
C	y = -27* + 0.0208x	71.6
D	y = 294 + 0.0108x	34.7
E	y = 90 + 0.0109x	88.8
F	y = 276 + 0.0139x	49.3
H	y = 813 + 0.0058x	38.9
J	y = -75* + 0.0223x	73.3
K	y = 361 + 0.0175x	93.4
L	y = 106* + 0.0170x	85.9
M	y = 142 + 0.0178x	93.8
X	y = 727 + 0.0071x*	16.1

Table 2.4.2(b). Regression analysis of bulk tank electricity (y) (kWh) on volume of milk produced (x) (litres). All coefficients significant (P>0.95) except those marked with an asterisk.

are designed to cool their capacity of milk to 4°C when the milk is added to the tank in two filling periods, one in the afternoon and one the following morning. The design and testing of the tank assume that up to 40% of the milk will be added to the tank at the afternoon milking and this will be cooled to 4°C before the remaining batch of up to 60% of capacity is added at the following morning's milking. At farm X it was often the practice to direct the afternoon milking to one of the tanks and the morning milking to the other. On these occasions, it was not uncommon for a tank to receive more than 40% of its capacity at a single milking. The cooling reserve, in the form of the ice-bank, is not guaranteed, in these circumstances, to enable the tank to comply with the requirement to cool the milk to 4°C within half an hour of the end of the filling period. Consequently, the ice-bank was often exhausted, failing to cool the milk within the required limits. In these circumstances, collected data will be both variable and unreliable.

The remaining farms all have significant (P>0.95) gradient terms.These may be compared with the cooling costs in kWh/m^3 from table 2.4.2(a), by multiplying by 1000 to convert from litres to cubic metres.The range of gradients thus produced is from 5.8kWh/m^3 at farm H to 32.2kWh/m^3 at farm A, a rather broader range than that seen in Table 2.4.2(a). Results from farm H need to be treated with some caution as the R^2 figure of 38.9% does not suggest the equation is very reliable. A similar comment might apply to farm D which also had a low gradient coefficient, but farm E, with a very similar gradient coefficient to farm D, had a very high R^2 (88.8%). The other farms had more encouraging figures for the R^2 value, going up to over 90% at two of the farms. The difference between the means of the cooling costs in kWh/m^3 from table 2.4.2(a) and the gradients from the regression equations is accounted for by the presence of the intercept term in the regression analysis. However three of the intercept term coefficients were not significant (P>0.95) and a fourth (farm A) needs to be treated with caution as a negative intercept term is clearly impossible in practice.

Further analysis was carried out to investigate the effect of ambient temperature upon bulk tank electricity use and the results are presented in Table 2.4.2(c).

All the intercept terms were significant (P>0.95) but these were extremely variable, ranging from 386 kWh at farm A to 2089 kWh at farm K. Four of the gradient terms were not significant (P>0.95) and the remainder were very variable. The significant but negative gradients at farms H and K seem highly

Farm	Regression Equation	R^2(%)
A	y = 386 + 28.2x	53.3
B	y = 473 + 1.08x*	-3.7
C	y = 409 + 23.8x	45.5
D	y = 416 + 9.16x	22.0
E	y = 1121 + 44.9x	53.9
F	y = 965 + 5.88x*	3.5
H	y = 1364 - 19.1x	17.6
J	y = 477 + 50.1x	50.8
K	y = 2089 - 46.6x	15.3
L	y = 657 + 57.9x	41.0
M	y = 1141 + 0.022x*	7.3
X	y = 1120 - 8.55x*	0.1

Table 2.4.2(c). Regression analysis of Bulk Tank Electricity (y) (kWh) on Ambient Temperature (x) (°C). All coefficients significant (P>0.95) except those marked with an asterisk.

unlikely in practice. The R^2 values were variable and only just exceeded 50% at three of the farms.

The conclusion must again be drawn that the effect of ambient temperature alone is being swamped by other effects and that this factor is unreliable as a sole predictor. However, this does not necessarily mean that ambient temperature is not influential. A further regression analysis was carried out to investigate the effects of ambient temperature and milk volume in combination on the electricity use by the bulk tank. The results of this analysis are presented in Table 2.4.2(d).

Farm	Regression Equation			R^2(%)
A	$y = -196$	$+ 15.8x_1$	$+ 0.0254x_2$	95.1
B	$y = -47^*$	$+ 9.8x_1$	$+ 0.0186x_2$	91.6
C	$y = -95$	$+ 17.4x_1$	$+ 0.0176x_2$	96.6
D	$y = 76$	$+ 13.6x_1$	$+ 0.0147x_2$	87.7
E	$y = 160^*$	$- 4.1x_1^*$	$+ 0.0103x_2$	88.5
F	$y = -229$	$+ 24.9x_1$	$+ 0.0192x_2$	98.1
H	$y = 287^*$	$+ 23.8x_1^*$	$+ 0.0104x_2$	43.2
I	$y = -216$	$+ 33.8x_1$	$+ 0.0178x_2$	93.7
K	$y = 44^*$	$+ 18.1x_1$	$+ 0.0195x_2$	95.8
L	$y = -15^*$	$+ 27.1x_1$	$+ 0.0144x_2$	97.7
M	$y = 156^*$	$+ 10.5x_1^*$	$+ 0.0197x_2$	98.5

Table 2.4.2(d). Regression analysis of bulk tank electricity (y) (kWh) on Ambient Temperature (x_1) (°C) and volume of Milk cooled (x_2) (litres). All coefficients significant (P>0.95) except those marked with an asterisk.

A higher degree of consistency is now to be seen in the results and the very high values of R^2(over 90% for 9 farms) are very encouraging. The intercept terms were not significant (P>0.95) at seven of the farms and it seems reasonable to expect the regression equation to pass through or very close to the origin. The coefficients of the x_1 terms were not significant (P>0.95) at three of the farms and the limitations of the data from farm X have already been commented upon. The coefficients of the x_2 terms were all significant (P>0.95). When multiplied by 1000 to convert to cubic metres, the coefficients of the x_2 terms indicate a range of 10.3 to 25.4 kWh to cool each additional cubic metre of milk. Nine of the farms have x_1 term coefficients in the range 14.4 to 19.7kWh/m^3

In order to provide a comparison with the work by A.D.A.S reported in Section 1.5.2, the data for all farms were merged and the weekly figures for milk cooling cost per unit volume of milk (kWh/m^3) were computed. Regression analysis of this figure on Ambient Temperature (^oC) was carried out, resulting in the equation:

$$y = 13.6 + 0.66x$$

where y is the milk cooling cost
x is the ambient temperature (^oC)

The A.D.A.S. work produced the comparable equation:

$$y = 15.8 + 0.53x$$

Section 2.4.1 showed that the bulk milk tank used approximately 44% of all the electricity used on all the farms and that approximately two-thirds of the variation in total electricity use was associated with variation in the bulk tank electricity use. The further analysis (Table 2.4.1(d)) has shown that some 90% or more of the bulk tank electricity is associated with the combination of variation in the volume of milk handled and variation in the ambient temperature.

The high degree of consistency found in the regressions of bulk tank electricity on volume of milk and ambient temperature is very encouraging and suggests the presence of a general relationship which may describe the bulk tank electricity at any farm. In order to determine an equation to describe this general relationship, these three data items were merged for all farms. The regression analysis was then repeated, using all the weekly data for all the farms. The resulting regression equation is:

$$y = -35.2 + 5.25x_1 + 0.0178x_2 \qquad R^2 = 84\%$$

Where x_1 is the weekly average ambient temperature (°C)

x_2 is the volume of milk cooled (litres)

The intercept term was not significant (P>0.95), but the x_1 and x_2 terms were significant (P>0.95). The high value of the Coefficient of Determination shows that 84% of the variation in bulk tank electricity is attributable to the combination of variation in the ambient temperature and volume of milk cooled.

This regression analysis was carried out using the weekly data and the x_1-term coefficient of 5.25 refers to the number of kilowatt hours attributable to each degree Centigrade above zero, over the period for which the temperature was averaged, in this case one week. On a daily basis this term would become 0.75kWh/°C/day.

A negative intercept term is impossible in practice and this suggests there is some limit to the linearity of the model. The earlier analysis also frequently showed this term to be non-significant. Ignoring the intercept term the equation may be restated as:

The electricity use by a bulk milk tank of the type and size range examined will be 0.75kWh/day for each degree Centigrade that the average temperature is above zero plus 0.0178 kWh for each litre of milk cooled.

2.4.3 The Vacuum Pump.

During the two years of the audit, the vacuum pumps on the twelve farms used 107.09 MWh or 17.6% of the total electrical input. The breakdown by various parameters is given in Table 2.4.3(a).

Farm	Parlour size	No. of cows	Milk prod.	V.P. Electricity	% of total Electricity	V.P. Electricity /cow/year	V.P. Electricity /unit milk
			m^3	kWh		kWh	kWh/m^3
A	5/10	64	650.5	4693	17.28	36.65	7.21
B	5/10	54	552.1	3922	17.41	36.31	7.10
C	5/10	67	767.7	5114	12.39	38.16	6.66
D	5/10	70	481.0	7846	21.08	56.04	16.31
E	5/10	124	1362.6	12272	27.20	49.48	9.01
F	12/12	112	1202.4	12183	26.16	54.39	10.13
H	8/16	124	1460.1	11231	17.79	45.29	7.69
J	8/16	122	1151.5	11131	19.14	45.62	9.67
K	10/10	163	1784.7	14043	17.99	43.08	7.87
L	12/12	139	1347.4	7510	12.21	36.02	5.57
M	10/20	162	1448.0	11848	16.04	36.57	8.18
X	6/12	90	1062.1	5299	10.05	29.44	4.99
Totals		1291	13270.1	107092			
Means					17.63	41.48	8.07

Table 2.4.3(a) Vacuum Pump Electricity Use on twelve farm dairies in 1980-82.

The milk production and vacuum pump figures for farm L cover an 18-month period and farms E and K increased the size of their parlours to 12/12 and 16/16 respectively during the audit.

Generally the vacuum pump is the third highest user of electricity in the dairy. The percentage of total figures should again be treated with caution as the total may vary for reasons not connected with the vacuum pump.

The electrical cost of running the vacuum system varied from 29.44 kWh/cow/year at Farm X to 56.04 kWh/cow/year at farm D where an unusually large pump motor (3kW) for the size of the plant, was in operation. Farm F also had a high electrical cost, but the remainder of the farms were all in the range 35 to 50 kWh/cow/year. The effect of the low yield of the Jersey breed at farm D is seen when the figures for vacuum pump electricity are related to the volume of milk extracted. Here the electricity cost was just over twice the mean for all the farms. The range for the remaining farms was from just under 5kWh/m^3 to just over 10 kWh/m^3.

The energy use by any particular vacuum pump will be a function of the power drawn and the running time. In normal circumstances the pump will be running only during milking and the plant cleaning period which follows. The period of plant cleaning will not vary greatly from day to day and consequently the main variation in vacuum pump running costs for any farm will be due to variation in the duration of milking. This in turn will vary with both the number of cows to be milked and the volume of milk to be extracted.

Regression analysis was used to investigate this association. Separate regressions of the vacuum pump electricity on the number of cows in-milk and on the volume of milk extracted, were carried out, followed by multiple regression analysis using both predictors. Regression of vacuum pump electricity on the number of cows in-milk produced Coefficients of Determination ranging from zero at farms J and X to 78.7% at farm M. The

Farm	Regression Equation	R^2(%)
A	$y = 165 + 1.64x_1 - 0.246x_2^*$	28.9
B	$y = 62 + 2.49x_1 + 0.944x_2^*$	73.4
C	$y = 69 - 0.99x_1^* + 3.270x_2$	49.1
D	$y = 205 + 3.25x_1 + 0.918x_2^*$	61.3
E	$y = 396 + 11.20x_1 - 4.800x_2$	76.0
F	$y = 223 + 2.67x_1^* + 1.640x_2^*$	52.8
H	$y = 259 + 1.77x_1 + 1.000x_2^*$	79.4
J	$y = 307 + 3.09x_1 + 0.088x_2^*$	56.6
K	$y = -50^* + 4.11x_1^* + 2.450x_2^*$	10.3
M	$y = 183 + 4.15x_1 + 0.500x_2^*$	90.5
X	$y = 339 + 3.27x_1 - 2.990x_2^*$	12.9

Table 2.4.3(b). Multiple Regression Analysis of Vacuum Pump Electricity (y) (kWh) on Number of Cows in-milk (x_1) and Volume of milk produced (x_2)(m^3) for 11 farm dairies in 1980-82. All coefficients significant (P>0.95) except those marked with an asterisk.

intercept terms were significant (P>0.95) at all farms except E and K and the gradient terms were significant (P>0.95) at all farms except A, J and X. Regression analysis of vacuum pump electricity on volume of milk extracted produced marginally higher Coefficients of Determination at all the farms, the range being from zero to 90.5% at farm M, with seven farms having figures of over 50%. The multiple regression analysis results are given in Table 2.4.3(b). Use of both factors as predictors added little to the accountability of the variation. This should be expected since the volume of milk extracted and the number of cows milked are highly correlated. The intercept term was significant (P>0.95) at all farms except farm K and the x_1-term coefficient at all farms except C, F and K. The x_2-term coefficients were only significant (P>0.95) at farms C and E. Seven of the farms had R^2 figures of over 50%.

Given that there is a relationship between vacuum pump electricity and the volume of milk to be extracted, it follows that the vacuum pump electricity use will follow a seasonal trend similar to that of the milk production pattern. Figure 2.4.3 shows the weekly electricity use by the vacuum pump and the weekly milk production for farm B for the first year of the audit.

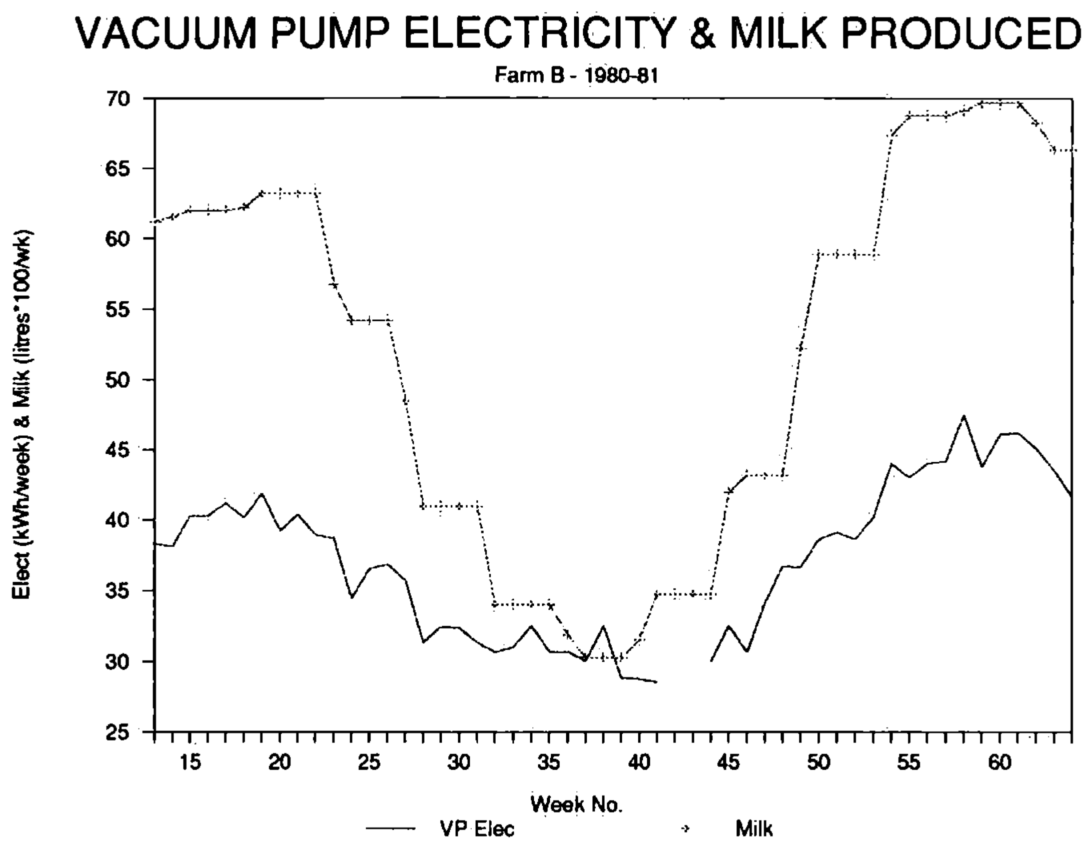


Figure 2.4.3 Vacuum Pump Electricity use and Milk Production at Farm B during 1980-81.

In view of the variability of the R^2 figures for this analysis, it would be dangerous to attempt to develop a representative equation which could describe the vacuum pump electricity in any circumstances. It has been noted that duration of milking time will be the major influence in the variation in vacuum pump electricity use and that this variation may be approximated by the equations shown above. However, the basic duration of milking, before any variation takes place, will depend on a number of other factors such as established work routines, individual cows' inherent speed of milk release, extent to which stripping out is practised, and the extent to which feeding and medication are carried out in the parlour. It seems reasonable, however to expect vacuum pump electricity to fall generally within the range 5 to 10kWh/m^3 of milk extracted, or, on an annual basis, 35 to 50 kWh/cow.

2.4.4 The Water Heater.

The review of literature suggested that heating water in the farm dairy was likely to be the major use of electrical energy and that this area probably offered the greatest potential for energy saving. As a consequence a separate study of heated water in the farm dairy was recommended. This parallel study was carried out by Norman, A.J. and has been reported separately. The present report will therefore confine itself to general comments insofar as they relate to electricity use by the water heater in the context of the total parlour and dairy electricity use.

The first year of the audit revealed that the electrical energy input for water heating for plant cleaning was not normally the highest, but in fact usually used rather less electricity than the bulk milk tank. Only at farms C, D and L was the water heater the highest user of electrical energy in the dairy. Farms C and L used the Acidified Boiling Water (ABW) method of plant cleaning, which is known to have a higher requirement in respect of temperature and volume than the more commonly practised Circulation Cleaning (CC) method used by the other farms. At farms C and L the proportion of the total electrical energy input to the dairy and parlour attributable to the water heater was 50.7 and 40.4% respectively.

2.4.5. The Udder Washer

All the monitored farms have a system for providing warmed water for washing udders. However the extent of the use made of this system varies considerably between farms. Many of the farms take advantage of this supply to wash the outside of the jars and clusters at the end of each milking. Farm C makes use of the facility in winter only, using cold water for udder washing in the summer. Table 2.4.5 summarises the audit of the udder washing system on 12 farms. The percentages of total electricity used by the udder washer show that it is not a major user. The heating of water to, typically, 40°C represents a potential use for low-grade, reclaimed heat and farms E and K have taken this approach, using a plate cooler and heat recovery unit respectively to provide this energy, and have achieved a relatively low electrical cost per cow per milking as a result. The high cost of electricity for udder washing at farm M requires explanation. Here there is a relatively large heating cylinder with two 3kW elements which remain switched on with no time controls. On several occasions leaking nozzles were noticed, resulting in excessive wastage.

Personal attitudes account for a great deal of the between-farm variation. Management policy will determine the state of general cleanliness, through control of the cows' environment, namely housing and grazing or feeding conditions. Beyond this, the herdsman is then required to make a subjective decision as to what is sufficiently clean at the time of milking. This can lead to a great deal of variation as seen in the final column of the table.

The detailed study of electrical energy for use by udder washing systems forms part of the study into heated water in the farm dairy previously referred to.

Farm	Mean No. of cows in-milk	Electricity use by the Udder Washer	Percentage of total electricity	Electricity used per cow per milking
		kWh		Wh
A	53	1304	9.9	33.7
B	46	1091	9.9	32.5
C	49	588	2.8	16.4
D	61	1042	5.6	23.4
X	79	1518	5.3	26.3
E	106	1373	6.0	17.7
F	106	2986	12.7	42.6
H	96	1948	6.3	27.8
J	96	2241	7.0	32.0
K	121	1297	4.2	14.7
L	125	1942	4.7	21.3
M	164	7947	17.1	66.4

Table 2.4.5 Electricity use by the udder washing system on 12 farms during 1980-81.

2.4.6. Lighting

Lighting in the dairy and parlour accounts for about 2% of the total electrical input. The variation is associated with differences in penetration of natural light, which relates to the type of building housing the dairy complex.

The surveyed farms have been classified in table 2.4.6 by three levels of light penetration and three types of building.

Building Type	Light Level	No. of farms	Mean electricity used for lighting	% of total electricity
			kWh/annum	
New	Light	2	301	1.5
Traditional	Light	1	806	2.8
Traditional	Medium	3	449	2.1
Traditional	Dark	1	1560	5.1
Old	Dark	4	733	2.3

Table 2.4.6 Electricity used for lighting classified by building type on 11 farms in 1980-81.

Both of the new purpose-built installations had very good penetration of natural light and also had the lowest lighting costs. The five traditional buildings showed some variation in the light penetration, the darkest of these having the highest lighting cost of any of the farms.The old buildings were all classified as dark, but in fact had a very similar lighting cost (733 kWh/farm/annum) to the mean of the five traditional buildings (743 kWh/farm/annum).

The annual figures for lighting cost disguise the seasonal variation present in the data. Almost all farms show a variation with daylength. However, the poorly lit parlours require artificial illumination during the summer months when the well-lit parlours require little or no artificial lighting. This is illustrated in figures 2.4.6(a) and (b). Farm H is poorly lit and the summer requirement is approximately half the winter requirement. In contrast, farm F, a purpose-built parlour with good natural light penetration has little or no artificial lighting cost in the summer.

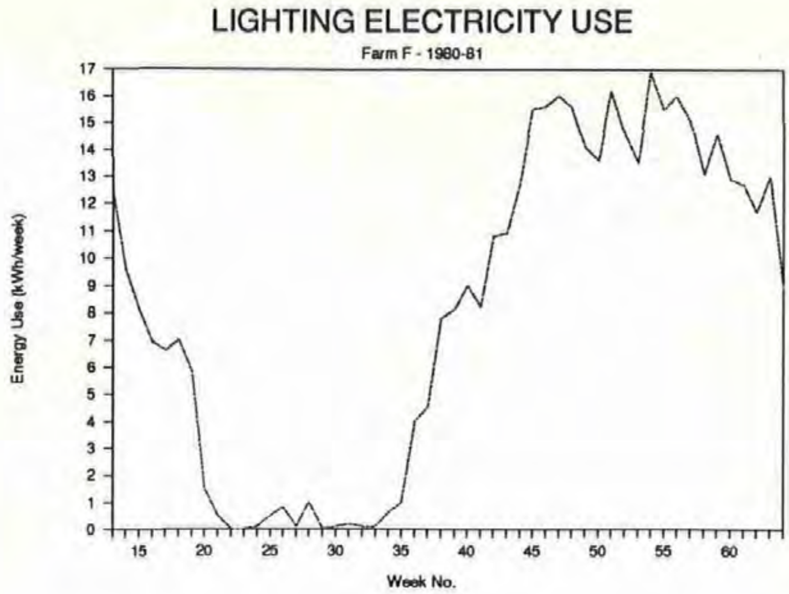


Figure 2.4.6 (a) Weekly electricity use for lighting at farm F during 1980-81

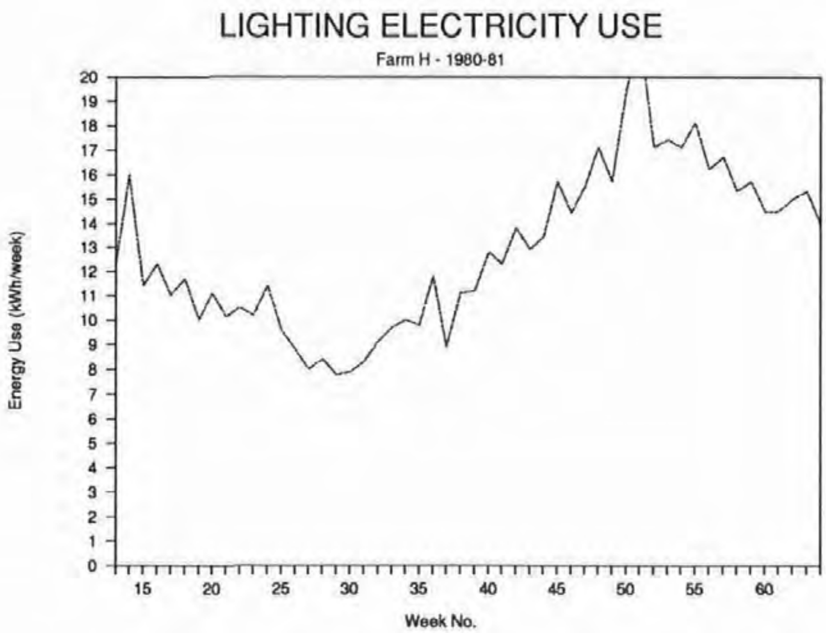


Figure 2.4.6 (b) Weekly electricity use for lighting at farm H during 1980-81

2.4.7 Minor Components of the System.

The remaining components of the milking and cleaning system account for only 1 - 3% of the total electricity used. However these have been individually metered at farm X and the results are now presented.

During the two years of metering at farm X, the weekly electricity use by the milk lift pump varied from a minimum of 0.8 kWh/week to a maximum of 1.6 kWh/week. The lower consumptions were associated with lower seasonal levels of milk production.

Weekly electricity use by the pulsator varied from 0.6 kWh/week to 1.4kWh/week, with the lower consumptions again associated with the lower seasonal levels of production.

At farm X there are two bulk milk tanks each with an automatic tank rinser. Weekly electricity use for each was 0.1 or 0.2 kWh/week, the variation being due to resolution of meter reading accuracy.

Electricity use by the power hose pump was significantly correlated ($P>0.99$) with the volume of water used. The mean use of water for cleaning the parlour was $9.8m^3$/week and the mean electricity use by the pump was 3.8 kWh/week.

2.5 Conclusions from the Audit

The audit has suggested that previous estimates of the total electricity use in the dairy and parlour were rather high. Previous estimates together with the two years of audit data are presented in Table 2.5.1

	Total Electricity Use	
	kWh/cow	kWh/m^3
Bayetto et al. (1974)	344	-
Shropshire Farm Institute (1967)	406	82.8
Shropshire Farm Institute (adjusted)	339	-
Electricity Council (1978)	299-357	-
Audit Year 1	251	46.9
Audit Year 2	237	48.5

Table 2.5 .1 Summary of previous and present estimates of total electrical energy use in the parlour and dairy.

Against the other estimates, the audit data for the two years shows a high degree of consistency. Both years, however, produce figures noticeably lower than the other estimates.

There are two reasons to have confidence in the audit data compared with the other estimates:

- The data are based on two whole years of detailed auditing. Limitations relating to this point in other work have already been mentioned.
- The data are the result of auditing a range of farms with a variety of herd sizes, season of calving, milk yield and equipment installed. The resulting database is considerably larger than any previous work has generated.

The audit data are not without limitations themselves. Geographical limitations confined the survey to an area of South Devon. This region differs from the remainder of the country in generally having milder weather. The effect of the higher temperature will be an increase in milk cooling costs and possibly a small decrease in water heating costs. On balance it seems likely that the total energy costs might be slightly higher in the South West than elsewhere.

The farms surveyed do not, strictly, represent a truly random sample from the population of all farms. It may be argued that farmers were willing to participate because of an inherent interest in energy conservation, and there can be no doubt that this comment may be applied to the owners of farms E and K. However this argument does not necessarily invalidate the results from any farm as being atypical, and in fact farm E had to be excluded from the analysis of total electricity for the reasons referred to earlier. It may also be argued that a sample of farms where the owners and operators had a genuine concern for energy efficiency, was necessary in order to ascertain reasonable targets for all farms.

The conclusion drawn therefore was that the audit has produced a good estimate for the total electricity use in the farm dairy and parlour for the South Devon area and other areas where similar ambient conditions prevail, and a reasonable estimate for other areas. That estimate is that the electricity use will be approximately 250 kWh/cow/year (The standard error of this mean was ±14 kWh/cow/year). Colder areas of the country will have a slightly lower figure, unless space heating is in use, a factor excluded in the current survey. It is important that this figure is considered over a full annual cycle and not scaled down, for to do so introduces such variables as calving pattern which will greatly influence the figure for any period other than a whole year.

The lowest figures achieved were 204 kWh/cow/year in the first year of the audit and 200 kWh/cow/year in the second year of the audit. Both of these results were achieved without the use of any form of conservation equipment.

The best results for each component were extracted from the first year's data in an attempt to estimate whether still better performances were possible. The results of this analysis are presented in Table 2.5.2.

Component	Farm	kWh/cow/annum
Bulk Tank	L	108.77
Vacuum Pump	X	29.44
Water Heater	A	31.80
Udder Washer	C	9.80
Lights	A	2.67
Others		3.52
Total		186.00

Table 2.5.2 Lowest mean electricity consumptions per cow for each of the components of the dairy and milking parlour for the first year of the audit.

The allowance for other items, 3.52 kWh/cow/year was calculated by taking the median values from the ranges for tank rinsers, power hose pump, pulsators and feeders at Farm X, multiplying by 52 and dividing by the mean number of cows in the herd.

The resulting total of 186 kWh/cow/year represents the theoretical figure which any farm might have returned had they operated each component at the same level of performance as the best farm for that component. The influence of any energy conservation equipment has been removed in compiling the table.

It may also be concluded that variation in the total electricity is likely to be most influenced by variation in the milk volume. Here it seems that a figure of

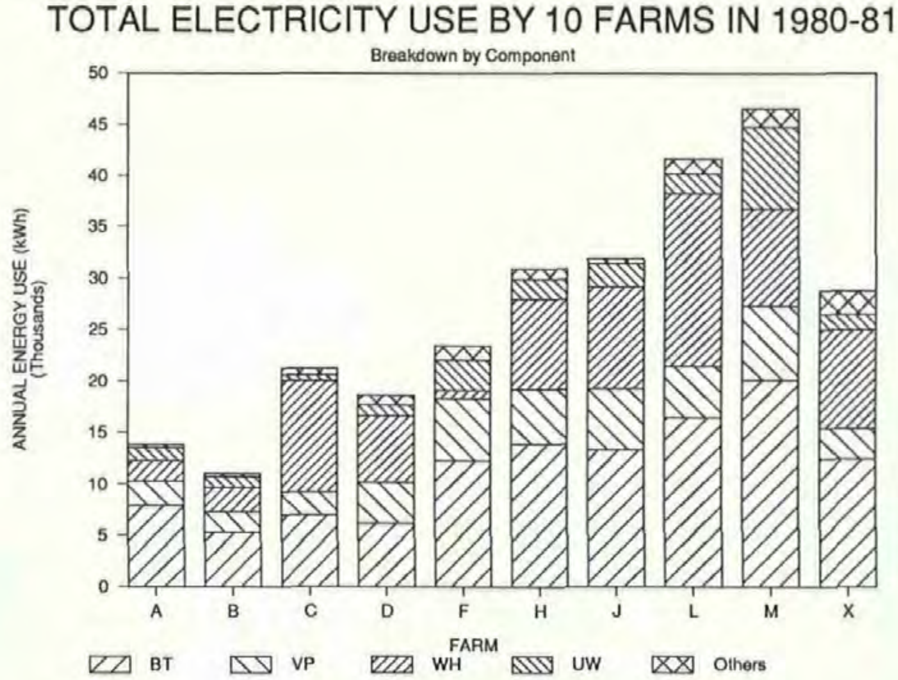


Figure 2.5 Breakdown of total electricty use by component at ten farms during 1980-81.

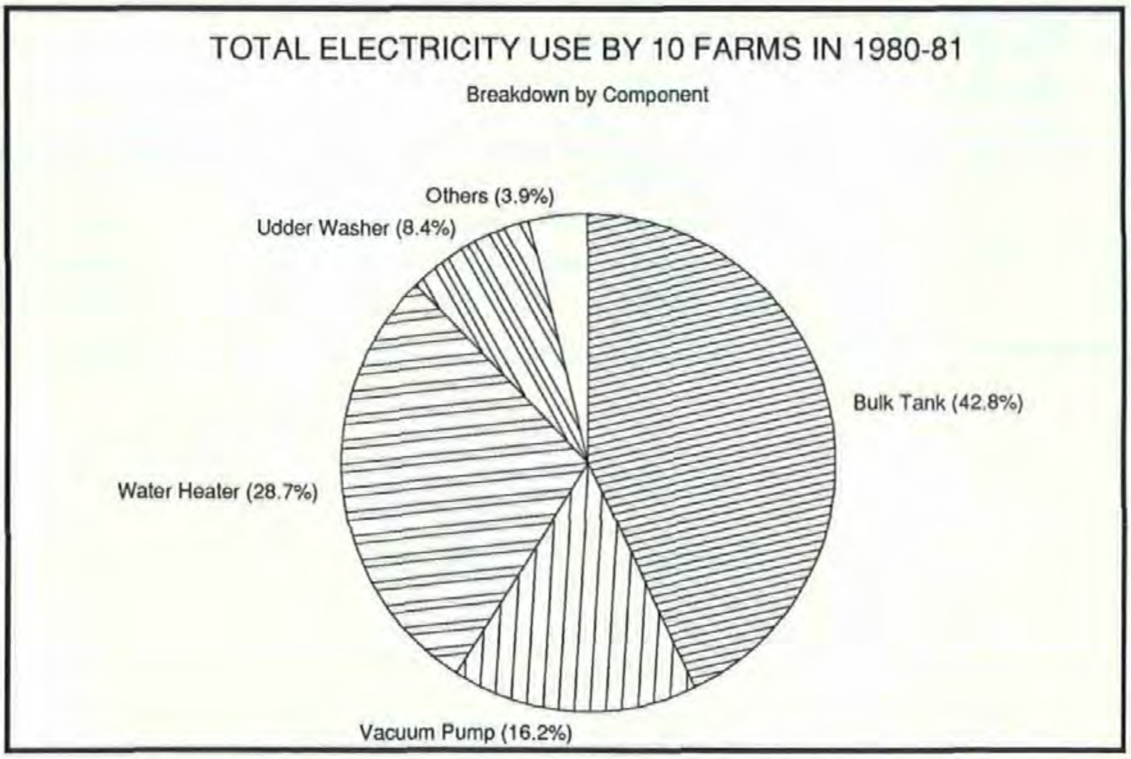


Figure 2.6 Breakdown by component of the total electricity use in 10 farm dairies in 1980-81.

between 45 and 50 kWh/m^3 can be expected as typical, but Jersey herds can expect a significantly higher figure.

Figure 2.5 shows the breakdown of the total electricity use by component for the first year's data for each of the farms and figure 2.6 shows the breakdown diagrammatically for all farms.

The bulk milk tank has been identified not only as the heaviest user (43% of the total) of electrical energy in the dairy but as the component whose variation highly influences the variation in total electricity. Again the figures should be considered only in the context of a whole year.

The two major factors to affect the bulk tank's electricity consumption have been seen to be the volume of milk to be cooled and the ambient temperature, these factors accounting for a very high proportion of the variation, and a representative equation has been proposed as a working model for predicting the annual energy use for cooling milk in tanks of the size and type examined. This equation is unable to predict the variation in energy requirements within the annual or daily cycle, and the modelling stage of the work has attempted to address this problem.

The vacuum pump was found to show some relationship with the volume of milk extracted but the predictability of this relationship was poor. It seems that a number of factors, not considered quantitatively in this work, are also involved. These factors relate specifically to the basic work processes in the parlour and possibly to genetic or acquired basic differences in the milking speed of individual cows. A further contribution towards understanding the variation in vacuum pump electricity might be made by research in the area of method study where it applies to the milking process.

The electricity used by lights in the dairy and parlour is not a very significant proportion of the total and offers little scope for reduction except in the case of new building design, where a consideration of natural light penetration will result in lower costs for lighting throughout the life of the building. Frequently, though, the parlour and dairy are sited in old converted buildings or in traditional buildings where the natural lighting was not a major design feature.

3. THE BULK TANK MODEL

3.1 Modelling Methodology

The audit yielded a series of regression equations, one of which predicted the electricity use by the bulk milk tank over a period of time, given the ambient temperature and the volume of milk to be cooled. An intermediate stage of development of this equation was in close agreement with other work. The equation may be regarded as a static, empirical model. While this is useful in providing confirmation of earlier work, and as a predictive tool over a period of time, its limits are not known and it does not describe the course of events within the time period. There is no indication of peak demands or whether the tank's objectives are being met in respect of the rapid cooling of milk after filling.

What is required to satisfy these points is a dynamic model containing the time variable. This would allow examination of the electricity use and timing over a daily cycle and a full annual cycle. Where possible this model needs to be mechanistic in that it needs to provide a description of the behaviour of the bulk tank in terms of the processes involved in cooling milk.

The model developed examines the performance of a bulk milk tank from the time the milk arrives at the tank to the time when it has been cooled to the target temperature, and the cooling reserve has been restored. It has, as output, information showing the use of electricity over the period and information relating to the milk temperature since the prime objective of a bulk milk tank is to cool its nominal capacity of milk to 4°C within 30 minutes of the end of each of its two filling periods and to maintain this temperature until the milk is removed.

Development of the model commenced with an examination of the bulk tank system.

3.2 Bulk Tank System Analysis

The bulk milk tank system is designed to achieve a rapid flow of heat from the milk arriving at the tank and stored in it, into a chilled water medium which is maintained at a low temperature by the presence of an ice-bank, acting as a cooling reserve. The ice bank is built up by a refrigeration system which is ultimately responsible for disposing of the heat originating in the milk. The heat transfer and mass transfer are represented diagrammatically in figure 3.2.

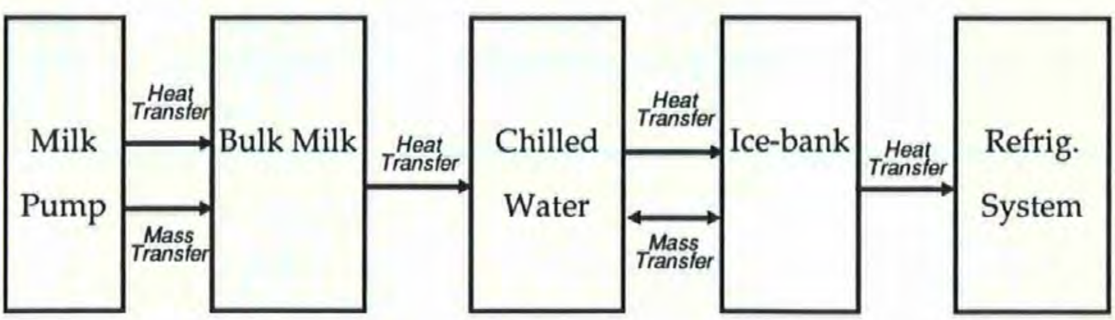


Figure 3.2 Diagrammatic representation of the processes operating in a Bulk Milk Tank.

Because the mass, and therefore the enthalpy, of the milk in the milk vessel increases throughout the milking period, the rate of heat transfer to the chilled water is not constant. Consequently the flow of heat through the rest of the system is also not constant. This feature justifies the use of a dynamic model in which the time variable features.

The model which has been developed, simulates the process shown in figure 3.2 from the additions of milk up to the point where heat is transferred from the tank by the refrigeration system. This process is examined in three stages:

i) The addition of milk to the contents of the milk vessel

ii) The cooling of milk by heat transfer through the milk vessel walls and floor into the chilled water medium.

iii) Heat transfer from the chilled water to the ice-bank and the associated mass transfer.

The major proportion of the electricity use by the bulk tank as a whole is attributable to the compressor, the minor users being the milk agitator motor and the chilled water agitator motor. Operation of the compressor is under the control of a sensor which starts the operation as the ice-bank diminishes in size and stops the operation when the ice-bank is restored to a pre-set level. The physical dimensions of the ice-bank are therefore major variables controlling the extent and timing of the electricity use by the compressor.

A number of the rate variables in the model have been derived by empirical methods, there being no reference in the literature to previous work of modelling any similar systems.

The model was developed initially by reference to the system and practice associated with the Seale-Hayne bulk milk storage system, which consists of two 1365 litre sump and spray bulk tanks. This system was selected for convenience of measurement and checking. Empirical determination of parameters and variables was carried out on a 2500 litre sump and spray bulk tank in laboratory conditions at Plymouth Polytechnic.

3.3 Addition of Milk to the Milk Vessel.

The milk vessel is constructed of stainless steel and is approximately rectangular in shape. The floor is shaped as a shallow vee to enable milk to drain towards the central lateral line when emptying. The floor also has a shallow fall towards the end with the drain plug. Milk enters the vessel from a pipe connecting the tank with the milk receiver jar delivery pump. The pump does not operate continuously, but switches on when the receiver jar above it is approaching full capacity and switches off when the jar has been emptied. Milk therefore arrives at the tank in intermittent, discrete quantities. Milk is agitated in the tank by a flat-bladed paddle suspended into the tank and driven by an electric motor above. Larger tanks may have two agitators. A thermometer is also suspended in the milk. Agitation is under control of a thermostat and will be in operation whenever the milk temperature exceeds 4°C.

At this stage the model needs to calculate two state variables. These are the mass and temperature of the milk in the tank. The product of these and a constant, namely the specific heat capacity of milk, will yield an auxiliary variable, the enthalpy of the milk in the tank, which is the subject of the subsequent cooling process.

The mass of milk in the tank is added to intermittently by deliveries from the receiver jar, and a simple additive model describes this for a time period, t

$$M_3 = M_1 + M_2 \tag{3.3.1}$$

where M_1 is the mass of milk added in time t

M_2 is the mass of milk in the tank at time T

M_3 is the mass of milk in the tank at time T+t

Calculation of the temperature of milk in the tank following an addition of milk, depends upon the assumption that the enthalpy of milk in the tank and milk added may be treated additively to give the enthalpy of the increased contents. Thus:

$$M_3CpT_3 = M_1CpT_1 + M_2\,CpT_2 \tag{3.3.2}$$

where M_1, M_2 and M_3 are masses of milk as in equation 3.3.1

Cp is the specific heat capacity of whole milk (3918 $JKg^{-1}K^{-1}$)

T_1 is the temperature of the milk added from the delivery pump (K)

T_2 is the temperature of milk in the tank before the addition,(K)

T_3 is the temperature of the milk in the tank after the addition, (K)

Equation 3.3.2 may be rearranged to make T_3 the subject:

$$T3 = \frac{Cp(M_1T_1 + M_2T_2)}{M_3Cp}$$

The specific heat capacity term cancels and equation 3.3.1 may be substituted to give:

$$T_3 = (M_1T_1 + M_2T_2)/(M_1 + M_2) \tag{3.3.3}$$

Equation 3.3.3 assumes a steady state, in which there is no loss or gain of temperature during the timestep t. In practice the cooling process takes place continuously if the milk temperature exceeds 4°C. The cooling effect upon the accuracy of equation 3.3.3 will become progressively less significant as the timestep variable, t, is reduced. The model was initially developed with a one-minute timestep.

The delivery pattern of milk to the tank was recognised as being an important feature. In practice the filling pattern of a bulk milk tank will depend on a number of factors relating to the characteristics of the milking parlour and equipment and to the herdsman's operating practices. These factors include:

- The cow throughput rate and the volume of milk to be extracted.

- The ratio of milking units to receiver jars. Some larger parlours have two receiver jars which are emptied in parallel. In such cases the volumes delivered to the tank will be greater and less frequent than a similar parlour with only one receiver jar.

- Operator practice. Some herdsmen will release milk from the jars at each milking point to the receiver jar after each cow has finished milking. Others will only release milk to the receiver jar when each milking jar is almost full. In the latter case larger volumes of milk will arrive at the receiver jar and these larger volumes may continue arriving after the milk pump has commenced emptying the receiver jar. This is likely to be followed by longer periods of inactivity.

- The sensitivity and setting of the milk pump controls. Generally the controlling mechanism will be one of two types. The milk pump may be triggered by the mass of milk in the receiver jar above. In this case the jar is spring-mounted and the pump is operated by a float switch. Alternatively, the milk receiver jar may contain two probes which will sense the depth of milk in the jar and operate the pump when a pre-set depth has been reached.

Investigations were carried out to establish typical milk delivery patterns and temperatures.

3.3.1. Investigation of the milk delivery pattern.

Six of the audit farms were investigated to gain further knowledge of the milk delivery patterns. Variation may involve changes in the frequency of delivery pump operation or may involve changes in the volume of milk delivered at each delivery.

Differences in the frequency of milk pump operation are likely to be related to individual farm practices and equipment, such as the herdsman's routine or the ratio of milking places to receiver jars. Thus the frequency of milk pump operation will be a farm-related function, whereas seasonal variations in the volume of milk handled will be associated with variation in the volume delivered at each delivery.

An appropriate approach to modelling this aspect therefore involved establishing a suitable estimate of the frequency of milk pump operation. Knowing the total volume of milk handled and the length of the milking period, the volume delivered each time may then be calculated.

The six farms investigated included a spread of parlour sizes from 5/10 to 10/20. The results are given in Table 3.3.2.

Farm	Parlour Size	Frequency (mins)
A	5/10	3.4
G	10/10	2.7
J	8/16	3.7
K	12/12	1.4
M	10/20	1.8
X	6/12	4.2

Table 3.3.2. Frequency of milk pump operation with parlour sizes at six farms in South Devon.

It is difficult to draw a statistically sound inference from these data , but there seems to be a trend for the larger parlours (e.g. K and M) to show more frequent milk pump operation (every 1.4 and 1.8 minutes respectively). Farm J, the same size as Farm M, however, does not support the argument very well. The two smaller parlours at A and X certainly had lower frequencies of operation, while G was approximately mid-range. The frequency was measured as the mean time between starts of the milk pump motor.

The approach taken to the problem was to incorporate a two-minute frequency of pump operation for larger parlours, i.e. 8 or more milking units, and a four-minute frequency of operation for smaller parlours, i.e. 7 or less milking units.

3.3.2 Investigation of the milk delivery temperature.

Milk is produced at a temperature very close to the cow's body temperature, 38°C. In its passage through the milk jar and the milk pipe to the delivery jar, the milk will lose some of its heat to the surrounding atmosphere.

A total of 30 investigations was carried out on six of the audit farms without pre-cooling. The mean temperature at delivery was 32.5°C with a relatively narrow range from 31.0 to 33.9°C. Temperatures were measured with the hand-held digital thermometer whose calibration has been previously described.

3.4 Cooling of Milk.

Milk is cooled by heat transfer through the milk vessel walls into the chilled water medium surrounding it. The heat transfer occurring here is an extremely complex process and the literature contains no references to work examining it.

In the case of a sump and spray tank the milk vessel is not submerged in the sump of chilled water. The chilled water in fact forms a sump underneath the milk vessel, and is pumped to the top of the milk vessel walls where it gravitates as a thin film back to the sump. There is a cooling effect caused by the impinging jet of chilled water on the wall of the milk vessel, but this effect is limited to the top 2 to 3 cm at the top of the wall. This aspect has been ignored in the current work for three reasons. Firstly the milk only reaches this level on the inside of the tank on the occasions when the tank is filled to capacity. Secondly, by the time the milk reaches this level it is substantially cooled already. Thirdly the area affected is a very small proportion of the total wetted area.

The current work therefore assumes that the heat transfer is by convective heat transfer on both sides of the milk vessel wall with conductive heat transfer through the wall itself. The approach to modelling this stage of the process has been to develop a model of the heat flow across the wall from theoretical considerations using an overall heat transfer coefficient. The objective was to develop a means of predicting the milk temperature inside the milk vessel at the end of a timestep during which the heat transfer has proceeded.

From first principles the reduction in energy content of the mass of milk must equal the convective heat losses to the cooling water during the time period t, assuming zero inputs of power to the system.

$$-\Delta E/\Delta t = Q_C \tag{3.4.1}$$

where $\Delta E/\Delta t$ is the rate of change of energy content of the milk

Q_C is the convective heat loss

Multiplying by Δt and rearranging gives:

$$0 = \Delta E + Q_C\Delta t$$

But the energy change ΔE is given by:

$$\Delta E = MCp(T_{\tau+1} - T_\tau)$$

where M is the mass of milk in the milk vessel (Kg)

Cp is the specific heat capacity of milk (3918 $Jkg^{-1}K^{-1}$)

$T_{\tau+1}$ is the temperature of milk at the end of the timestep,(K)

T_τ is the temperature of the milk at the start of the timestep, (K)

The convective heat transfer rate Qc is given by:

$$Qc = UA\theta$$

where U is the overall heat transfer rate, ($Wm^{-2}K^{-1}$)

A is the area through which heat is transferred,(m^2)

θ is the difference between the mean milk temperature and the mean chilled water temperature, (K)

Combining these equations gives:

$$0 = MCp(T_{\tau+1}-T_{\tau}) + UA\Delta t\ ((T_{\tau+1}+T_{\tau})/2-Tc)$$

where Tc is the chilled water temperature,(K)

This expression relies upon a finite difference approximation, i.e. $(T_{\tau+1}+T_{\tau})/2$ to represent the mean temperature of the milk throughout the timestep. This approximation becomes more valid as the timestep becomes smaller.

Rearranging gives:

$$0 = MCp(T_{\tau+1}-T_{\tau}) + UA\Delta t((T_{\tau+1}+T_{\tau})/2) - UA\Delta tTc$$

Removing the brackets gives:

$$0 = MCpT_{\tau+1} - MCpT_{\tau} + UA\Delta tT_{\tau+1}/2 + UA\Delta tT_{\tau}/2 - UA\Delta tTc$$

Rearranging gives:

$$-UA\Delta tT_{\tau}/2 + UA\Delta tTc + MCpT_{\tau} = MCpT_{\tau+1} + (UA\Delta t\ /2)T_{\tau+1}$$

The right-hand side of the equation may be rearranged to read:

$$T_{\tau+1}(MCp + UA\Delta t/2)$$

Finally, the whole equation may be rearranged to make $T_{\tau+1}$ i.e the milk temperature at the end of the timestep, the subject of the equation:

$$T_{\tau+1} = \frac{-UA\Delta tT_{\tau}/2 + UA\Delta tTc + MCpT_{\tau}}{MCp + UA\Delta t/2} \qquad (3.4.2)$$

This equation relies on three assumptions:

- That all the heat loss from the milk is through the milk vessel walls and floor to the chilled water. In practice, a small amount of heat will be lost into the air volume above the milk. This volume of air is approximately 1 to 4m^3, depending on the size of the tank. The small mass of air, 1 to 5 kg, was considered insignificant and this factor was ignored. Similarly a small volume of heat will be utilised in raising the temperature of the stainless steel walls of the milk vessel. The mass of stainless steel involved will vary with the size of the tank but is unlikely to exceed 100kg. If the entire mass were to rise by 10°C, then approximately 0.5MJ would be taken up. 2500 litres of milk cooling from 32.5°C to 4°C will lose approximately 300 MJ, and the effect of the warming of the walls and floor, which is only transitory, has been ignored.

- That the chilled water remains at the same temperature throughout the timestep. Observation of tanks in operation showed that the chilled water at the start of the milking process was usually at about 1°C and during a two-hour filling period this might rise to a temperature in the range of 4°C to 7°C, before returning to the starting level. The change of temperature within a short timestep was therefore considered to be insignificant and the temperature at the start of the timestep was assumed to prevail throughout the timestep. It was, however, recognised that the chilled water temperature should be recalculated between timesteps.

- That the mass of milk remains unchanged throughout the timestep. This requires the assumption that within a timestep when there is a delivery to the tank, the milk arrives over an infinitely short period at the beginning of the timestep. The error associated with this assumption becomes less significant as filling proceeds, because each subsequent addition of milk increases the total mass of milk by a less significant amount.

Equation 3.4.2 may be used to calculate the milk temperature after a suitable timestep during which cooling has taken place. At the end of the timestep the resulting milk temperature may be used as the starting temperature for the following timestep. Also at the end of the timestep a further calculation needs to be carried out to recalculate the chilled water temperature as a result of the heat it has gained from the milk. It has been noted that, for the assumptions to remain valid, the timestep should be as short as possible. This type of repetitive, detailed recalculation lends itself to computer-based methods and further development of the model was carried out using the programming language BASIC on PDP11 and Apple II computers and later using the programming language 'C' on IBM PC and AT compatible computers.

Equation 3.4.2 contains a constant, Cp, the specific heat capacity of whole milk, which is 3918 $Jkg^{-1}K^{-1}$. It contains two parameters, Δt and U, the timestep in seconds, and the overall heat transfer coefficient ($Wm^{-2}K^{-1}$) respectively. It also contains four state variables which need to be calculated before the equation can be solved. The mass of milk in the tank, M (kg), remains the same as the previous timestep unless there is an addition to the tank, in which case it is given by equation 3.3.1. The area over which heat transfer takes place, A (m^2), can be calculated, given the physical dimensions of the tank and a knowledge of the volume of milk in the tank. The volume of milk was calculated using 1.032 kgm^{-3} as the specific gravity of whole milk. The chilled water temperature, Tc (°C) was taken as 1°C at the start of the filling period and this temperature applies to the first timestep. Subsequently the chilled water temperature as calculated from the next stage of the process, was fed back into equation 3.4.2. The milk temperature at the beginning of the timestep was taken as the milk temperature at the end of the previous timestep, unless there was an addition of milk to the tank in which case it was given by equation 3.3.3.

All the variables and the constant in equation 3.4.2 can therefore be calculated, or are known. The timestep parameter was set at one-minute as a compromise between the accuracy required and the length of processing time to simulate a complete cooling process. The overall heat transfer coefficient (U) was not known.

The heat transfer process from the milk to the chilled water is complex, involving convective heat transfer in the two fluids on either side of the stainless steel wall and conduction through the wall itself. During the cooling process, the milk is agitated by means of the agitator paddle and conditions are such that turbulent flow at the inner face of the wall is likely to be in operation. On the cold face, the chilled water is in the form of a thin film of water of varying thickness gravitating down the wall and along the underside of the floor. Forced convection is likely to be in operation here. The literature gives no guidance towards quantifying these convective heat transfer coefficients and there is no record of work attempting to determine them for this tank geometry. Experiments were therefore designed to produce an empirical determination of the overall heat transfer coefficient.

3.4.1. Experimental determination of the 'U'-value of the milk vessel.

The heat transfer process is a function of the mass of milk to be cooled, the milk contact area ("wetted area") and the temperature gradient across the wall or floor. By measuring the fall in temperature of a known mass of milk, cooled through a known area, it is possible to calculate the overall heat transfer rate.

To carry this out in farm conditions was impracticable. For the accuracy required, it would have been necessary to record the mass of each addition of milk. Alternatively recording could have started when the last addition to the tank had arrived, but by this time the bulk of milk would have been substantially cooled leaving only a short period of time, with a relatively small temperature gradient, available for recording, before the cooling process ended.

Instead, it was decided to carry out the experiment in the laboratory. A 2500 litre sump and spray bulk tank was made available by the manufacturers and this was installed in the thermodynamics laboratory at Plymouth Polytechnic. Warm water was used in place of milk. This avoided the risk of waste of a valuable consignment of milk and allowed examination of the 'U'-value over a wider temperature range.

Since the convective heat transfer coefficient, and consequently the overall heat transfer coefficient, will differ for a horizontal plate and a vertical plate, it was necessary to repeat the experiment with different volumes of warm water to quantify this difference. The experiment was performed three times. On the first occasion only sufficient warm water to cover the floor was added. The second and third experiments involved the tank being approximately half full and full respectively.

Before the experiments commenced, the internal dimensions of the milk vessel were carefully recorded in order to calculate the floor and wall areas. Water was metered into the tank and it was found that 305 litres were required to cover the floor area before any significant wall area became wetted. The chilled water vessel was filled to the recommended level, but the compressor motor was left switched off. Temperatures were recorded by connecting low thermal inertia thermocouples to an analogue to digital converter installed in an Apple II computer. The analogue to digital converter used was an AI13 Analogue Input System with 12-bit (0.024%) resolution. The system was calibrated by reference to a mercury-in-glass thermometer of known accuracy

In the first experiment, 305 litres of warm (60°C) water was pumped rapidly into the milk vessel. The milk agitator motor and chilled water pump motor were switched on and allowed to run for one minute to ensure an even temperature distribution in each of the two fluids. Recording of the "milk" and chilled water temperatures then started and continued at one minute intervals until the temperatures of the two fluids were within 2°C of each other.

In the second experiment, 1354 litres of warm water was pumped rapidly into the milk vessel. This was allowed to settle and the depth carefully recorded for subsequent calculation of the wetted wall area. The milk agitator and chilled water agitator were then operated for one minute and recording proceeded as before.

The third experiment followed the same pattern, except that 2383 litres of warm water was used, to take the tank very close to full capacity, utilising as much of the wall area as possible.

By recording the warm water temperature at one-minute intervals, and knowing the mass of warm water, it was possible to calculate the heat transferred in each period by equation 3.4.1.1:

$$Q = MCp\Delta T \tag{3.4.1.1}$$

where Q is the heat transferred, (J)

M is the mass of warmed water, (kg)

Cp is the specific heat capacity of water, (4190 $Jkg^{-1}K^{-1}$)

ΔT is the temperature drop over the period, (K)

It was then possible to substitute the value of Q into the equation:

$$Q = UA\theta \tag{3.4.1.2}$$

where Q is the overall heat transferred, (J)

U is the overall heat transfer coefficient, ($Wm^{-2}K^{-1}$)

A is the area of heat transfer, (m^2)

θ is the temperature difference between the two fluids, (K)

This equation was solved repeatedly to give a series of values for 'U'.

Examination of the resulting values showed that, towards the end of each experiment, the values of 'U' became extremely variable. The variability of the results increased as the temperatures of the two fluids came closer together. Both equations 3.4.1.1 and 3.4.1.2 rely on a subtraction of one temperature from another. In the first case this is the temperature at the end of the period and the temperature at the beginning of the period. In the second case this is the temperature on one side of the wall and the temperature on the other side. Where one value is being subtracted from another very similar value, any errors associated with the accuracy of the equipment or techniques used will take on a greater significance than where the two values are further apart. It was decided therefore to use the first twenty results from each experiment, discarding the other values.

In the first experiment, where only the floor was involved in heat transfer, the resulting mean 'U'-value from the first twenty readings was 698 ± 44.5 $Wm^{-2}K^{-1}$.

The second and third experiments were both designed for the same purpose, i.e. to estimate the 'U'-value of the milk vessel walls, already knowing the value for the floor.

Equation 3.4.1.1 was again used to calculate the total heat transferred from the warm water in each period. The heat transferred through the floor of the milk vessel was then calculated for each period using equation 3.4.1.2 but this time substituting the value for 'U' obtained in the first experiment and solving the equation for Q. The resulting heat transfer through the floor of the vessel was then subtracted from the total heat transfer to give a value for the heat transfer through the walls. This value was then substituted into equation 3.4.1.2 and solved for 'U'. The second experiment therefore yielded twenty estimates of the 'U'-value of the milk vessel walls. The mean value was 612 ± 99.5 $Wm^{-2}K^{-1}$.

The third experiment, in which the tank was almost full, yielded a further 20 estimates of the 'U'-value of the milk vessel walls. The mean value was 538 ± 98.6$Wm^{-2}K^{-1}$.

The data from the second and third experiments were examined for consistency. The twenty estimates from experiment 2 and the twenty estimates from experiment 3 were tested using Student's t-test for unpaired samples, to test the null hypothesis:

$$H_0: \mu_1 = \mu_2$$

The resulting value of t was 0.5273, which was not significant (P>0.7). The conclusion was drawn that the two sets of estimates were not significantly different and were drawn from the same population. The 'U'-value of the milk vessel walls may therefore be represented by the mean of all 40 estimates, 575 ± 98.2 $Wm^{-2}K^{-1}$.

3.5 Heat Transfer to the Ice-Bank.

At this stage the model has simulated the addition of milk to the tank and its mixing with the bulk of milk already in the tank. It has calculated the reduction in temperature of the milk in a timestep by cooling across the milk vessel walls and floor into the chilled water. The amount of heat transferred in a timestep is given by:

$$Q = MCp(T_\tau - T_{\tau+1}) \tag{3.5.1}$$

where Q is the heat transferred in time t, (J)

M is the mass of milk, (kg)

Cp is the specific heat capacity of milk, ($Jkg^{-1}K^{-1}$)

$T_{\tau+1}$ is the milk temperature at the end of the timestep, (K)

T_τ is the milk temperature at the start of the timestep, (K)

The first destination of the heat transferred from the milk is the chilled water and the effect upon its temperature may be calculated. Within the chilled water sump, however, is the ice-bank, and as the chilled water gains heat from the milk vessel, some of this heat will pass to the face of the ice-bank. When the refrigeration process is in operation there will be a temperature gradient between the evaporator surface at the centre of the ice-bank, and the surface of the ice-bank. This will cause heat to flow by conduction from the surface of the ice-bank to the evaporator, where the refrigeration cycle will remove it to the external environment. Conduction of heat through the ice-bank during refrigeration will occur at a different rate to the convective heat transfer from the liquid chilled water onto the ice face, and this is likely to be a limiting factor to the rate of heat dissipation from the system. When more heat arrives at the surface of the ice-bank than is being removed by conduction through the ice, the net effect will be a melting of ice at the surface. This will increase the mass of chilled water slightly and also affect its temperature. Melting of the ice will reduce the radius of the annulus of ice on the evaporator, and consequently reduce its surface area. In the reverse situation where more heat is being removed by conduction than is arriving at the ice-bank surface, there will be a freezing effect, increasing the mass and surface area of the ice-bank and reducing that of the chilled water.

Estimation of the changes in the ice-bank dimensions is critical to the modelling methodology employed. Operation of the compressor unit is under the control of a sensor which switches on the motor as the ice-bank diminishes in size and switches it off when a pre-set size is reached. Cutting out of the compressor indicates that the full cooling reserve has been restored. This point will be reached under normal control conditions at some stage before afternoon milking commences, and a daily cycle may be regarded as starting at this point. The full cooling reserve may also be restored at other times during the daily cycle, for example in the early hours of the morning before the second filling period commences. If the full cooling reserve is not restored and the refrigeration cycle is still in operation at the start of either filling period then the ice-bank will further diminish and there is a risk of milk being inadequately cooled. Ideally this will never happen, unless the tank is being mis-used or the equipment is faulty. Nevertheless it was considered important enough to build into the model in the form of a warning if calculations revealed the ice-bank totally melting.

A full cycle of activity commencing with the start of the afternoon milking would typically follow the following phases.

Phase one is a short period between the start of milking and the beginning of the cooling phase. There will be a short delay before the first milk arrives at the tank. There will be a further short delay while the milk becomes deep enough to make contact with the sensor controlling the agitator and pump motors. When the sensor is able to test the milk temperature, it will switch on the agitator and chilled water pump if the milk temperature exceeds 4°C. This point marks the termination of the first phase. The model delays addition of the milk to the tank at the beginning of the period by one milk pump frequency in recognition of this phase.

Phase two commences with the agitator and chilled water pump cutting in. Until this point there is no heat transfer between the two fluids, because the chilled water is not in contact with the milk vessel walls or floor. Milk continues to arrive at the tank in a pattern which is determined by the frequency of the milk pump operation and heat is being transferred into the chilled water. Modelling of the reduction in milk temperature has already been described, and the change of temperature of the chilled water is given by:

$$\Delta Tc = Q/MCp \qquad (3.5.2)$$

where Q is the heat transferred from the milk, (J)

M is the mass of chilled water, (kg)

Cp is the specific heat capacity of water, (4214 $Jkg^{-1}K^{-1}$)

Transfer of heat from the chilled water to the surface of the ice-bank occurs by convection, and the amount of heat transferred in a timestep is given by:

$$Q = th\theta 2\pi rl \qquad (3.5.3)$$

where t is the timestep, (s)

h is the convective heat transfer coefficient, ($Wm^{-2}K^{-1}$)

θ is the temperature gradient between the chilled water and the surface of the ice-bank, (K)

$2\pi rl$ is the surface area of the ice-bank, (m^2)

The convective heat transfer coefficient, h, is approximately 175 $Wm^{-2}K^{-1}$ for a temperature difference of 1K and an ice-bank diameter of 0.075m. Appendix I gives the calculation of the convective heat transfer coefficient from first principles, but in fact the actual value will vary as the temperature of the chilled water varies and as the radius of the ice-bank varies, and the model takes these changes into account as it recalculates the coefficient at each step.

Thus, during the second phase, heat is being transferred from the milk into the chilled water, with a resulting rise in temperature. Heat is also being transferred to the ice face and this heat is not dispersed by the refrigeration system during this phase, but is dissipated by melting ice. This is because the compressor motor is not started at the beginning of the cooling period. Most bulk tanks have a mechanism to control the compressor motor, which allows approximately a 5% reduction in ice-bank radius before starting up the compressor. The purpose of this is to prevent short-cycling of the refrigeration system when the tank is empty. Consequently there will be no temperature gradient from the surface of the ice-bank to the evaporator at its centre, and therefore no conduction of heat away from the surface of the ice-bank. As a result all the heat arriving at the surface will be dissipated by melting ice. The observable effect of this is a reduction in the radius of the annulus of ice on the evaporator coil. Knowing the total length of the evaporator and the radius at the beginning of the timestep, the radius at the end of the timestep is given by:

$$r_{\tau+t} = \sqrt{(\pi r_\tau^2 - (Q/FDl)\pi)} \qquad (3.5.4)$$

where r_τ is the radius at the beginning of the timestep, (m)

Q is the thermal energy available for melting, (J)

F is the enthalpy of fusion of ice, (337734 Jkg^{-1})

D is the density of ice, (920 kgm^{-3})

l is the length of the evaporator coil, (m)

As a result of ice melting the mass of chilled water will increase by an amount given by:

$$\text{Mass melted} = (\pi r_\tau^2 - \pi r_{\tau+t}^2)lD \qquad (3.5.5)$$

where:

r_τ is the radius at the start of the timestep,(m)

$r_{\tau+t}$ is the radius at the end of the timestep, (m)

l is the length of the evaporator coil, (m)

D is the density of ice, (920 kgm^{-3})

The resulting chilled water temperature is then given by:

$$T_3 = (M_1T_1 + M_2T_2)/(M_1 + M_2) \qquad (3.5.6)$$

where T_1 is the temperature of the chilled water before melting, (K)

T_2 is the temperature of the newly-melted ice, (273K)

M_1 is the mass of chilled water before melting, (kg)

M_2 is the mass of ice melted, (kg)

The second phase continues in this way, repeatedly taking heat into the chilled water and using as much of this heat for ice melting as the convective heat transfer coefficient will allow. This phase ends when the radius of the ice-bank has been reduced to 95% of its starting level, at which point the compressor motor starts the refrigeration cycle.

Phase three commences at this point. A temperature gradient now builds up between the evaporator surface at the centre of the ice-bank and the surface of the ice-bank. The result is a conduction of heat from the chilled water at the ice face through the ice to the evaporator, where it is carried off by the evaporating refrigerant.

The rate of heat flux through an annulus is given by Fourier's equation:

$$Q = -kA\frac{dT}{dr} \tag{3.5.7}$$

where k is the thermal conductivity, ($Wm^{-1}K^{-1}$)

A is the surface area of the annulus, (m^2)

$\frac{dT}{dr}$ represents the temperature gradient through the annulus (K)

The surface area, A, may be represented by $2\pi rl$, giving:

$$Q = -k2\pi rl\frac{dT}{dr}$$

Rearranging gives:

$$\frac{dr}{r} = \frac{-k2\pi l dT}{Q}$$

Integrating between the limits of r_1 and r_2:

$$\log_e(r_2/r_1) = \frac{-k2\pi l}{Q}(T_2-T_1)$$

Rearranging:

$$Q = \frac{-k2\pi l(T_2-T_1)}{\log_e(r_2/r_1)} \tag{3.5.8}$$

where r_2 is the outer radius of the annulus, (m)

r_1 is the radius of the evaporator pipe, (m)

T_2 is the temperature of the evaporator surface, (K)

T_1 is the temperature of the ice surface, (273K)

The ice surface, being bathed in water, is assumed to remain at 0°C. Knowing the evaporating temperature and the ice-bank dimensions, the thermal conductivity at each timestep may be calculated. This process represents the removal of heat from the system and its rate is unaffected by activities elsewhere in the system.

The effect is to remove heat from the chilled water/ice face. Heat will be arriving at the ice face throughout this phase at a rate determined by the calculated convective heat transfer coefficient, but heat is now being removed by conduction. The net effect manifests itself at the ice face. If there is more heat arriving at the surface than is being removed by conduction, there will be a melting of ice. The change in mass and temperature of the chilled water is again calculated by equations 3.5.5 and 3.5.6 and the new radius is calculated by equation 3.5.4. If, on the other hand, the amount of heat being conducted away from the ice surface exceeds the heat arriving by convection, then the excess heat originates in the enthalpy of fusion and there will be a freezing effect. Again, equations 3.5.4, 3.5.5 and 3.5.6 calculate the variables.

Throughout phase three, the chilled water is still gaining heat from the milk vessel. This phase ends when the milk temperature has been reduced to 4°C and the agitator and chilled water pump have cut out.

Phase four is the restoration of the ice-bank to its pre-set dimensions after the milk has been cooled. During this phase there is no further heat transfer from the milk, since the chilled water is no longer in physical contact with the milk vessel walls. Heat is being conducted to the evaporating refrigerant. The source of this heat is a further reduction of the chilled water temperature by convection, and the enthalpy of fusion of ice. As the chilled water temperature falls towards zero, the convective heat transfer rate will also fall and most of the conducted heat will derive from the freezing of water onto the ice face. This phase ends when the radius of the ice-bank has been restored to its starting level.

Throughout phases three and four the rate of heat conduction through the ice to the evaporator, which is given by equation 3.5.8, is dependent upon the temperature gradient through the ice. The outer surface is assumed to remain at 0°C, but the inner surface temperature was not known. Experiments were therefore put in hand to determine this temperature empirically.

3.5.1. Experimental determination of the evaporator surface temperature.

The 2500 litre sump and spray tank previously used for the 'U'-value experiments was used for the evaporator temperature determination. The milk vessel was removed to allow access to the chilled water vessel and the evaporator coils. The internal dimensions of the chilled water vessel were carefully recorded along with the length and layout of the evaporator coils.

Low thermal inertia thermocouples were strapped to the surface of the evaporator coils in three places. The first point was close to the point where the evaporator enters the chilled water sump but below the water surface. The second point was approximately halfway along the length of the evaporator and the third point was close to the point where the evaporator exits from the sump, but below the water surface. The thermocouples were connected to an analogue to digital converter in an Apple II computer as in the 'U'-value experiments.

The recommended volume of water (1000 litres) was then added to the chilled water sump, and the compressor unit connected up. The system was then started up and allowed to build up an ice-bank. Temperatures were recorded every 15 minutes until the ice bank sensor cut out the compressor. Ambient temperature close to the condenser surface was also recorded at the same interval and by the same method as the evaporator surface temperature.

The experiment was performed a total of four times. On three occasions the experiment was performed during the daytime with mean ambient temperatures near the condenser of 17.2, 15.7 and 15.9°C. One experiment was run during the night in order to observe performance at a lower ambient temperature and on this occasion the mean ambient temperature was 8.6°C.

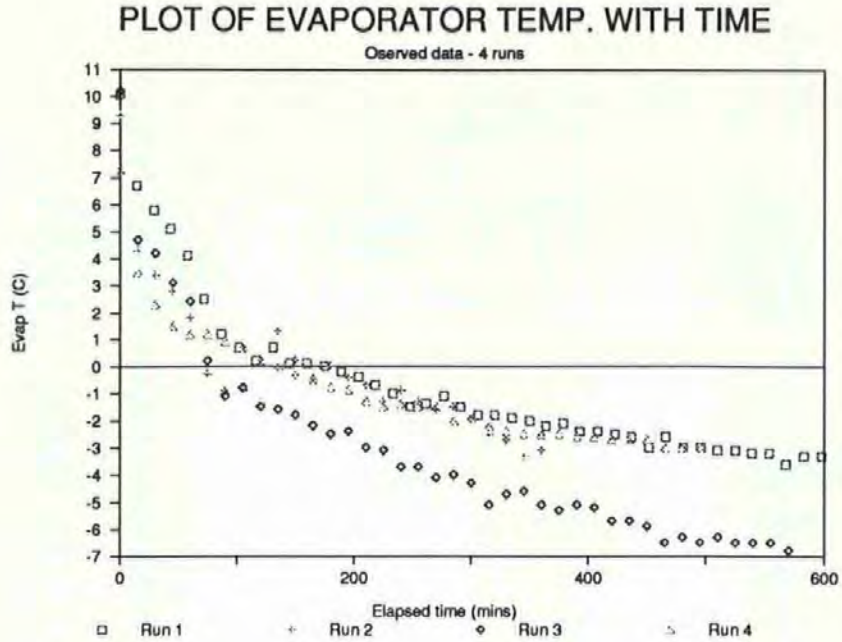


Figure 3.5.1.1. Decline of the evaporator surface temperature with time. Results from four experimental runs.

Results of the experiment are shown in figure 3.5.1.1 in which temperature at the evaporator surface is plotted against time from the time the compressor was switched on until the time when it cut out automatically.

The pattern was similar for each experiment. The evaporator temperature declined rapidly to start with but the rate of decline gradually diminished until, at the cut-out time, the curve had taken an almost flat shape.

The four curves belong to a family of curves, which may be represented by the following equation:

$$y = A - \log_e(x^n)$$

where y is the evaporator surface temperature at a particular time after startup, (K)

A is the evaporator surface temperature at startup, (K)

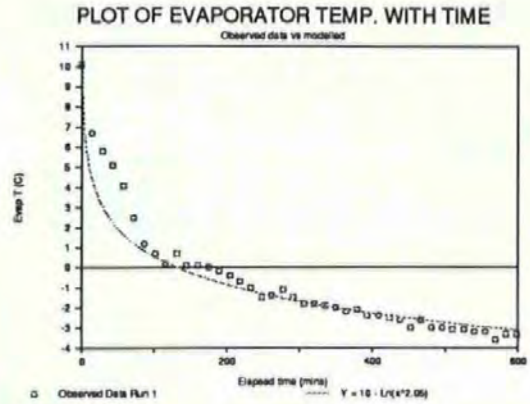


Figure 3.5.1.2 Evaporator temperature decline with time during the first experimental run.

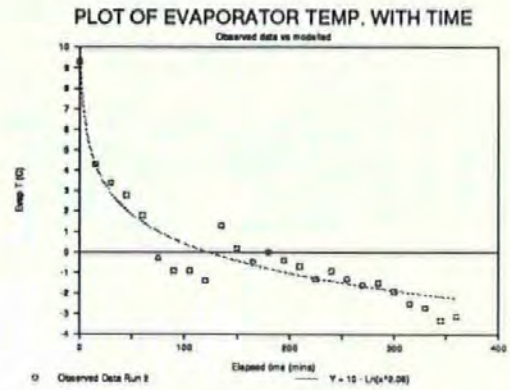


Figure 3.5.1.3 Evaporator temperature decline with time during the second experimental run.

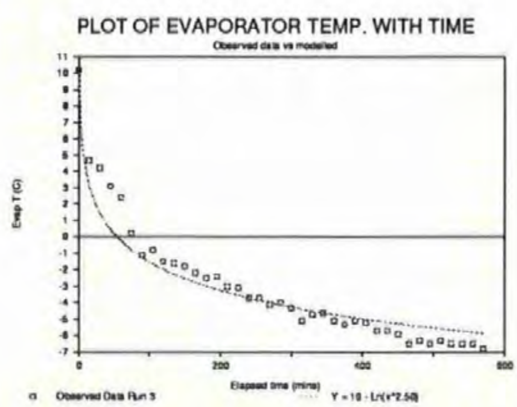


Figure 3.5.1.4 Evaporator temperature decline with time during the third experimental run.

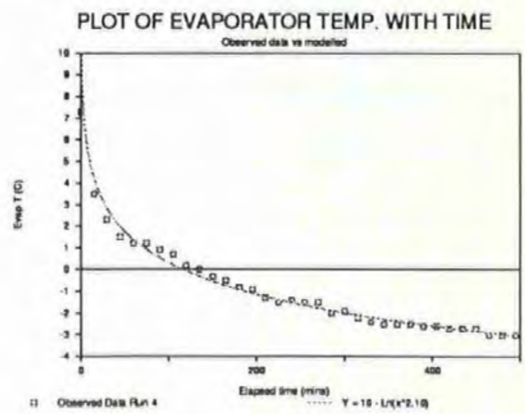


Figure 3.5.1.5 Evaporator temperature decline with time during the fourth experimental run.

x is the time elapsed since startup, (minutes)

n is a factor governing the steepness of the decline.

Experiment No.	Mean T.amb. (°C)	Best fit Equation
1	17.3	$y = 10\text{-}Log_e(x^{2.05})$
2	15.7	$y = 10\text{-}Log_e(x^{2.08})$
3	8.6	$y = 10\text{-}Log_e(x^{2.50})$
4	15.9	$y = 10\text{-}Log_e(x^{2.10})$

Table 3.5.1 Results from four experimental observations of ice-building in a 2500-litre bulk milk tank.

For each of the four sets of data a "best-fit" curve was applied and the equation describing each curve was calculated. Figures 3.5.1.2 to 3.5.1.5 show the data from each experiment with the best-fit curves superimposed. The equations describing these curves, along with the mean ambient temperature associated with them are given in table 3.5.1. The similarities are clear, the equations only differing by the rate of decline.

The decline factor appeared to be related to the mean ambient temperature. This was particularly noticeable in the third observation which was carried out at night. Regression analysis was carried out on the data resulting in the following relationship:

$$\text{Decline factor} = 2.96 - (0.054 * \text{T.amb.})$$

This relationship was built into the model to enable simulation of the performance of the bulk tank in different ambient conditions.

Finally a routine was built into the model to make allowance for the diurnal temperature variation. An assumption was made that the diurnal temperature range would be from 6 deg C below the daily mean to 6 deg C above the daily mean. It was also assumed that alterations would occur at the rate of 1 deg C per hour, so that the daily mean occurred at 6 am and 6 pm, and the minimum temperature of 6 deg C below the daily mean at midnight and the maximum of 6 deg C above the daily mean at mid-day.

Appendix II contains a description of the Bulk Tank Model program, including a full list of variables, constants and default values, along with a flowchart to describe program execution.

4. MODEL VALIDATION.

The model validation was carried out in four stages. The limits to the model's applicability were determined. The model's sensitivity to variations in the values ascribed to the various parameters was examined with a view to determining the relative significance of these parameters. The output from the model was compared with a simulation using a new 2500 litre tank in laboratory conditions. Finally the output of the model was compared with a relevant sample of data from the energy audit of dairy farms in South Devon.

4.1 Limitations of the Model.

The model, as written, simulates the performance of a sump and spray tank. It is not directly applicable to a fully jacketed tank, nor is it applicable to a direct expansion tank. A direct expansion tank, as has been noted earlier, operates on a fundamentally different principle, and modelling of this type of tank would require a radically different approach. Fully jacketed tanks differ in that the milk vessel is submerged in the sump of chilled water and therefore heat transfer from the milk to the chilled water can occur by natural convection, even when the agitation process is not in operation. Some fully jacketed tanks have a different geometry, being semi-cylindrical in shape.

The model is designed to stop running and produce a warning message if the ice-bank is reduced to zero. In practice a tank would not cease its operation in these circumstances. The compressor would continue running, removing heat from the liquid chilled water medium by direct expansion. This would continue until the heat arriving at the evaporator surface was less than that being removed by evaporation of the refrigerant, at which time ice would begin to accumulate again. This is a serious situation since it would be likely to result in inadequate cooling of the milk, and would only be caused by either a malfunction of the equipment, incorrect setting of the controls or misuse of the tank. The model suggested that the tank could operate at its full milk capacity at mean daily temperatures of up to 16°C before there was a risk of the ice-bank becoming exhausted. At this mean daily temperature, a peak temperature of 22°C would be simulated at noon. During the first year of the audit, mean weekly temperatures of 16°C or more were only reached during five weeks of the year. Under these simulation conditions the model suggested a total compressor running time in a full 24-hour cycle of 17.9 hours. The potential for improvement in performance is suggested by the fact that the remaining 6.1 hours were in the middle of the night and the early hours of the morning when the ambient temperature is at its lowest.

The model has been developed to simulate a 2500 litre sump and spray tank. Tanks of the same operating principles whose geometry is of the same standard design and whose dimensions were proportionately altered could also be simulated by the model. The internal dimensions of the milk vessel would need to be known as would the length of the evaporator coil.

The model assumes that the tank will not be mis-used in respect of its filling pattern. The tank is designed to receive its load of milk in two fillings, the first being 40% of the daily capacity and the second the remaining 60%. Similarly the starting time of the am milking is assumed to be 14 hours and 30 minutes, being 60% of a full day, after the starting time of the pm milking. These ratios and the actual starting times can all be varied but serious misuse of the tank cannot be simulated because exhaustion of the ice-bank will abort the program.

4.2 Sensitivity Analysis.

The model's sensitivity was examined in respect of the following parameters:

- The 'U'-value of the milk vessel walls and floor.
- The evaporator surface temperature.
- The tank filling pattern.
- The milk delivery temperature.

In order to achieve true comparability of results from successive runs of the model, a number of default values for the major variables were built in. These values were used unless specifically changed for a particular run.

The default values used were:

Tank Size in litres	2500
Floor Area in square metres	2.9925
Maximum Wall Area in square metres	5.38
Mass of Chilled Water in kg	1000
'U'-value of floor in $Wm^{-2}K^{-1}$	700
'U'-value of walls in $Wm^{-2}K^{-1}$	550

Ice-bank radius in metres	0.0375
Evaporator length in metres	92.964
Daily milk volume in litres	2500
Start time of pm milking	16:00
Start time of am milking	06:30
No. of milking units	6
Milk Delivery temperature in °C	32.5

4.2.1 The 'U'-value of the milk vessel walls and floor.

The 'U'-values were determined empirically (section 3.4.1) and as such had to rely on a number of assumptions relating to the heat transfer process. The values determined were 700 $Wm^{-2}K^{-1}$ and 550 $Wm^{-2}K^{-1}$ for the floor and walls respectively. The model was run with all the default values in operation, including the two 'U'-values, and an average ambient temperature of 10°C. The model was then run with 'U'-values 10% higher than the default values at an ambient temperature of 10°C and also with the 'U'-values 10% lower than the default values at the same ambient temperature. The whole process was repeated for an ambient temperature of 5°C. In each case the total compressor running time in a complete 24-hour cycle was noted and the milk cooling time in minutes following the end of the filling period was also noted. The results are presented in Table 4.2.1.

Ambient Temp.	U-value Walls	Floor	Compressor Run Time	Cooling Time pm	am
(°C)	($Wm^{-2}K^{-1}$)		(mins)	(mins)	(mins)
10	632	770	1016	24	64
10	575	700	1017	29	70
10	518	630	1018	33	75
5	632	770	876	21	58
5	575	700	877	25	64
5	518	630	877	28	68

Table 4.2.1 Simulated compressor running times (minutes) and milk cooling times (minutes after the end of filling) for two mean ambient temperatures and three sets of 'U'-values.

The results show that the compressor running time is not influenced by changes of ±10% in the 'U'-value of the milk vessel walls and floor. This is to be expected since the compressor running time will be a function of the thermal energy to be removed and not affected by the rate at which that energy becomes available for removal.

The milk cooling time, however, is influenced strongly by variation in the 'U'-value. Variations of ±10% in the 'U'-value result in variations of a similar order in the time taken to cool the milk after the end of filling. The apparent failure of the tank to comply with the requirement to cool the morning milk within 30 minutes of the end of filling gave cause for concern, and this led to further observations of tanks operating in farm conditions.

4.2.2. The Evaporator Temperature.

The evaporator temperature was determined empirically (section 3.5.1) and its calculation incorporates two variables. The equation developed included an intercept term and a factor governing the rate of decline of the temperature.

The model was run with three values as the intercept term, 9, 10 and 11°C, i.e. the developed value plus 10% and minus 10%. All other default values were used and a mean ambient temperature of 10°C. The process was repeated with a mean ambient temperature of 5°C. The results of varying the intercept term at the two ambient temperatures are shown in Table 4.2.2(a)

T.amb.	T.evap. Intercept	Compressor Run time
(°C)	(°C)	(mins)
10	11	*
10	10	1017
10	9	929
5	11	954
5	10	877
5	9	950

Table 4.2.2 (a) Variations in compressor running times for two ambient temperatures and three evaporator temperature starting levels.

* Ice exhausted

At an ambient temperature of 10°C, increasing the intercept term from 10°C to 11°C resulted in the tank failing when the ice-bank was completely exhausted shortly after the end of the morning filling period, with the milk temperature still at 7.2°C. The previous evening's milk had been cooled 32 minutes after the end of the filling period, compared with 29 minutes for the standard run. Reduction of the intercept term from 10°C to 9°C resulted in the total compressor running time in a 24-hour cycle being reduced from 1017 minutes to 929 minutes, a reduction of 8.65%.

The three runs were repeated at an ambient temperature of 5°C. Increasing the intercept term to 11°C increased the compressor running time from 877 minutes to 954 minutes, an increase of 8.9%. With an intercept term of 9°C, the compressor running time was 950 minutes compared with 877 minutes for the standard run with an intercept of 10°C. This increase in the running time, against an expected decrease is accounted for by the pattern of the compressor's activity. During the standard run for an ambient temperature of 5°C the compressor would have only a single period of inoperation during the 24-hour cycle. This would occur during the night, from 01:05 when the ice-bank had been restored from the evening milking until 39 minutes after the start of the morning milking. Following the morning milking the compressor would run throughout the daytime period and by the start of the afternoon filling period would still be running with the ice-bank a little short of the target radius. The most significant aspect of this is that the evaporator temperature was already at a very low level at the start of afternoon milking, much lower than if the compressor had just switched on. The effect of this is to remove, by conduction, much more heat during the filling period than would be the case if the compressor had cut out before the start of the filling period. Removal of more heat by conduction means that less heat is accounted for by melting of ice. Consequently, although the radius was not fully restored at the start of filling, it then reduced at a much lower rate than otherwise, and there was still sufficient ice to cool the milk without running out.

However, when the intercept term was reduced to 9°C, the system, as expected, achieved its objectives rather quicker. The effect of this was that during the daytime period the compressor was able to restore the ice-bank to the target radius before the start of afternoon milking and then cut out. When the arrival of the afternoon milk started the compressor up again the evaporator temperature had to start descending again from the intercept value. In practice it seems reasonable to expect a certain amount of time at the beginning of a running period to be devoted to reducing the temperature of the evaporant and its associated pipework to a level at which a working temperature gradient exists between the evaporant and the ice-bank. This overhead will exist for each time the compressor starts up and is illustrated in the example of these two intercept terms which are just sufficiently different to result in an extra start up during the 24-hour cycle for the lower value.

The second term in the calculation of the evaporator surface temperature is the rate of decline from the initial starting temperature. As with the intercept term, the model was run with ambient temperatures of 10°C and 5°C and decline rates increased and decreased by 10% in each case. All other default values were used. The results are summarised in Table 4.1.2(b).

At an ambient temperature of 10°C the ice-bank was again exhausted when the evaporator temperature decline rate was reduced. Increasing the decline rate

T.amb.	T.evap. Decline Rate	Compressor Run time
(°C)		(mins)
10	-10%	*
10	Default	1017
10	+10%	893
5	-10%	1010
5	Default	887
5	+10%	902

Table 4.2.2(b). Variations in compressor running time at two different ambient temperatures and three different evaporator temperature decline rates.

* Ice exhausted

by 10% at this ambient temperature brought about a reduction in the compressor running time of 12.2%.

At 5°C ambient, reducing the decline rate by 10% increased the compressor running time by 13.8%. Increasing the decline rate again altered the pattern of operation of the compressor, as has been previously described, resulting in a small increase in running time.

The conclusion which has to be drawn at this stage is that the important output parameters, particularly the compressor running time, are very sensitive to the accuracy of both terms in the equation used to calculate the evaporator surface temperature.

The evaporator surface temperature has been assumed, in its calculation, to be influenced only by the air temperature at the condenser face and the elapsed time since starting. In practice this temperature will be influenced by a number of other factors relating to the operation of the refrigeration equipment, including such aspects as expansion valve pressure settings. A detailed examination of the refrigeration cycle was beyond the scope of the current work, but there is little doubt that the results from such an investigation would supplement the precision of the model.

4.2.3 The Milk Tank Filling Pattern

Variations in the milk delivery pattern produced only slight variations in the model's output. Increasing the number of milking units from six, as the default setting, to eight is sufficient to trigger a more rapid operation of the milk delivery pump by increasing the frequency of milk deliveries to the tank from four minutes to two minutes. The effect of this variation was slight. The evening milk load cooled one minute quicker than in the standard run and the morning milk load cooled two minutes quicker than standard. Cooling time is defined as the number of minutes required after the end of the filling period to reduce the milk temperature to its target of 4°C. The reduction in cooling time, compared with the standard, is largely accounted for by the fact that milk will arrive at the tank earlier in the filling period with a higher number of milking units than a lower number. For eight or more milking units, the model allows for a two-minute milk pump delivery frequency compared with a four-minute frequency for less than eight units. The model delays the first delivery of milk to the tank for one milk pump frequency after the start of the milking period to allow the recorder jars, milk line and delivery pump to become charged with milk. Consequently, with eight or more units, milk will first arrive at the tank after two minutes compared with a delay of four minutes for a smaller number of units. It is likely therefore that the total cooling time for milk drawn through a high number of units will not be different from the total cooling time for milk drawn through a small number of units, but in the former case the cooling process will start and end slightly earlier.

Increasing the number of milking units from six to eight had no significant effect upon the compressor running time, the starting time being one minute earlier and the stopping time being two minutes earlier than in the standard run. Again, this would be largely accounted for by the slightly earlier arrival at the tank of the first milk.

A very slight alteration in the pattern of milk delivery to the tank would not reasonably be expected to have any influence on either the time taken to cool the milk or the time taken by the compressor to restore the ice used in cooling the milk. Only if the pattern or timing changes were substantial enough to move the start of the compressor running time to a period when the ambient temperature had changed would there be an alteration in the absolute time taken to restore the ice-bank.

4.2.4 The Milk Delivery Temperature.

As would be expected, the milk delivery temperature is a very significant factor in determining the compressor running time and the time taken to cool the milk. The model was run with milk delivery temperatures of 30°C, 25°C, 20°C and 15°C as well as the default value of 32.5°C. Milk might be delivered to the tank at the lower end of this range if it had been pre-cooled in a plate heat

Milk Delivery Temp.	Compressor Running Time	PM Milk Cooling Time	AM Milk Cooling Time
(°C)	(mins)	(mins)	(mins)
32.5	1017	30	70
30	997	26	57
25	946	17	33
20	852	7	15
15	962	0	0

Table 4.2.4. Compressor running times and milk cooling times following pm and am milkings for five different milk delivery temperatures.

exchanger. The compressor running times and milk cooling times after the end of filling are shown in table 4.2.4. The ambient temperature was 10°C and all other default values were used.

The unexpectedly high compressor running time for the lowest milk delivery temperature was again accounted for by a change in the pattern of operation. The compressor had successfully restored the ice-bank following the morning milking before the afternoon milking had started, and therefore the evaporator temperature was not as low, during the afternoon filling period, as it was during circumstances where the compressor had still been running at the start of the afternoon filling period.

A dramatic decline in the time taken to cool the bulk of milk after the end of the filling period, is seen as the delivery temperature is reduced.

The sensitivity of the model to this factor is particularly important in respect of the possibilities for pre-cooling milk before delivery to the tank. It is noticeable that the reduction in running time does not appear to bear a linear relationship to the milk delivery temperature.

4.3 Comparison with Laboratory Simulation.

The 2500 litre bulk milk tank used in previous experiments was set up in the laboratory to simulate normal use, as closely as was practicably possible.

The tank was fitted with low thermal inertia thermocouples, as before, to measure the bulk milk temperature, the sump chilled water temperature, the evaporator surface temperature and the air temperature in the region of the condenser. The thermocouples were connected to the analogue to digital converter in the Apple II computer as in previous experiments. Recordings were taken at one minute intervals.

During the simulation warm water was used in place of milk and the tank's automatic controls were in operation.

4.3.1 Simulation Details and Results.

Commencing at 17:30, 1013 litres of warm water was pumped into the tank over an approximately two-hour period. The quantity and timing were intended to represent typical conditions for an evening milking where the tank was to be filled to the limit of its capacity over a 24-hour cycle at a relatively high ambient temperature.

The water was added intermittently over the period, at approximately ten-minute intervals. A more frequent delivery of smaller volumes would have been preferable but this was not possible with the equipment used for generating and delivering the warmed water. A total of 11 additions of warm water were made, of average duration 42 seconds. Temperatures of the water at the point of delivery into the tank were recorded by means of the hand-held digital thermometer. As many recordings of delivery temperature as were possible during each delivery period were taken and the mean temperature for each delivery calculated. The mean for all the milk delivered was derived as a weighted mean of the temperature of each delivery, making allowances for the different masses of water involved. The mean delivery temperature was 35.5°C.

The diameter of the ice-bank was measured with calipers at five-minute intervals in two locations, the mean of the two being accepted as representative. The diameter at the start of the process was 0.077m.

An events log was maintained to record the operational times of the agitator and compressor, and an electricity meter was fitted into the supply to the tank.

The agitator cut in very quickly after the first addition to the tank and continued to run throughout the filling period. The compressor cut in at 18:05, 35 minutes after the start of the process.

At 19:30, the end of the filling period, the milk temperature had been reduced to 10.7°C, and 30 minutes later it had only been reduced to 8.1°C. The tank thus failed by a considerable margin to comply with the requirements for rapid cooling after filling.

At 20:20 the tank had completely run out of ice, but it had been noted some 35 minutes earlier that some turns of the evaporator coil were bare. The exhaustion of ice was undoubtedly the reason for the agitator running for a period of 3 hours and 4 minutes after the end of the filling period before cutting out. The milk had, in fact, been overcooled by this stage, having been cooled down to 3.6°C, and had reached the target of 4°C 25 minutes earlier.

The mean air temperature at the condenser face was 19°C. The chilled water temperature at the beginning of the process was 3°C.

The model was then run using the following values:

Mean Ambient Temperature	19.0°C
Milk Delivery Temperature	35.5°C
Starting Radius of Ice-bank	0.0385m
Daily Milk Volume	2500l
Start of PM milking	17:30
Chilled Water Temperature at start	3.0°C

The model correctly predicted that the tank would fail to cool its 'milk' load and that it would exhaust its ice-bank soon after the completion of the filling period. Table 4.3(a) compares the predicted values from the model with the observed data from the simulation in the laboratory.

The milk temperatures generally were higher than those predicted by the model, as can be seen in figure 4.3(a). However the trends were relatively similar. Both patterns have a similar saw-tooth appearance, the inclines immediately following an addition of warm 'milk' to the tank and the declines being the

	Observed Data	Model Prediction
Milk Temperature at 19:30	10.7°C	8.5°C
Milk Temp. at ice exhaustion	6.8°C	6.8°C
Evap.Temp. at ice exhaustion	4.5°C	1.0°C
Time of compressor cut-in	18:05	17:47
Time of ice exhaustion	20:22	19:39

Table 4.3(a) Comparison of observed data from the simulation run with model predictions.

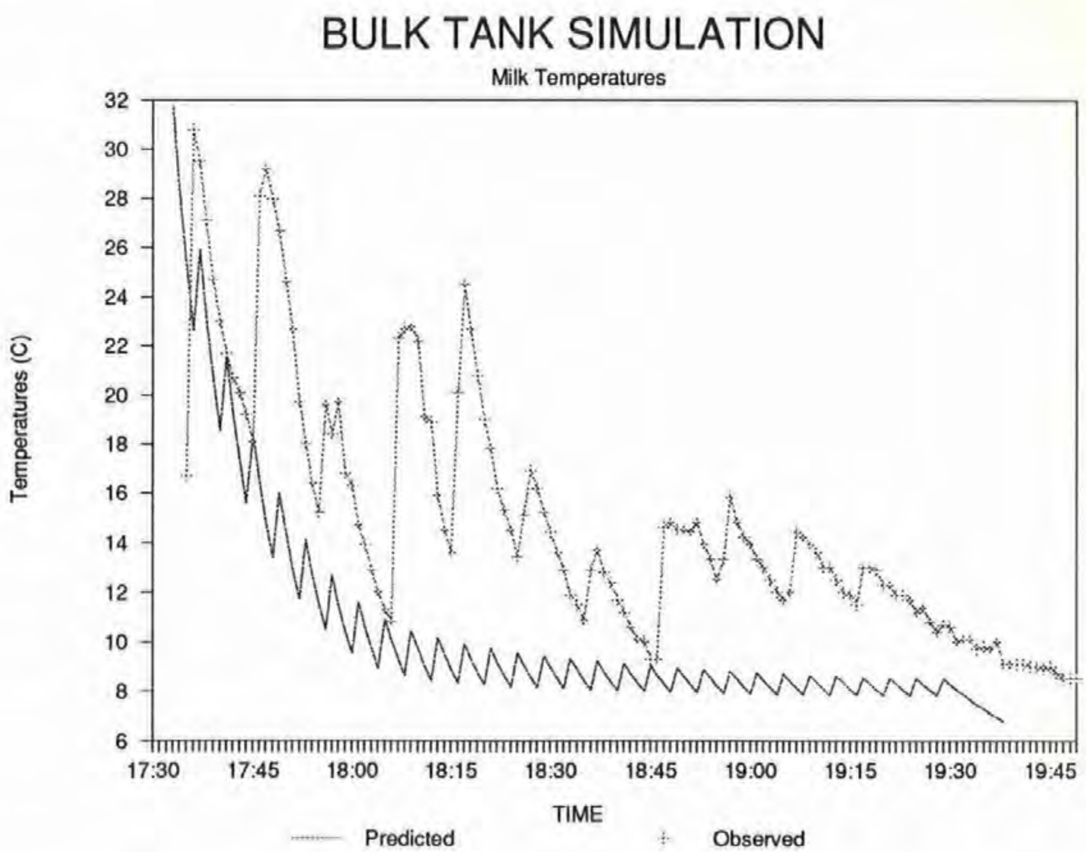


Figure 4.3 (a) Observed and predicted milk temperatures from the laboratory simulation.

cooling of the bulk milk until another addition arrives. The general trend is downwards in both cases with the rate of decline being highest towards the beginning of the filling period. Later additions of milk to the tank had a less dramatic effect upon the temperature of the bulk. After the end of the filling period (19:30) both graphs show a steadier decline, being no longer affected by further additions. The overall higher temperatures of the observed data may be due to the difference in filling pattern. The model has milk deliveries to the tank every four minutes, whereas the observed data has milk deliveries approximately every ten minutes. Larger individual deliveries were therefore the case with the observed data, and this would cause higher peaks of bulk temperature immediately after an addition. The two graphs are relatively similar up to the point where the second observed arrival occurs at 17:47.

The chilled water temperatures are compared in Figure 4.3(b). Again the observed temperatures were a little higher than the predicted ones, but the trends were very similar. The overall difference between the two sets of data will be accounted for by the difference between the two sets of milk data referred to above. The fall in chilled water temperature between 18:00 and approximately 18:15 is difficult to explain, but it was accompanied by a very similar change in the pattern of the evaporator surface temperature.

The observed and predicted ice-bank radius is shown in figure 4.3(c). The decline patterns are very similar, but the predicted values decline faster than the observed.

Figure 4.3 (b) Observed and predicted chilled water temperatures from the laboratory simulation.

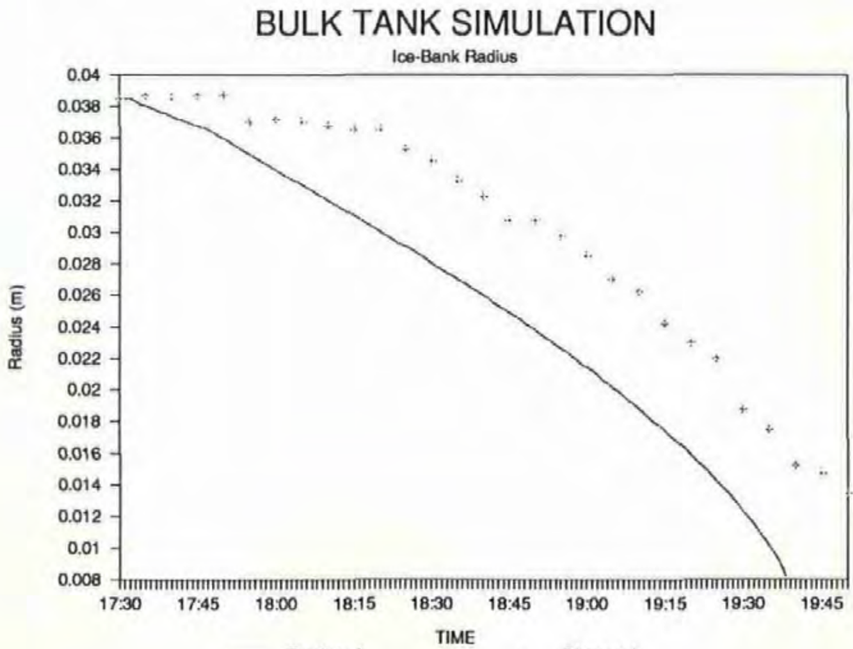


Figure 4.3 (c) Observed and predicted ice-bank radius measurements from the laboratory simulation.

4.3.2 Modification to the Model.

The comparisons between the model output and the observed data from the simulation suggested that minor modifications to the model might improve the accuracy of its predictions. In particular the model showed the radius of the ice-bank as being lower than in practice. This parameter is the final stage in determining whether or not the compressor is active, and therefore determines the actual times of operation and the duration of operation.

The radius of the ice-bank is determined at the end of a timestep by reference to the radius at the end of the previous timestep and taking into account the melting or building of ice during the timestep. The melting or rebuilding of ice during a timestep depends upon the balance between heat arriving at the ice face and heat being removed from the ice face by conduction inwards. The removal of heat from the ice-face by conduction, depending as it does on the evaporator surface temperature, is likely to be the major source of error throughout the whole modelling process. Section 4.2 established that the model is particularly sensitive to variations in the equation used to predict the evaporator surface temperature, and it seemed reasonable that modification of this equation could lead to improvement in model performance.

Section 3 derived the following equations as a means of predicting the evaporator surface temperature:

$$y = A - \log_e(x^n)$$

where y is the evaporator surface temperature at a particular time after startup, (K)

A is the evaporator surface temperature at startup, (K) x is the time elapsed since startup, (mins)

n is a factor governing the steepness of the decline.

$$\text{Decline factor} = 2.96 - (0.054 * \text{T.amb.})$$

The experiments which were carried out to determine the pattern of evaporator temperature changes produced an intercept term (A in the equation above) of 10°C, and this value was used in the model when comparing output with the first simulation run. However there is a fundamental difference in the operating conditions when the tank is running under normal use, compared with the conditions during the experimental determination of the evaporator temperature. The experiment to determine evaporator temperatures involved observation of the temperature during build-up of ice from a starting position of no ice. During normal operation the tank commences its cycle of activities with a full ice-bank, some of which then melts and is restored. This difference in operating conditions will have one major influence upon the evaporator temperature in respect of the insulating effect of the ice-bank. In the experimental situation the evaporator surface at the start of the process was directly in contact with the chilled water mass and therefore influenced by it, at least in the early stages of the process. During normal operation of the tank, as in the simulation run, the evaporator surface temperature will not be in direct contact with the chilled water mass and the ice-bank itself will provide a degree of insulation.

A modification to the model was therefore carried out. The intercept term for the evaporator temperature equation was reduced from 10°C to 8°C in recognition of this limitation of the experimental determination.

At the same time, the model was adjusted to allow for a less frequent milk delivery pattern as typified by the simulation. A delivery interval of ten minutes was incorporated.

On rerunning the model with these modifications, the milk temperature was found to be a closer approximation to the observed temperature (fig 4.3(d)). The predicted and actual ice-bank radius are shown in figure 4.3(e) and again the predicted values are a closer approximation of the observed data.

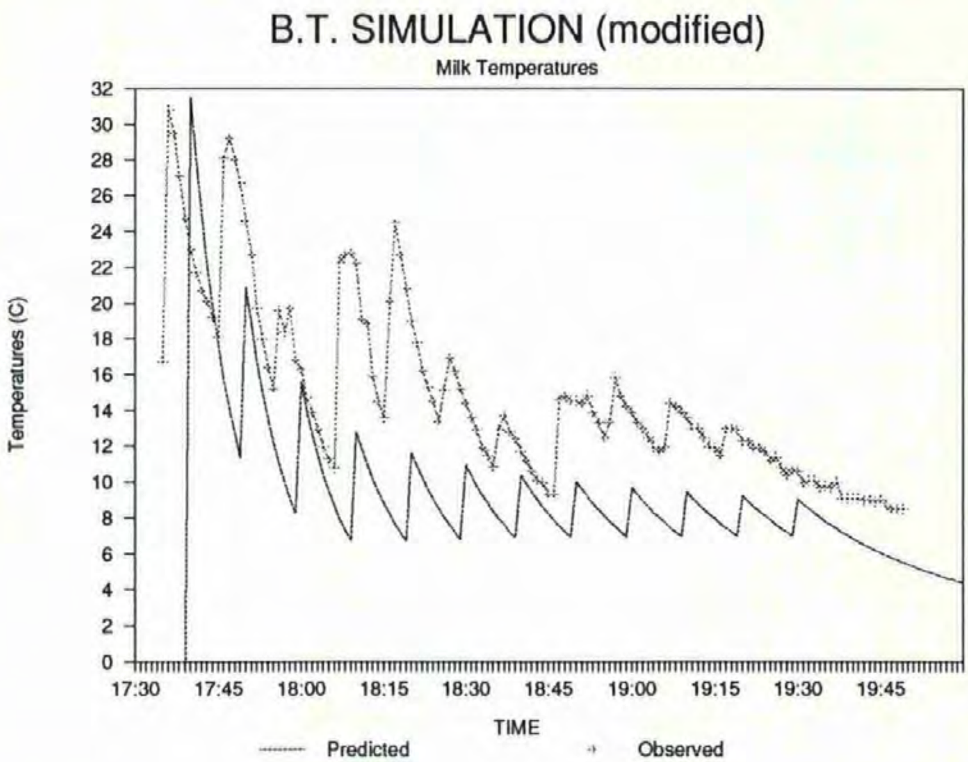


Figure 4.3 (d) Observed and predicted milk temperatures from the laboratory simulation after modification of the evaporator temperature calculation.

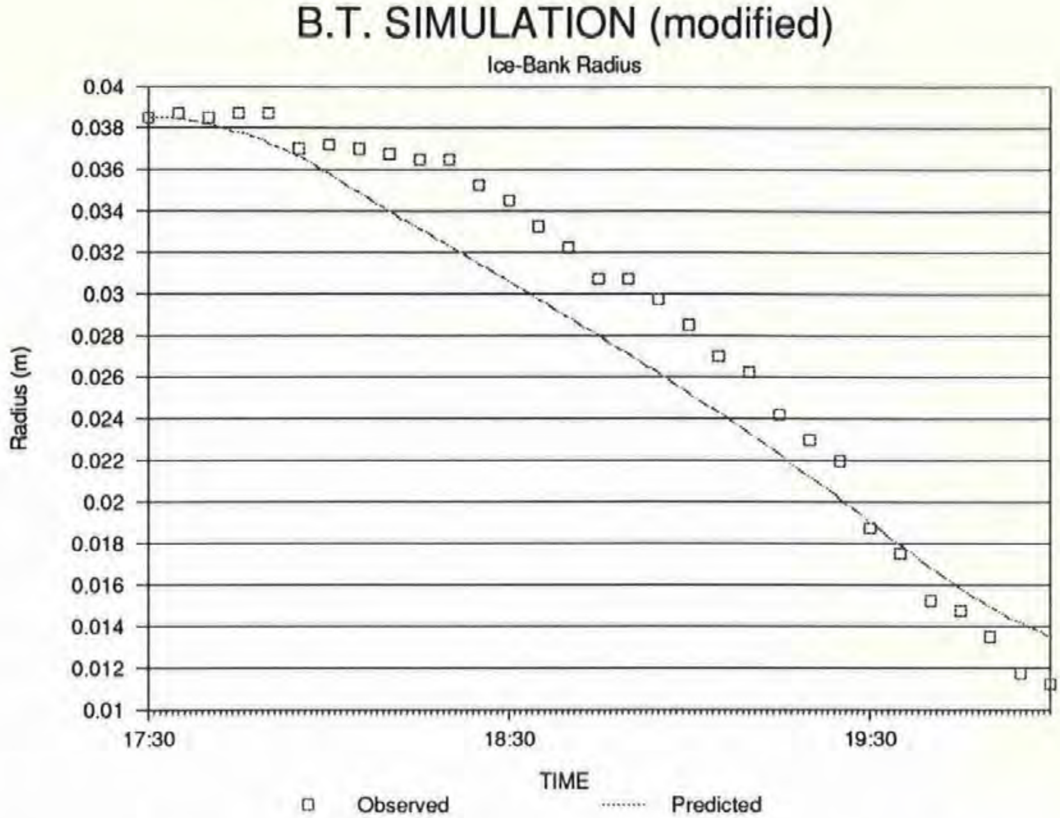


Figure 4.3 (e) Observed and predicted ice-bank radius measurements from the laboratory simulation after modification to the evaporator temperature calculation.

Table 4.3 (b) compares the observed and predicted results after the modification to the evaporator calculation. With this modification the milk temperature at the end of the filling period was closer to the observed temperature and the compressor cut in time was only eight minutes different between the observed and predicted times. The model now predicted that the milk temperature would reach 4°C 35 minutes after the end of milking and that the ice-bank would just survive exhaustion.

	Observed Data	Model Prediction
Milk Temperature at 19:30	10.7°C	9.1°C
Time of Compressor cut-in	18:05	17:57
Milk reduced to 4°C	22:09	20:05

Table 4.3(b). Comparison of observed data from the simulation run with model predictions, after modification to the evaporator temperature calculation

4.4 Comparison with Audit Data.

Two farms were selected from the audit group for a more detailed comparison of performance with the model. These were farms A and F. Both have sump and spray tanks of the same design as that modelled. In the case of farm A the tank was smaller (1545l) than that used in the laboratory and in the case of farm F it was larger (2730l) than the laboratory tank. Physical details of the tanks were taken from the N.I.R.D. technical examination report for each of the tanks, in order to run the model with the correct values for wall area, floor area, chilled water volume and length of evaporator. The milk volume and ambient temperature data were extracted from the audit database for the first week in each month of the first year of the audit. The model was then run twelve times for each farm with the appropriate inputs for milk volume and ambient temperature. The model yielded running times for the compressor during a 24-hour cycle. Multiplication of the running time by the compressor's power rating yielded the predicted energy use which was then compared with one-seventh of the recorded electricity use for the week being modelled. The results are shown in figures 4.4 (a) and (b).

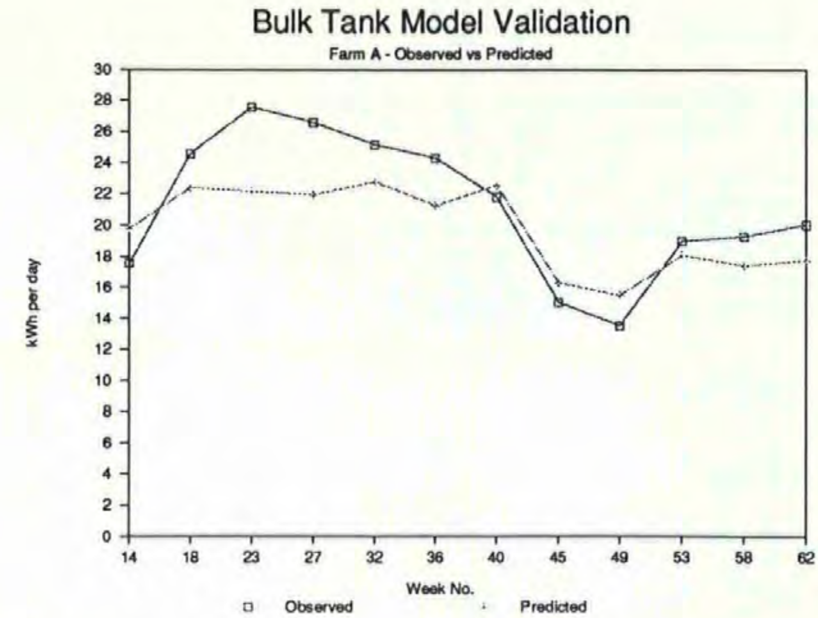


Figure 4.4 (a) Comparison of the energy use predicted by the bulk tank model for farm A with the actual energy use for twelve dates during 1980-81.

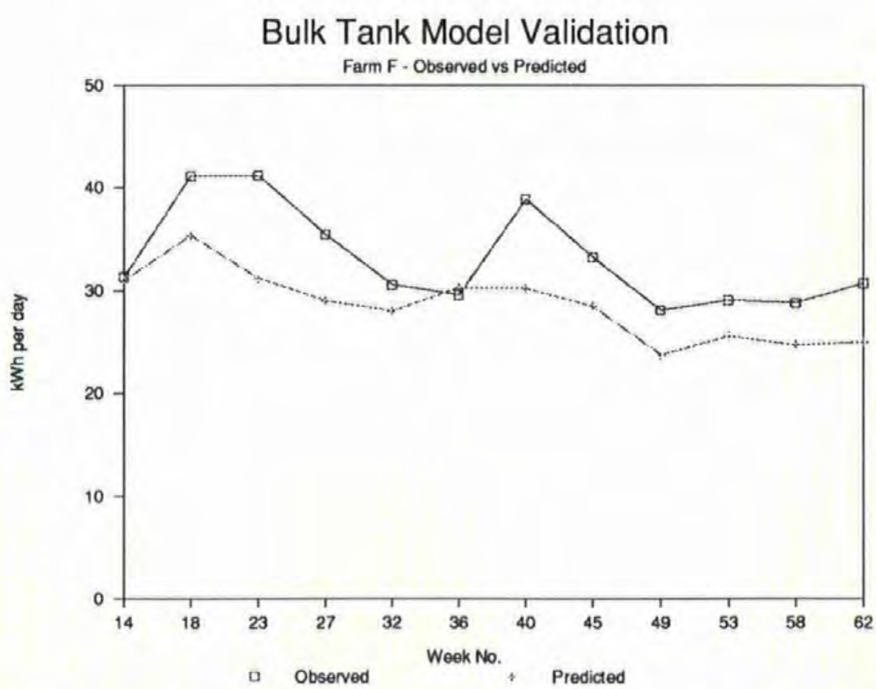


Figure 4.4 (b) Comparison of the energy use predicted by the bulk tank model for farm F with the actual energy use for twelve dates during 1980-81.

Both graphs show that the model predictions followed very similar trends to the actual readings, particularly during the second half of the recording year. It is noticeable that changes in direction of the observed data follows fairly closely changes in direction of the predictions. This suggests that the modelling approach has correctly selected the major variables. The most apparent difference between the observed and predicted data is that the predictions are generally a little lower than the observed data. The average error of the predictions at farm A was -4.6% and at farm F was -13.4%.

The inaccuracies of the model's predictions may be due to errors being brought forward from the experimental determination of some of the variables or may be due to the limitations referred to earlier, such as an inability precisely to model the heat removal by the refrigerant. Alternatively the discrepancies may be due to the tanks on the farms working in less than optimum conditions and, in fact, the compressors at these two farms were sited facing south-west (farm A) and south-east (farm F), whereas a north facing site would have been preferable. It is noticeable that both cases showed a better predictability during the second half of the recording period, namely the winter.

Regression analysis was carried out on the two sets of predicted data using the ambient temperature and the volume of milk produced as independent variables. The resulting regression equations are compared in table 4.4 with the regression equation developed in section 2.4 using the audit data for the whole of the first year for all the farms. Intercept terms were not significant ($P>0.95$) and have been ignored.

The equation from the audit is derived from a much larger database and therefore can be regarded as the most representative equation, with individual

Source	Regression Equation	R^2(%)
Audit	$y = 0.75x_1 + 0.0178x_2$	84
Farm A	$y = 0.43x_1 + 0.0169x_2$	72
Farm F	$y = 0.72x_1 + 0.0125x_2$	83

Table 4.4 Comparison of the regression equations for bulk tank electricity use (y kWh) on ambient temperature (x_1 °C) and volume of milk cooled (x_2 litres) from the entire audit and from the predictions for twelve dates at farms A and F.

farm equations varying around this. The general similarities in the three equations is encouraging and gives further support to confidence in the reliability of the audit equation.

5. DISCUSSION

5.1 Justification for farmers' concern

This research project commenced partly as a response to farmers' expressed concern about the level and cost of their electrical energy use. It followed a period when purchased energy had been subjected to dramatic price rises at a time when dairy farming had been under severe economic pressures for other reasons. Farmers wishing to expand their herds were looking for ways to keep the growth of their energy bills under control. Conservation equipment of various types was becoming available and claims for their potential appeared to be largely anecdotal. Annual electricity bills approaching £1000 were being faced by herds of only a little more than average size and future energy prices were becoming very difficult to predict

The literature provided little clarification of any significance either in respect of typical levels of use, factors affecting variation in levels of use or the effect of conservation equipment. The long term prognostication for energy prices appeared gloomy.

In the light of these points it is not surprising that farmers were becoming concerned. Nor is it surprising that some of the more adventurous farmers were prepared to make investments in equipment whose return on capital invested could not be reliably assessed.

5.2 Typical Levels and Ranges of Use.

It must first be pointed out that electricity costs are, and are likely to remain, a relatively small proportion of the total costs of milk production. Accepting the audit figure of approximately 50 kWh/m^3, the electricity cost at typical mid 1980s prices is approximately 0.25 pence/litre or less than 2% of the farm-gate value of the milk from non Channel-Island herds.

The scale of operation on a typical dairy farm is such that this relatively small proportion of the total is likely to amount to several hundred pounds per annum even for a small herd. The audit produced a figure of 250 kWh per cow which, again at mid 1980s prices, represents approximately £12.50 per cow. A herd of 80 cows, considered as only a small to medium sized herd today, would therefore face an annual expenditure of £1000 on electricity in the dairy and parlour alone. The largest farm in the survey, with over 200 cows, will have incurred costs of around £2500 per year in the early 1980s, assuming standard tariff arrangements. Approximately £1000 of this will have been solely attributable to cooling milk.

The audit suggested a figure of 250 kWh/cow/year as being a typical energy use. This was lower than previous estimates, but reasons for confidence in the audit have been expressed. A figure as low as 204 kWh/cow/year was achieved by one farm without conservation equipment. This figure was undoubtedly attained as a result of the exceptional level of care taken by the owner who was also the only person on the farm to do the milking. In the second year of the audit an even lower figure of 200 kWh/cow/year was achieved by another farm, also a small family farm without conservation equipment.

Laudable though these achievements are, they may be regarded as a reasonable target for most farms if care is exercised.

A lower target might still be possible without recourse to conservation equipment. A figure of 186 kWh/cow/annum was calculated as the theoretical optimum for the farms examined.

At the other extreme, a figure of 357 kWh/cow was recorded by the worst farm in the first year of the audit. This figure was produced by a conscientious farmer who made changes to his plant cleaning practice, following advice, with dramatic improvements in the second year. This example serves to illustrate the fact that electricity consumption of 40% above average may be achieved in all innocence by conscientious personnel unaware of deficiencies in their methods. It would not be unreasonable to assume that there is a large number of dairy farms in the country in a similar position. It is unfortunate that most dairy farmers will be unable to extract the cost of electricity for their dairy and parlour from their total electricity consumption since most farms will have a single supply and meter.

Farmers with little degree of concern or badly malfunctioning equipment can probably expect figures higher than any of those experienced in the audit and there must be in existence some farmers who are unknowingly consuming over 400 kWh/cow/year. These herds will be incurring costs of over £20/cow/year or twice the target suggested as possible by the performance of the leading herds in the audit.

5.3 Factors affecting Levels and Cost of Use.

The use of electrical energy in the farm dairy, and the cost of this energy are influenced by four major groups of factors:

- Political
- Environmental
- Technical
- Managerial

5.3.1 Political Factors.

Political influence is seen at many stages from the effect upon milk production levels and patterns, through to the cost of electrical energy used to produce that milk.

The Milk Marketing Boards determine the wholesale price of milk. Many considerations govern the determination of price; principal among these is the need to balance supply and demand. An all year round level milk price would lead to a glut of liquid milk in the summer and a relative shortage during the winter. This is because summer milk can be produced from grass at a lower nutritional cost than winter produced milk. The Boards therefore operate a seasonal variation in milk price to encourage some farmers to produce winter milk from autumn calving herds. Manipulation of the seasonal milk price differential will have a great influence upon the farmer's choice of calving pattern. Variation of energy use as a result of seasonality of production is likely to have a lesser influence upon the farmer's management policy than will the seasonal price differential.

There is not necessarily a direct relationship between the electrical energy used and the cost of this energy. The electricity supply industry are keen to optimise the use of generating capacity by levelling off demand during the daily cycle. This is achieved by providing financial incentives for off-peak use of electricity. In the South Western Electricity Board (S.W.E.B.) area, the Farm Day/Night Tariff is a two-tier pricing system. Units used during the night-time period (a 7-hour period between 23:00 and 08:30 GMT, starting time determined by the Board) are charged at a discount of approximately 60% compared with the standard tariff rate. Units used during the remaining 17 hours of the day suffer a 7% surcharge. A number of farmers have fitted timeswitches to their equipment to take advantage of this tariff. It is possible in some circumstances for the electricity use to be higher than it would without such controls, but the cost may be lower. For example, heating water during the night period followed by a short period of maintaining temperature may be cheaper than timing the peak temperature to coincide with the time of use, if this time is later in the morning. The whole farm supply has to be committed to the tariff and the higher cost of day-time units may dissuade some farmers with equipment which has to run during the day.

5.3.2 Environmental Factors

Environmental factors will have a very great influence upon both the volume of milk produced and the energy used for handling and storing it. The audit has revealed the importance of ambient temperature variations on electricity consumption for cooling milk. This was seen in Section 2 as a seasonal variation in the electricity used for cooling unit volumes of milk related to weekly mean ambient temperature. This suggests that there should be a diurnal variation in the efficiency of cooling milk due to the daily cycle of ambient variation.

The contribution of ambient temperature variations to the within-farm variation in cooling costs also suggests that condenser siting and working conditions will account for a significant proportion of the between-farm variation.

Ambient variations will also have an effect upon water heating energy requirements. Low ambient temperatures will result in lower heater inlet temperatures and greater heat losses from the heated vessel and the surfaces being cleaned. Colder areas in the north of the country are also more likely to have a need for space heating within the parlour and pipe-tracing for prevention of freezing.

Rainfall, soil type and possibly housing conditions will have an indirect effect upon energy use, in that certain conditions will lead to greater soiling of udders with a greater need for udder washing water.

5.3.3 Technical Factors

Technical and technological factors will greatly affect the energy use in the dairy. These include the availability and initial selection of equipment suitable for a given installation. The vacuum pump rating for a particular size of parlour is a matter for the design engineer. However, within the surveyed farms, there was variation in installed equipment for similar sized parlours. Farms B and D both had 5/10 parlours, but the pump ratings were 1.5 and 3 kW respectively. Energy used by the vacuum pump is not a simple function of the running time and nominal motor rating. Measurements of the current drawn by the motors in relation to the electrical energy used suggest that the power factor of similar units is very variable between farms, and that the power factor of a given unit may vary with time.

Reference has been made to the Federation of Milk Marketing Boards' Specification BC56, with which all new tanks are expected to comply. The most important aspect of this specification relates to the capacity of the cooling system to reduce milk temperatures to 4°C within 30 minutes of the end of the morning milk addition. Some of the tanks observed did not comply with this requirement. Ten tanks were observed and only two succeeded. One of these two was only filled to 17% of its capacity. Conclusions should be moderated as it was only possible to carry out a small series of observations of this feature. However, if this pattern were to be repeated there would be cause for concern that the technical performance of some tanks is not up to the standard expected. The implications for the farmer may be serious. Inadequate cooling of milk may lead to rejection by the buyer.

There is also cause for concern over the accuracy of instrumentation fitted to bulk tanks. The Milk Marketing Board examined over 4000 milk tank thermometers and found more than a quarter of the sample to be outside the accuracy range required by the Specification (Newell, 1980). The buyer may reject milk which is inadequately cooled according to the reading on this instrument.

5.3.4 Managerial Factors

These factors are of three types. The individual farmer has very little control over the political, technical and environmental factors which influence his energy use and cost. However it may be possible for him to make decisions related to these factors which are to his advantage. These effects should be distinguished from the second type of managerial effect which results from decisions taken for overriding agronomic or economic reasons, which will subsequently affect his energy use. Finally the farmer or manager may decide to take direct action to reduce his energy cost by the use of energy saving equipment or alternative energy sources.

The farmer may take advantage of the greater efficiency of the refrigeration system at night by fitting timeswitches to the compressor. This is usually carried out to take advantage of off-peak tariff charges, but those farmers not wishing to commit themselves to the tariff for the reasons mentioned, may still obtain an advantage from improved Coefficients of Performance at night. For farmers practicing seasonal production this will be possible for a large part of the year, when the bulk tank is not filled to capacity. At peak production periods, the compressor will need to run for most of the 24-hour cycle, and limiting the ice-building period to the night time will result in inadequate cooling reserves. Care must therefore be exercised over the management of such controls. A recent development has been that of a fully automatic timeswitch with ice-bank controller. This maximises the ice-building at night but also allows an override of the timeswitch during the day if the ice-bank is not sufficiently large to cool the milk.

The farmer may also take advantage of ambient temperature variations by careful siting of the condenser unit. This should be sited in a North-facing position away from any sources of warm air which may affect the efficiency of heat removal, such as the vacuum pump exhaust. Similarly, heat leakage into the tank itself should be avoided by siting in a cool position, away from direct sunlight and avoiding such practices as discharging waste hot water close to the tank. Artificial illumination is not a very great proportion of the electricity use but it may be possible, if there is no other disadvantage to the farmer, to alter the timing of milking to take advantage of natural daylight. In addition there is available a number of prefabricated milking parlour buildings which make very good use of natural illumination through the use of transparent materials.

It is desirable to ensure that all the parlour and dairy equipment is maintained in optimum working condition. Service contracts are available for both the milking plant and the refrigeration system. It is also within the farmer's power to ensure the equipment operates satisfactorily on a day to day basis. The vacuum regulator should be checked regularly in conjunction with the vacuum gauge, to ensure optimum milking and cleaning vacuum levels. Condenser fins should be kept clean and clear of obstructions to the flow of air. Leaks in hot water systems should be rectified immediately and timeswitches and thermostats set as carefully as possible and checked frequently.

The second group of management effects upon energy consumption and cost concerns decisions relating to farming policy which may have an indirect, but significant, effect upon the energy use.

Choice of breed is one such effect. The Jersey herd in the survey had a very high electricity cost per unit volume of milk. This breed has a low average milk yield per cow, but a higher compositional quality of milk, and the farmer receives a higher price per litre of milk. However, all the parlour and dairy equipment has to run for a lower volume extraction with the consequences noted.

Another such effect will be the selection of herd size and the appropriate equipment. Size of the herd will be governed by a number of factors including land availability, alternative possibilities, and labour and capital considerations. Many farmers aim to restrict the milking period to a maximum of 2-2.5 hours, and the size of the parlour is usually selected to accommodate this rate of milking. The bulk tank will need to be of sufficient size to accommodate maximum production, including a contingency for short term fluctuations in cow numbers or the calving pattern.

Seasonality of calving can be a crucial factor affecting equipment sizing and subsequent energy use. Equipment will need to be matched to peak throughputs. This applies both to the parlour and vacuum pump and to the bulk milk tank. At other times of the year this equipment will be underused. Seasonal variations in the electricity used for cooling a unit volume of milk have been noted in the audit results. The autumn calving herd will have the greatest volume of milk to cool during the winter months when the cooling system operates most efficiently. However the spring calving herd will have a greater cooling load during the summer months, leading to a higher year-round average cost of cooling milk. This higher cost is unlikely to be fully compensated for by reduced electricity costs of the other components of the system, and will result in a higher total electricity cost.

Choice of housing or grazing system for the herd may also indirectly affect the energy requirement in the dairy. Badly designed housing systems or the practice of grazing poached grass and forage crops will lead to increased soiling of the udder. This will result in increased udder washing requirements and reduce the throughput.

Farmers should also be aware of the effect of work routines on the throughput of cows and the subsequent effect upon vacuum pump running times.

Given that management has a significant effect upon energy use in the dairy, there is a need for feedback of information between the herdsman operating the equipment and the farm manager or financial controller. The degree of communication may deteriorate within a long chain of command. Farms D, J, and X are all under institutional control, and had an average electricity cost of £13.5 per cow. The remaining farms, all family farms, had an average cost of £12.0 per cow. The statistical significance of this aspect is difficult to confirm with such a small sample, but it seems likely that this aspect will bear further scrutiny.

5.4 Recommendations for Reduction of Energy Levels and Cost

5.4.1 Good energy husbandry

Siting of equipment should be considered with regard to working conditions. The bulk milk tank should be sited in a shaded position to avoid direct sunlight striking any part of the tank and away from any other major heat source such as wash tanks, space heaters and the vacuum pump. The compressor/condenser unit should also be carefully sited away from direct sunlight and other heat sources. The author has observed a number of cases where vacuum pump exhausts have been located very close to condenser units, a practice to be avoided. A north-facing site is the most desirable location for a condenser unit, but the availability of a free air flow through the condenser unit is also important. To facilitate this air flow, the condenser unit must be kept free of any obstruction by regular observation and cleaning. The presence of grease, oil or other similar materials on or in the vicinity of the condenser will encourage dirt, straw and other matter to stick to the fins of the condenser and reduce the air flow. The positioning of refrigeration pipes should ensure the minimum possibility of damage and resulting leaks of refrigerant. Any lagging present on these pipes should be regularly inspected for deterioration and replaced if necessary.

The refrigeration equipment should be regularly serviced, ideally by taking out a regular service contract with a specialist refrigeration engineering firm. The tank's controls and instrumentation should be regularly checked and recalibrated if necessary. The temperature indicated on the milk thermometer should be noted at the point where the agitator cuts out at the end of the cooling period. If this differs significantly from 4°C the temperature of the milk should be checked with another instrument of known accuracy to determine whether the instrument is at fault or whether the cooling process is terminating incorrectly. If the milk thermometer is at fault it should be replaced immediately, bearing in mind that the buyer may reject milk as a result of the reading on this instrument and that a faulty instrument will not give a reliable indication of whether the milk is being properly cooled. If the thermometer is found to be accurate, then variation from 4°C in the cut-out temperature should be immediately investigated. A cut-out temperature in excess of this level indicates inadequate cooling of milk. This may lead to rejection of the milk, but will also create conditions in the milk more favourable to bacterial multiplication with consequent penalties. Cut-out temperatures below 4°C will indicate over-cooling of the milk and the input of more energy than necessary to meet the buyer's requirements.

The chilled water compartment should be filled according to the manufacturer's recommendations. This will involve filling to an indicated level and then maintaining the volume at that level. Such additives as are recommended should be included; these may include a wetting agent to ensure a smooth flow of water over the milk vessel walls. Observations of the flow of chilled water should be made from time to time to ensure that the whole wall is being wetted, creating the maximum heat transfer area.

Any loss of thermal energy by the milk before it reaches the tank will reduce the amount of energy to be removed by the tank. It seems reasonable to expect milk passing into recorder jars rather than flowmeters for milk recording to lose more thermal energy due to the larger surface area. The longer milk remains in the recorder jar, the greater will be the energy loss to the ambient resulting in milk of a slightly lower temperature being delivered to the tank. Less frequent emptying of the recorder jars is therefore recommended.

Farmers and herdsmen should make regular observations of the ice-bank and develop a management strategy relating to the ice-building. The refrigeration system operates most efficiently against a higher temperature gradient, i.e. at night. With no control influenced and normal operating conditions, the daily cycle of two milkings will be followed in each case by a period of ice-rebuilding. The afternoon milking will be of approximately 40% of the total load. Thus the night time rebuilding period will be the shorter of the two periods and the main period of compressor inactivity will be during the night and the early hours of the morning when it could be operating at its most efficient. To make matters worse, the daytime rebuilding period not only has the greater mass of ice to replace, but it has to do this during the warmest hours of the day. It is obviously desirable to attempt to shift some of the daytime ice-rebuilding into the night period, but caution must be exercised.

Whatever policy is exercised in respect of ice-bank control the adequate cooling of a batch of milk must not be put at risk. At the same time the producer must take care to ensure he does not contravene any contractual arrangements he may have with the buyer of the milk. These may include a guarantee on the part of the producer to maintain a continuous cooling facility or an agreement only to use only such control equipment as has been approved by the buyer.

Over-riding the control of the ice-bank by manual control methods is unlikely to be satisfactory and is therefore not recommended.

The fitting of ordinary timeswitches to the electrical circuits controlling the operation of the refrigeration unit would theoretically be sufficient to control the process. The settings would be made to cut out the compressor at some point during the daytime and allow the system to restart later when the ambient temperature is lower. This method of control requires a high level of observation and anticipation on the part of the operator. The timing of the cut-out must not be before the morning milk load has been adequately cooled, and preferably not before it has been removed from the tank. Cutting off the compressor artificially during the daytime results in the commencement of afternoon milking with less than a full ice-bank. Such ice-bank as there is must be sufficient to cool the afternoon milk load without exhaustion and it would be prudent to have a contingency reserve so that unanticipated increases in the volume of milk are not put at risk. The method therefore requires the operator regularly to observe the remaining ice at the end of the afternoon cooling. The timing of the cut-in is also critical since the full ice-bank must be restored by the commencement of morning milking. For most farms, for a large part of the year, it is possible to manage the ice-bank control in this way, even if the time switch is set to allow 24-hour supply at the high risk times of the year, namely the mid-summer period and when the tank is being filled close to capacity. However, a very high level of vigilance is required on the part of the operator with regular observations of the ice-bank, and frequent adjustments of the time-switch to allow for anticipated changes in the volume of milk or the ambient temperature.

Electronic ice-bank controlling devices are now becoming available. Such devices will attempt to optimise the timing of the ice-bank rebuilding process, while allowing an over-riding of such controls in the event of the ice-bank becoming close to exhaustion. Such equipment is not expensive in the light of possible savings by running the compressor unit more efficiently and shows further advantages when considered in the context of off-peak electricity prices.

In the longer term, the development of a fully programmable microprocessor-based controller capable of anticipating the required ice-bank given information relating to herd size, milk production pattern and the range of local ambient conditions would be a way of optimising the tank's performance while removing from the operator the need to be vigilant.

The responsibility for correct use of the tank will always remain with the operator and it should always be remembered that the tank has been designed to receive its milk in two loads over a 24-hour period, the first being 40% of the total. Producers with more than one milk tank should avoid the temptation to fill one tank at each milking. Such a demand upon the cooling reserve is unlikely to be met, and milk will be inadequately cooled.

The operator should check frequently whether the tank is fulfilling its requirement to cool the milk within 30 minutes of the end of the filling period. If it is not doing so, and the thermostat and thermometer are known to be working accurately then the causes should be immediately investigated with technical advice being sought if necessary.

The vacuum pump and milking equipment should all be serviced and maintained regularly and thoroughly by skilled, technical staff. Again, service contracts are available and should be considered. The vacuum level should be precisely set and accurately maintained by keeping the regulator in good working condition. Similarly the pulsator should receive regular attention to ensure the correct vacuum regime at the cluster. The vacuum gauge is an important instrument and it should be regularly checked and recalibrated if necessary.

The vacuum pump itself should be sited sensibly for the disposal of the heat carried in its exhaust, and the outlet should be maintained in a clean condition.

Reasonable attempts should be made to minimise the running time of the vacuum pump by not starting the system until the first cows are ready for milking, and ensuring that the milking period and the following cleaning period are as short as possible.

Although lighting only accounts for a very small proportion of total electricity use, it is still worth exercising well disciplined procedures with respect to the use of lights. The lighting system should be designed with the correct type, wattage and siting for the situation and specialist advice should be taken if necessary.

Finally, one should not overlook the other activities taking place in the parlour. Washing down the parlour after milking only incurs a very small electricity cost for the water pump, but the volume of water itself may be very large (e.g. approximately 10 tonnes per week at farm X). Water itself is no longer a resource to be taken for granted as it has a value, both economically and energetically.

5.4.2 Reduction of unit costs

In addition to taking appropriate steps to minimise the absolute level of energy consumption, farmers should consider attempting to reduce the unit cost of their purchased electricity by taking advantage of off-peak electricity tariffs. Reference has been made in section 5.3.1 to the Farm Day/Night tariff which offers a substantial discount for electricity used during the night period and a small surcharge for electricity used during the remainder of the day. The whole farm supply has to be committed to the tariff and consequently there will only be a benefit if a sufficient proportion of the electricity use can be shifted into this time period. Benefits resulting from maximising the running of the compressor at night have already been commented upon, but these benefits can be added to significantly if the unit cost of electricity is also reduced. Where hot circulation cleaning or Acidified Boiling Water cleaning are practised only once per day, this should be in the morning to take advantage of heating the water during the night period. If milking starts early enough then some of the vacuum pump running time will also be accounted for during the off-peak period.

5.4.3 Conservation measures.

From a national point of view, any attempt to conserve energy is to be commended in view of dwindling resources. However, farmers cannot be expected to be any more altruistic than the remainder of society, and they are therefore likely to invest in conservation equipment only if the investment is justified on economic grounds rather than energetic.

Opinion is still divided on the subject of economic viability of investment in heat recovery units and plate coolers. The benefit from a heat recovery unit is in the recapture of some of the thermal energy extracted by the milk cooling process before this heat is expelled to the atmosphere. The most obvious application for this energy is a further transfer into heating (or pre-heating) water for use by the plant cleaning system or as udder washing water and the rewards from using such a system are in the form of reduced heating bills for this water. However, the system is likely to cost several hundred pounds, depending on the size of the installation and the benefits are difficult to quantify. A number of major variables need to be investigated before a recommendation can be made; these include the overall heat transfer efficiency and the matching of the supply with the requirement for heated water in terms of both temperature and timing. Reference has been made to the work by Norman on the use of heated water in the farm dairy.

Plate coolers would seem to offer a more easily quantifiable opportunity. A description of the process has been made earlier and the work by A.D.A.S referred to in section 1.5.2 has attempted to measure the effects. The benefits are seen in a lower milk cooling cost caused by reducing the milk temperature before its arrival at the tank. However, the precise effects of a plate cooler on the temperature of milk are dependent upon a number of variables, such as the ratio of milk volume to water volume, the temperature of the cooling water and the presence or absence of a balance tank to smooth the flow of milk through the cooler. Until these influences have been more carefully modelled it will still not be possible precisely to determine the reduction in milk cooling cost.

Again, the installation is likely to cost several hundred pounds, and the return on this investment will be partly dependent on whether the water has to be purchased or is re-used, as A.D.A.S pointed out. The capital investment might be partly offset by the reduction in cooling capacity needed. However, this is only likely to be possible on a new installation where both the plate cooler and compressor are being installed at the same time. This approach also leaves the producer at risk of having an under-rated compressor which is incapable of cooling the milk properly should the pre-cooling process fail for any reason. Producers contemplating this approach should examine carefully their position with respect to their contractual arrangements with the buyer and the warranty or service arrangements for the tank.

Equipment for optimising the ice-bank rebuilding time has been referred to in the previous section.

The use of specialised controllers which switch on the lights only when the presence of an animal or the operator is detected would help to optimise the use of electricity but seems unlikely to gain a widespread acceptance since the benefits from installing such a system are likely to be small.

There is even more doubt about the viability of alternative energy sources. For example, it is extremely improbable that solar systems typical of those currently available can be justified on purely economic grounds (Carpenter et al., 1980).

6. CONCLUSIONS

Farmers' concern about the present and future price of energy is justified and the advice available to them is wanting.

Levels of energy use are a little lower than previously suspected. The average energy use for all purposes, except space heating, in the dairy and parlour is approximately 250 kWh per cow per annum, or 45-50 kWh per cubic metre of milk. Farmers exercising careful conservation practices, but without resorting to specialist conservation equipment, can reduce this figure to 200kWh per cow per annum. This saving of 20% is worth about £250 per year in a 100-cow herd. For farmers whose electricity consumption is higher than average the savings will be correspondingly higher. For the national dairy herd of 2.5 million cows, the saving is approximately 125 GWh per year worth over £6million at end-user prices.

To achieve savings of this level would clearly be of great national benefit in terms of reduced demand for generating capacity, but will not be entirely without cost. The author encountered many examples of well-intentioned but misguided practices. Farmers will need to be made aware of the possibilities and educated in methods of reaching the targets. Such an objective will involve a well-designed and on-going publicity programme, a positive training rôle and a means of demonstrating to farmers that progress is being made.

Exploring and quantifying the effects of installing conservation equipment has been beyond the scope of the current work. However it is worth noting that those farms in the survey which had conservation equipment were unable to perform any more economically than those farms without conservation equipment but where good energy housekeeping is rigourously practised. It may therefore be concluded that conservation equipment should not be used to reduce consumption figures to the target of 200 kWh per cow per year since this is possible without resource to such equipment. Only when the maximum savings have been achieved by improving operating practices, should investment in conservation equipment be considered. It is likely that much of the anecdotal evidence for savings achieved by conservation equipment in fact involves savings that could have been made without such an investment. When conservation equipment is applied to the task of lowering consumption below the 200 kWh per cow per year level the investment might become rather difficult to justify at electricity prices currently prevailing. As a consequence further savings might become dependent upon either a very dramatic rise in the price of electricity or some other form of financial incentive.

The bulk milk tank is the heaviest individual consumer of energy in the dairy and its consumption is heavily influenced by the level of production and the ambient temperature. An equation has been proposed to predict the electricity consumption by the tank using the level of production and ambient temperature as variables. Failure to achieve this level of consumption would indicate that the tank is working in less than optimum conditions.

Development of the bulk tank model has brought about a realisation of the dependence of the cooling rate on tank geometry. The traditional design of a sump and spray tank has been constrained by requirements for rigidity and a known specific cross-sectional area to facilitate measurement of the milk volume by means of a dipstick. Non-volumetric methods of establishing the quantity of milk leaving the farm would remove these constraints. Designers might then be able to consider methods of providing a much larger heat transfer area enabling cooling to proceed more efficiently. Such a design must not overlook the need for automated cleaning systems.

The model suggested that some tanks may have difficulty in meeting the requirement to cool milk to 4°C within 30 minutes of the end of the filling period in certain conditions. The failure of a new tank to achieve this target in laboratory conditions and the similar failure of a large proportion of the observed tanks in farm conditions has given further cause for concern. It should be remembered that all farm bulk milk tanks are subjected to a rigourous testing procedure by N.I.R.D., a process which includes testing the tank's ability to meet this cooling target under very severe ambient conditions. Each model of tank has to complete this test successfully before being licensed for use. It was not possible in the current work to investigate this apparent anomaly in any detail, but it is clear that the matter requires investigation.

6.1 Recommendations for Further Work.

Development of the model has illuminated a number of areas worthy of further study. While the model provides a reasonable testbench for further investigations and predictions, further refinement would add to the precision and accuracy of its output. In particular a further study and modelling of the conditions controlling the heat transfer away from the evaporator surface and through the refrigeration system would lead to a better understanding of the temperature regime at the evaporator surface. This temperature is crucial in determining the temperature gradient through the ice bank and therefore the rate of conduction of heat from the ice-bank surface. In turn this determines the changes in radius and consequently the status of the compressor.

Further studies of the conditions prevailing in and around the ice-bank should also consider ice-bank geometry. When the annulus of ice becomes large in radius and adjacent turns of the evaporator coil are relatively close together there is a real risk of adjacent annuli of ice beginning to coalesce. Continuation of this process results in the total surface area of the ice-bank increasing at a much slower rate than if separate annuli were increasing in radius. Eventually, the ice-bank may take the form of a rectangular slab with a considerably lower surface area than the separate annuli would have. Absolute rates of convective heat transfer from the chilled water to the ice would then be very different to those calculated in the current version of the model.

The overall heat transfer rate from the milk to the chilled water has been developed empirically in the current work and this aspect would bear further study in order to improve understanding of this complex process. Such an understanding could lead to possible design improvements resulting in a more efficient transfer of heat out of the bulk milk.

Having established reasonable guidelines for current levels of energy use and targets for possible levels of use before installation of conservation equipment, further work should now be undertaken to quantify reliably the potential for savings resulting from the installation of such equipment.

APPENDIX I

Calculation of the Convective Heat Transfer Coefficient, h, for chilled water at the ice face.

The Prandtl number is given by:

$$Pr = \frac{\mu Cp}{k}$$

where μ is the fluid viscosity of water, $1.7317*10^{-3}$ Nsm^{-2} at 274K

Cp is the specific heat capacity of water, 4214 $Jkg^{-1}K^{-1}$ at 274K

k is the thermal conductivity of water, 0.5715 $Wm^{-1}K^{-1}$ at 274K

Thus:

$$Pr = 1.7313*10^{-3} * 4214 / 0.5715 = 12.7659$$

The Grasshof number is given by:

$$Gr = \frac{\rho^2 l^3 B g \theta}{\mu^2}$$

where ρ is the density of water, 1000 kgm^{-3} at 274K

l is the representative length. For a horizontal cylinder this is the outer diameter, D

B is the fluid coefficient of cubical expansion, $2.1*10^{-4}K^{-1}$

g is the gravitational acceleration, 9.81 ms^{-2}

θ is the temperature gradient, K^{-1}

μ is the fluid viscosity of water, $1.7313*10^{-3}$ Nsm^{-2} at 274K

Thus:

$$Gr = \frac{1000^2 * D^3 * (2.1*10^{-4} * \theta) * 9.81 * \theta}{(1.7313*10^{-3})^2}$$

$$= 6.867*10^9 * D^3 * \theta^2$$

For a horizontal cylinder, the Nusselt number is given by:

$$Nu = 0.525 * (GrPr)^{0.25}$$

Thus: $$Nu = 0.525 * (6.867*10^9 * D^3 * \theta^2)^{0.25}$$

For a diameter of 0.075m and a temperature gradient of 1K, this gives:

$$Nu = 23.02$$

The convective heat transfer coefficient, h, is given by:

$$Nu = \frac{hl}{k}$$

The representative length, l, for a horizontal cylinder is the outer diameter, D and the thermal conductivity of water, k, is 0.5715 $Wm^{-1}K^{-1}$ at 274K.

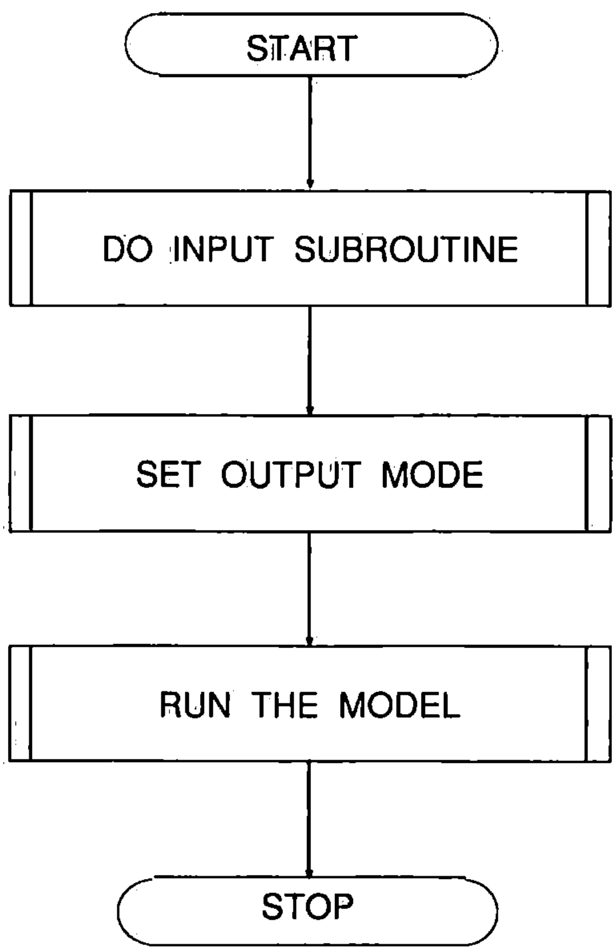
Thus, for a diameter of 0.075m:

$$h = \frac{23.02 * 0.5715}{0.075} = 175 \ Wm^{-2}K^{-1}$$

APPENDIX II

Description of the Bulk Tank Model Program

The program was written as a menu-driven program, the main menu being composed of four options which should be taken in turn. After completion of each option the program returns to the main menu in order to proceed. The complete program may therefore be described as follows:



The Input Subroutine

This routine presents a list of variables with default values. If changed, the new values will be used. Variables and constants are then initialised with the new or default values.

List of variables and Default values.

Variable	Default	Units
Tank size	2500	litres
Floor Area	2.99	m^2
Maximum Wall Area	5.38	m^2
Mass of Chilled Water	1000	kg
'U'-value of floor	700	$Wm^{-2}K^{-1}$
'U'-value of walls	575	$Wm^{-2}K^{-1}$
Maximum ice-bank radius	0.0375	m
Length of evaporator	92.96	m
Milk Delivery Temperature	32.5	°C
Daily Milk Volume	Tank size	litres
Number of milking units	4	
Mean Ambient Temperature for the day	10	°C
Chilled Water Temperature at start	1	°C
Start time of PM milking	16:00	HH:MM
Start time of AM milking	14hours 30 minutes after start of PM milking	
Print Frequency required	1	minutes

The input times are checked for legal values and rejected if not within the legal range. The daily volume is compared with the tank capacity and the program will not proceed if this figure is exceeded.

The following variables are also initialised:

Variable	Value	Units
Starting mass in tank	0	kg
Counter	0	minutes
Timestep	60	s
Ice radius to start compressor	0.95 * Maximum radius	
Ice radius to stop compressor	Maximum radius	
Compressor running time counter	0	minutes
Evaporator surface temperature	0	°C
Compressor status	"OFF"	
Agitator status	"OFF"	
Filling time	120	minutes

The following constants are initialised:

Constant	Value	Units
Density of ice	920	kg/m^3
Enthalpy of fusion of ice	337734	Jkg^{-1}
Thermal conductivity of ice	2	$Wm^{-1}K^{-1}$
Specific Heat Capacity of whole milk	3918	$Jkg^{-1}K^{-1}$
Specific Heat Capacity of water	4180	$Jkg^{-1}K^{-1}$

The following variables are then calculated:

Enthalpy of chilled water : Mass * Specific Heat Capacity * Temperature

Milk Pump Frequency : 2 minutes unless the number of milking units is less than 8 in which case 4 minutes.

Volume delivered by the pump : Pump frequency * 40% of the daily milk volume / Filling time.

Output Modes.

The second routine from the main menu sets the way in which the model's results will be presented. There are four options.

- Print the results on the screen.
- Print the results at a printer.
- Print the results to disc as a datafile.
- Print only a summary report on the screen.

If the first option is chosen, the results may appear either as a table of results or graphed. The graph option was included during the development stages of the program to give a visual indication of changes in some of the major variables. The graphing facility makes use only of low resolution and is not intended to provide the precision for taking readings, more to give an indication of trends or changes in direction. Four pairs of data sets may be plotted against time:

- Milk temperature and chilled water temperature against time.
- Milk temperature and milk volume against time.
- Milk temperature and ice-bank radius against time.

- Chilled water temperature and ice-bank radius against time.

If tabulated results is selected then a continuously scrolling table is presented showing values for the major calculated variables for each timestep. These variables are:

- The time (HH:MM)
- The volume of milk in the tank (litres)
- The Milk Temperature (°C)
- The Chilled Water Temperature (°C)
- The Ambient Temperature (°C)
- The Evaporator Surface Temperature (°C)
- The Ice-bank Radius (m)
- The Agitator Status (ON/OFF)
- The Compressor Status (ON/OFF)
- The accumulated Compressor Running Time (minutes)

The summary report option prints only the starting and ending time of the milking periods, the time of completion of milk cooling, and the time of all changes in status of either the agitator or the compressor.

Program Execution

The third item from the main menu executes the program to simulate a 24-hour cycle, starting at the set or default time for the start of afternoon milking.

The program progresses through a series of calculations representing the processes described in Section 3, simulating a single timestep. The first of these processes is to add a delivery to the tank if scheduled for the current timestep. The resulting mixed temperature and new mass of milk are calculated. Following this the wetted area and heat transferred to the chilled water are calculated. The resulting heat is removed from the milk and added to the chilled water. The convected heat to the ice face is next calculated, and the chilled water temperature adjusted as a result. The ice-bank radius provides an indicator for the compressor status. If this is on, then heat is conducted through the ice and away from the system. If it is off, no heat is conducted through the ice. If the heat being conducted away from the ice surface exceeds the heat arriving at the ice surface there will be a net freezing effect, otherwise a net melting effect, in each case followed by a recalculation of the radius, the chilled water volume and temperature. The radius is then checked for exhaustion. The timestep is then complete but program direction is dependent upon the outcome of three decisions. These are:

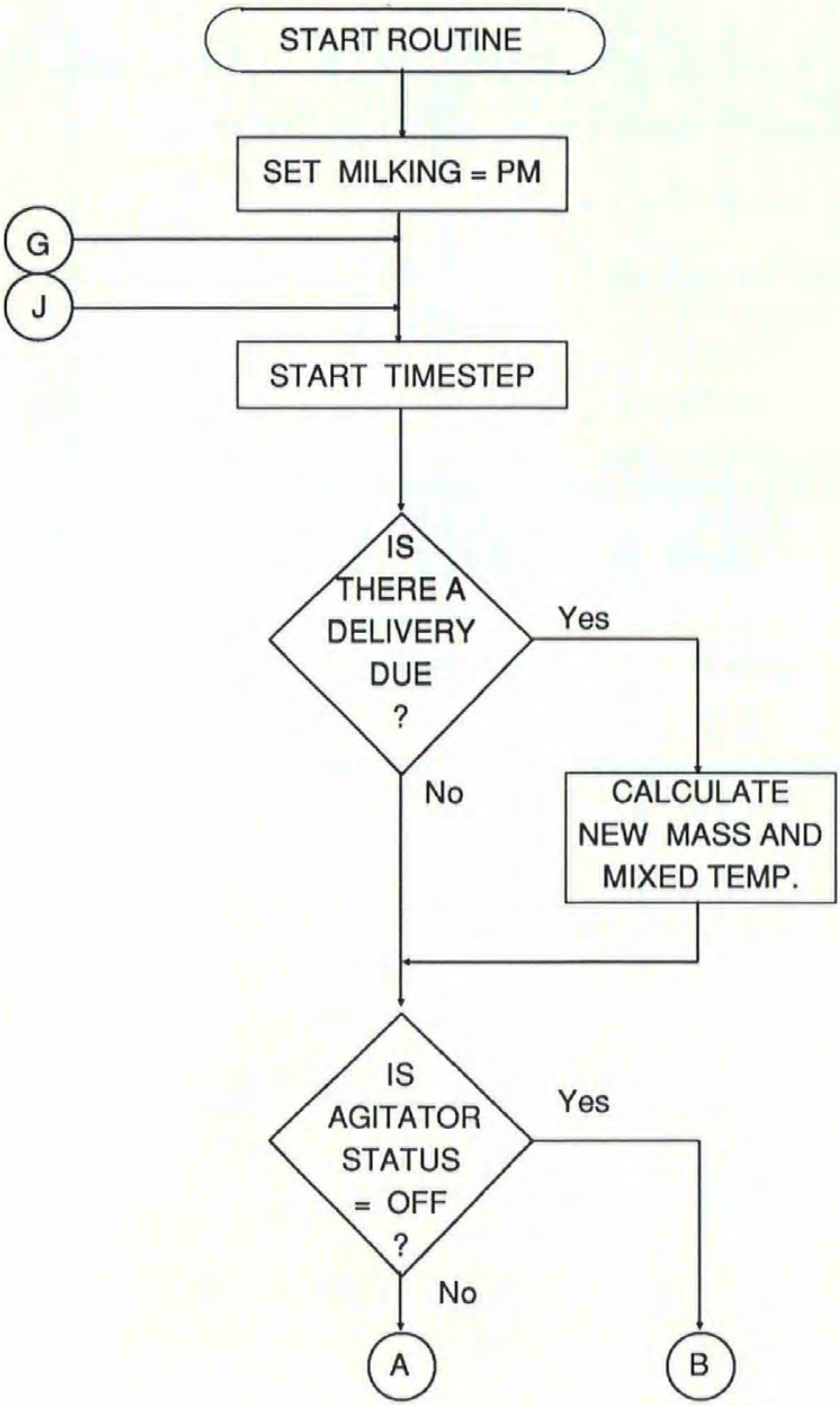
- Is the tank volume limit reached? This is 40% of the daily volume for a PM milking and 100% of the daily volume for an AM milking. If the limit is not reached, execution passes to the beginning of the next timestep, having updated the various counters. Otherwise execution passes to the next decision.

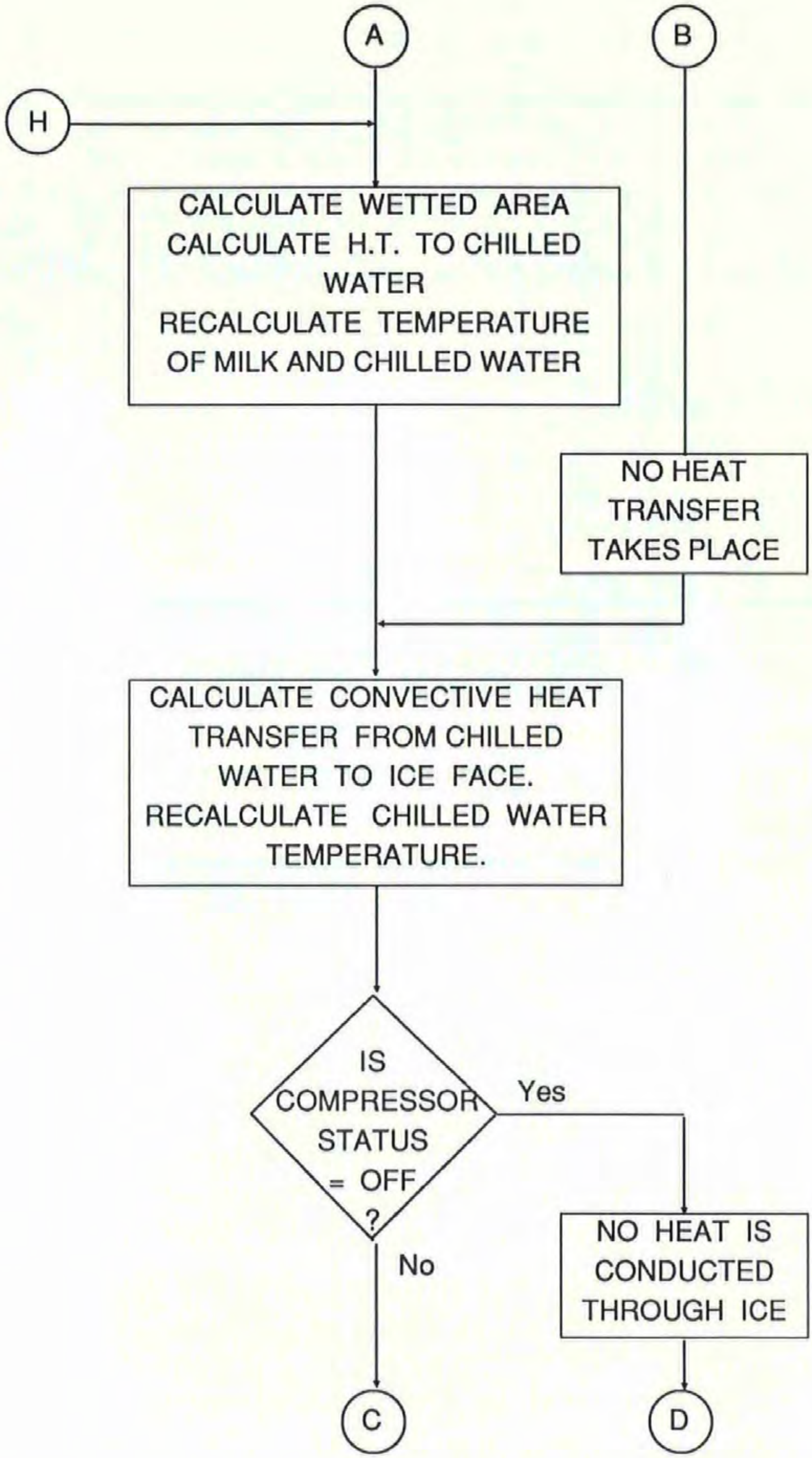
- Has the milk temperature been reduced to the target? If it has not, execution passes to the next timestep at the point where the milk is about to lose heat by heat transfer to the chilled water. If it has been adequately cooled, execution passes to the next decision.

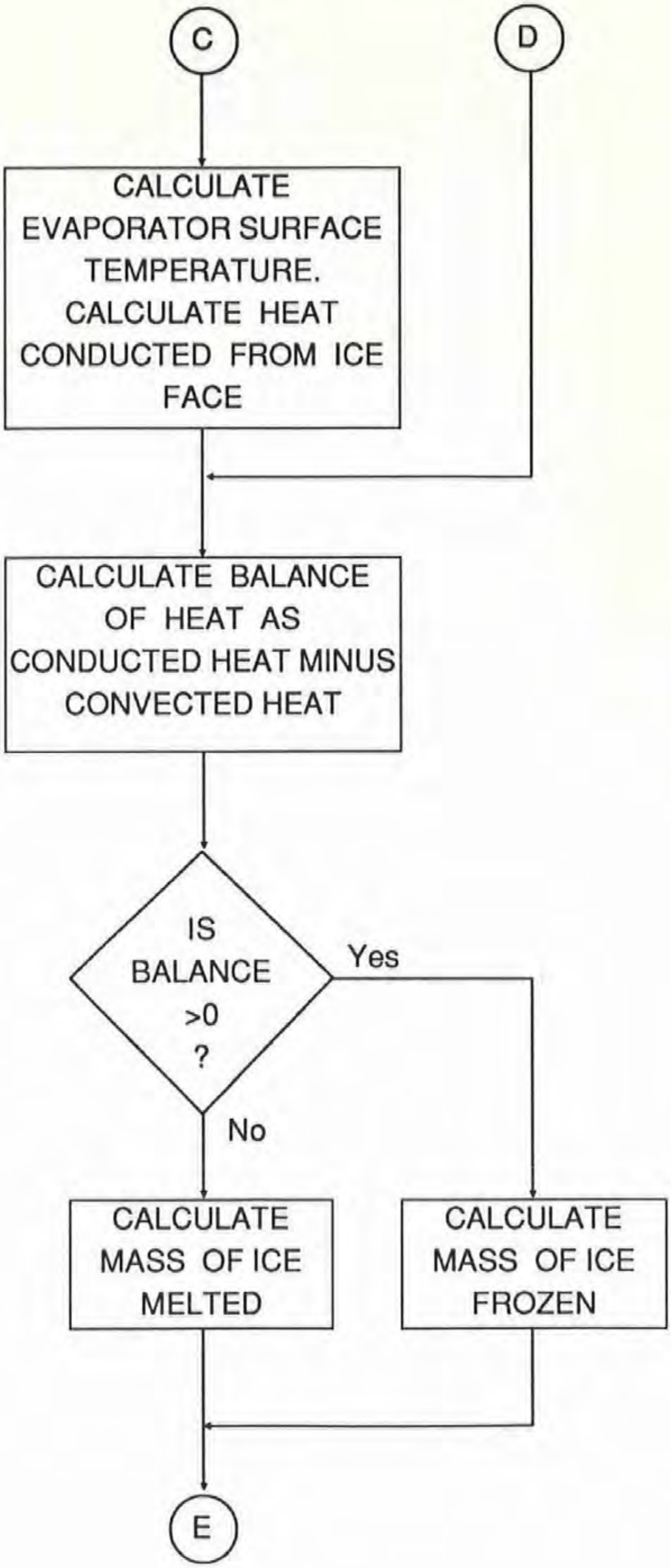
- Has the ice-bank been restored to its starting level **or** is the next milking due to start. If the ice-bank has been fully restored, the next step involves a check on whether the previous milking was the AM or PM milking. If the previous milking was an AM milking the program is complete and control passes back to the main menu. If the previous milking was a PM milking, the counter is advanced to the start time of the AM milking, the appropriate variables are reinitialised, and the AM milking proceeds, starting with a full ice-bank. If the next milking is due and the ice-bank is not restored, the program will proceed to the next milking, reinitialising the appropriate variables, but leaving the radius as calculated. If **neither** the ice-bank is restored **nor** is the time for the next milking due, then execution passes to the next timestep at the point where the convective and conductive heat transfers are calculated and compared. This may be summarised:

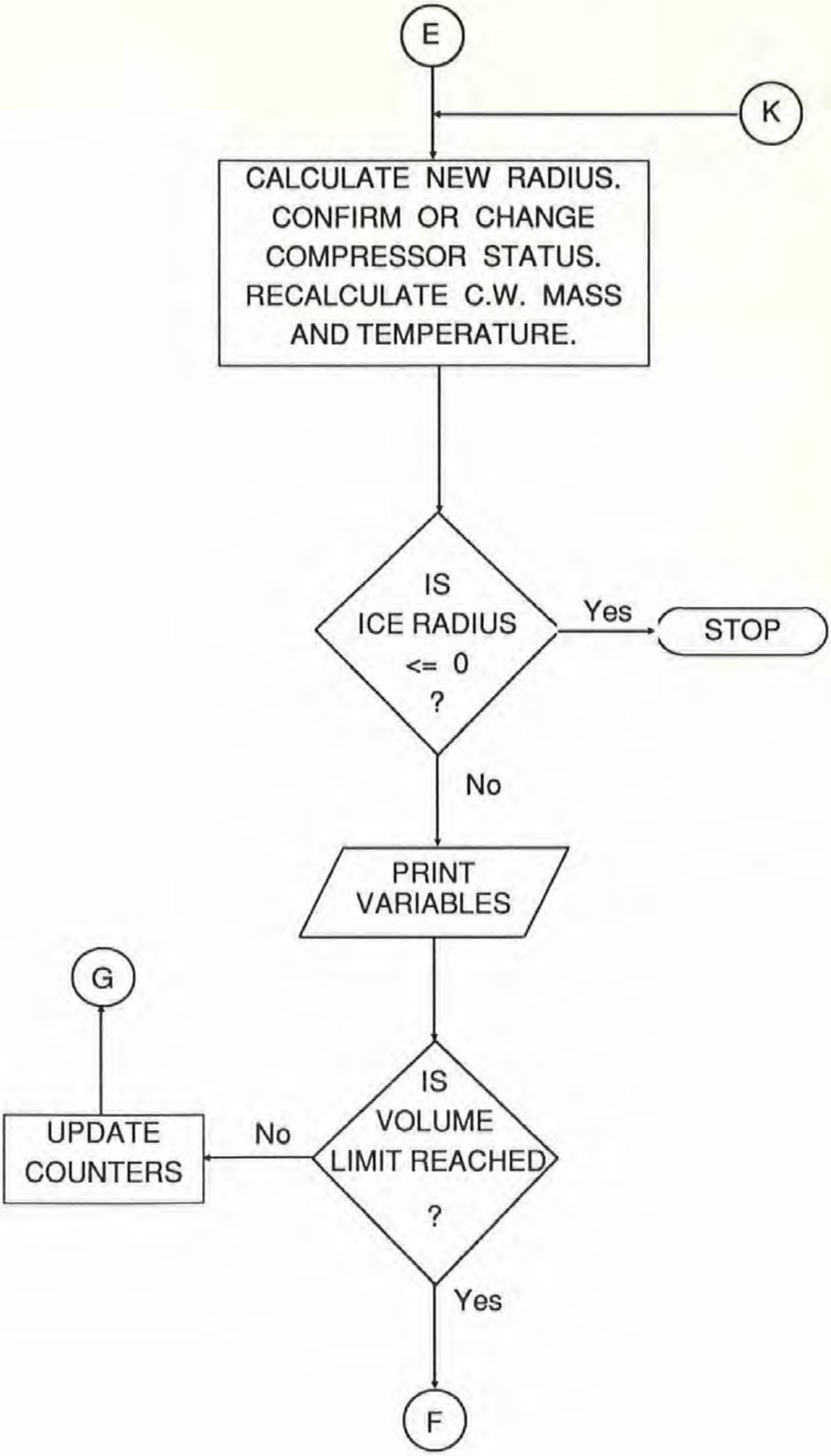
Ice-bank restored?	**Next milking due?**	**Action**
Yes	Yes	If previous milking was pm, next milking starts with full radius. If previous milking was am, returns to main menu.
Yes	No	Clock advances to next milking time.
No	Yes	Next milking starts with calculated radius.
No	No	Starts another timestep at the ice-building stage.

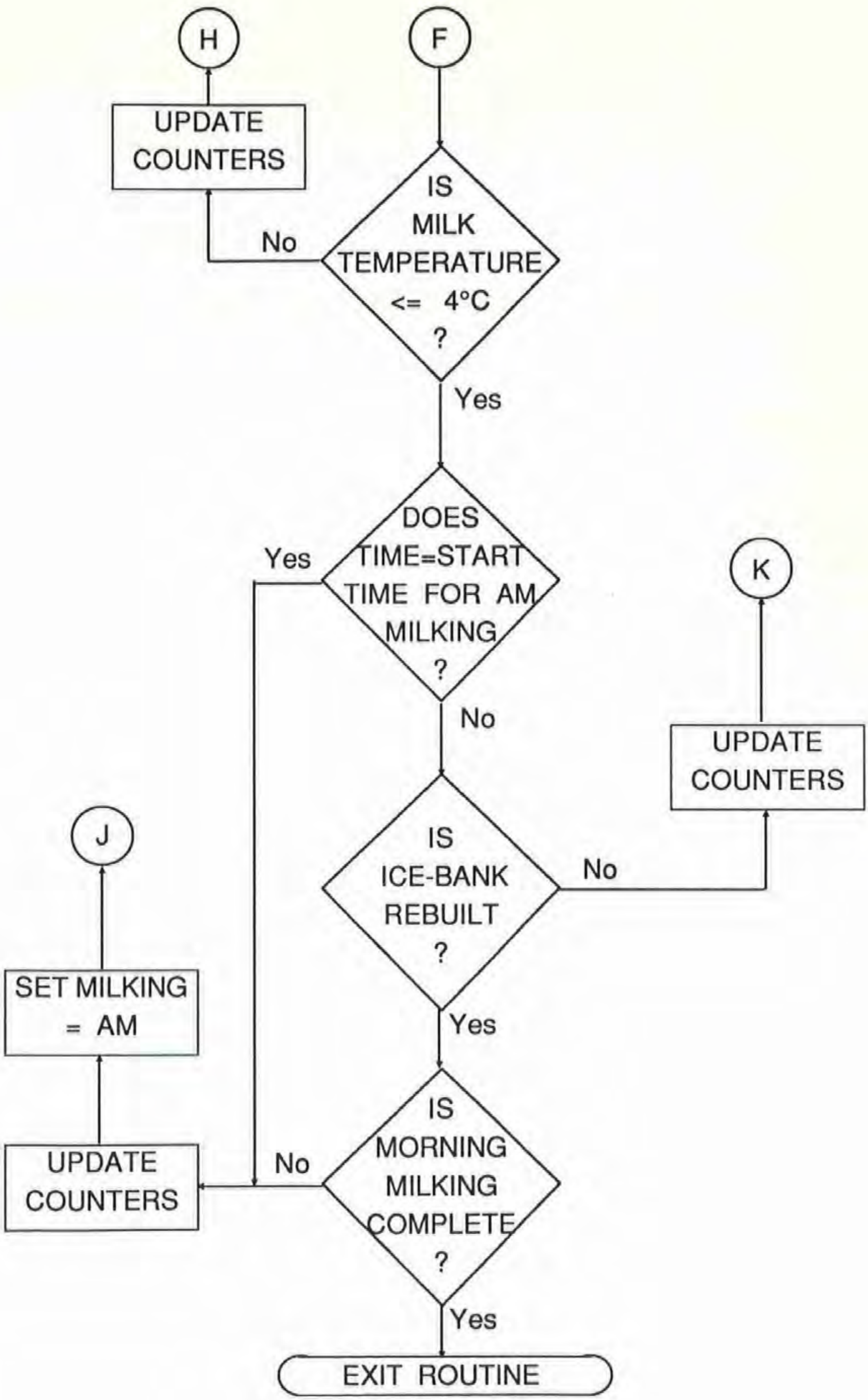
Flowchart of the main process.




A
B
H
CALCULATE WETTED AREA
CALCULATE H.T. TO CHILLED WATER
RECALCULATE TEMPERATURE OF MILK AND CHILLED WATER
NO HEAT TRANSFER TAKES PLACE
CALCULATE CONVECTIVE HEAT TRANSFER FROM CHILLED WATER TO ICE FACE.
RECALCULATE CHILLED WATER TEMPERATURE.
IS COMPRESSOR STATUS = OFF ?
Yes
No
NO HEAT IS CONDUCTED THROUGH ICE
C
D


C
D
CALCULATE EVAPORATOR SURFACE TEMPERATURE. CALCULATE HEAT CONDUCTED FROM ICE FACE
CALCULATE BALANCE OF HEAT AS CONDUCTED HEAT MINUS CONVECTED HEAT
IS BALANCE >0 ?
Yes
No
CALCULATE MASS OF ICE MELTED
CALCULATE MASS OF ICE FROZEN
E


E
K
CALCULATE NEW RADIUS.
CONFIRM OR CHANGE
COMPRESSOR STATUS.
RECALCULATE C.W. MASS
AND TEMPERATURE.
IS
ICE RADIUS
<= 0
?
Yes
STOP
No
PRINT
VARIABLES
G
IS
VOLUME
LIMIT REACHED
?
No
UPDATE
COUNTERS
Yes
F


H
F
UPDATE COUNTERS
IS MILK TEMPERATURE <= 4°C ?
No
Yes
DOES TIME=START TIME FOR AM MILKING ?
Yes
No
K
UPDATE COUNTERS
J
IS ICE-BANK REBUILT ?
No
Yes
SET MILKING = AM
UPDATE COUNTERS
No
IS MORNING MILKING COMPLETE ?
Yes
EXIT ROUTINE

APPENDIX III

List of References

A.D.A.S. (1977). Advisory leaflet No 602: Circulation Cleaning.

A.D.A.S. (1981). A study of water assisted milk cooling systems on farms in England and Wales. Unpublished internal communication.

BS 5226:1975. Cleaning and sterilisation of pipeline milking machine installations.

Bayetto, R.A., Patterson, H. and Wakeford, P.O. (1974). Electricity in Agriculture. Proc. I.E.E. Vol 121, No 11R, Nov 1974, I.E.E.Reviews.

Belcher, J.R. (1978). Laboratory assessment of heat recovery units for use with refrigerated farm tanks. XX International Dairy Congress, Vol E, 1978, 639-640.

Carpenter, J.L., Norman, A.J., Vallis, E.A. and Vranch A.T. (1980). The viability of solar water heaters in milking parlours in the U.K. In Energy conservation and use of renewable energies in the bio-industries. Ed. F.Vogt. Pergamon.

Castle, M.E. and Watkins, P. (1977). Modern Milk Production. Faber.

Central Statistical Office. (1980). Monthly digest of statistics. H.M.S.O., London.

Cromarty, A.S. (1968). Water heating with heat energy recovered from a refrigerated farm tank. J. Agric. Engng. Res. (1968) 13(3) 225-240.

Currier, J.W.R. (1976). Refrigeration energy in new milk storage. Bulletin de L'institut du froid - Annexe 1976-1 173-178.

Department of Energy. (1978). Energy Policy: a consultative document. Cmnd 7101, 1978, H.M.S.O., London.

Dodd, F.H. and Clough, P.A. (1955). Rept. Nat. Inst. Res. Dairying, 1955.

Dorfinger, H. (1978). Warm milk heats cold water: A contribution towards energy conservation and protection of the environment. XX International Dairy Congress, Vol E, 1978, 640.

Electricity Council. (1975). Monitoring electricity at the N.A.C. Farm Electric Focus, No.2, Dec. 1975.

Electricity Council. (1978). Farm Electric Handbook No.17: Milk Production. June 1972 (Revised 1978).

Fleming and O'Keefe (1982). Farm milk storage. J.Soc. Dairy Tech. 35(1) 13-15. January 1982.

Fleming, M.G. and O'Keefe, J. (1977). Energy can be saved in the farm dairy. Farm and Food Research (1977), 8(6) 139-140.

Hoyle, J.B. and Belcher, J.R. (1971). Which bulk tank? Farm Management Supplement, Dairy Farmer, 18 12 41-47.

Kidd, A. (1979). The energy equation during the eighties. Farmer's Weekly, 28th Dec. 1979.

Kingwill, R.G., Dodd, F.H. and Neave, F.K. (1979). Mastitis, in Machine Milking, ed's Thiel, C.C. and Dodd, F.H., publ. N.I.R.D. and Hannah Research Institute, 1979.

Lewis, D.A. and Tatchell, J.A. (1979). Energy in UK Agriculture. J. Sci. Food Agric. 1979, 30, 449-457

Milk Marketing Board. (1980). U.K.Dairy facts and figures, 1980. The Federation of United Kingdom Milk Marketing Boards.

Milk Marketing Board (1981). Shaping up for 1990. Milk Producer, May 1981

Milk and Dairies (General) Regulations. (1959). Statutory Instrument 1959, No. 277 Food and Drugs. H.M.S.O. London.

Ministry of Agriculture, Fisheries and Food. (1976). Milking Parlour Running Costs. Unpublished internal communication.

Ministry of Agriculture, Fisheries and Food. (1980). Annual Review of Agriculture. H.M.S.O., London.

Ministry of Agriculture, Fisheries and Food. (1982). Annual Review of Agriculture. H.M.S.O., London.

National Economic Development Office. (1981). Milk Production in the European Community - A comparative assessment. Agriculture E.D.C., N.E.D.O., London.

Newell, L. (1980). Cooling and storage of milk on farms. J.Soc.Dairy Tech. 33 (4) 136-139.

Norman, A.J. (1988). The appraisal and modelling of the production and use of hot water in the farm dairy. Ph.D. Thesis.

Norman, A.J., Vranch, A.T., Carpenter, J.L. and Vallis E.A. (1982). Solar water heating for the farm dairy in England. Proceedings of the Solar World Forum, Brighton, 1981. Pergamon, 1982.

Pollock, K.A. (1977). The energy crisis: defused or deferred? Delivered to a joint meeting of I.Agr.E and I.Mech.E., Exeter, 1977.

Prosser, H.W. (1977). Waste heat recovery in dairies on the farm. Presented at the "Energy on the Farm" conference at N.A.C., December 1977 - revised 11.6.79.

Rennie, N. (1979). Dairy Electrics. A cow costs 1.06 cents a day in electricity. N.Z.Farmer, March 22nd, 1979.

Shepherd, H.M. (1981). A study of energy saving equipment for farm dairies. Ag. Engnr., Winter, 1981.

Shropshire Farm Institute. (1967). Electricity on the farm at Walford and its cost effectiveness.

Sinclair, G. (1979). Bulk storage of milk at the farm. J.Soc.Dairy Tech. 32(2) April, 1979.

Ubbels, J. and Bouman, S. (1978). The saving of energy when cooling milk and heating water on farms - Heat pumps can be economically justified at large farms. I.I.F. - I.I.R. Commission BZ - Delft (the Netherlands) 1978-3.

Ubbels, J. (1977). A heat pump for cooling milk and warming water on the farm. Koeltechniek 70 (1977) nr 5 (mei).

Ubbels, J., van der Gaast, G. and Verheij, C.P. (1975). Energy saving in milk cooling and water heating on the farm. Zuivelzicht 67 (1975) 21.

White, D.J. (1977). Prospects for greater efficiency in the use of different energy sources. Phil. Trans. R. Soc. Lond. B. 281, 261-275 (1977).

White, D.J. (1979). Efficient use of energy in agriculture and horticulture. Ag. Engnr. Autumn, 1979.

APPENDIX IV

Related publications by the author.

Bowes, R.C., Carpenter, J.L., Vallis, E.A. and Vranch, A.T. (1981). The potential of energy saving in milking parlours in the United Kingdom. In Energy conservation and use of renewable energies in the bio-industries. Ed. F.Vogt. Pergamon.

Bowes, R.C., Carpenter, J.L., Norman, A.J., Vallis, E.A. and Vranch, A.T. (1980). The potential for the uses of solar water heaters in milking parlours in the United Kingdom. Department of Energy Solar Heating Workshop, November 1980.

Bowes, R.C., Carpenter, J.L., Vallis, E.A. and Vranch, A.T. (1981). A study of methods to optimise energy use in farm dairies in the United Kingdom. Symposium of Technical Section IV of Commission International du Genie Rural. Nottingham University, April 1981.

Carpenter, J.L., Bowes, R.C., Norman, A.J., Vallis, E.A. and Vranch, A.T. (1982). Energy use in herringbone parlours - an assessment of two years auditing in South Devon, United Kingdom. Presented to the Heat Pumps in Farming Symposium of the Institute of Refrigeration, March 1982.

Norman, Alice J, and Bowes, R.C. (1984). Electricity in the Farm Dairy: Requirements, use and conservation. J.Soc. Dairy Tech. 1984.

APPENDIX V

Notes on use of the accompanying disc.

The accompanying disc is formatted under MS-DOS version 3.3 to a capacity of 360K, for use on any IBM PC or AT compatible computer running this operating system. It is not a system disc and therefore cannot be used for booting the system. It contains 3 files:

- BULK.EXE
- AUDIT.WK1
- AUDIT.ASC

The first of these is the Bulk Tank program. To execute the program, type BULK at the DOS prompt and press RETURN. The program is menu-driven as outlined in Appendix II.

The file AUDIT.WK1 contains the audit data for the first year of auditing in a format prepared by the spreadsheet package Lotus 1-2-3, version 2.01.

The file AUDIT.ASC also contains the audit data for the first year, but in a standard ASCII format, which should be interpretable by a number of standard software packages.

ERRATUM:

When the BULK program is run, the tabulated results display has an error in the column headings. The column headed Cond. Temp should in fact be headed Evaporator Temp.

THESIS PREPARATION.

This thesis has been prepared on a variety of IBM AT compatible computers and printed on an Apple Laserwriter II NTX Postscript-compatible printer. Wordprocessing was carried out using Microsoft Word, version 4. Graphs were prepared using Lotus 1-2-3, version 2.01, and the diagram on page 5 was prepared using Microsoft Paintbrush.

The final document was laid out using Xerox Ventura Publisher, version 1.2. Chapter headings are Helvetica 28-pt bold, subheadings are Helvetica 15-pt bold and 12-pt bold italic. Body text is 12/24 pt Palatino.