Dynamic Modelling of Meat Plant Energy Systems

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ABSTRACT

The objective of this study was to develop dynamic mathematical models of the major energy use and recovery operations within the New Zealand meat industry. Ordinary differential equation based models were developed for the five most common rendering systems, for hot water use, generation and storage, and for the refrigeration system. These cover about 90% of process heat use and about two-thirds of electricity demand. Each model was constructed so that ultimately it could be linked to the others to develop an integrated energy supply and demand model. Strong linkages to product flow were developed for the rendering models, but those for hot water and refrigeration are less developed, although there is no technological impediment.

In developing the models for rendering it was assumed that cookers and dryers are perfectly mixed vessels and that time delays in materials transport are negligible. Model predictions could be improved by removing these assumptions, but taking into account the possible extent of data uncertainties, the present accuracy may be adequate for the overall meat plant energy model.

A major consequence of the development of a hot water demand model was that areas of low efficiency were identified. By attention to equipment designs for hand tool sterilisers and cleanup systems substantial heat savings are possible. Although not tested, both the model for heat recovery and the model for hot water storage and supply are expected to be accurate as few major assumptions were required in their development.

The main novel feature of the refrigeration model is that it treats the refrigeration applications in abstract terms rather than performing a room by room analysis. As a consequence data demands are lower than for refrigeration models which use a room-based approach, and the actual data needed are more easily obtainable. In spite of the lower data requirements good accuracy was demonstrated.

The models developed will have major benefits to the NZ meat industry, initially as stand-alone entities, but later as an integrated package to help in reducing energy use.

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1 INTRODUCTION

A survey by Wee and Kemp (1992) showed that the New Zealand Meat Industry used 4006 TJ of fuel energy and 1638 TJ of electrical energy during the 1989-90 season at a total cost of $63 million.

They also reported a specific energy cost ranging from $35 - $130/tonne of dressed carcass weight among the 31 meat plants they surveyed. While differing fuel types and electrical tariffs accounted for some of this disparity, a large portion was attributed to poor plant design/utilisation and energy management practice.

Wee and Kemp (1992) also described a "black box" model developed by the Meat Industry Research Institute of New Zealand (MIRINZ). The model would allow a user to compare an existing plant energy usage to a "model" plant built up from the data obtained with the survey. However, the "model" plant can only represent best existing practices found within the group of plants surveyed. It may well be that even more energy efficient regimes are possible.

Meat plant design has tended to be experience-based in the past. This has meant that if designs have been successfully implemented once they have then been repeated in subsequent new plants. "Safe" modifications at each new installation to improve design but still ensure successful operation may have been introduced.

Ministry of Agriculture directives have also had a large influence on design and management practices since the 1960's. Although primarily concerned with maintaining and enhancing meat quality, the directives have often been focused on effects of poor design rather than on encouragement of designs which would obviate objectionable effects and improve energy efficiency simultaneously.

The nature of many processing operations, particularly on those plants killing stock for only a few hours per day, are also not conducive to energy efficiency. For example, large heated vessels and cooled rooms are brought to operating temperatures at the start of daily production and then allowed to return towards ambient conditions at the end of the working day. This introduces thermal lags or inertia worsened in many cases by hot water hosing of cooled rooms prior to and after daily edible production. Rendering plants, traditionally suppliers of hot water to edible areas, may not start up until several hours after hot water requirements begin. The rendering plant is often designed with a throughput which ensures operation continues for several hours after edible production ceases. As a consequence excess hot water is produced and large storage vessels are required to provide storage. Even then it is common for excess hot water to be spilt in large quantities overnight. Cooling and freezing of product also continue through the night so that any heat recovery from the refrigeration system faces similar problems. The result of these factors is that any project seeking to establish methodology that will lead to minimum energy use, must consider the time sequencing of demands and potential for recovery.

Whilst pinch technology has the ability to analyse site wide energy conditions and optimise the use of heat recovery, it was developed for industries which traditionally run at steady state conditions and this is not the case in the meat industry. However, the principle of pinch technology, to routinely achieve the minimum realistic energy demand, is applicable if applied in a different manner.

The method of application is to define the concept of "good practice", what can be achieved if all realistically justified energy efficient practices are implemented. This is not a thermodynamic ideal, nor is it the best previously achieved (i.e. the MPEM approach), but a level of use determined from sound engineering analysis of the real process needs, and justifiable overheads. It is a target of real practical value.

Traditional plant designs have concentrated on developing structures which house product at the least possible cost and then designing the energy-based processes to conform to the structure. As a consequence the designer of the energy-based process has had to compromise "good practice", and subsequent energy requirements have been high. This is evidenced in the high baseloads which appear in every energy survey carried out within the meat industry in New Zealand.

The purpose of the present work is to define time-variable "good practice" energy requirements throughout a meat plant. This will be done by mathematical model development in which existing building structures and management practices will be ignored and model predictions will be based solely on reaction of processes to product flows within the plant. The development of a comprehensive model is complex, and beyond the resources available at present, so this work seeks to provide only some of the building blocks for a total integrated model. The specific areas addressed are:

(i) daily stock input and movement through the plant,

(ii) rendering system,

(iii) hot water system, and

(iv) refrigeration requirements.

Models in these areas will cover at least 90% of the process heat demands. It is recognised that wool dryers and blood dryers may form up to 7% of fuel energy use within a meat plant and there is also significant base load. (Downey and Fox 1987). Incorporation of the minor process heat users and base load fuel demands is left to others.

Refrigeration electrical energy use is typically two-thirds of the total plant load (Fleming 1976). It is thus the most important electricity user. Other electricity users (e.g. lights, process equipment drives, facility services) tend to be widely distributed and hard to control. Hence they represent a modest potential for electricity saving and due to the limited resources available to the project, they were not modelled.

Benefits from the use of models developed within this work include:

(i) the framework upon which to build an integrated time variable model to cover an entire meat plant,

(ii) an ability to optimise energy use and accurately predict heat recovery,

(iii) the establishment of "good practice" energy usage rates,

(iv) the ability to accurately size major items of capital equipment including:

- refrigeration systems,
- steam and hot water boilers, and
- rendering cookers or dryers,

(v) accurate sizing of associated pumps, piping, insulation and fans.

The models represent a systematic approach to minimisation or optimisation of energy use within the meat industry. The strategic importance of this work has been recognised by the Electricity Corporation of New Zealand (ECNZ) and Auckland Farmers Freezing Company New Zealand Limited (AFFCO NZ), the research sponsors, and by the involvement of both MIRINZ and Massey University in the research.

2 LITERATURE REVIEW

The purpose of the present project is to develop a group of mathematical models which will form the basic framework of an overall dynamic model of a meat plant energy system. This will require choice of an appropriate level of model complexity; selected such that the data requirements to use the model are not so large that this would discourage users from the meat industry, yet accurate enough to be a useful design and decision making tool.

In the present review of the literature papers have been selected for discussion if they meet one or more of the following criteria:

(i) they contain a dynamic model of an important process, and the model is not prohibitively complex for the type of model application envisaged,

(ii) they contain steady state models or analyses that may give insights into how a dynamic model can be constructed, or

(iii) they contain major data that can be readily applied with any model developed.

There is no discussion of general mathematical modelling methodology, nor is there any attempt to cover all potentially useful data. Models based on the use of partial differential equations have largely been ignored because it is the opinion of the author that these are too complex for the type of application envisaged. Having limited the bounds of the literature search in this manner it is then convenient to group the literature according to the four model application areas:

(i) daily stock input and movement through the plant,

(ii) rendering system,

(iii) hot water system, and

(iv) refrigeration requirements,

and then within each of these according to the three criteria discussed above.

2.1 DAILY STOCK INPUT AND DISTRIBUTION WITHIN THE PLANT

2.1.1 Dynamic Models

Darkey and Crosbie (1987) developed a time-variable model for individual lambs and carcasses progressing through a meat plant. The model first considered the lambs as they were unloaded from stock trucks, followed them through the stockyards, kill area and then through the cooling process to final cold storage. The focus was on time delays and their effect on process efficiency. No links to energy consumption were made.

2.1.2 Steady State Models

Loeffen *et al.* (1987) used regression analysis of raw material flow rate data from a single meat plant kill and boning areas. Yield coefficients to predict daily meat meal and tallow production from both departments were presented. These were tested against actual production data and results from an earlier MIRINZ interplant survey, (Anon 1972). Some errors were encountered in measuring equipment but agreement was generally good.

2.1.3 Useful Data

Data defining the composition of raw material for beef (prime and cow) and lamb (sheep and lamb) are presented by Oldfield (1987). The data set is the result of a review of earlier workers' findings and is generally accepted as a useful working guide within the meat industry. Various other compositional data available includes those of Davies (1989), Johnson (1980) and Spooner (1992). These contain more detail than presented by Oldfield.

2.2 RENDERING SYSTEMS

2.2.1 Dynamic Models

Langrish *et al.* (1990) describe a model which predicts the changing gas and particle conditions as a particle travels along a direct fired rotary dryer which was part of a low temperature rendering system. The model considers the co-current dryer as a process plant in which a plug of solids moves along with a volume of gas. The model was verified experimentally by the introduction of commercially available sterilisation indicators into the wet feed to the dryer with subsequent capture and inspection at the dryer discharge end. Results confirmed sterilisation time/temperatures predicted by their model were adequate to meet Ministry of Agriculture sterilisation regulations.

2.2.2 Steady State Models

Herbert and Norgate (1971) reported results of an on-site energy survey involving extensive instrumentation of a batch rendering cooker. Data for 20 batch runs were presented and heat transfer coefficients calculated for the steam-heated paddles and jacket at various product moisture contents. The accuracy of measurements for all variables was demonstrated by heat and mass balances. Steam usage was not accurately measured at short times which limits the usefulness of the data.

Fernando and Dunn (1979) propose design heat transfer rates for so-called dry rendering cookers obtained through the use of pilot plants. Their data for a pilot scale cooker suggest higher heat transfer coefficients than those of Herbert and Norgate, particularly at higher moisture contents. Fernando and Dunn state that using scale-up rules proposed by Haughey and McConnell (1973) the resultant full scale cooker heat transfer coefficients should be higher than those measured by Herbert and Norgate (1971).

Caddigan and Swan (1985) measured energy efficiency of two MIRINZ low temperature rendering systems, assessed by measuring raw material flows through the plant, and steam and electricity use. Detailed data are presented in the form of mass and energy balances. The plants chosen represented likely extremes of raw material moisture content (43 and 60%), thus covering a wide spectrum of industrial conditions.

2.2.3 Useful Data

Brown *et al.* (1988) carried out investigations to determine whether meal temperature could be used for end-point control in the drying of meat and bone meals. Laboratory tests were carried out to study the effect of meal fat content and a correlation was obtained between the meal drying rate and moisture content using data from eight experiments at each of three fat contents.

2.3 HOT WATER

2.3.1 Dynamic Models

Despite the importance of energy consumption within a meat plant hot water system, no dynamic models of hot water systems were found in the literature. This is perhaps a little surprising when it is considered that hot water usage may account for 30 to 80% of a meat processing plant's total fuel energy requirement (Downey and Fox 1987).

2.3.2 Steady State Models

Hansen *et al.* (1984) present a linear programming model for optimisation of water management and associated energy in a meat packing plant. Water and energy usage were plotted against the kill and curve fitted. The correlation coefficient for water usage was 0.83 and that for energy 0.74, indicating some lack of fit. The proposed model, based on the regression equations, looks at site-wide consumption of cold as well as hot water and provides a tool for modelling the effect of lowering or raising the daily kill level. Simulation of various energy, water and labour saving devices and different types of effluent disposal methods is also possible as are plant-wide predictions of financial savings. The model was tested against experimental data and agreement was always within ±16%. The model is of the "black box" type and the error was attributed in part to the relatively high base loads for water and energy consumption.

2.3.3 Useful Data

Data for various heated water user device flows including sterilisers, handwashes and apronwashes were collected at three meat plants by Peacham (1993). He also measured total daily plant and departmental hot water flows. The data do not form part of a national survey but arise from individual surveys of plants carried out over a number of years by MIRINZ.

Lively (1975) presents results of using high pressure (34 bars) hosing for cleaning which show hosing water consumption rates were about half those for conventional pressures when the technology was introduced into an American meat plant.

2.4 REFRIGERATION

2.4.1 Dynamic Models

Marshall and James (1975) developed what is recognised as the first major time-variable food refrigeration process model. The model described a vegetable freezing tunnel coupled to a two stage compression refrigeration plant. The model consisted of 46 ordinary differential and 105 algebraic equations and allowed simulation of a wide variety of system parameters.

Loeffen *et al.* (1981) proposed two methods for freezing time predictions of simple shapes which considered time-variability of heat transfer coefficient and cooling medium temperature. The two methods were based on numerical integration of an ordinary differential equation; the first method predicts the freezing front position and the second, the time for the product to freeze. Testing was carried out against a three time-level finite difference system for cooling medium temperatures and surface heat transfer coefficients which vary with time. Agreement between the two proposed methods and the equivalent finite difference was generally good (<10% difference).

Cleland (1983) presented a set of time-variable models to describe a typical New Zealand meat processing refrigeration requirements. There were more parameters to consider than the model of Marshall and James (1975) and so a methodology was sought which might reduce the level of model complexity yet still provide reasonably accurate predictions of heat load. One such method was to consider heat loads which had a rapid response to time as "pseudo steady state" thus allowing them to be treated using algebraic equations. Other parameters were modelled using ordinary differential equations, for example temperatures and humidities in airconditioned rooms, chillers, freezers and cold stores. Those are subject to heat loads such as heat given off by machinery, workers and door openings.

Assumptions made during model formulation were reported as being realistic from a practical point of view. These included:

(i) the food product model considered the unfrozen region within the product as having the same shape as the total object,

(ii) changes in suction line refrigerant mass flow rates between the compressor and surge pot were ignored,

(iii) pipeline pressure drop was assumed to be insignificant,

(iv) the numerous liquid and vapour streams other than vapour exiting a compressor were assumed to be saturated. This assumption had been made in an earlier model (Cleland *et al.* 1982) which was successfully tested against experimental data.

Testing of the model was carried out by hand calculations when various room model simulations had reached "stable conditions" and good agreement was achieved. Simulation of a carton freezer with a constant air temperature was carried out and these results tested against finite difference calculations. Agreement was within ±10% which is sufficiently good for engineering purposes.

In 1985 Cleland made modifications to the model and tested predictions against experimental data gathered from a large New Zealand meat processing plant. The modifications were mainly concerned with the product freezing sub-model and removed the earlier assumption that the unfrozen shape remained constant. The updated sub-model was extensively tested and found to be more accurate over a wide range of conditions and shapes than the method proposed in 1983.

Whilst the 1983 model was site specific, the 1985 model had been structured into a group of sub-models from which an appropriate one could be chosen depending on whether steady state would suffice or whether time-variable modelling was required. The increased choice also meant that a product, room or entire plant could be simulated by linking sub-models as the situation required. This had a beneficial effect on the amount of computation required.

The new group of models was named the "Refrigeration Analysis Design and Simulation" package (RADS), and was described as being capable of simulating most industrial refrigeration systems and all common refrigerants.

Comparisons between model predictions and experimental data suggested that:

(i) air temperatures in the carton freezers were generally underpredicted. Further investigation showed substantial pressure drop occurred in the return pipe line to the engineroom and when a correction for this was made to the model agreement was improved. Batch freezer air temperatures were also underpredicted and although also partly attributable to return pipeline losses it was suggested that the real evaporator performance could be lower than suggested by manufacturers' data. Similar evaporators had been tested independently and overall heat transfer coefficients were found to be 30% lower than those claimed by the manufacturer. If the heat transfer coefficient input to the model was reduced by 30% model predictions for the batch freezer air temperature matched experimental data both in shape of the time/temperature profile and in absolute terms.

(ii) cold store time-variable profiles did not always agree, due in part to the uncertainties in data for the door opening periods.

(iii) reasonable agreement was demonstrated between predictions and experimental data for air conditioned areas.

(iv) for cooling floors, agreement was reasonable given data uncertainties.

Overall, the model as proposed in 1985, provides predictions of time-variable temperatures and heat loads of reasonable accuracy. It was concluded by Cleland that lack of agreement between the model predictions and experimental data depends as much on the quality of the experimental data as on weakness in model formulation. The model complexity was significantly lower than that of Marshall and James (1975).

Cleland (1990) discusses model designs required for simulating the performance of food refrigeration equipment. He suggests that these may fall into three broad groups or types.

(1) Type I considers mechanical refrigeration systems in detail but utilises simple descriptions for refrigeration users.

(2) Type II describes the mechanical plant in similar detail to Type I but also describes the refrigeration user in detail.

(3) Type III uses simple descriptions for mechanical refrigeration and focuses more on time-variable conditions within the refrigeration user.

As an example, the model of Marshall and James (1975) in which the level of model complexity does not vary from the product heat load through to the engineroom could be described as a Type II model, whilst that of Cleland (1985) is categorised as Type III. Although a Type II approach is desirable in order to obtain accurate predictions across an entire refrigeration plant, the sheer complexity of such a model has encouraged many researchers to seek solutions by way of a Type I or III model approach.

Lovatt *et al.* (1993) further extended the work of Cleland (1986b) by combining chilling, freezing and subcooling models to form an improved product heat load model. Proposed transition points at which the sub-model for chilling product transposed to the freezing sub-model and the subsequent switchover point to the subcooling model were also developed. The model predictions of product heat load were tested against data obtained from freezing lamb carcasses in an experimental freezer. The model predictions were found to be within 10% of the data obtained experimentally and this is probably as accurate as may be expected given uncertainties of poor air distribution and differing heat transfer coefficients over the surface of the carcass. The new model is robust, relatively simple and requires low amounts of computational time when compared to finite difference type models.

Pham (1991) presents a method embedded in a software package for the design and/or simulation of stand-alone refrigerated rooms or entire refrigeration plants. The proposed approach considers product heat loads as time-variable, using the model of Lovatt *et al.* (1993) already described, but all associated product-related loads as steady state. Thus user input of data and computer operational time is reduced when compared to a totally time-variable model, but this is at the expense of some prediction accuracy. The software package was aimed at plant engineers.

2.4.2 Steady State Models

The RADS suite as described by Cornelius (1991) contains several steady state modelling systems each implemented in a specific computer program.

(i) "Applics" carries out steady state analysis of room environment and product loads.

(ii) "Room" has a similar purpose to Applics but offers much greater flexibility in integrating sub-models.

(iii) "Sybal" selects compressors, evaporators and condensers to meet user specified duties.

(iv) "Layout" models heat and mass balances on multistage compression plants.

2.4.3. Useful Data

Computationally-efficient subroutines to establish refrigerant thermodynamic properties were proposed by Cleland (1986a). Compared to the routines proposed by Chan and Haselden (1981), which had become an international standard, a minimal reduction in accuracy was found for many practical applications, but computation time was much lower.

Fleming (1969) present thermal properties for whole lamb carcasses, thermal conductivity for lamb products are presented by Pham and Willix (1989), and Pham *et al.* (1993), present measured thermal property data for a range of meat products.

2.5 SUMMARY

A time-variable stock flow model for a NZ meat processing plant has been developed. Its focus was on time delays for individual carcasses during processing, and not on energy use.

A time-variable model describing a direct fired rotary dryer operation exists, but no other rendering processes appear to have been described by time-variable models. Steady state models exist which describe mass flow rates for low temperature rendering systems. Correlations between moisture content and heat transfer coefficients for batch dryers have been demonstrated, as has correlation between meal moisture content and drying rates.

No time-variable models appear to exist in the area of hot water use.

Sophisticated time-variable models of meat plant refrigeration systems exist. However, the level of data input required to simulate all but a simple room requires considerable user expertise, time and data.

3. PRELIMINARY CONSIDERATIONS

The purpose of the present project is to develop mathematical models of important energy-using processes in the meat industry suitable for incorporation in an overall integrated dynamic meat plant model to be developed at a later date. The models should be kept as simple as possible while still enabling the user to obtain results with reasonable accuracy. Low levels of user data input are desirable.

Users should be able to model common animal species and categories being processed through a meat plant using heating and cooling processes which are in current practice. However, it is vital that the model development process is visionary so that the incorporation of new technology, and of "good practice" concepts as discussed in Chapter 1 is easily accomplished. For example, provision should be made within the refrigeration section to model the use of plate freezing which is expected to gain wide acceptance throughout the meat industry in the near future.

The modelling environment should be well structured and able to handle all types of ordinary differential equations likely to arise from the variety of plant layouts within the industry at present whilst still retaining predictions of reasonable accuracy. The modelling environment should be able to be run satisfactorily on a personal computer.

Within this framework, the specific objectives of this work were defined:

(i) A model will be developed which will be capable of simulating acceptance of all common species and categories of slaughter animals. The user will be able to specify various kill weights, rest periods and category change times. The model will then calculate various time-variable mass flow rates to production departments.

(ii) Models will be developed and tested for the most common types of rendering:

- continuous conduction heating cooker,
- batch cooker, and
- low temperature rendering utilising,

  (a) continuous conduction heating dryer,
  (b) batch cooker, and
  (c) direct fired rotary dryer.

(iii) Time-variable models will be developed to describe overall plant functions in terms of:

- hot water usage,
- hot water storage and generation, and
- hot water recovery.

(iv) A time-variable model will be developed which predicts heat loads arising from the refrigeration needs of the product flow rates specified by the user through the stock input and distribution model. Once the time-variable product-related loads (e.g. fan power, door and insulation gains) and baseloads have been added, the total heat loads will be apportioned to various suction pressure levels. The response of the refrigeration system to these loads will be modelled to enable prediction of the overall time-variable refrigeration-related electrical loads to be made.

4. DAILY STOCK INPUT AND DISTRIBUTION ("GENERIC") MODEL

4.1 MODEL PHILOSOPHY

In order to quantify required energy flows and possible heat recovery within a plant as accurately as possible, it is necessary to begin with daily proposed carcass numbers or weights for processing. These should then be broken down into product streams to the various processing departments. Product parameters that change with time should be considered, including mass flow rates and proportions of constituents such as fat-free solids, moisture and fat. The most important ways that energy interacts with product are:

(i) The flow of product through production departments such as kill chains, boning rooms and offal departments, produces product flows to energy intensive processes downstream. The rendering department is one of the major process thermal heat demands, and varying degrees of hot water recovery are possible depending on the type of rendering.

(ii) Actual thermal energy is expended within the meat processing departments themselves by hot water hosing, carcass, hand and apron washes and sterilisers. Space heating will not have a large dependence on product flows.

(iii) Refrigeration demands will vary depending on the mass flow rate from the kill chains to chillers and cooling floors. Freezing requirements will also be governed by the time-variable flows from boning rooms and offal departments. Air-conditioning demands will not be significantly affected by product flows except when short or extended days are worked.

Although not modelled within the present work, smaller thermal energy users also depend on the flows from the so-called production departments e.g. wool drying and blood processing. Similarly non-refrigeration electrical energy demands will be affected by product flows.

The so-called "generic" model converts user inputs of live animal numbers to product flows through various production departments and provides a vehicle for interaction of energy use with production. It will determine appropriate product mass flow rates so that energy usage within the production departments themselves may be predicted.

4.2 PRODUCT MOVEMENT INTO AND THROUGH THE PLANT

Preparations for daily red meat production usually start at 5 to 6 a.m. with an early morning hygiene washup. Kill chains start at about 7 a.m. but boning rooms may start as early as 6 a.m., although this will vary from plant to plant and season to season. Production is divided into runs that are traditionally of 2 hours duration with a 20 minute break between runs and a meal break of 45 minutes after every second run. A day or production shift normally ceases after 8 hours, but can continue as long as 10 hours. Two or even three such shifts may be worked each day.

Different categories will be processed within each species type, e.g. for beef the day's production could start off with boner cow, switch to prime steer part way through the second run and then switch to bull sometime in the third run. Short days often occur due to a lack of stock and conversely overtime beyond the normal 8 hours may also be worked when stock is available.

Models such of that of Darkey and Crosbie (1987) were considered unnecessarily complicated as the fine detail of individual carcass movements from stock truck to freezer storage is not important when attempting to define plant wide energy demands. A simpler approach was considered more appropriate.

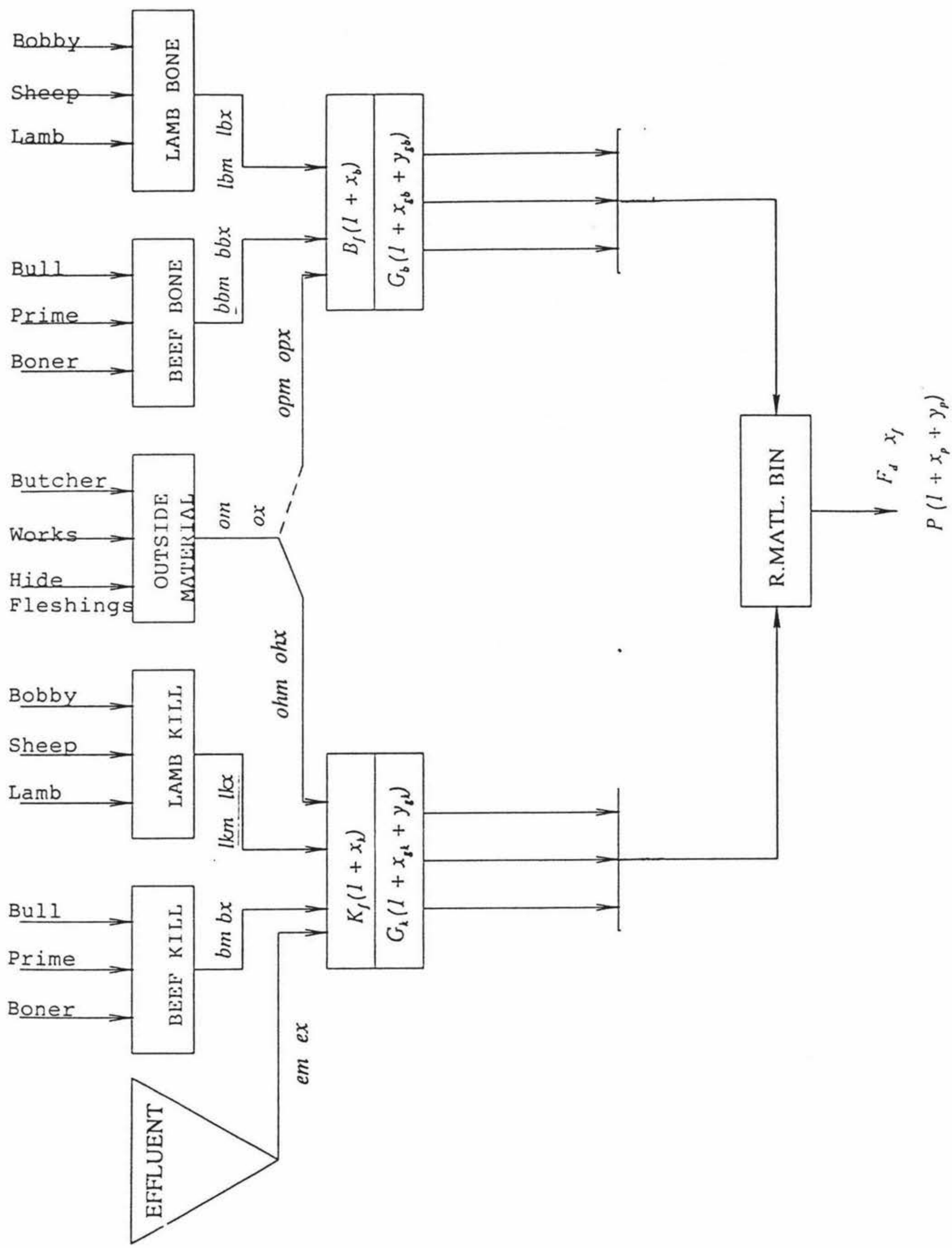


Figure 4.1 Schematic diagram of the generic model for rendering. (Nomenclature is defined in Section 4.3.1)

4.2.1 Departmental Event and Batch Times

In order to use the generic model the user will be required to input the following kill and boning area event times so that simulated product flow rates may be switched off and on or altered at the appropriate times:

- (i) start time,
- (ii) time rest break starts,
- (iii) time rest break finishes,
- (iv) time that category changes,
- (v) time that production finishes,
- (vi) time that cleanup finishes,
- (vii) time that input of outside material and recovered effluent solids to rendering starts,
- (viii) time that the input of outside material and recovered effluent solids to rendering finishes.

4.2.2 Chain Speeds

Users will also be required to input chain speed data for both the kill areas and boning rooms.

4.3 FLOWS OF MATERIAL TO RENDERING

As carcasses proceed along kill floors, various inedible components are separated from the carcass to be processed into meat meal and tallow. A similar system operates in the boning room where the material for rendering consists largely of bone. Significant amounts of fat can be recovered from both the offal and the trimming rooms and this material is directed to rendering. Other sources of rendering material include fat scrapings from the effluent solids recovery system and stock which has died in transport or mercy kills. Material is also sometimes bought in from off-plant sources such as small meat plants, meat trimmings from stand-alone fellmongeries and waste from butchers' shops.

The generic model is required to predict mass flows to rendering from production departments and outside sources at any time of the day. Although flows from effluent recovery systems are not directly related to production flows, it is convenient to also consider them within the generic model. The model will also predict the time-variability of the mass stored in the raw material bin prior to the rendering system and the composition of this material. This allows the rendering finish time to be predicted as a function of the rate of rendering feed withdrawal. This in turn has consequences for potential energy requirements and hot water generation.

Some variations of animal weights and condition have been observed from region to region and season to season. These affect mass flow rates and ratios between fat-free solids, fat and moisture content for rendering materials. Whilst it is desirable for individual plants to be able to input data which is pertinent to local weights and conditions, a default standard was required that could be accepted as representative of an overall average with regard to animal weights and conditions. Loeffen *et al.* (1987) used data from a 1982 MIRINZ inter-plant survey that covered 15 plants and provided yield coefficients for meat meal and tallow, (fat-free dry solids and fat). These had been divided into two streams: kill, and boning. No new surveys have been carried out over such a wide data base in New Zealand since 1982 so it was decided to adopt these data as a standard. The boning room waste is characterised by a higher bone and lower fat content than the kill chain offal.

Whilst boning room waste and kill chain offal are the two major streams, there are other minor streams. In the lack of better information each of the other streams was considered to have the composition of either boning or kill chain material. Effluent solids that are returned to rendering departments have a high fat content so this stream was included in the kill stream (which had a similarly high fat content).

If an outside meat plant both kills and bones the combined material would still have a relatively high fat content so this material was directed to the kill stream. However, material from a fellmongery or butchers' shops would be expected to have a lower fat content and was thus directed to the boning stream.

Most rendering systems will require data from the generic model in terms of dry solids flow rate (kg/s) and moisture on a dry weight basis (kg water/kg dry solids). However the low temperature rendering system mechanically separates some moisture and fat from the fat-free solids prior to the dryer. This means that the output from the generic model must be supplied in more detail: fat-free dry solids flow rate (kg/s), fat content (kg fat/kg fat-free dry solids) and moisture content (kg water/kg fat-free dry solids).

As stated earlier, the materials to be rendered do not flow directly to the rendering equipment but rather to a raw material bin that acts as a buffering vessel. This vessel is not mechanically agitated, but there is some mixing of material by the action of the conveying system used. The model for the supply of material to the rendering system must include provision for modelling the behaviour of this buffering vessel. Simple models such as plug flow or perfectly mixed do not describe the physical reality, but the latter was considered the more realistic and so it was adopted.

4.3.1 Mass Balances

Time-variations of mass flow rates during the day were considered important and these were primarily handled with logic statements for start/stop times and changes in production mass flow rates due to category changes. Mass flow rates were summed in algebraic equations and then the results passed to ordinary differential equations which were integrated to arrive at the total mass accumulating in the raw material bin. Figure 4.1 illustrates the stream aggregation involved.

A dry solids summation in the kill stream is:

$$K_f = bm + lkm + em + ohm \tag{4.1}$$

where K_f = flow rate of dry solids to rendering from all kill areas (kg dry solids/s)

bm = flow rate of dry solids to rendering from the beef kill area (kg dry solids/s)

lkm = flow rate of dry solids to rendering from the lamb kill area (kg dry solids/s)

em = flow rate of dry solids to rendering from the effluent recovery area (kg dry solids/s)

ohm = flow rate of dry solids to rendering within outside-sourced material (kg dry solids/s)

A moisture summation is:

$$(K_f\, x_k) = bm\; bx + lkm\; lkx + em\; ex + ohm\; ohx \tag{4.2}$$

where $(K_f\, x_k)$ = flow rate of moisture to rendering from all kill areas (kg water/s)

bx = moisture content of the raw material passing to rendering from the beef kill area (kg water/kg dry solids)

lkx = moisture content of the raw material passing to rendering from the lamb kill area (kg water/kg dry solids)

ex = moisture content of the effluent solids passing to rendering from the effluent solids recovery area (kg water/kg dry solids)

ohx = moisture content of the outside raw material passing to rendering (kg water/kg dry solids)

The mean moisture content of the total kill material is given by:

$$x_k = \frac{(K_f\, x_k)}{K_f} \tag{4.3}$$

where x_k = mean moisture content of the combined raw material passing to rendering from the kill areas (kg water/kg dry solids)

A summation of dry solids in the boning stream is:

$$B_f = bbm + lbm + opm \tag{4.4}$$

where B_f = flow rate of dry solids to rendering from all boning areas (kg dry solids/s)

bbm = flow rate of dry solids to rendering from the beef boning area (kg dry solids/s)

lbm = flow rate of dry solids to rendering from the lamb boning area (kg dry solids/s)

opm = flow rate of dry solids to rendering within outside-sourced material (hide fleshings/butchers shop) (kg dry solids/s)

A moisture summation across the boning stream is:

$$(B_f\, x_b) = bbm\ bbx + lbm\ lbx + opm\ opx \tag{4.5}$$

where $(B_f\, x_b)$ = flow rate of moisture to rendering from all the boning areas (kg water/s)

bbx = moisture content of the raw material passing to rendering from the beef boning area (kg water/kg dry solids)

lbx	=	moisture content of the raw material passing to rendering from the lamb boning area (kg water/kg dry solids)
opx	=	moisture content of the outside material passing to rendering (kg water/kg dry solids)

The mean moisture content of the total raw material flow from the boning areas may be found from:

$$x_b = \frac{(B_f\, x_b)}{B_f} \tag{4.6}$$

where x_b	=	mean moisture of the combined raw material passing to rendering from the boning areas (kg water/kg dry solids)

The relationship between a two component and three component description of the mass flow rate from the kill chains may be described as:

$$K_f\ (1 + x_k) = G_k\ (1 + x_{gk} + y_{gk}) \tag{4.7}$$

where G_k	=	flow rate of fat-free dry solids to rendering from all kill areas (kg fat-free dry solids/s)
x_{gk}	=	moisture content of the raw material passing to rendering from all kill areas (kg water/kg fat-free dry solids)
y_{gk}	=	fat content of the raw material passing to rendering from all kill areas (kg fat/kg fat-free dry solids)

For the kill stream the data of Loeffen *et al.* (1987) suggest that G_k equals 0.45 K_f. Substituting this result and conducting a water mass balance yields:

$$x_{gk} = 2.222\ x_k \tag{4.8}$$

whereas a mass balance for fat yields:

$$y_{gk} = \left[\frac{K_f}{G_k}\right] - 1 \tag{4.9}$$

A similar relationship between a two component and three component description of the mass flow rate from boning may be described as:

$$B_f\ (1 + x_b) = G_b\ (1 + x_{gb} + y_{gb}) \tag{4.10}$$

where G_b = flow rate of the fat-free dry solids to rendering from all boning areas (kg fat-free dry solids/s)

x_{gb} = moisture content of the raw material passing to rendering from all boning areas (kg water/kg fat-free dry solids)

y_{gb} = fat content of the raw material passing to rendering from all boning areas (kg fat/kg fat-free dry solids)

For the boning stream G_b equals 0.562 B_f (Loeffen *et al.* 1987). The boning stream moisture content may be found by:

$$x_{gb} = 1.78\ x_b \tag{4.11}$$

and the boning fat content by fat mass balance:

$$y_{gb} = \left[\frac{B_f}{G_b}\right] - 1 \tag{4.12}$$

The kill and boning streams can then be combined. The combined fat-free dry solids mass flow rate is:

$$P = G_k + G_b \tag{4.13}$$

where P = combined fat-free dry solid flow rate to the raw material bin (kg fat-free dry solids/s)

The combined moisture flow rate is:

$$(P\ x_p) = G_k\ x_{gk} + G_b\ x_{gb} \tag{4.14}$$

where $(P\ x_p)$ = combined moisture flow rate to the raw material bin (kg water/s)

The overall mean moisture content is:

$$x_p = \frac{(P\ x_p)}{P} \tag{4.15}$$

where x_p = mean moisture content of the combined material passing to the raw material bin (kg water/kg fat-free dry solids)

The combined fat flow rate is:

$$(P\ y_p) = G_k\ y_{gk} + G_b\ y_{gb} \tag{4.16}$$

where $(P\ y_p)$ = combined fat flow rate to the raw material bin (kg fat/s)

The overall mean fat content is:

$$y_p = \frac{(P\ y_p)}{P} \tag{4.17}$$

where y_p = mean fat content of the combined material passing to the raw material bin (kg fat/kg fat-free dry solids)

A fat-free dry solids mass balance over the raw material bin is:

$$\frac{d\ Rmg}{dt} = P - G \tag{4.18}$$

where Rmg = mass of fat-free dry solids in the raw material bin (kg fat-free dry solids)

G = fat-free dry solids flow rate to rendering (kg fat-free dry solids/s)

The moisture balance over the raw material bin is:

$$\frac{d\,(Rmg\ x_g)}{dt} = P\ x_p - G\ x_g \tag{4.19}$$

where $(Rmg\ x_g)$ = mass of water in the raw material bin (kg water)

The moisture content of the raw material in the bin may be calculated from:

$$x_g = \frac{(Rmg\ x_g)}{Rmg} \tag{4.20}$$

where x_g = moisture content of material in the raw material bin (kg water/kg fat-free dry solids)

A fat mass balance over the raw material bin is:

$$\frac{d\,(Rmg\ y_g)}{dt} = Py_p - Gy_g \tag{4.21}$$

where $(Rmg\ y_g)$ = mass of fat in the raw material bin (kg fat)

The fat content of raw material in the bin is found by:

$$y_g = \frac{(Rmg\ y_g)}{Rmg} \tag{4.22}$$

where y_g = fat content of material in the raw material bin (kg fat/kg fat-free dry solids)

To inter-convert flows of fat-free dry solids and total dry solids equation (4.23) is used:

$$G = \frac{F}{(\ 1\ +\ y_g)} \tag{4.23}$$

where F = total dry solids flow rate (kg total dry solids/s)

The total dry solids mass within the bin is:

$$Rm = Rmg + (Rmg\ y_g) \tag{4.24}$$

The mean moisture content of the raw material in the bin may also be expressed on the basis of total solids as:

$$x_f = \frac{(Rmg\ x_g)}{Rm} \tag{4.25}$$

where x_f = moisture content of raw material (kg water/kg dry solids)

Some rendering models will use F and x_f to describe the flows, and others G, x_g and y_g.

4.3.2 Energy Balances

As no energy input or output occurs within the process area covered by the generic model energy balances are not required. No other energy input occurs within the process covered by the generic model.

4.4 RELATIONSHIP OF GENERIC TO THE HOT WATER MODELS

The hot water models have no direct use for product mass flow rates available from the generic model. Heat recovery for hot water production is indirectly connected but this is described in the hot water and refrigeration models. However departmental event times and chain speeds as input to the generic model are of importance to the hot water models.

For convenience hot water use was grouped according to production departments, and then within each department three separate flow modes were recognised:

(i) normal production,

(ii) tea breaks, and

(iii) end of production (use of showers and cleanup hoses).

The transitions between modes are determined by the user and described in Section 4.2.1. The hot water model also uses the chain speeds input by the user and described in Section 4.2.2.

4.5 FLOW OF MATERIALS TO REFRIGERATION

As has been outlined, the generic model is required to predict the flow rates of materials to refrigerated areas on the plant so that the energy-consuming response of the refrigeration system can be modelled. Product can enter refrigerated areas in one of three forms - beef sides (*bs*), lamb carcasses (*lc*) or offal (*o*). Examples of product pathways are shown in Figure 4.2. Once it enters a refrigerated area it generally does not leave the refrigeration until being dispatched from the plant. Thus only the first flows of the product into refrigerated areas need be modelled as part of the generic model. The refrigeration model will handle the transfers between types of rooms.

4.5.1 Product Streams

The generic model will sum product in three distinct streams, beef sides, lamb carcasses and common offals as shown in Figure 4.2. Within the three streams product mass flow rates will alter by categories for each species . Table 4.1 contains default data used, but users will be able to overwrite these values to better reflect local conditions. Although beef and lamb offals are processed and cartoned separately, their thermal properties are similar and they both proceed directly to freezing. They were therefore considered as one common stream. Thermal properties for carcasses, cartoned primals and offal of typical composition are available so it is unnecessary to further break product streams down into dry fat free solids, moisture and fat as has been done in the rendering section of the generic model.

4.5.2 Product Batches

Product flow to refrigerated areas occurs in both continuous and discrete modes. As will be discussed in Section 7, to simplify calculations when modelling the product heat loads it was decided to consider all product movements into refrigerated areas in batch mode. Some decision then had to be made on the number and size of each batch. It was decided that the entire daily production would be represented by up to thirty batches irrespective of whether the plant being modelled was a single, double or triple shift operation.

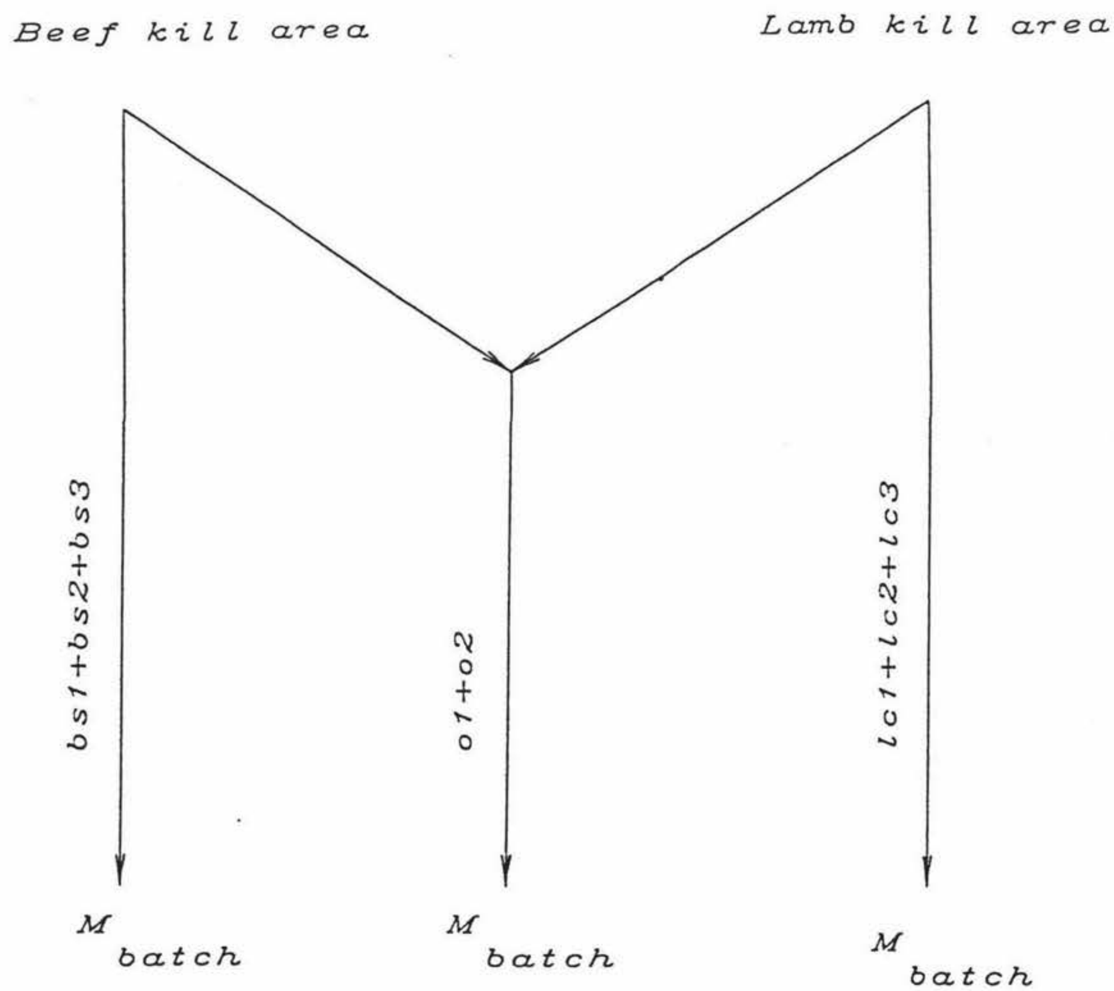


Figure 4.2 Product flows to the refrigeration model

Table 4.1 Typical average product masses derived from Oldfield (1987).

Type	Carcass mass $M_{average}$ (kg)	Edible offal mass $M_{average}$ (kg)
Prime Beef	286.0	6.0
Bull Beef	400.0	8.0
Boner Cow	186.0	3.3
Lamb	14.1	0.7
Sheep	20.0	1.4
Bobby calves	20.0	0.0

Note Although bobby calves would normally be listed within the beef section they are processed on lamb chains in New Zealand because of their small size - hence their inclusion in the lamb product group.

Each batch would have a distinct time of entry to refrigeration (t_{start}). All product of an appropriate type produced for a certain time range either side of the entry time would be assigned to this single time of entry.

The time range must be sufficiently small so that model predictions are accurate, yet the number of batches small enough to avoid unnecessarily long computation times. Thirty batches was considered a reasonable compromise, but the structure used to implement the program was constructed so that the number of batches could be changed easily.

A further requirement was that all the material in a batch must undergo the same refrigerated treatment. This means that it is not possible to mix lamb, beef or offal in the same batch, and product that will ultimately end up chilled must be kept in a separate batch to the material to be frozen. In the most extreme cases five batches would need to be simultaneously defined:

(1) beef, ultimately frozen,

(2) beef, ultimately chilled,

(3) lamb, ultimately frozen,

(4) lamb, ultimately chilled,

(5) offal, ultimately frozen.

This means that in the worst case, only 6 time periods would exist during the day. However, in practice, it was considered unlikely that more than 2 to 3 batches on average would need to be simultaneously defined meaning that the production day could be divided into at least 10 segments of time. Given user input data on start and stop times for each batch, the generic model will then sum product batch masses (M_{batch}).

The chain speed in bodies per hour is available so the mass flow rate is then calculated using equations of the following form:

$$bs1 = \frac{M_{averagepr}\ Chspd_{bk}}{3600} \tag{4.26}$$

where $bs1$	=	flow rate of prime beef to refrigeration (kg/s)
$M_{averagepr}$	=	average mass of a prime carcass (kg)
$Chspd_{bk}$	=	chain speed beef kill (hours^{-1})

Default data for $M_{average}$ are in Table 4.1, but the model user may overwrite these.

The model calculates the mass flow rates for other product streams similarly. Finally integration of the appropriate ordinary differential equation between the batch start and stop times will yield the batch mass:

Beef:

$$\frac{dM_{batch}}{dt} = bs1 + bs2 + bs3 \tag{4.27}$$

Lamb:

$$\frac{dM_{batch}}{dt} = lc1 + lc2 + lc3 \tag{4.28}$$

Offals:

$$\frac{dM_{batch}}{dt} = o1 + o2 \tag{4.29}$$

where M_{batch}	=	Mass of product in batch (kg)
$bs2$	=	flow rate of bull beef to refrigeration (kg/s)
$bs3$	=	flow rate of boner cow to refrigeration (kg/s)
$lc1$	=	flow rate of lamb to refrigeration (kg/s)
$lc2$	=	flow rate of sheep to refrigeration (kg/s)
$lc3$	=	flow rate of bobby calves to refrigeration (kg/s)
$o1$	=	flow rate of beef offals to refrigeration (kg/s)
$o2$	=	flow rate of lamb offals to refrigeration (kg/s)

4.6 MODEL IMPLEMENTATION

The component of the generic model related to rendering was incorporated into an advanced continuous system simulation language software package (Hay *et. al.*1988). Logical statements were included for changing variables such as feed in and out as functions of time. An example programme listing is shown in Appendix A1. Time did not permit the integrated implementation of other sections of the generic model; they were incorporated into the specific models themselves to allow model testing.

4.6.1 Rendering Section Model Testing

The rendering section of the generic model was tested by comparing model predictions to hand calculations at various time intervals and good agreement was found.

4.7 DISCUSSION AND CONCLUSIONS

The rendering section of the model sums fat-free solids, fat and moisture contents within the raw material bin. There is a provision within the model to also provide compositional data in the form of dry solids and moisture content for rendering systems other than the LTR system. There will be some uncertainties over exact mass flow rates on individual plants so the generic model provides an opportunity for individual details to be entered. This should ensure that accurate modelling of material flows to the rendering department occurs.

Overall model prediction accuracy will depend on the accuracy of data entered for a particular plant being modelled. The accuracy of the compositional data for kill and boning streams taken from Loeffen *et al.* (1987) will also have some effect on accuracy. As mentioned in Section 4.1.1 it is recognised that within the raw material bin, neither true plug flow nor perfectly mixed vessel conditions exist. The inaccuracy introduced by assuming perfect mixing has not been assessed.

The hot water and refrigeration sections of the generic model do not require assumptions which should cause significant model prediction uncertainties, there are however, some uncertainties associated with data quality.

It is only when a fully integrated meat plant energy model is tested against plant data that verification of the generic model can be completed. This task was beyond the resources available at the present time.

5.1 CONTINUOUS DRY RENDERING

5.1.1 Mechanistic Process Description.

Raw material is fed from a raw material bin into a hogger where it is broken into pieces approximately 25 * 25 * 5mm and then stored in a surge bin prior to being fed into the cooker. The cooker consists of a large long cylindrical vessel with the longitudinal axis horizontal, steam jacketed and with heated beaters or paddles which rotate at 0.5-0.9 s^{-1}. The raw material is screwed into one end and takes approximately 90 to 120 minutes to emerge out the other end through a paddle wheel. Figure 5.1 shows a sectioned Keith Cooker which is typical of this type of cooker. Feed into the cooker is controlled by a preset temperature controller with a differential or dead band which is usually about $\pm$5°C, and an ideal temperature of 130°C. The operating level varies according to the individual operator but is usually about 65 to 75% full. Cooked material is screwed over a perforated screen casing which removes about 60% of the free tallow. The exiting meal may either be fed directly onwards to the tallow press or recirculated back into the front of the cooker again if the operator wishes to raise the amount of tallow present in the cooker. The tallow press extracts the last of the free tallow from the meal cake to leave a tallow concentration of 9-10% in the final meal. The meal is then milled and is either bulk stored or bagged. Ideally it should have a moisture level of about 10%. The tallow is passed through a decanter which removes solids and then through a polishing separator which removes any moisture before going on to be bulk stored. With the exception of 1-2% evaporation in the hammer mill, moisture removal by this type of rendering is carried out completely within the cooker itself. This requires almost the entire thermal energy usage for the process, so the mathematical model has been developed for the cooker only. The generation of hot water is also directly driven by the cooker process. Although not considered in this work, some heat recovery could be possible from the meat meal and tallow. Such heat recovery would also lower rendering plant ventilation requirements.

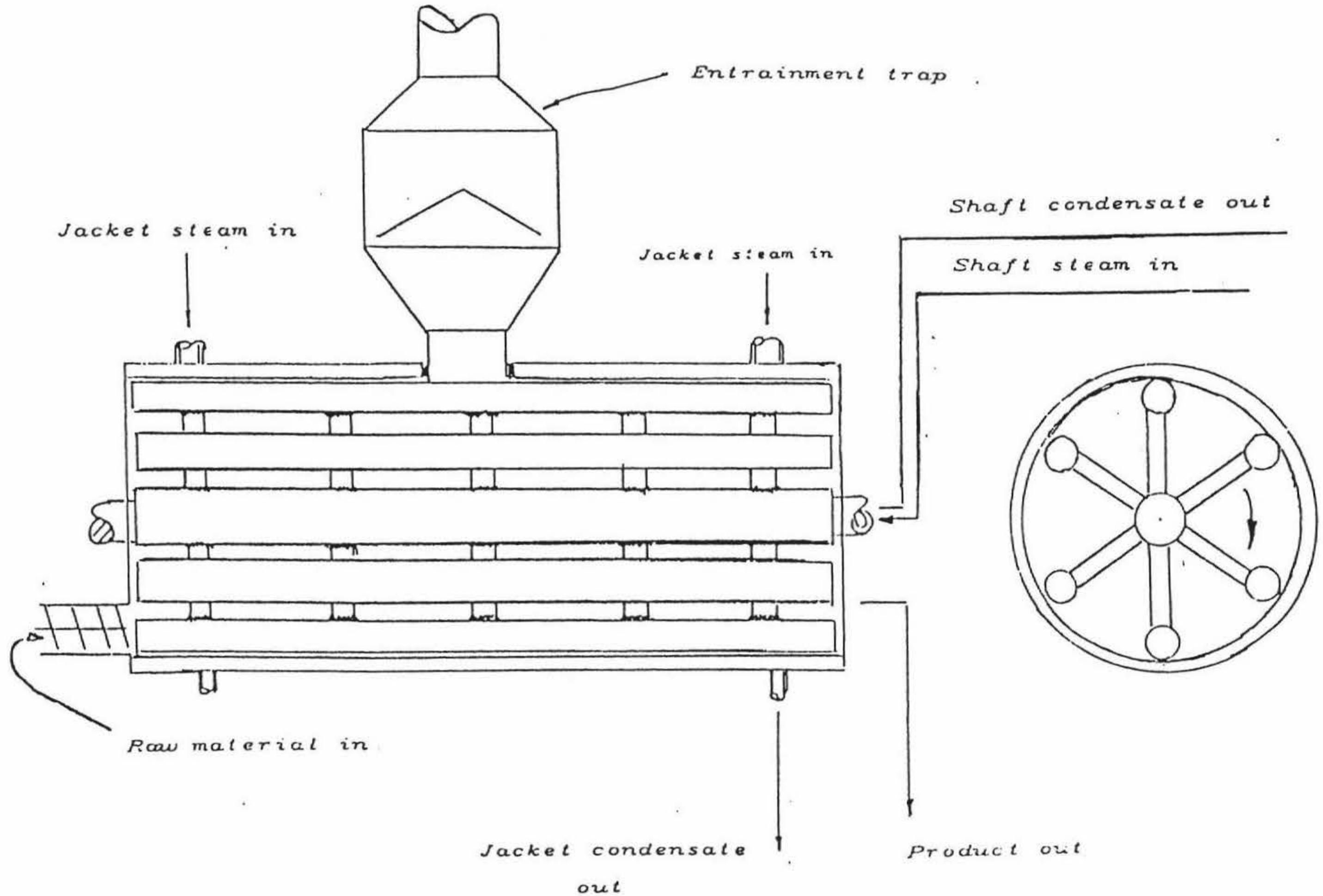


Figure 5.1: Sectioned Keith Cooker.

5.1.2 Basis of Model Development

The model sought should have minimum mathematical complexity, low requirements for data, yet predict real plant behaviour with reasonable accuracy. Time-variations were considered important, and it was decided to model these using ordinary differential equations - partial differential equations were considered too complex, and use of algebraic equations alone would have made modelling of time variability difficult. To derive ordinary differential equations the model of the cooker must use so-called "lump-sum" descriptions of items i.e. variations with position within the cooker must largely be ignored, and a single equation used to represent the entire cooker. Following this philosophy, the condition of the contents of the cooker had to be defined by a single moisture content and temperature, implying that the model treated the system as well-mixed. This does not exactly match what is known to occur in practice, but it was hoped that the resulting simplified description would be sufficiently accurate. Only experimental data collection and model testing would resolve the validity of the assumption.

As shown in Figure 5.2, the incoming feed from the raw material bin occurs at a flow rate of F_d with the accompanying moisture flow rate in at $F_d\, x_f$. The withdrawal of dry material is at flow rate F_p, with an accompanying water flow of $F_p\, x$. The total mass of material, and the mass of dry matter in the cooker can change with time. The application of heat in the cooker leads to temperature change in the contents all of which are assumed to be at uniform temperature T_{int}. Heat applied via the steam jacket at flow rate Y_d may lead to a temperature change in the contents, but some of the energy is lost in the form of evaporated water at flow rate W. Further energy is lost, embodied in the product stream K and from the cooker outer shell to the ambient air at flow rate Z. Energy is required to raise the full structural components of the cooker from ambient to the operating temperature.

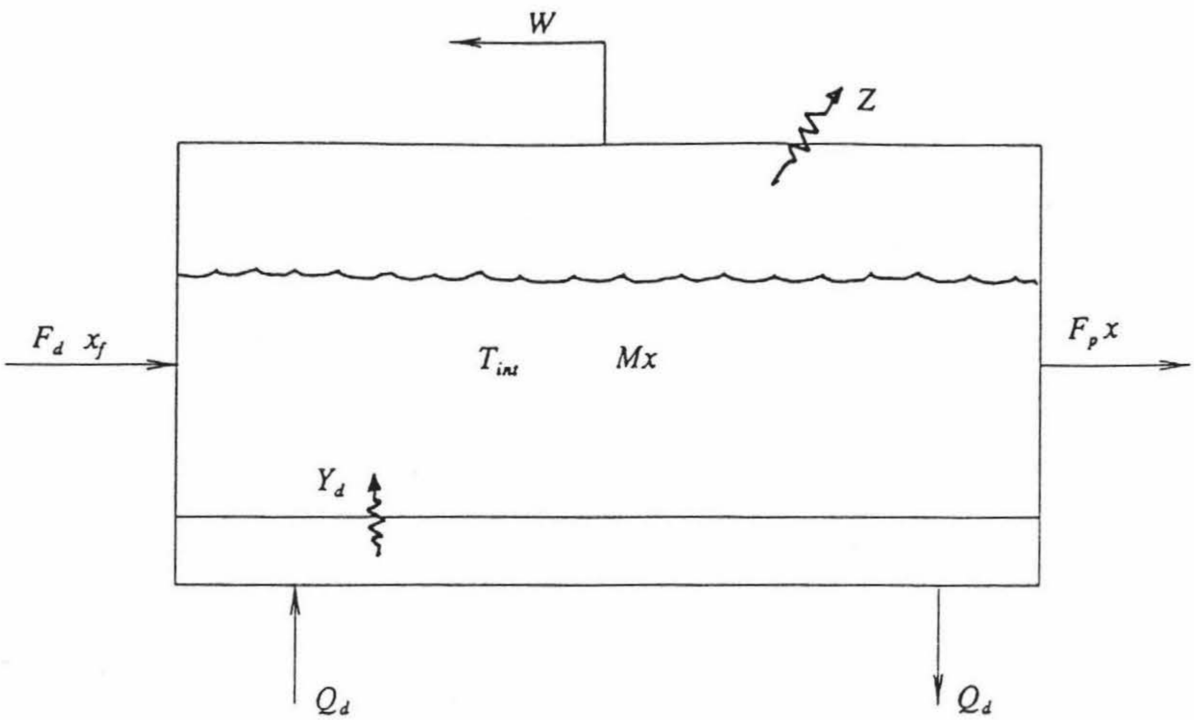


Figure 5.2: Schematic diagram of Keith cooker model.

5.1.3 Mass Balances

In the modelling it was decided to express all moisture contents and product flows on a dry weight basis because conservation equations are easier to derive by this approach.

A dry solids mass balance in the cooker is:

$$\frac{dM}{dt} = F_d - F_p \tag{5.1}$$

where F_d = feed from raw material bin (kg dry solids/s)

F_p = product flow from cooker (kg dry solids/s)

A moisture mass balance is :-

$$\frac{d(Mx)}{dt} = F_d\, x_f - W - F_p\, x \tag{5.2}$$

where x_f = moisture content of the raw material (kg water/kg dry solids)

x = moisture content in the cooker (kg water/kg dry solids)

W = moisture evaporation rate (kg/s)

The cooker internal moisture content is then found by:

$$x = \frac{Mx}{M} \tag{5.3}$$

where Mx = mass of moisture in cooker (kg water)

M = mass dry solids in cooker (kg dry solids)

The rate of evaporation W depends on the following factors:

(i) the mass of material within the cooker,

(ii) the surface area to mass ratio of the material,

(iii) the exposed top surface area of the material in the cooker,

(iv) the temperature and water activity of the material, and

(v) the conditions in the moisture sink (the heat exchanger for heat recovery).

As the mechanisms are complex it was decided to model the rate of evaporation using a mass transfer relationship:

$$W = k_g\, A\, (\, a_w\, p_{wp} - H_r\, p_{wa}\,) \tag{5.4}$$

where k_g = mass transfer coefficient (s/m) or (kg/m^{2}sPa)

A = area surface (m^2)

a_w = water activity of meal

p_{wp} = vapour pressure of water at meal temperature (Pa)

H_r = relative humidity of ambient air

p_{wa} = vapour pressure of water at air temperature (Pa)

It was decided to use H_r and p_{wa} values for typical ambient air conditions existing at the exit of the heat recovery heat exchanger. The results were found to be insensitive to changes in either of these parameters, so no refinement was considered necessary. The relationship between ambient air conditions and vapour pressure for water was expressed using the well-known Antoine equation and a relative humidity of 70% assumed to yield:

$$H_r\, p_{wa} = 0.7 \exp\left(23.4795 - \frac{3990.56}{T_{amb} + 233.83}\right) \tag{5.5}$$

where T_{amb} = ambient temperature (°C)

The Antoine equation was also used to calculate the vapour pressure of water at the meal temperature:

$$p_{wp} = \exp\left(23.4795 - \frac{3990.56}{T_{int} + 233.83}\right) \tag{5.6}$$

where T_{int} = meal temperature in the cooker (°C)

The relationship between water activity and meal moisture content was assumed to have the following form:

$$a_w = 1 - e^{-\alpha x} \tag{5.7}$$

where α = empirical constant (kg dry solids/kg water)

Values of a_w at different meal moisture contents were calculated from the data of Brown *et. al.* (1988) by assuming that a_w was proportional to the ratio of the drying rate at a particular moisture content to the drying rate at high moisture content (for which it could be assumed that a_w approached 1.0). The values of a_w thus obtained were curve-fitted against moisture content to derive a value of $\alpha = 2.4$. Because of the difficulties in obtaining independent estimates of k_g and A, it was decided not to separate them. Values for W from specification sheets for the Keith cooker, and in one case (Model 900) commissioning data for a Keith cooker, were available, as shown in Table 5.1.

Table 5.1

Keith cooker data

Keith cooker model	400	600	900
A. Keith Specifications			
Heating surface A_l (m^2)	43.47	53.88	88.71
Shell mass M_{st} (kg)	12600	16700	29000
Steam pressure (bars absolute)	9.25	9.60	9.60
Steam usage Q_d (kg/s)	0.53	0.79	1.19
Water evaporated W (kg/s)	0.35	0.53	0.79
B. Derived Data			
k_gA (s/m)	0.0089	0.0134	0.0211
Shell heat transfer coeff. U_l (W/m^{2}K)	627	754	689
Cooker dry solids start mass M_{min} (kg)	1740	2173	3763
Cooker dry solids full mass M_{max} (kg)	4267	5338	9229
Dry solids feed F_d (kg/s)	0.35	0.53	0.79

Equation (5.4) was then rearranged:

$$k_{gA} = \frac{W}{(a_w \, p_{wp} - H_r \, p_{wa})} \tag{5.8}$$

The internal meal temperature, T_{int} was assumed to be 130°C, and the values of $k_g A$ were calculated using Equation (5.8).

5.1.4 Energy Balances

An overall energy balance on the cooker is :

$$\frac{dB}{dt} = ((F_d \, c_{dry}) + (F_d \, x \, c_w)) \, T_f + Y_d - Z - K - (W \, h_w) \tag{5.9}$$

where	B	=	total energy content of the cooker (J)
	c_{dry}	=	specific heat capacity of dry solids (J/kg K)
	c_w	=	specific heat capacity of water (J/kg K)
	T_f	=	temperature of the feed (°C)
	Y_d	=	steam energy input (W)
	Z	=	energy loss from cooker shell to ambient air (W)
	K	=	energy embodied in the product leaving the cooker (W)
	h_w	=	enthalpy of exiting water vapour (J/kg)

T_{int} is defined by dividing the total energy content by the thermal capacity of the cooker:

$$T_{int} = \frac{B}{(M \, c_{dry}) + (M \, x \, c_w) + (M_{st} \, c_{st})} \tag{5.10}$$

where	M_{st}	=	mass of cooker steel components (kg)
	c_{st}	=	specific heat capacity of steel in cooker shell (J/kg K)

h_w the enthalpy of the vapour being driven off the product at atmospheric pressure may be approximated to within $\pm$ 0.5% in the range 100 - 150°C by :

$$h_w = 2.476 \times 10^6 + 2000\ T_{int} \tag{5.11}$$

The rate of energy supply from the steam is defined by:

$$Y_d = U_1\ A_1\ (\ T_{st} - T_{int}) \tag{5.12}$$

where U_1 = cooker shell heat transfer coefficient (W/m^2K)

A_1 = cooker shell heating surface area (m^2)

T_{st} = temperature at which steam condenses in the jacket (°C)

The steam consumption rate is :

$$Q_d = \frac{Y_d}{\Delta h_s} \tag{5.13}$$

where Q_d = steam consumption rate (kg/s)

Δh_s = enthalpy change of steam in cooker (J/kg)

and

$$\Delta h_s = h_{fg} + c_w(\ T_{st} - T_{ex}\ ) \tag{5.14}$$

where h_{fg} = latent heat of condensation at T_{st} (J/kg)

T_{ex} = condensate exit temperature (°C)

The energy loss from the shell to ambient air is :

$$Z = U_2\ A_2\ (\ T_{st} - T_{amb}) \tag{5.15}$$

where U_2 = cooker outer shell heat transfer coefficient (W/m^2K)

A_2 = area of the cooker outer shell surface (m^2)

The energy embodied in product leaving the cooker is:

$$K = (F_p \, c_{dry} + F_p \, x \, c_w) \, T_{int} \tag{5.16}$$

5.1.5 Other Model Data

To use equation (5.1) to (5.14) a variety of data are required.

(1) Table 5.1 contains data from Keith specification sheets and further values were derived as follows:

(i) $k_g A$ was calculated using equation (5.8) as has been discussed.

(ii) Values of the overall heat transfer coefficient in Table 5.1 calculated using:

$$U_1 = \frac{Q_d \, (h_1 - h_2)}{A_1 \, (T_{st} - T_{int})} \tag{5.17}$$

where h_1 = enthalpy of dry steam at 9.0 bars absolute.

h_2 = enthalpy of condensate at 130°C

Due to the lack of better information the condensate exit temperature was chosen as the meal temperature within the cooker, but this was an arbitrary assumption. Although Keith Engineering Ltd. specify the slightly higher pressures shown in Table 5.1 industry-based observations show that 9 bars absolute is a more realistic figure. Actual commissioning data for the Rangiuru cooker produced a result of 764 W/m^{2}K for the Model 900 cooker. Because this value was very close to the top of the range in Table 5.1 and as the 400 and 600 models are geometrically identical except for length a value of 750 W/m^{2}K was selected for all models.

(iii) White (1992) reported that Keith cookers are usually run down to one third of their vertical height at the end of daily production. M_{min} values were calculated at this height for each of the three models.

(iv) The cooker dry solids full mass was calculated to correspond to a level of two thirds vertical height.

(v) Dry solids feed F_d was calculated by assuming that the moisture content of the raw material was 1 kg water/kg dry solids. (50% moisture on a wet weight basis). This moisture content represents the driest likely feed material, and so if it is in error it is likely that the real F_d will be lower than that shown in Table 5.1.

(2) The feed into the cooker is at ambient conditions thus $T_f = T_{amb}$.

(3) Steam temperature, T_{st} was taken from steam tables for the correct operating pressure.

(4) Observation of a number of Keith cookers in operation indicated that at startup, the initial internal temperature, T_{int} would normally be of the order of 60°C and moisture content would be about 0.05 kg moisture/kg dry solids. This is the expected finishing value from the previous day.

5.1.6 Model Implementation

The mass and energy balances equations were incorporated into an advanced continuous system simulation language software package (Hay *et al.* 1988). Logical statements were included for changing variables such as feed in and out as functions of time, for modulating temperature and for modulating mass of material in the cooker. An example programme listing is shown in Appendix B1.

5.1.7 Model Testing

Initial model tests taken were mathematical e.g. overall mass and energy balances on simulated behaviour. Once satisfactory results were obtained in these tests the next stage was testing against real plant performance.

5.1.7.1 Test data collection

Measurements were taken at AFFCO's Rangiuru plant and the following variables recorded:

(i) Steam pressure readings were taken off a pressure gauge adjacent to the steam flow meter.

(ii) Steam flow, Q_d was recorded from a flow integrator situated upstream of the flow control valve in the cooker steam main, except for the first three readings which were collected using a bucket and stop watch on the condensate line.

(iii) Evaporated moisture flow, W was measured with a bucket and stop watch.

(iv) Meal temperature in the cooker, T_{inl} was obtained from a probe located within the cooker shell.

A copy of these data in spreadsheet form is given in Appendix B1.1.

There were also several other variables that had to be measured on-site to use the model. The moisture content of the raw material was unknown, and could change during the day. Measuring equipment was not available to sample feed moisture throughout the day so a single average value was the best information that could be obtained. This was determined by a mass balance under stable operating conditions, using the measured real moisture content, the meal production rate and the evaporation rate. The value obtained was 1.242 kg water/ kg dry solids (55.4% on a wet weight basis).

It had been hoped to measure the mean dry solids flow rate from the cooker under stable operating conditions, and to relate this to the feed rate of dry solids. However, sufficiently stable operation of the cooker was never achieved during the data collection period and so no satisfactory estimate could be obtained by this method. Therefore, the value of F_d from Table 5.1 was used.

The steam condensate exit temperature, T_{ex} was measured to be 110°C and this value was used in simulations.

It is noted that the values x_f and T_{ex} do not match the assumption made to derive the data in Table 5.1, and that the value of F_d in the Table would change if x_f was changed. It was considered that there was no strong reason why values measured on a single plant, (Rangiuru) should supplant values derived on a systematic basis from the manufacturer's data. In practice changing T_{ex} alters results only slightly, but both F_d and x_f were identified as variables for later consideration by sensitivity analysis.

5.1.7.2 Model customisation

Keith rendering cookers are usually connected directly to the boiler house steam main. However Rangiuru has a steam flow rate control valve fitted into the steam main upstream of the cooker which is preset to a maximum flow rate of 1.4 kg/s. This prevents sudden large cooker demands upsetting the overall plant steam flow rate and allows more rational boiler loadings. When the preset maximum steam flow rate is reached, further steam demand by the cooker causes a pressure reduction downstream of the valve. The drop in steam pressure causes a corresponding drop in T_{st} so that the temperature driving force (T_{st} -T_{inl}) decreases. The steam flow rate is proportional to (T_{st} - T_{inl}) so pressure changes alter steam flow rate. If flow rates greater than 1.4 kg/s are demanded by the cooker, then the model should adjust T_{st} so that exactly 1.4 kg/s is used. Logic steps were written into the program which had the effect of limiting T_{st} to a value which made Q_d = 1.4 kg/s.

The operator can override the preset maximum steam flow rate. If not overridden, steam pressure should be 9 bars absolute adjacent to the cooker heating surfaces, equating to a temperature of 175 °C. The operator made 3-4 changes from startup to stable operation in which the steam flow rate and hence steam pressure downstream of the control valve were altered. This included 1800 seconds with T_{st} = 159°C for initial warmup, 3000 seconds at 152°C before 900 seconds at 159°C and finally the remaining time at 175°C. T_{st} was switched by logic statements at appropriate times within the model to simulate the actions of the operator.

In the model if T_{st} becomes low and T_{int} is high then $(T_{st} - T_{int})$ can become negative implying negative steam demand. This is physically impossible, so further logic steps were put in place which prevented Q_d falling below 0.0 kg/s.

5.1.7.3 Comparison of measured and predicted data

Figure 5.3 shows both measured and predicted data for; A: steam flow, Q_d , B: rate of evaporation, W, and C: meal temperature within the cooker, T_{int}.

Considering first the steam flow rate, the maximum imposed on the model was reached twice. The minimum steam flow rate was reached once because the predicted T_{int} was higher than measured and when at one stage T_{st} was lowered it fell below T_{int}. Step changes in T_{int} meant that Q_d underwent three sharp changes in the model curve.

Early measured data points for steam flow rate are very similar to each other and do not agree with model predictions. As discussed earlier, these data were measured with a bucket and stop watch on the condensate line, whereas later, data were read from the steam flow rate meter. The cooker condensate may "pond" and thus be time-delayed in appearing from the cooker shaft and shell heat exchangers. Therefore the instantaneous condensate flow rate may differ from the steam flow rate. Thus the disagreement between the model and the early data may be partly explained.

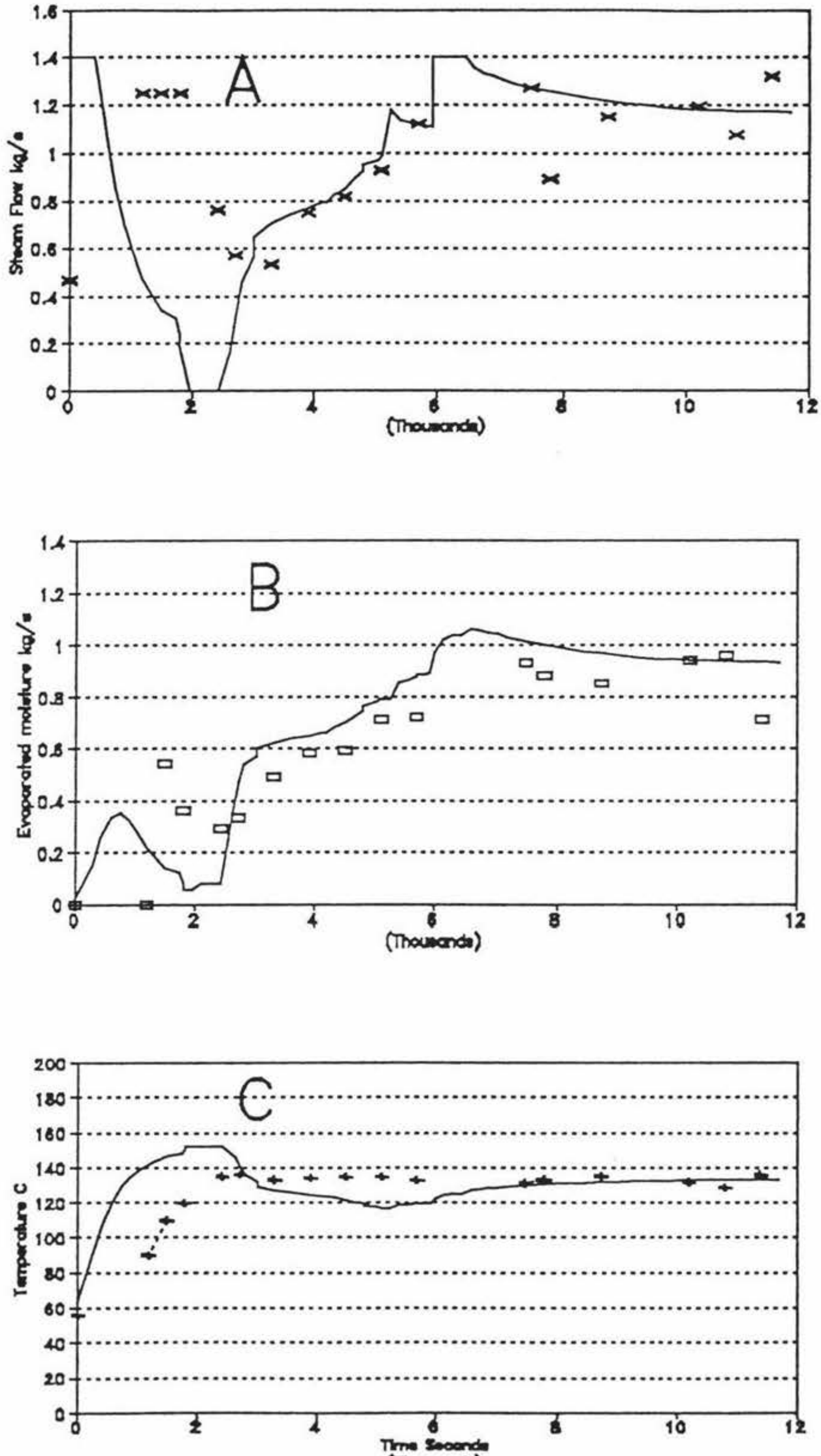


Figure. 5.3. Plot of A: Steam usage, Q_d (kg/s), B: Evaporated moisture, W (kg/s), and C: Meal temperature, T_{int} (°C) vs time (s) in the Keith cooker at AFFCO Rangiuru. Full line indicates model prediction, measured points are represented by symbols.

Turning to graph B, a "hump" is predicted by the model before a more general rise in the rate of evaporation. The hump is due to residual moisture removal from the meal left in the cooker overnight. It peaked when the cooker temperature, T_{int} reached about 100 °C and then dropped away until new feed was introduced at 1800 seconds. Another rapid rise occurred in the model results at 5800 seconds, but no measured data were available to confirm whether the effect was real.

An apparent consistent displacement of about 700 seconds occurred between model predictions and measured data. This may be due to real time delays ignored by the model which assumed instantaneous transport processes. Recovered evaporated moisture did not commence flowing until 1200 seconds which may be due to the need to heat up the ductwork and entrainment trap. Moisture would not appear downstream of the heat recovery heat exchanger until this had occurred. Thus the disagreement between the model and the early measured data may be partly explained.

Considering graph C, the meal temperature within the cooker, the model predictions rose much faster and higher than the measured data for the first 2000 seconds. The measured data is apparently displaced about 1000 seconds behind the model data. This displacement may be partly explained by the position of the temperature probe for the measured data which is located at the far end of the cooker on an unheated wall. The model assumes a perfectly mixed vessel whereas in reality material moves systematically from one end to the other with a mean residence time of several thousand seconds. Thus the lack of agreement may be largely caused by the deviation of the real system from perfectly mixed.

As well as deviation caused by imperfect mixing, the overprediction of T_{int} early in the process may in part result from changes in heat transfer conditions. In the model U_1 was assumed constant so the predictions would overpredict if the real U_1 was lower. A lower U_1 would also have diminished the early steam demand. In practice U_1 may depend on the material moisture content, dropping as the material becomes drier. A lower U_1 would have reduced the early steam demand as well as the early temperature rise.

5.1.7.4 Sensitivity analysis

The observed lack of fit is the net result of result of uncertainties arising in three areas:- errors in test data, model weaknesses and error in data for the model parameters. Experimental errors in test data have already been discussed in earlier sections.

There are four parameters for which the estimates used could only be determined approximately. Each of these was subjected to sensitivity analysis. The U_l value used was already at the higher limit of the range in Table 5.1. If U_l was in error it was considered more likely that the true value would be lower, perhaps by as much as 20% so a U_l value of 600 W/m^{2}K was tested. The results are shown in Figure 5.4: A, B and C. The line produced by the model at 600 W/m^{2}K in graph A lies closer to the measured data than the original run at 750 W/m^{2}K to around 5800 seconds. At 1800 seconds the model steam demand does not fall to 0.0 kg/s. Model predictions for moisture evaporation in graph B also better match the measured data using a lower U_l value. Overshoot in Graph C is less, but once initial warmup has occurred and raw material feed $F_d x_f$ starts after 2500 seconds the lower U_l value appears unable to sustain the required operating temperature of 135°C.

As discussed earlier, practical difficulties had prevented measurement of dry solid feed mass F_d during data collection. The operators considered that the flow rate was higher than that specified by the manufacturer so the sensitivity analysis was restricted to consider only a value 10% higher. Results are shown in Figure 5.5: A, B and C. An increased feed F_d will mean that more sensible heat is required to heat the increased dry solids and moisture to operating temperature. Latent heat requirements by the subsequent increase in moisture evaporation also add to the increase in steam usage in graph A when stable conditions are reached. The increase in moisture evaporation is shown in graph B. There is also a decrease in T_{int} as shown in graph C. Overall, uncertainty in F_d would not affect predictions during startup very much, but would lead to different predictions under stable operating conditions.

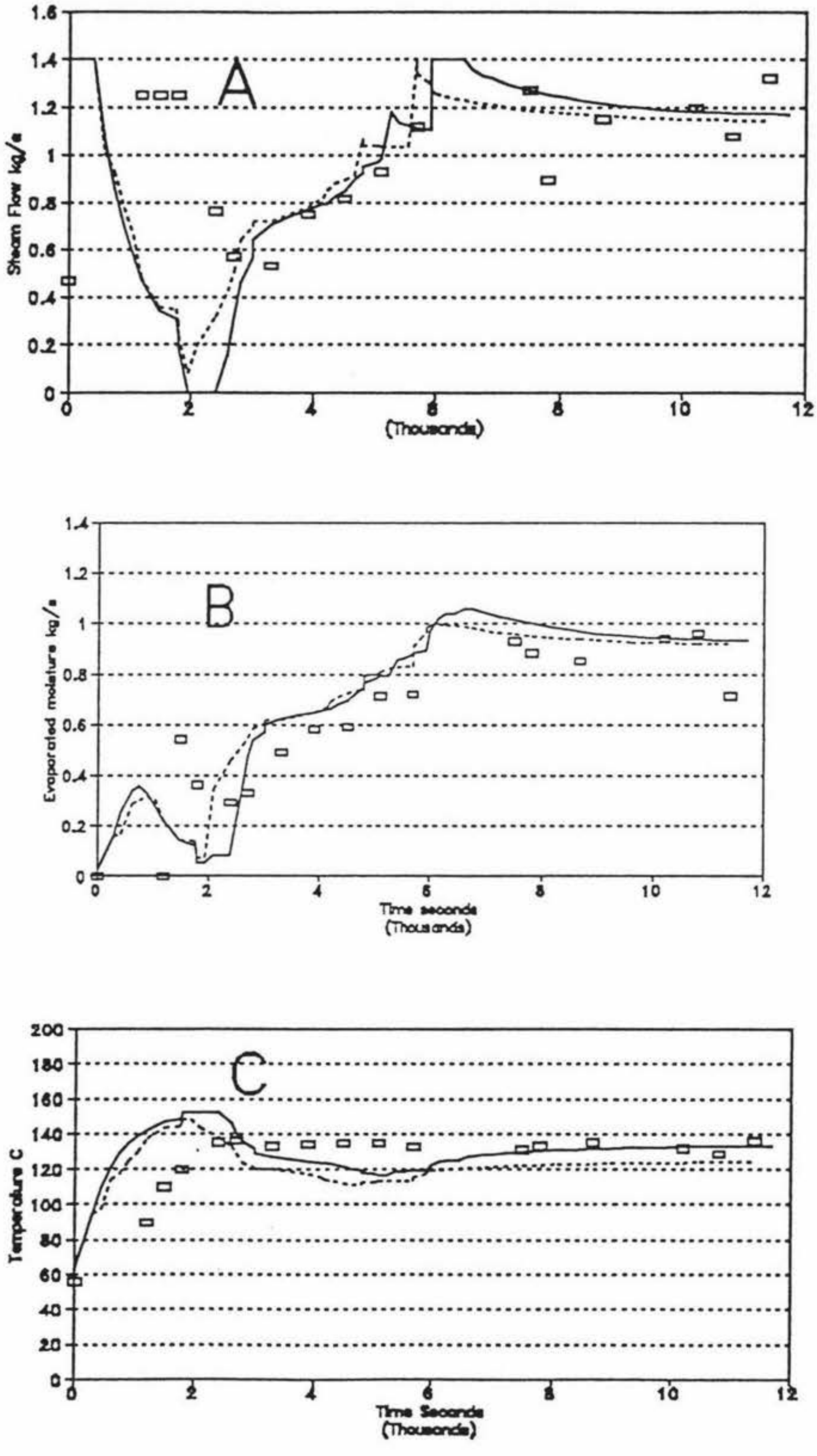


Figure 5.4. Plot of A: Steam usage, Q_d (kg/s), B: Evaporated moisture W (kg/s), and C: Meal temperature T_{in} (^{0}C) vs time (s) in the Keith cooker at AFFCO Rangiuru. Full line indicates base case with U_l = 750 W/m^{2}K, dotted line indicates sensitivity analysis with U_l = 600 W/m^{2}K and symbols represent measured points.

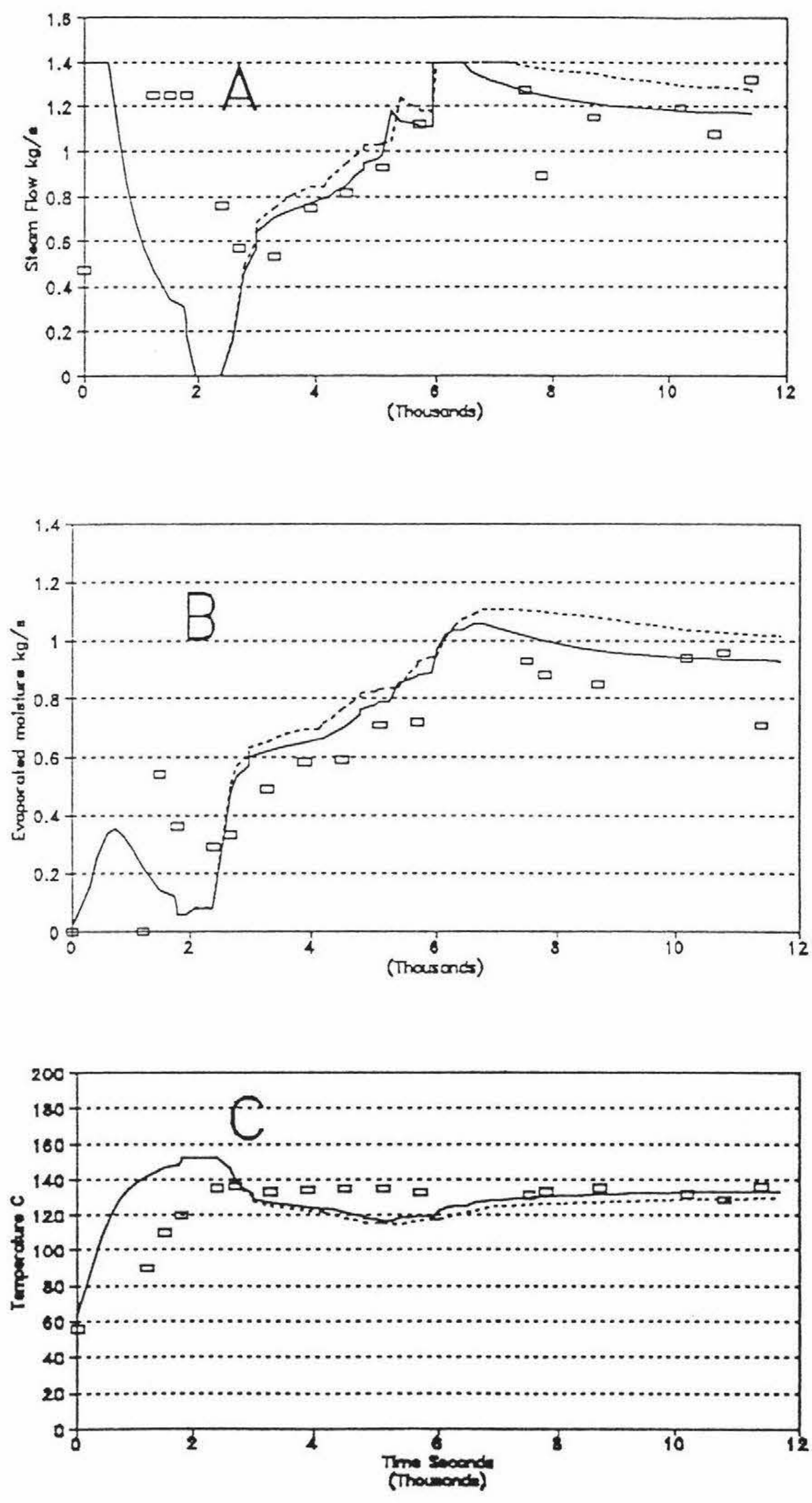


Figure 5.5. Plot of A: Steam usage, Q_d (kg/s), B: Evaporated moisture, W (kg/s), and C: Meal temperature, T_{int} (°C) vs time (s) in the Keith cooker at AFFCO Rangiuru. Full line indicates $F_d = 0.790$ kg/s, dotted line indicates $F_d = 0.869$ kg/s and measured points are represented by symbols.

Accurate analysis of feed moisture content was not possible during the measured data collection time and also the feed moisture content may vary with time. The value used for x_f was derived from a mass balance across the plant when stable conditions were reached, but as these conditions were not steady state some error may have resulted. Errors of ±2.5% on a wet weight basis were considered possible and so a sensitivity analysis was performed to see if this magnitude of error would have any significant effect on model predictions. Results are shown in Figure 5.6: A, B and C. At a moisture content decreased by 2.5% the model predicts results more closely aligned to measured data to around 6000 seconds in graphs A and B. In stable operating conditions the predictions are very sensitive to changes in x_f. A model run using the higher moisture content predicted an outlet meal moisture level x well above acceptable values. In practice the real x_f almost certainly changes during the day. Thus uncertainty in, and variations of x_f are likely to be major contributors to lack of fit.

The k_gA value was derived from Keith data and original Rangiuru commissioning data. A number of assumptions were involved, the accuracy of which could be questioned. Sensitivity analysis was carried out with arbitrarily selected changes of ±20%. Results are shown in Figure 5.7: A, B and C. Altering the k_gA values by ±20% does not appear to have an important effect on the predictions. It appears that inaccuracy of k_gA is not a major contributor to lack of fit.

The sensitivity analyses discussed so far showed that uncertainties in both U_l and x_f may be important. However, the analysis had considered each parameter in isolation. Another run was undertaken with both parameters changed together to U_l = 600 W/m^{2}K and x_f = 1.1 kg water/kg dry solids. The results are shown in Figure 5.8 : A, B and C. There is interaction and the agreement with measured data has improved particularly in the first 5000 seconds.

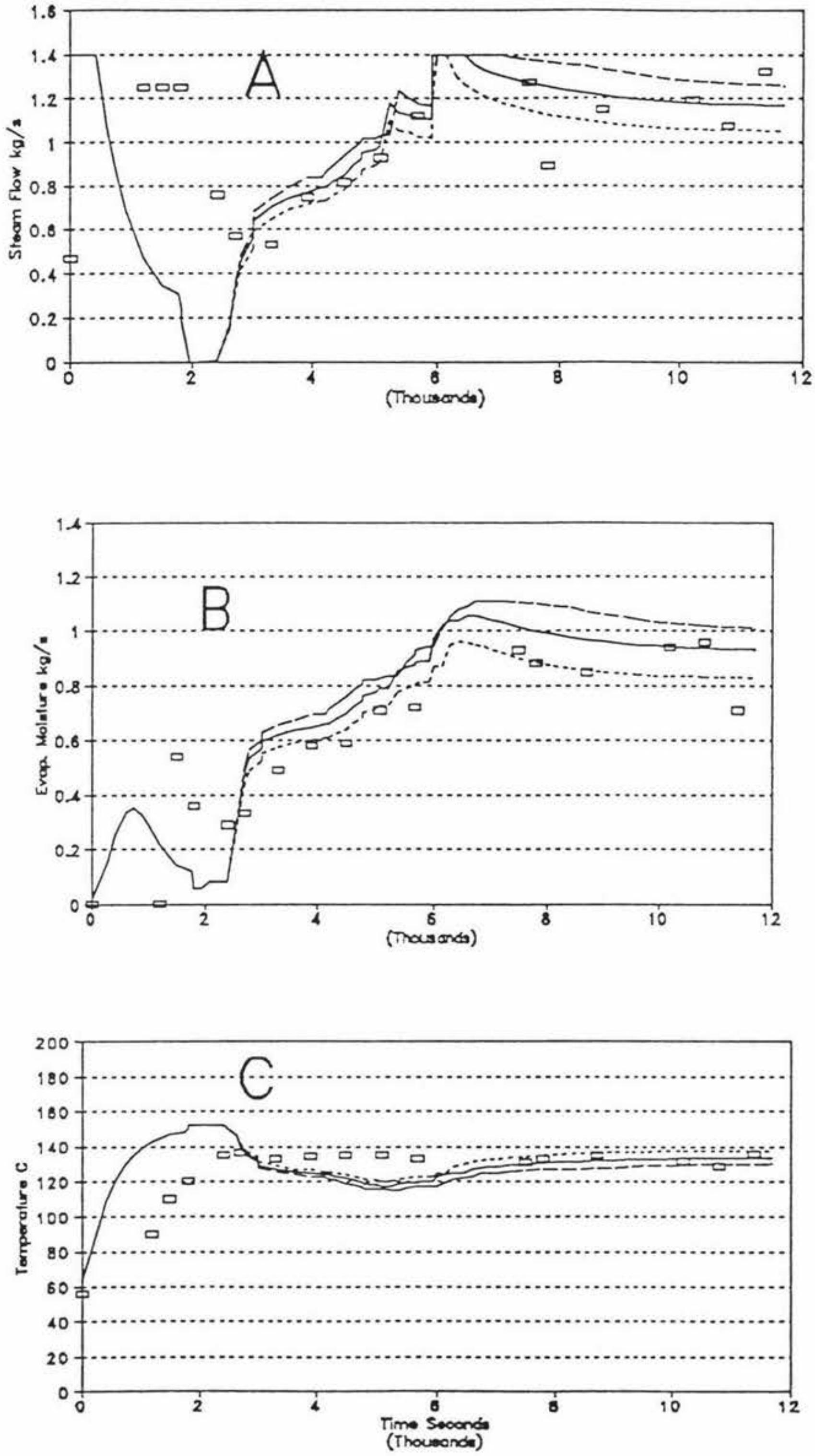


Figure 5.6. Plot of A: Steam usage, Q_d (kg/s), B: Evaporated moisture, W (kg/s) and C: Meal temperature, T_{int} (°C) vs time (s) in the Keith cooker at AFFCO Rangiuru. Dotted line indicates x_f = 1.100 kg water/kg dry solids, Full line indicates x_f = 1.242 kg water/kg dry solids, dashed line indicates x_f = 1.347 kg water/kg dry solids and measured points are represented by symbols.

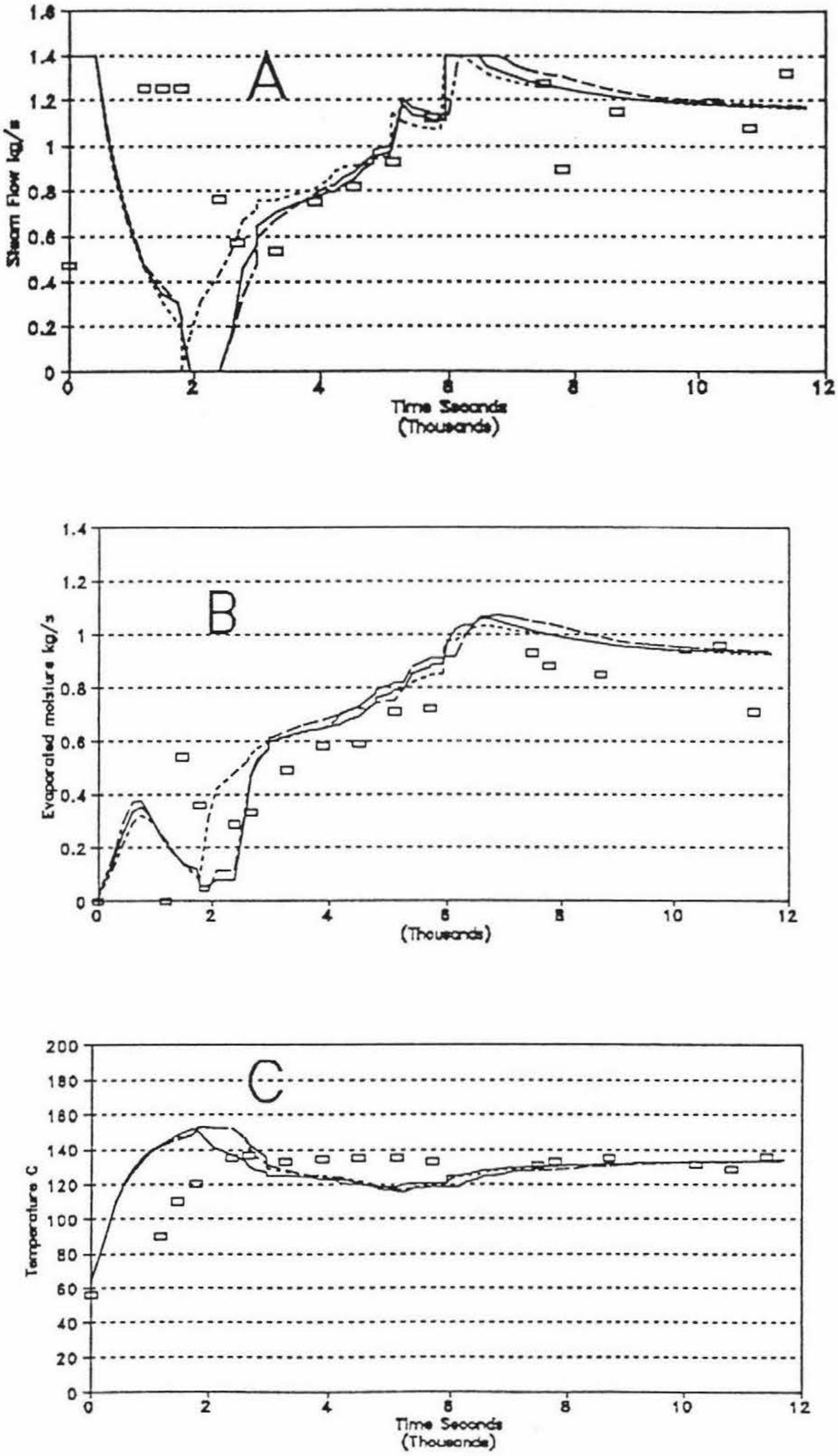


Figure 5.7. Plot of A: Steam usage, Q_d (kg/s), B: Evaporated moisture, W (kg/s) and C: Meal temperature, T_{int} (°C) vs time (s) in the Keith cooker at AFFCO Rangiuru. Dotted line indicates k_gA = 0.0169 (s/m), Full line indicates k_gA = 0.0211 (s/m), dashed indicates k_gA = 0.0253 (s/m) and measured points are represented by symbols.

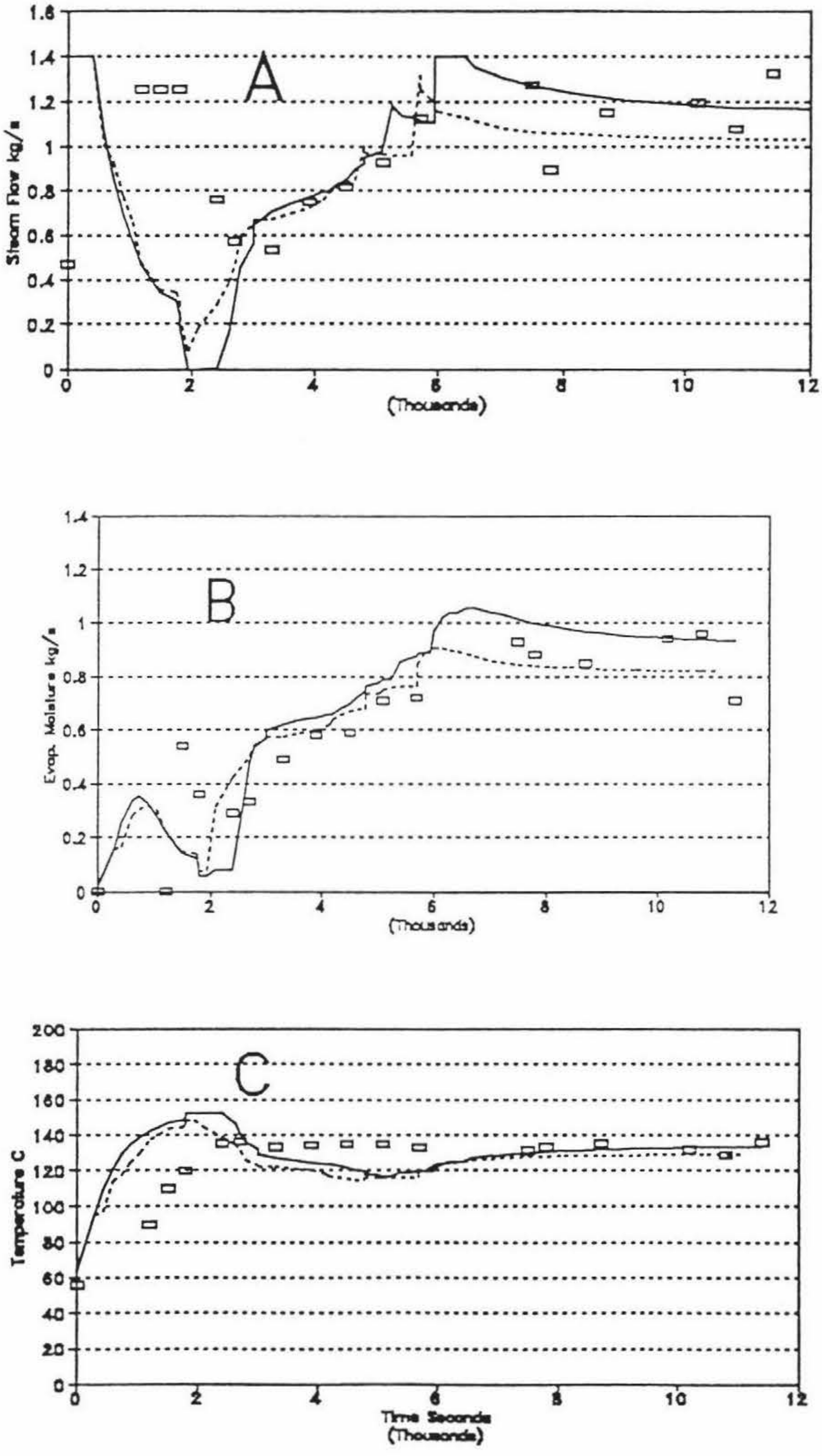


Figure 5.8. Plot of A: Steam usage (kg/s), B: Evaporated moisture (kg/s) and C: Meal temperature (°C) vs time (s) in the Keith cooker at AFFCO Rangiuru. Full line indicates U_1 = 750 W/m^{2}K, x_f =1.242 kg water/kg dry solids, dotted line indicates U_1 = 600 W/m^{2}K, x_f = 1.100 kg water/kg dry solids and and measured points are represented by symbols.

5.1.8 Discussion and Conclusions

This section focuses on whether the model proposed in Section 5.1.2 is a sufficiently adequate predictor of energy use by a continuous dry rendering system for the model to be adopted in the overall meat plant energy model.

As has been discussed, data errors are significant, both in the test data shown in Figs. 5.3 to 5.8, but also in the parameters required to use the model. The sensitivity analysis showed that results are particularly sensitive to any error in x_f or U_l, insensitive to error in k_gA, and modestly affected if F_d is in error. There is reasonable evidence to suggest that U_l could be lower than 750 W/m^{2}K, and that the mean x_f value could differ from 1.242 kg water/kg dry solids. Figure 5.8 which tested a combination of likely extremes had better fit than the original base case, (Figure 5.3) prior to stable operation being achieved. Nevertheless, data errors alone probably did not explain the total lack of fit.

This suggests that assumptions made in deriving the model are a partial cause of lack of fit. Two specific assumptions seem to be most important.

(1) The model assumed all transport processes were instantaneous yet the data and personal observations on the plant suggested that there were appreciable time delays e.g. from the time of steam consumption to condensate appearing.

(2) The model assumed that the whole cooker was a perfectly mixed vessel whereas material moves systematically from one end to the other. The reading from the temperature probe at one end of the cooker was not representative of the total cooker contents.

The model could be made more complex to remove these assumptions e.g. by introducing time delays, and by replacing the single mixed vessel with a series of smaller mixed vessels with interlinking flows. As well as the extra equations and computation time there would be significant new data needs e.g. flows between mixed vessels, size of time delays, local heat transfer conditions in each vessel. Time delays would be difficult to determine. Measurements on particular sites would be necessary as each would have different piping configurations.

The requirements in the overall meat plant energy model are not to fit energy use in each piece of equipment exactly, but to predict an overview of the entire energy usage pattern. It is considered that as it stands, the model proposed does in fact meet this criterion so the benefits of introducing much greater model complexity were insufficient to justify the considerable work involved. The model of Section 5.1.2 was therefore adopted in the overall meat plant model.

5.2 BATCH DRY RENDERING

5.2.1 Mechanistic Process Description.

Raw material is fed from a raw material bin into a hogger where it is broken into pieces approximately 25 * 25 * 5mm and then stored in a surge bin prior to being fed into the batch cooker. The batch cooker usually consists of a large long cylindrical vessel with the longitudinal axis horizontal and is steam jacketed. Steam heated beaters or paddles rotate at 0.5-0.9 s^{-1} as shown in Figure 5.9. The raw material is either screwed or dumped by bins into a charging tower fitted on top of the vessel. The entire charge is usually loaded within about 15 minutes with the paddles rotating and steam heating occurring via the jacket. Sufficient head space above the charge in the vessel must be left so boil over, causing carryover of the solids into the vents, does not occur. The charging tower port is then closed and steam flow to the paddles turned on. Moisture boiled off the charge material is led away through vents located on the side of the charging tower to a heat recovery unit. There is often a slight back-pressure in the head space caused by the vent valves resulting in a restriction to the flow of evaporated moisture. A pressure cycle within the batch vessel is frequently created by shutting off the vent valves and letting the interior vessel pressure to rise to about 3.2 bar absolute. This allows microbiological sterilising regimes to be met and hydrolyses any wool that may cause downgrading of meat meal.

The moisture endpoint is monitored by measuring the moisture endpoint with a conductance device, observation of a internal temperature gauge, or, drawing off a small sample and checking it by appearance. Both the last two methods are highly subjective and some experience is required in using them. The batch cooker cycle time will vary depending on the size and material composition of the charge mass. When the endpoint moisture is judged to be acceptable the cooker is depressurised, the bottom door is opened, the paddles reversed and the load emptied out into a receiving bin. The receiving bin has a perforated metal bottom and auger screws. As the auger screws the material along the bin length free tallow drains out through the perforated metal.

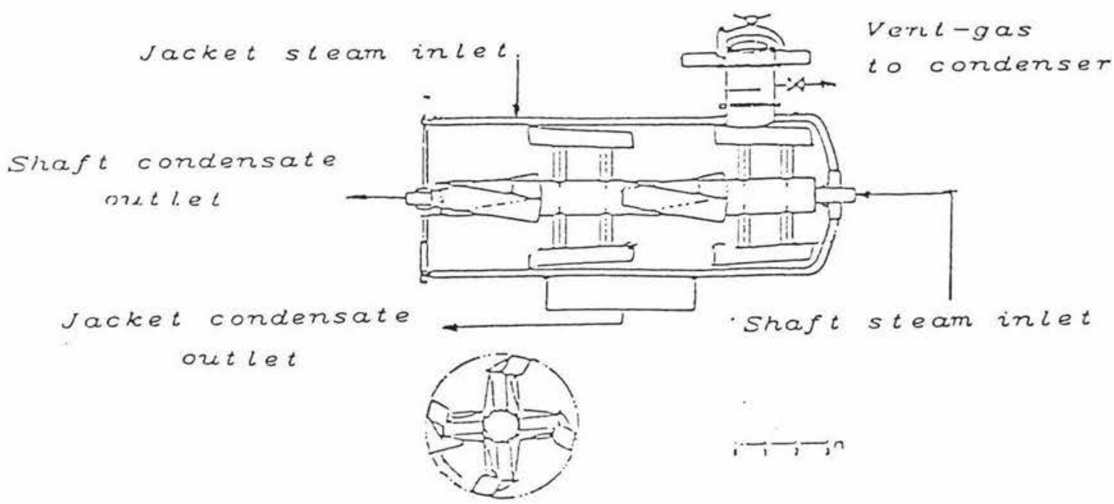


Figure 5.9: Sectioned Batch Cooker

The exiting meal is fed directly onwards to the tallow press which extracts the last of the free tallow from the meal cake to leave a tallow concentration of 9-10% in the final meal. The meal is then milled and is either bulk stored or bagged. Ideally it should have a moisture level of about 10%. The tallow is passed through a decanting centrifuge which removes solids and then through a polishing separator which removes any moisture before going on to be bulk stored. With the exception of 1-2% evaporation in the hammer mill moisture, removal by this type of rendering is carried out completely within the batch cooker itself. Figure 5.9 shows a sectioned diagram of a batch dry cooker.

Most meat plants that use this type of system may have 4 to 8 of these batch cookers with overlapping cycles. The rendering steam demand can therefore fluctuate significantly so that accurate dynamic steam and evaporated water flow rate predictions from the model are probably more important for this type of rendering than any other. Accurate flow rate predictions for boiler loads and heat recovery at any time of day could be calculated by running a number of batch rendering submodels with the appropriate start times entered in. Flow rates for each model could then be summed to give a total rendering steam demand and potential heat recovery.

5.2.2 Basis of Model Development

As with all other models developed within this work, the model sought should have minimum mathematical complexity, low requirements for data, yet predict real plant behaviour with reasonable accuracy. Time variations were considered important and ordinary differential equations were used to model these. The use of paddle mixing implied that the model could be developed as a perfectly mixed vessel. The model will differ from the continuous dry rendering system model insofar as the heat transfer coefficient U_l may be expected to change as the moisture content alters significantly over time.

The model will need to consider the pressure buildup in the pressure cycle. During the pressure cycle there is a buildup of steam in the headspace, changing the pressure and thus the mass of steam in the space. At the pressures commonly used, (1.5 to 3.5 bars absolute), the steam density changes from about 0.86 kg/m^3 to 1.9 kg/m^3. The total headspace volume is typically 0.6m^3 increasing to 2.7m^3 when the batch cycle is completed so the maximum mass in the headspace is only 5 kg. Compared to the total evaporation of about 4500 kg during the batch cycle the effect of the steam storage in the headspace is small. The model therefore neglects steam storage within the headspace. This means that the evaporation flow rate from the wet material can be effectively coupled at all times to the flow rate through the vent valve; thus no differential equations for the head space are required.

As shown in Figure 5.10, the incoming feed from the raw material bin occurs at a flow rate of F_d with the accompanying moisture flow rate in at $F_d\, x_f$. The withdrawal of dry material is flow rate F_p, with an accompanying water flow rate of $F_p\, x$. These flow rates occur for only short times, so for most of the cycle, the total mass of dry solids will not change with time. The application of heat in the cooker leads to temperature change in the contents, all of which are assumed to be at uniform temperature T_{inr}. Heat applied via the steam jacket and paddles at rate Y_d may lead to temperature change in the contents, but some of the energy is lost in the form of evaporated water at flow rate W.

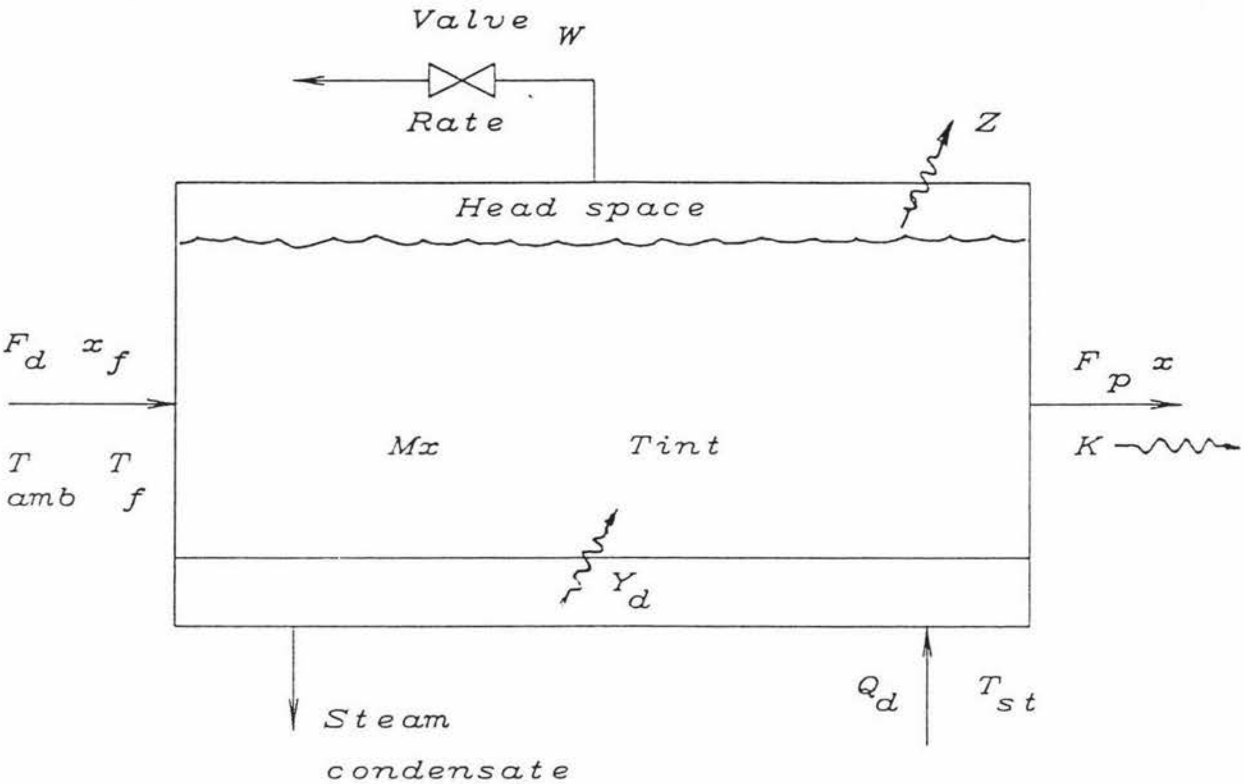


Figure 5.10 Schematic diagram of the batch cooker model.

Further energy is lost, embodied in the product stream K, when the cooker is batch discharged and from the cooker outer shell to the ambient air at flow rate Z. Energy is required to raise the full structural components of the cooker from ambient to the operating temperature.

5.2.3 Mass Balances

As was the case for the continuous dry rendering system it was decided to express all moisture contents and product flow rates on a dry weight basis because conservation equations are easier to derive by this approach. Most of the equations and nomenclature match those in Section 5.1:

A dry solids mass balance in the cooker is:

$$\frac{dM}{dt} = F_d - F_p \tag{5.18}$$

A moisture mass balance is :-

$$\frac{d(Mx)}{dt} = F_d\, x_f - W - F_p\, x \tag{5.19}$$

The cooker internal moisture content is then found by:

$$x = \frac{Mx}{M} \tag{5.20}$$

Determination of W requires separate consideration of three operating modes. There is a period when the batch cooker is open to atmosphere through the vent gas line, a period when the vent gas line is isolated by way of a valve which causes the pressure cycle and then lastly a period when the internal pressure cycle is reduced by gradually opening the isolation valve on the vent gas line.

The moisture evaporation flow rate in all non-pressurised portions of the batch cycle was modelled in the same manner as used for continuous dry rendering:

$$W = k_g\, A\, (\, a_w\, p_{wp} - H_r\, p_{wa}\,) \tag{5.21}$$

During the pressure cycle when the vent valve is closed there is no evaporation:

$$W = 0.0 \tag{5.22}$$

The third operating mode was the period during which the vent valve partially restricted the evaporation flow rate so that the cooker remained partially pressurised. This was represented by defining a fractional flow rate parameter v_f for the valve. When the valve was fully open $v_f = 1.0$, whereas, when the valve was fully closed $v_f = 0.0$. At any time the actual flow rate through the partially open valve was given by:

$$W = v_f\, k_g\, A\, (p_{wp}\, A_w - H_r\, p_{wa}) \tag{5.23}$$

The implementation philosophy was to integrate an ordinary differential equation, from the initial condition $v_f = 0$ when t = the end of the valve isolation period.

$$\frac{dW}{dt} = v_f\, Rate\, k_g\, A\, (\, p_{wp}\, A_w - H_r\, p_{wa}\,) \tag{5.24}$$

where $Rate$ = rate of valve opening (s^{-1})

Integration of equation (5.24) continues until:

$$W \geq k_g\, A\, (\, p_{wp}\, A_w - H_r\, p_{wa}\,) \tag{5.25}$$

at which time the valve is deemed fully open and W is then determined once more from equation (5.21). The parameter Rate is chosen so that 1/Rate approximately equals the time from when valve opening commences until the valve is fully open. A value of Rate = 0.001 s^{-1} gives realistic results as will be shown.

5.2.4 Energy Balances

Equations (5.8) to (5.16) which were developed in the context of the continuous dry rendering system also apply to the batch process.

5.2.5 Other Model Data

The model comprises equations (5.8) to (5.16) and (5.18) to (5.29). To use these equations a variety of data are required.

Table 5.2

Keith batch cooker data

Keith Batch cooker model	12*5	14*5
A. Keith Specifications		
Heating surface A_l (m^2)	26.27	30.27
Shell mass M_{st} (kg)	10250	12750
Steam pressure (bars absolute)	7.9	7.9
Steam usage Q_d (kg/s)	0.306	0.397
Water evaporated W (kg/s)	0.230	0.264
B. Derived Data		
k_g A (s/m)	0.0030	0.0034
Cooker total start mass M_{min} (kg)	0.00	0.00
Cooker total full mass M_{max} (kg)	2721	3402
Dry solids feed F_d (kg/s)	0.35	0.53

(i) Table 5.2 contains data from Keith specification sheets and further values were derived as follows:

- k_g A was calculated using equation (5.8). The data in Table 5.2 for W supplied by Keith Engineering were for non-pressurised operations. Observation of industrial operations suggests that an internal temperature, T_{int} of 110°C is normal so this value was used to determine p_{wp}.

- Values of the overall heat transfer coefficient were calculated as follows:

Work done by Haughey and McConnell (1973) and Fernando and Dunn (1979) suggests that heat transfer coefficients are directly related to the moisture content of the material within the cooker. However, fixed heat transfer coefficients were found to be adequate in the model of continuous dry rendering systems which are typified by a large mass of material within the cooker being held within a relatively stable moisture content range.

Considering the batch type of rendering, a charge of raw material with a high moisture content is completely loaded into the cooker in 900 seconds. Thereafter, the moisture content of the entire charge changes as moisture is evaporated off the wet material. A fixed heat transfer coefficient as had been used for the continuous dry rendering systems would not, therefore be an accurate model.

Herbert and Norgate (1971) carried out a detailed study of the type of batch rendering vessel modelled by this work. They calculated heat transfer coefficients for the jacket as follows:

$$U_{jacket} = \frac{(F_j - Z_l) \times L_J}{(T_j - T_2) \times A_J} \qquad (5.26)$$

where U_{jacket} = heat transfer coefficient of jacket (W/m^2K)

F_j = steam flow rate (kg/s)

L_J = latent heat of steam at jacket flow rate meter pressure (kJ/kg)

Z_l = estimated steam usage flow rate to overcome losses (kg/s)

T_J = temperature of steam, saturated at jacket pressure (°C)

T_2 = temperature of contents (°C)

A_J = heating surface of jacket (m^2)

A similar expression was used to calculate the heat transfer coefficient for the shaft (U_{shaft}).

The measured data are plotted in Figure 5.11. These were curve fitted by the following empirical equations:

$$U_{jacket} = 256\ e^{1.25\,x} \qquad (5.27)$$

$$U_{shaft} = 332.3\ e^{1.012\,x} \qquad (5.28)$$

Equation (5.27) is subject to significant uncertainties. Herbert and Norgate (1971) stated that the steam flow F_j on which the estimate of U_{jacket} was based, was subject to uncertainties in the early part of their study, due to the steam flow rate recorder going out of range. Further, the estimated steam flow rate, to overcome losses to ambient air from the shell, was 68 kg/hr. This represents a significant part of the steam use over the process, so any error would also lower the accuracy of the measured data. Nevertheless, it was decided to use equations (5.27) and (5.28) but to examine the impact of errors later.

- Dry solids feed F_d was calculated by assuming that the moisture content of the raw material was 1 kg water/kg dry solids. (50% moisture on a wet weight basis). This moisture content represents the driest likely feed material, and so if it is in error it is likely that the real F_d will be lower than that shown in Table 5.2.

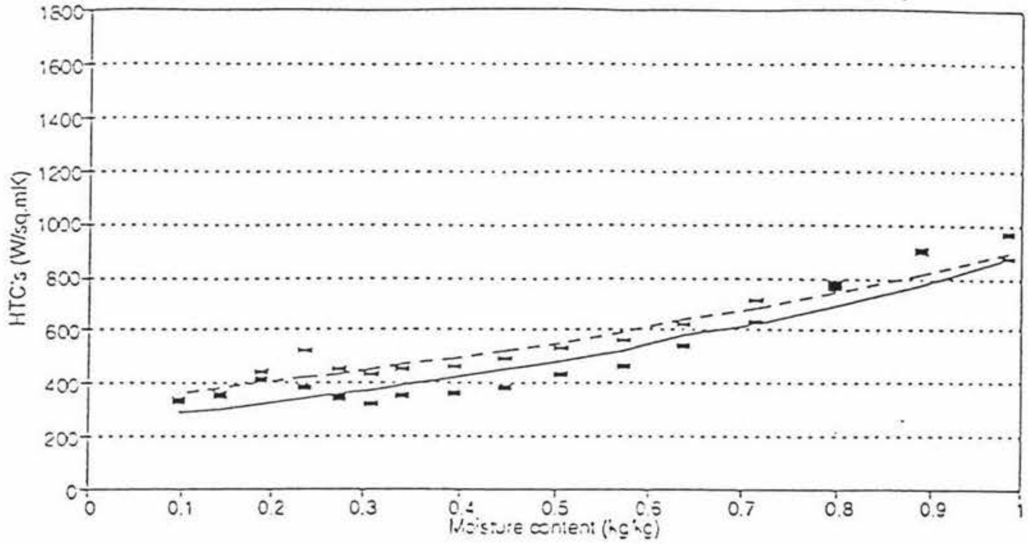


Figure 5.11 Plot of overall heat transfer coefficients (W/m^{2}K) against moisture content (kg water/kg dry solids). Full line represents predicted U_{jacket} from equation (5.27), dashed line represents U_{shaft} from equation (5.28) and the measured data of Herbert and Norgate (1971) are represented by symbols.

(ii) The feed into the cooker is at ambient conditions thus $T_f = T_{amb}$

(iii) Steam temperature, T_{st} was taken from steam tables for the correct operating pressure.

5.2.6 Model Implementation

The mass and energy balances equations were incorporated into an advanced continuous system simulation language software package (Hay *et al.* 1988). Logical statements were included for changing variables such as feed in and out as functions of time, for modulating temperature and for modulating mass of material in the cooker. An example programme listing is shown in Appendix B2.

5.2.7 Model Testing

Initial model tests taken were mathematical e.g. overall mass and energy balances on simulated behaviour. Steady state conditions would not be reached because of the batch nature of the process being modelled. Once satisfactory results were obtained in these tests the next stage was to test against real plant performance.

5.2.7.1 Test data collection

The data of Herbert and Norgate (1971) were considered comprehensive enough to provide a good comparison to model predictions. An account of their methodology and experimental work is also contained within their report. Proportions of fat and fat-free solids were stated allowing compositionally based specific heats from Caddigan and Swan (1985) to be used. It was noted that the actual charge of raw material measured by Herbert and Norgate (1971) was considerably more than that normally recommended by Keith Engineering Ltd.

5.2.7.2 Model customisation

Herbert and Norgate (1971) observed varying conditions when measured data were collected. These are noted below together with the model customisation necessary to simulate them.

(i) Time zero in the test data was the end of loading, so the model used this time as its initial condition.

(ii) Logic steps were put into place to simulate the manual shut off and restart of steam supply by the operator.

(iii) Herbert and Norgate (1971) recorded low steam pressures and thus low steam temperatures, T_{st} at the start of the process. These rose slowly during the batch cycle. The pressure/temperature rise data was modelled by 5 steps through the range and logic steps introduced as follows:

(1) $0 < t \leq 360$ seconds $T_{st} = 135°C$

(2) $360 < t \leq 1080$ seconds $T_{st} = 148°C$

(3) $1080 < t \leq 2520$ seconds $T_{st} = 154°C$

(4) $2520 < t \leq 4320$ seconds $T_{st} = 158°C$

(5) $t > 4320$ seconds $T_{st} = 162°C$

(iv) The pressure cycle simulation was initiated at 4400 seconds both experimentally and in the model.

5.2.7.3 Comparison of measured and predicted data

Figures 5.12 and 5.13 show the comparison between measured and predicted behaviour for Run 20 of Herbert and Norgate's work, the only run for which full data are given in their original paper. Although the steam flow rate appears to be reasonably well predicted except at short times the predicted evaporation is quite different to the measured data. The material temperature is generally under-predicted and as a result the exit moisture content of the meal is unrealistically high. Sensitivity analysis shows that improved fit on graphs B, C and D could only occur if either the heat transfer coefficients or the steam temperature were increased. There was no reason to doubt the steam temperature data so attention focused on the heat transfer coefficients.

As discussed earlier, the heat transfer coefficients of Herbert and Norgate (1971) depend on an accurate measurement of steam flow rate, and of steam use to overcome heat losses. At short times Herbert and Norgate (1971) state that the steam flow rates are not well measured, and at longer times the estimated losses comprise 10-15% of the total steam flow rate.

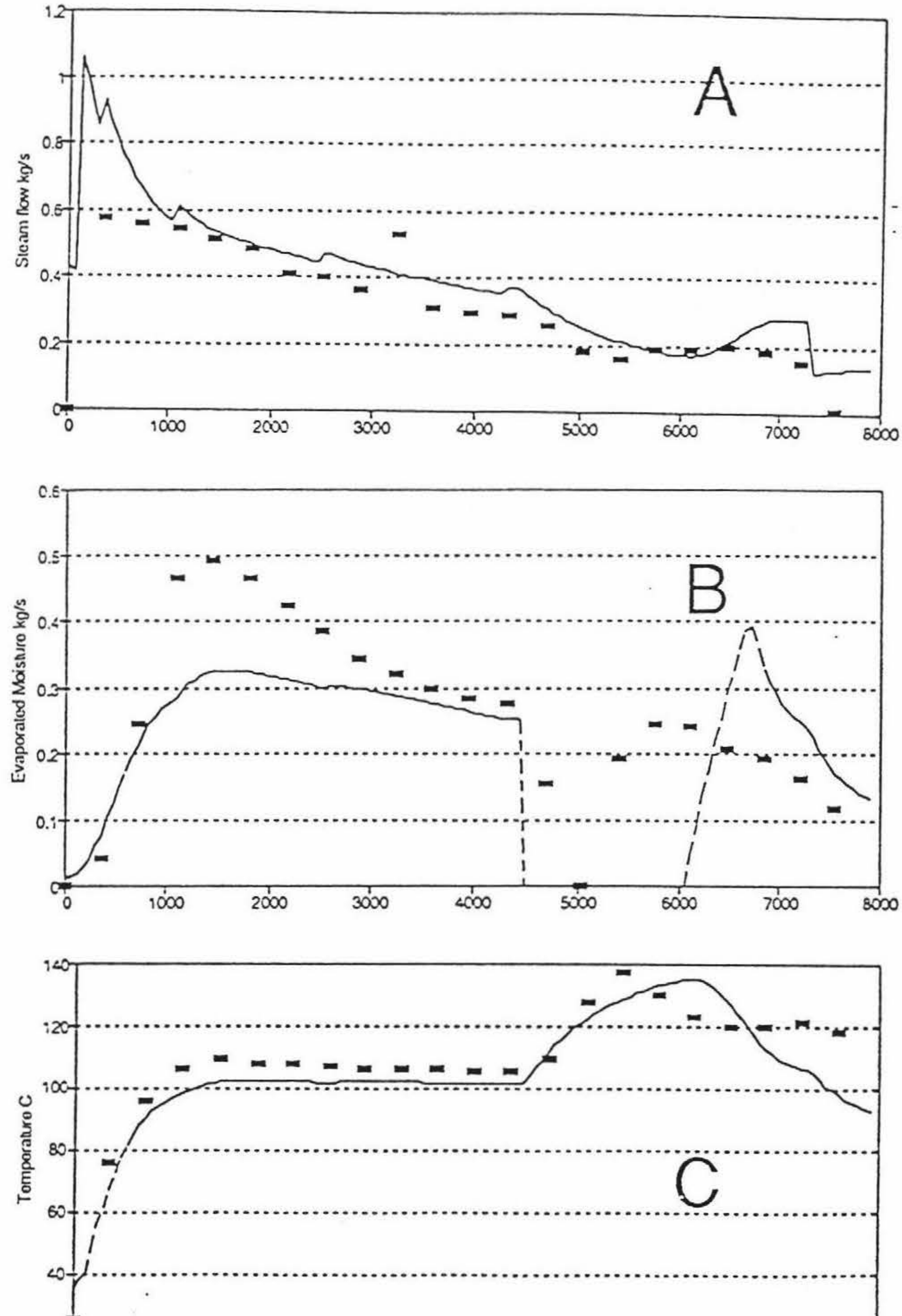


Figure 5.12. Plot of A: Steam usage, Q_d (kg/s), B: Evaporated moisture, W (kg/s), and C: Meal temperature, T_{int} (°C) vs time (s) for Run 20 in the batch cooker studied by Herbert and Norgate (1971). Full line indicates model predictions using heat transfer coefficients calculated by equations (5.27) and (5.28) and measured points are represented by symbols.

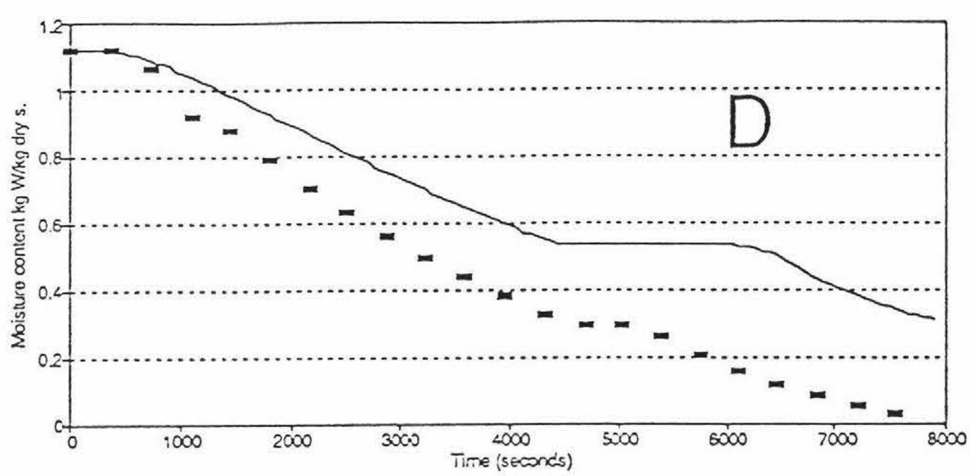


Figure 5.13 Plot of D: Moisture content of the wet material, x (kg water/ kg dry solids) vs time (s) for run 20 in the batch cooker studied by Herbert and Norgate (1971). Full line indicates model predictions using heat transfer coefficients calculated by equations (5.27) and (5.28) and measured data are represented by symbols.

As a result the heat transfer coefficients derived from equations (5.27) and (5.28) are subject to significant uncertainty. Also the Herbert and Norgate (1971) data does not extend to x values above 0.985 kg/kg, yet data from x = 1.12 kg/kg were required in the simulation. Fernando and Dunn (1979) state that much higher heat transfer coefficients arise in the period where the water phase is continuous (high x values) than later when the fat becomes the continuous phase. This, in part, explains the relatively flat heat transfer coefficients vs x

graph for $x < 0.4$ kg water/kg dry solids, but the climbing relationship for higher x values as the water phase becomes more and more dominant. Fernando and Dunn's data for a pilot scale cooker gives higher heat transfer coefficients than Herbert and Norgate, particularly at high x values. They state that using scale-up rules proposed by Haughey and McConnell (1973), the resultant full scale cooker heat transfer coefficients should be higher than those in the pilot scale cooker.
It was therefore decided to postulate a heat transfer coefficient vs x relationship that predicts heat transfer higher than Herbert and Norgate, but generally consistent with Fernando and Dunn.

The equation used was:

$$U_{jacket} = U_{shaft} = 350\ e^{1.5\,x} \tag{5.29}$$

which is also plotted with the data of Herbert and Norgate (1971) in Figure 5.14. The cooker operation was simulated and the results are shown in Figures 5.15 and 5.16. Overall the fit to the measured data is much improved. Major disagreement occurs in only two areas.

At short times, the steam flow rate is badly predicted, but this is the time that Herbert and Norgate state that the steam flow rate meter was out of range. The small "blips" on the graph are due to the real smooth change in steam pressure and temperature being approximated by step changes in the model. Smooth lines in only marginally different positions would result if more sophisticated customisation than that reported in Section 5.2.7.2 had been used.

At short times, measured evaporated moisture flow rate starts later and reaches a higher peak than the model prediction, but the cumulative moisture removals over the time period from 0 to 2500 seconds are close to the same. The moisture content prior to 1500 seconds is greater than 0.9 kg/kg, and thus this time period used heat transfer coefficients for conditions beyond the range of Herbert and Norgate's measurements. Thus there is more uncertainty in this time range. Another indicator that is consistent with this hypothesis is the lack of fit of the temperature rise between 0 and 1000 seconds.

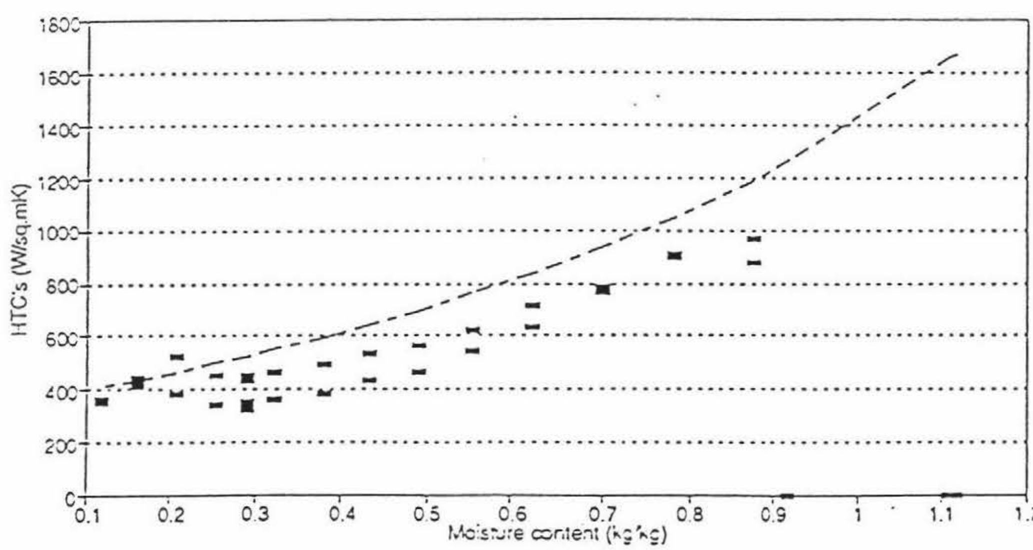


Figure 5.14 Plot of heat transfer coefficients (W/m^{2}K) generated by equation (5.29) against moisture content (kg water/kg dry solids). The dashed line represents $U_{shaft} = U_{jacket}$ generated by equation (5.29) and the measured data is represented by symbols.

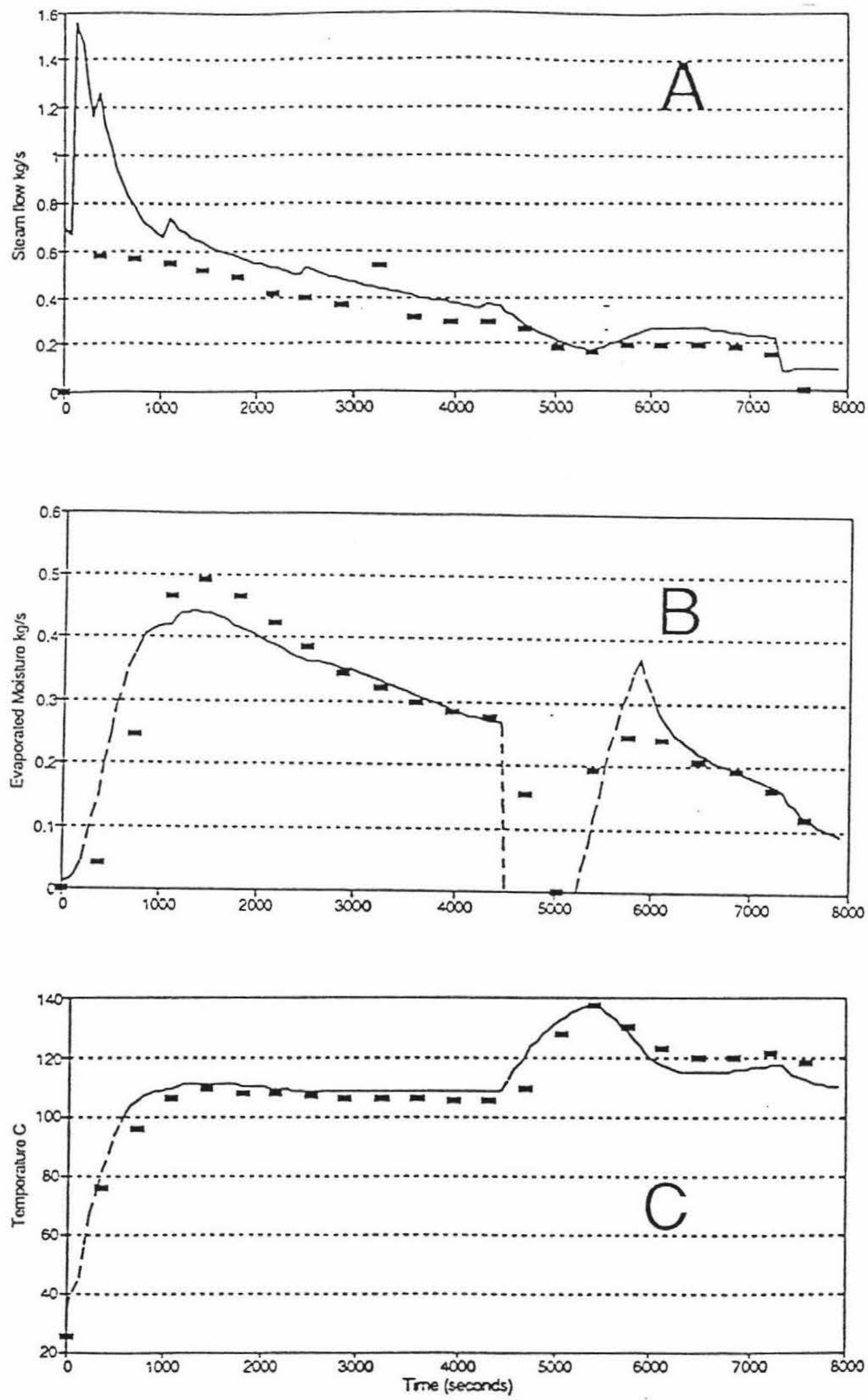


Figure 5.15 Plot of A: Steam usage, Q_d (kg/s), B: Evaporated moisture, W (kg/s), and C: Meal temperature, T_{int} (°C) vs time (s) for Run 20 in the batch cooker studied by Herbert and Norgate (1971). Full lines indicates model predictions using heat transfer coefficients calculated by equation (5.29) and measured points are represented by symbols.

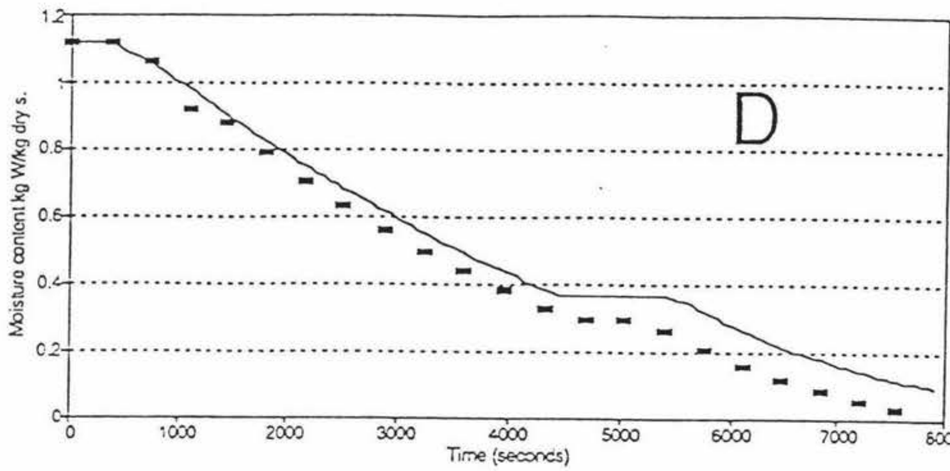


Figure 5.16 Plot of D: Moisture content of the wet material, x (kg water/kg dry solids) vs time (s) for Run 20 in the batch cooker studied by Herbert and Norgate (1971). Full line indicates model predictions using heat transfer coefficients calculated by equation (5.29) and measured data are represented by symbols.

The second area of lack of fit is the venting after the pressure cycle. Use of the parameter Rate = 0.001 equation (5.24) in the simulation led to slower rise in the flow rate of vènt gas emission than appeared to be the case in practice. The real operator actions would vary from one batch operation to another and at best the equation (5.24) is only a rough approximation. To better match reality, the parameter Rate may have to be time variable, but there was no information on which to base improved estimates.

The last area of lack of fit is that even with enhanced heat transfer coefficients, (equation (5.29) instead of equations (5.27) and (5.28)), the final moisture content is still a little high. The only way to improve fit in graph D would be to increase heat transfer coefficients or steam temperature further.

5.2.8 Discussion and Conclusions

This section focuses on whether the model proposed in Section 5.2.2 is a sufficiently adequate predictor of energy use by a batch dry rendering system for the model to be adopted into the overall meat plant energy model. As discussed in section 5.2.5, uncertainty in the heat transfer coefficients has a major impact on the quality of fit of the model predictions to measured data variables. Once new estimates that were realistic, but higher than those measured by Herbert and Norgate (1971) were adopted, the model predicts sufficiently accurately for the purposes of the present study. It was concluded that the model has the correct physical and conceptual basis, and that in spite of the problems experienced there is sufficient evidence that the reason for lack of fit lies elsewhere. The model of Section 5.2.2 was therefore adopted into the overall meat plant energy model.

5.3 LOW TEMPERATURE RENDERING (LTR) MODEL

5.3.1 Mechanistic Process Description

As was the case with the continuous dry rendering, raw material is prebroken and transported to a raw material bin. This may include the usual by-products from slaughterhouse, offal, boning, hide and fellmongery meat trimmings together with sludge from effluent solid recovery systems and material from outside the plant. Figure 5.17 shows a schematic diagram of the process. The raw material is passed through a grinder which reduces the size to around 10mm *10mm *25mm. Water, normally at 82°C, is added and the raw material is raised to about 95°C in a reactor vessel. The heated raw material is then fed into a decanting centrifuge which mechanically separates the liquid phase containing some of the moisture and approximately 95% of the fat from the solid material. The liquid phase is sent to a surge tank and then fed through a separator which separates off the so called stick water to be discharged to waste and the fat phase which is sent to storage. The fat may be acid buffered as required. Solids leaving the centrifuge are fed into one of the dryers listed below.

(i) The continuous conduction heating dryer utilises steam condensing inside multiple hollow discs placed very closely to each other. The discs are fixed to a shaft which runs through the horizontal centre axis of the dryer. The shaft assembly rotates slowly to present a very large heated surface area to the material in a relatively small volume. This type of drier does not have an outer steam jacket. The Stord dryer studied within this work and shown in Figure 5.18 is typical of this design.

(ii) The Iwell batch system is a high temperature batch dry system incorporating a top loading design. A complete charge is heated by steam through a jacket and paddles and the moisture within the raw material evaporates over a period of about 1.75 hours. The dried meat meal is then discharged and the complete cycle repeated. This type of drying operation bears a close similarity to the batch dry rendering process. The two major differences are that the fat is removed prior to entry to the system, and that the material is preheated to about 95°C. The actual operation of each batch cycle is otherwise similar.

(iii) The direct fired rotary dryer consists of a rotary drum with internal helical baffles as shown in Figure 5.19. The baffles are designed to drive the material forward and partially up the drum wall before it cascades down through the passing air. Direct firing of natural gas heats air which is introduced cocurrently to the wet feed material at temperatures between 640 and 800°C and in sufficient volume to carry away the moisture evaporated off the solids.

Fat-free solids are dried to an ideal moisture content of about 0.08 kg water/kg dry solids before they exit the dryer. As is the case with the other rendering systems the energy embodied in the exit air is largely recovered in a shell and tube heat exchanger located downstream of the dryer. However, in this case, the gas flow to the heat exchanger contains much larger amounts of air than in the other dryer types, and after passing through the heat exchanger, some of the gas is recycled back to the secondary inlet of the gas burner.

The feed in and out of all the above dryers is usually controlled by the internal meal temperature which is correlated with the end point moisture of the dried meal (Brown *et al.* 1988). Meat meal is milled and sent to bagging or bulk storage.

5.3.2 Basis of Model Development

The model design philosophy was similar to that used for continuous dry rendering. However, in the LTR process, heat and mass stream divisions are not confined to within the cooker, so model boundaries were expanded. Figure 5.17 shows the general arrangement of the model for a typical low temperature rendering plant. Makeup water is added at rate of F_j to assist heat transfer within the reactor.

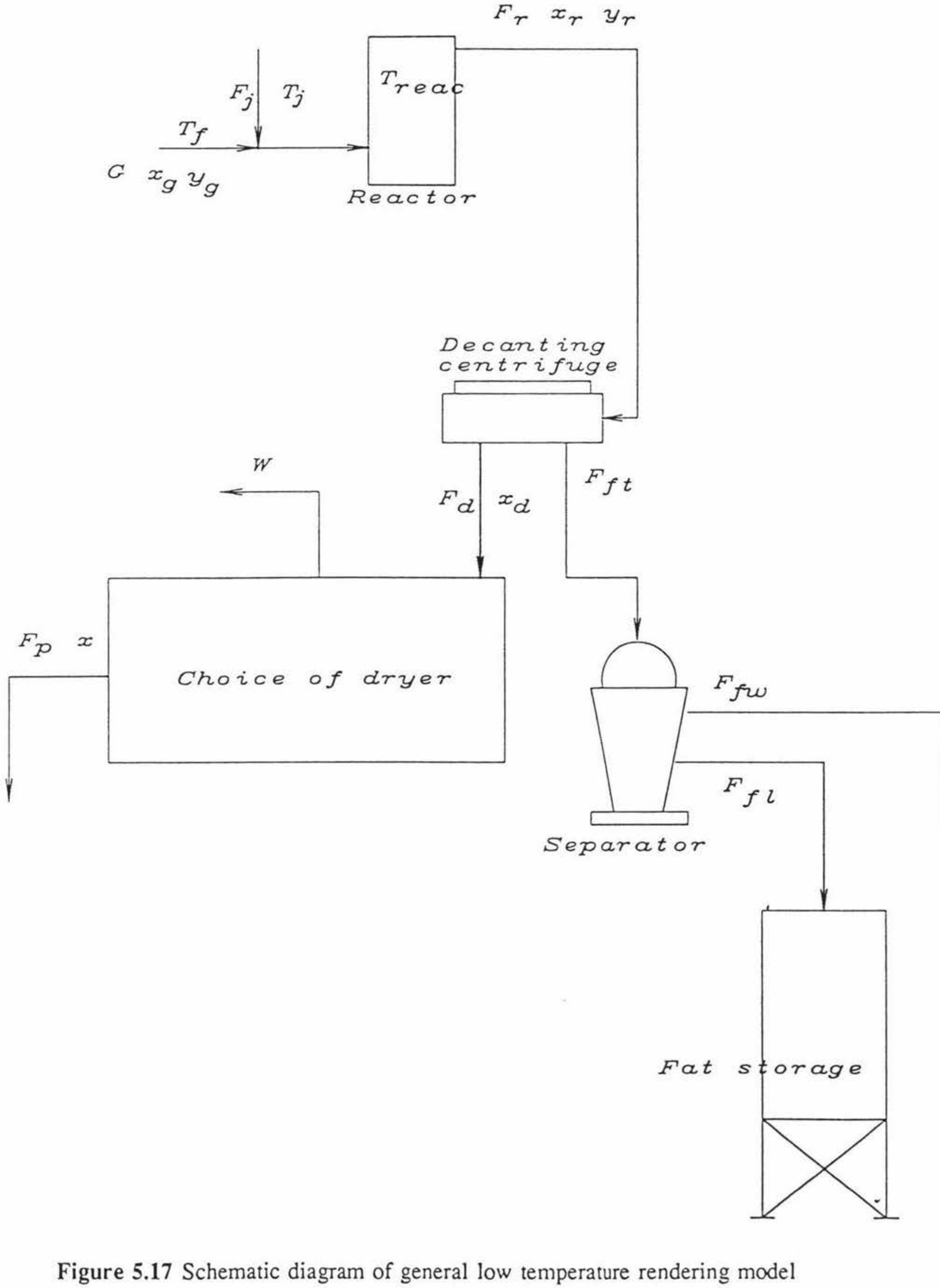


Figure 5.17 Schematic diagram of general low temperature rendering model

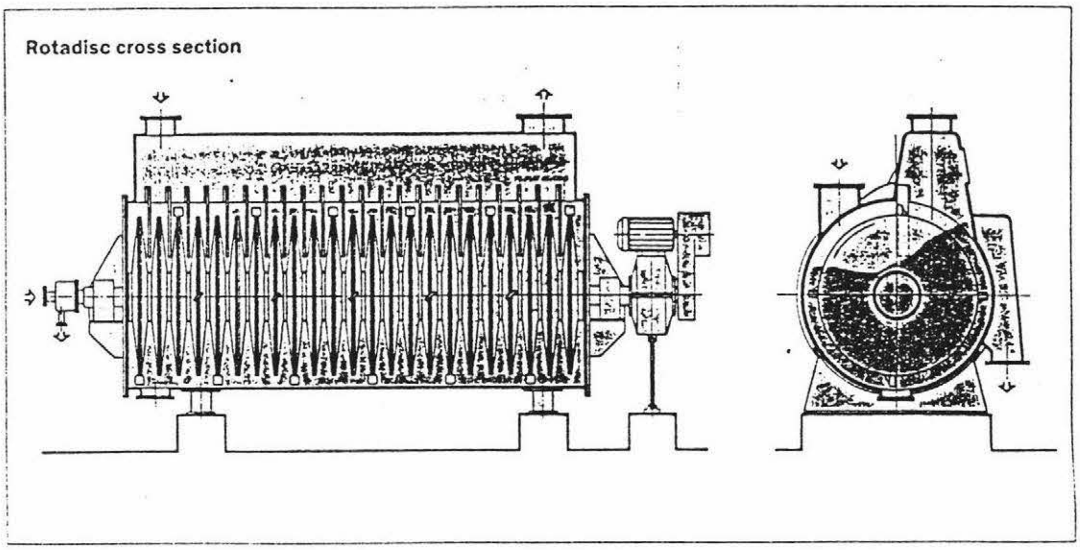
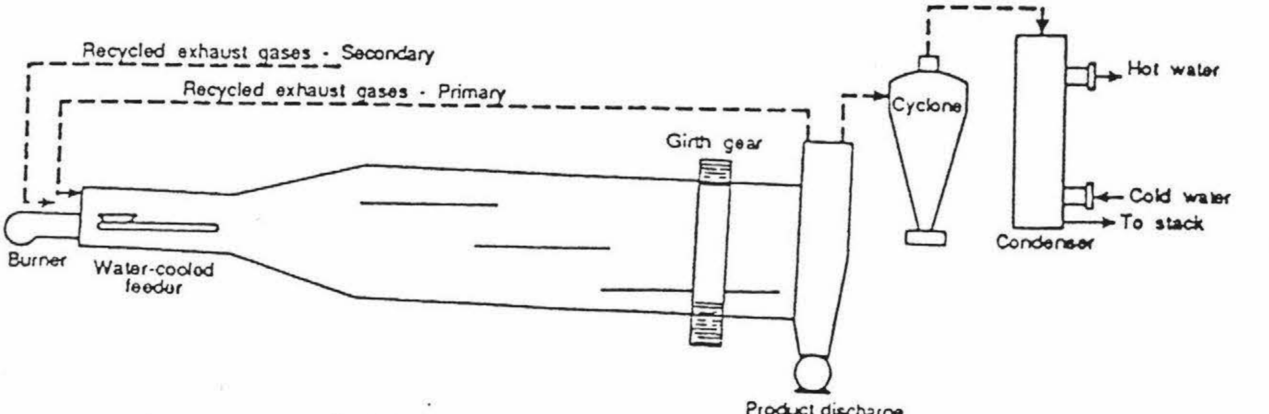


Figure 5.18 Sectioned view of the continuous conduction heating dryer



Arrangement of a Flo-Dry cascading rotary dryer.

Figure 5.19 Sectioned view of a direct fired rotary dryer

The reactor is small and material has a typical residence time of 10-15 minutes. It is filled at the start of rendering production and then remains full for the rest of the day. Because the startup fill is rapid it was decided to treat the reactor operation as steady state so modelling of it would require only algebraic equations. The combined flow rate exiting the reactor vessel and entering the decanting centrifuge is at temperature T_{reac}.

Inspection of the data of Caddigan and Swan (1985) suggests that both the fat content of solids exiting the decanting centrifuge and fat-free dry solids content of the liquid phase are low and in mass flow terms approximately equal each other. For simplicity it was assumed that the decanting centrifuge solids stream was free of fat and that the liquid phase contained no fat-free dry solids. The decanting centrifuge thus separates the stream into fat-free solids which are fed to the dryer at flow rate F_d, with an accompanying moisture flow of $F_d x_d$, and a liquid flow rate to the separator of F_{fr}. The separator splits the liquid flow rate into a fat flow rate F_{fl} and stickwater flow rate F_{fw}.

Low temperature rendering is usually operated in conjunction with one of the three dryer types previously described.

5.3.2.1 Continuous conduction heating dryer

The formulation for this dryer type is very similar to that for the continuous dry rendering system which was described in Section 5.1. Withdrawal of product from the drier occurs at a flow rate of F_p with an accompanying moisture content of x_r. The total mass of material and the moisture content within the dryer may change with time. Heat applied through the dryer will not only raise the contents temperature, but some energy will be lost in the form of evaporated water at a rate of W. Further energy is lost embodied in the product stream (K) and from the cooker outer shell to the ambient air (Z). Energy is also required to raise the total structural components of the cooker from ambient to the operating temperature.

The formulation of the model originally considered the dryer as one perfectly mixed vessel, similar to the continuous dry rendering system as shown in Figure 5.20.

Simulations with this model predicted evaporation rates, internal temperatures and steam usage that were not realistic. It was decided to reformulate the model, dividing the vessel into two compartments in series so that the outlet of one would be fed into the inlet of the other. This would more realistically model the product movement in the dryer than a single perfectly mixed vessel. Figure 5.21 shows a schematic of the two compartment system. The actual Stord dryer has a weir level control fitted to the product outlet but this was not considered within the model. Use of the weir tends to produce instability with regard to the outlet meal moisture content (Brown *et al.* 1988).

5.3.2.2 Iwell batch dryer

The model developed in Section 5.2 for the batch dry rendering system can be adapted to describe the equipment used as a dryer only.

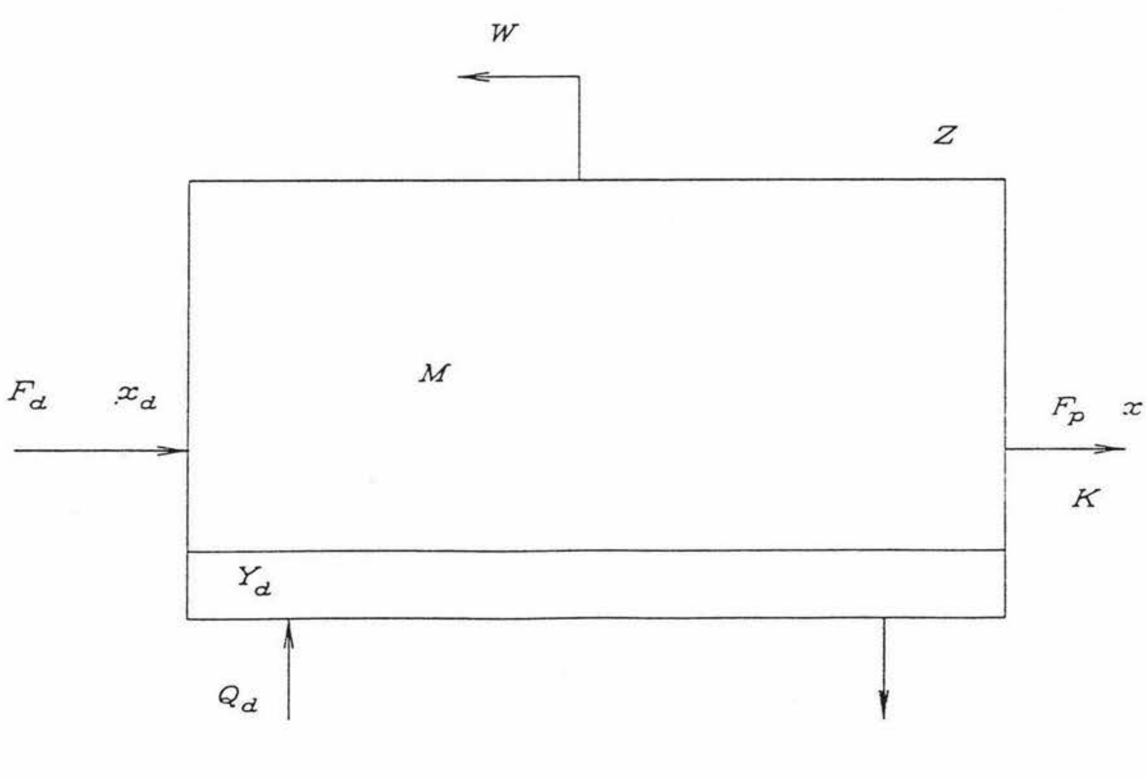


Figure 5.20 Schematic diagram of continuous conduction heating dryer

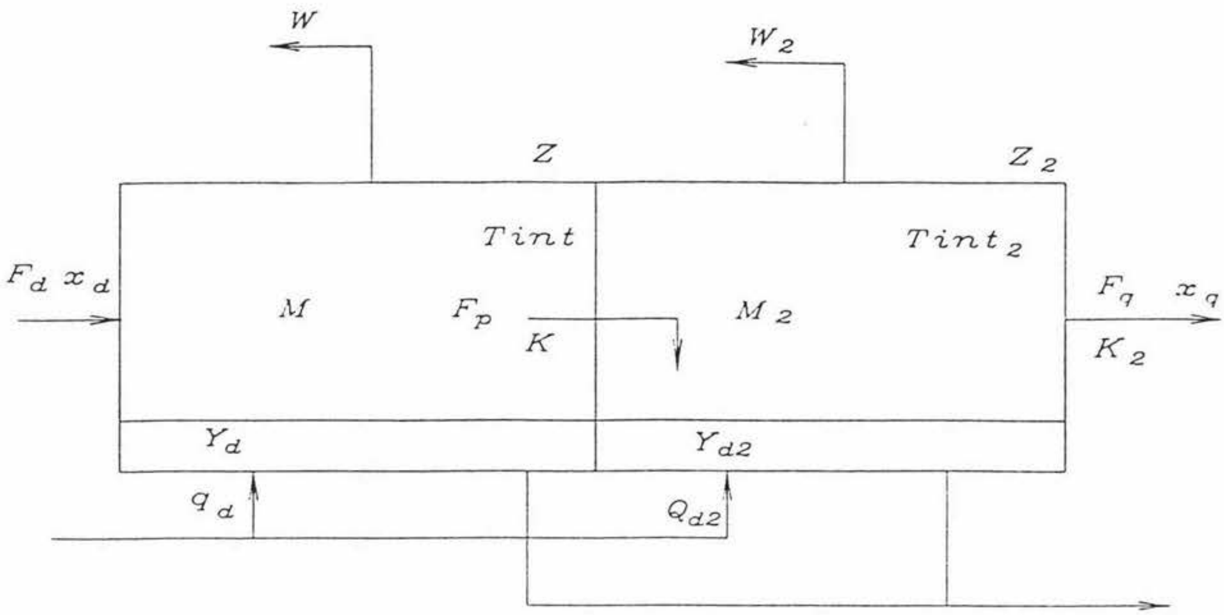


Figure 5.21 Schematic diagram of the two compartment model for the continuous conduction heating dryer.

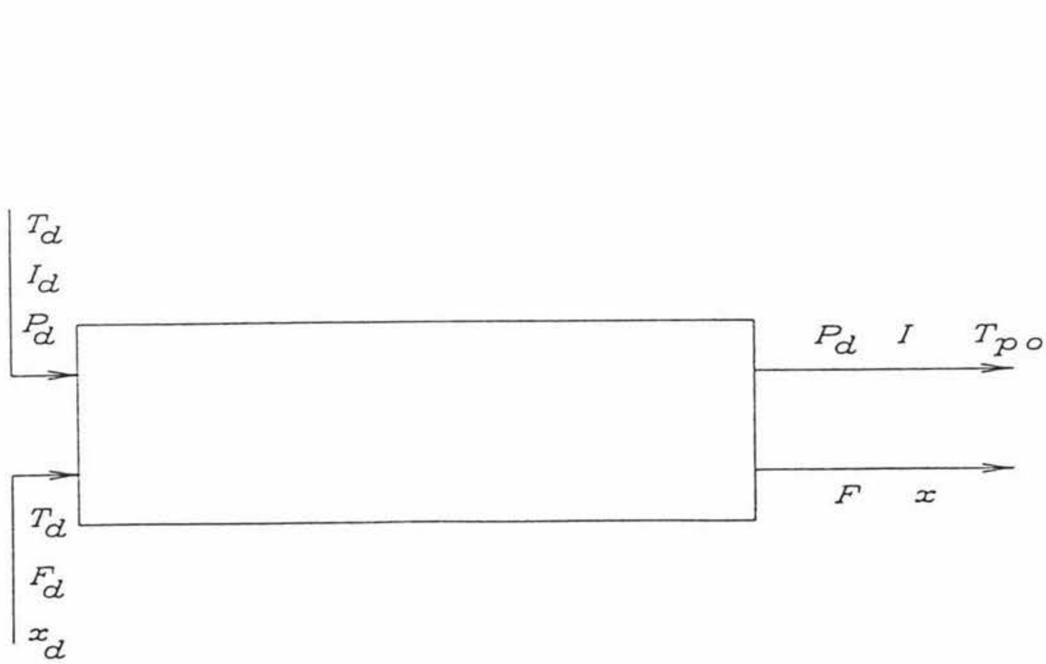


Figure 5.22 Schematic diagram of direct fired rotary dryer

5.3.2.3 Rotary dryer

The product movement in this dryer is best described as a plug flow because wet material is dried progressively as it moves through the dryer at a steady rate with virtually no mixing taking place. Langrish *et al.* (1990) investigated time/temperature relationships within a typical direct fired rotary drier in order to establish sterilisation times for pathogenic bacteria within rendering raw material. They developed a number of ordinary differential and algebraic equations to describe mass transfer, heat transfer and product transfer. They found it was necessary to consider the dryer divided up into a series of compartments or controlled spaces to apply the ordinary differential equations.

In the present work, it was decided to use a simpler model because the process is continuous and stable conditions are reached quickly after startup. It is only required to calculate the energy use and the energy flow available for hot water production, and with the assumption of steady state operation algebraic equations are adequate. Provided inlet conditions (entering flow of wet solids from the decanting centrifuge, gas flow, temperature and humidity) and the outlet conditions of the meat meal are known (Figure 5.22), it is possible to calculate the outlet gas moisture and energy flow rates.

5.3.3 Low Temperature Rendering Mass Balances

It was decided to continue to express all moisture, fat contents and product flows on a fat-free dry solids mass basis in the model because conservation equations are easier to derive by this approach. As with other models, the rate of moisture evaporation within the dryer remains the major constraint for product throughput. Thus the raw material infeed flow rate is constrained by the flows of fat-free dry solids and moisture delivered to the dryer from the decanting centrifuge discharge. The feed rate G is selected by the model user y_g, the fat content and x_g the moisture content of the feed, are predetermined by the generic model (Section 4.2).

A mass balance across the reactor vessel is:

$$G(1 + x_g + y_g) + F_j = F_r (1 + x_r + y_r) \tag{5.30}$$

where F_r = feed rate to decanting centrifuge (kg fat-free dry solids/s)

y_r = fat content of material to the decanting centrifuge (kg fat/kg fat-free dry solids)

x_r = moisture content of material fed to the decanting centrifuge (kg water/kg fat-free dry solids)

F_j = makeup water flow rate (kg/s)

Because the reactor vessel is assumed to operate at steady state a mass balance for fat-free dry solids across the reactor vessel is:

$$G = F_r \tag{5.31}$$

A moisture balance across the reactor vessel is:

$$G x_g + F_j = F_r x_r \tag{5.32}$$

The value of x_r may be found by rearranging equation (5.32):

$$x_r = \frac{G x_g + F_j}{F_r} \tag{5.33}$$

A fat mass balance across the reactor vessel is:

$$G y_g = F_r y_r \tag{5.34}$$

which may be further simplified using equation (5.31) to imply:

$$y_g = y_r \tag{5.35}$$

With the assumptions made earlier about complete partitioning of fat and other solids, a total mass balance across the decanting centrifuge is:

$$F_r (1 + x_r + y_r) = F_d (1 + x_d) + F_{ft} \tag{5.36}$$

where F_d = feed rate to dryer (kg fat-free dry solids/s)

x_d = moisture content of feed to dryer (kg water/kg fat-free dry solids)

F_{ft} = total liquid phase flow (kg/s)

A total mass balance across the separator is:

$$F_{ft} = F_{fw} + F_{fl} \tag{5.37}$$

where F_{fw} = flow rate of fat-free stickwater (kg/s)

F_{fl} = flow rate of fat (kg/s)

As discussed earlier the total fat-free dry solids flow rate entering the decanting centrifuge is assumed to exit to the dryer, and equals the feed fat-free dry solids flow rate i.e:

$$G = F_r = F_d \tag{5.38}$$

Data from Caddigan and Swann (1985) further indicate that the fat-free solids exiting the decanting centrifuge have an associated moisture content of between 50 and 53% on a wet weight basis when sourced from raw material to the rendering system with a moisture content of between 40 and 60% wet weight. For simplicity in the model it was assumed that all solids exiting the decanting centrifuge would contain a moisture content of 50% on a wet weight basis. Thus:

$$x_d = 1.0 \tag{5.39}$$

This enables F_{ft} to be found by rearranging equation (5.36):

$$F_{ft} = F_r (1 + x_r + y_r) - F_d (1 + x_d) \tag{5.40}$$

The moisture mass balance across the decanting centrifuge and separator is:

$$F_r x_r = F_d x_d + F_{fw} \tag{5.41}$$

Rearrangement of equation (5.41) gives:

$$F_{fw} = F_r x_r - F_d x_d \tag{5.42}$$

The fat mass balance across the separator is:

$$F_r y_r = F_{fl} \tag{5.43}$$

To use these equations the following calculation logic was adopted:

(i) The fat-free solids flow rate, G is determined using equation (5.31),

(ii) The moisture content of the stream exiting the reactor is calculated using equation (5.33),

(iii) The fat flow rate from the reactor, and hence from the separator is found using equations (5.25) and (5.43),

(iv) The total liquid flow rate to the separator is then calculated using equation (5.40),

(v) The stickwater flow rate from the separator follows from equation (5.42).

5.3.3.1 Continuous conduction heating dryer

Although the feed into the continuous conduction heating dryer is assumed to contain no fat, the model adopted for evaporation of moisture is the same as that for the continuous dry rendering. The mass balances therefore remain the same, provided they are arranged on a fat-free dry solids basis rather than total dry solids.

Considering the first dryer compartment, a dry solids mass balance in the compartment is:

$$\frac{dM}{dt} = F_d - F_p \tag{5.44}$$

where F_d = feed flow rate from raw material bin (kg fat-free dry solids/s)

F_p = product flow rate from dryer first compartment (kg fat-free dry solids/s)

A moisture mass balance is:

$$\frac{d(Mx)}{dt} = F_d\, x_d - W - F_p\, x \tag{5.45}$$

where x_d = moisture content of the raw material (kg water/kg fat-free dry solids)

x = moisture content in the dryer first compartment (kg water/kg fat-free dry solids)

W = moisture evaporation flow rate in the dryer first compartment (kg water/s)

The dryer first compartment internal moisture content is then found by:

$$x = \frac{Mx}{M} \tag{5.46}$$

where Mx = mass of moisture in the dryer first compartment (kg water)

M = mass of fat-free dry solids in the dryer first compartment (kg fat-free dry solids)

The rate of evaporation W is:

$$W = k_g\, A\, (a_w\, p_{wp} - H_r\, p_{wa}) \tag{5.47}$$

where k_g = mass transfer coefficient (s/m)

A = exposed surface area of the meal (m^2)

a_w = water activity of meal

p_{wp} = vapour pressure of water at meal temperature within the dryer first compartment (Pa).

Other symbols retain their previous meanings. In the second dryer compartment the same equations, but with substitute nomenclature, were used.

5.3.3.2 Iwell batch dryer

The mass balances for the batch system used as a dryer are identical to those developed in Section 5.2, other than the need to express them on a fat-free basis. The equations involved are equation (5.18) to (5.25).

A dry solids mass balance in the cooker is:

$$\frac{dM}{dt} = F_d - F_p \tag{5.18}$$

A moisture mass balance is:

$$\frac{d(Mx)}{dt} = F_d\, x_f - W - F_p\, x \tag{5.19}$$

The cooker internal moisture content is then found by:

$$x = \frac{Mx}{M} \tag{5.20}$$

The moisture evaporation rate in all non-pressurised portions of the batch cycle was modelled in the same manner as used for continuous dry rendering:

$$W = k_g\, A\, (a_w\, p_{wp} - H_r\, p_{wa}) \tag{5.21}$$

During the pressure cycle when the vent valve is closed there is no evaporation:

$$W = 0.0 \tag{5.22}$$

The third operating mode was the period during which the vent valve partially restricted the evaporation flow rate so that the cooker remained partially pressurised:

$$W = v_f\, k_g\, A\, (p_{wp}\, a_W - H_r\, p_{wa}) \tag{5.23}$$

The implementation philosophy was to integrate an ordinary differential equation, from the initial condition $v_f = 0$ when t = the end of the valve isolation period:

$$\frac{dW}{dt} = v_f\, Rate\; k_g\, A\, (p_{wp}\, a_w - H_r\, p_{wa}) \tag{5.24}$$

where Rate = rate of valve opening (s^{-1})

Integration of equation (5.24) continues until:

$$W \geq k_g\, A\, (\, p_{wp}\, a_w - H_r\, p_{wa}\,) \tag{5.25}$$

at which time the valve is deemed fully open and *W* is then determined once more from equation (5.21).

5.3.3.3 Rotary dryer

Langrish *et al.* (1990) developed the following equation, based on the model description shown in Figure 5.22, for a mass balance across a controlled space or compartment for steady state conditions:

$$F_d\, (x_d - x) = P_d\, (I_d - I) \tag{5.48}$$

where P_d = flow rate of dry gas (kg dry gas/s)

I_d = moisture content of inlet gas (kg water/kg dry gas)

I = moisture content of outlet gas (kg water /kg dry gas)

Equation (5.48) may be rearranged to find the outlet gas moisture content:

$$I = I_d + \frac{F_d}{P_d} (x_d - x) \tag{5.49}$$

Applied across the dryer as a whole, provided the inlet feed and gas conditions are known the recoverable evaporated moisture can be calculated.

5.3.4 Energy Balances

As has been discussed the reactor is assumed to operate under steady state conditions. An energy balance over it is:

$$Q_r = \frac{(G\ c_s + G\ y_g\ c_{fat} + G\ x_g\ c_w)\ (T_{reac} - T_f) + F_j\ c_w\ (T_{reac} - T_j)}{\Delta h_s} \tag{5.50}$$

where Q_r = reactor steam consumption flow rate (kg/s)

c_{fat} = specific heat capacity of fat (J/kgK)

c_s = specific heat capacity of fat-free dry solids (J/kgK)

T_{reac} = temperature of the raw material exiting the reactor vessel (°C)

T_j = temperature of makeup water (°C)

5.3.4.1 Continuous conduction heating dryer

The model is based on that for continuous dry rendering which was stated in detail earlier.

An overall energy balance on the dryer first compartment is :

$$\frac{dB}{dt} = (F_d\ c_s + F_d\ x_d\ c_w)\ T_d + Y_d - Z - K - W\ h_w \tag{5.51}$$

where B = total energy content of the dryer first compartment (J)

T_d = temperature of solids exiting the decanting centrifuge (°C)

Y_d = steam energy input to dryer first compartment (W)

Z = energy loss from dryer first compartment shell to ambient air (W)

K = energy embodied in the product leaving the dryer first compartment (W)

h_w = enthalpy of exiting water vapour dryer first compartment (J/kg)

T_{int} is defined by dividing the total energy content by the thermal capacity of the cooker:

The model of the second dryer compartment uses the same equation, but with substitute nomenclature.

5.3.4.2 Iwell batch dryer

As was the case with the mass balances, the energy balances from the continuous dry rendering system in Section 5.1.4 (equations (5.9) to (5.16)) can be applied provided total dry solids is replaced by fat-free dry solids.

An overall energy balance on the cooker is :

$$\frac{dB}{dt} = ((F_d \, c_{dry}) + (F_d \, x \, c_w)) \, T_f + Y_d - Z - K - W \, h_w \qquad (5.9)$$

5.3.4.3 Rotary dryer

As has been discussed the dryer is assumed to operate under steady state conditions. The total energy embodied in the incoming air and wet solids may be approximated in the manner of Langrish *et al.* (1990) by:

$$Y_d = F_d \left(c_s + c_w x_d \right) T_d + P_d \left[\left(c_{pd} + c_{vd} I_d \right) T_{pd} + H_{fg} I_d \right) \right] \qquad (5.52)$$

where c_{pd} = specific heat of inlet dry gas (J/kgK)

c_{vd} = specific heat of inlet water vapour (J/kgK)

T_{pd} = temperature of inlet gas to dryer (°C)

H_{fg} = latent heat of vapourisation of water at 0°C (J/kg)

Y_d = total inlet energy (W)

I_d = moisture content of inlet gas (kg water/kg dry gas)

An energy balance relating this embodied energy to the energy embodied in the outlet streams and the heat loss Z, allows T_{po}, the gas outlet temperature, to be determined:

$$T_{po} = \frac{Y_d - Z - F_d \left(c_s + c_w x\right) T_{int} - P_d \left(H_{fg} I\right)}{P_d \left(c_{po} + c_{vo} I\right)} \qquad (5.53)$$

where c_{po} = specific heat of outlet dry gas (J/kgK)

c_{vo} = specific heat of outlet water vapour (J/kgK)

In the derivation of equations (5.52) and (5.53) a number of approximations were made:

(i) Equation (5.52) describes an energy balance which considers all the energy contents relative to a datum of 0°C. The incoming dry air is heated from ambient (15°C) to a maximum temperature of about 800°C. The relationship between specific heat for dry air and temperature rise within this range is not linear so a representative average value should be used across the temperature range. This average specific heat capacity is 1070 J/kgK. An average specific heat for water vapour contained within the inlet air of 2100 J/kgK was derived similarly.

(ii) The structure of equation (5.52) deals with the sensible heating of the water vapour contained within the inlet air on the basis of water vapour creation at 0°C. The latent heat of vapourisation of 2500 J/kg is therefore taken at 0°C.

The energy input required to heat the incoming air is approximately:

$$Q_p = P_d \left[(c_{pd} + c_{vd} I_d) (T_{pd} - 15) \right] \tag{5.54}$$

where Q_d = Energy input required to heat incoming air (W)

The presence of combustion gases has a small effect, both on gas composition, and in determining total energy requirement to achieve T_{pd} but this was considered sufficiently small (<5%) to be ignored.

5.3.5 Other Model Data

To use the LTR model with any of the dryer types, a variety of data are required, depending on the type of dryer system used.

(i) The steam pressure in the LTR process is normally lower than that used in the continuous dry rendering process, so actual operating values of 6-7 bars absolute were used.

(ii) For all drying systems, the dry solids feed flow rate F_d was calculated by assuming that the moisture content of the raw material was 1 kg water/kg dry solids. (50% moisture on a wet weight basis). This moisture content represents the driest likely feed material, and so if it is in error it is likely that the real F_d will be lower.

(iii) The moisture and fat contents on a fat-free basis were calculated using the generic model (described in Section 4) for a typical combined sheep/beef plant. The resultant values were:

x_g = 2.08 kg water/kg fat-free dry solids
y_g = 1.06 kg fat/kg fat-free dry solids

(iv) Continuous dry rendering systems such as the Keith cooker have a relatively high heat transfer coefficient (typically 700 W/m^2K compared to a Stord continuous conduction heating dryer which has similar heating surface characteristics but a heat transfer coefficient of about 120 W/m^2K. This may partly be explained by the large amount of tallow present in the dry continuous rendering process. It is thought that the fat phase within the dry rendering system becomes the continuous phase and forms a link within the heat transfer mechanism allowing greater heat transfer between the heating surface and the particles of material within the cooker. However, the high fat content both in the continuous phase and within the particles, acts as a barrier to final moisture removal particularly at moisture contents below 20% on a dry weight basis.

As well as affecting heat transfer coefficients the absence of fat in the LTR system affects the relationship between water activity and moisture content. Brown *et al.* (1988) demonstrate that higher rates of drying occur in the absence of fat, and as a result in the LTR systems lower meal end-point temperatures are required to achieve the desired exit moisture contents as Table 5.3 shows. It was thus necessary to establish the relationship between water activity and moisture content anew.

An equation of the form:

$$a_w = 1 - e^{-\alpha x} \tag{5.55}$$

had been used for continuous dry rendering and had proved sufficiently accurate. In the absence of good quality data relating water activity to moisture content, it was decided to retain the same equation, but to adjust the value of α. In the continuous dry rendering system the value of α had been selected as 2.4. At a 10% moisture content this implies a_w = 0.213. Consider data from Table 5.3. Material from continuous dry rendering would approximately correspond to the far right column. At 124°C the vapour pressure of water is approximately 225 kPa, giving a calculated partial pressure over the meal of 0.213 * 225 = 48 kPa. For LTR material, approximately the same partial pressure of water vapour must be developed at 114°C. The vapour pressure is about 164 kPa so this implies a_w = 48/164 = 0.293 which implies α is approximately 3.5. This suggests that the required value of α is about 50% higher in LTR systems then in continuous rendering systems, and for convenience a value exactly 50% higher was used.

(v) k_gA values in Table 5.4 were then calculated using manufacturers data for rates of evaporation (W).

5.3.5.1 Stord rotodisc dryer

Table 5.4 contains data from Stord continuous conduction dryer specifications and information supplied by the local agents, IST Engineering Ltd. The values given for the rate of water evaporation and steam consumption are approximate because no test data were available. Further values were derived as follows:

(i) $k_g A$ was again calculated using equation (5.5) and (5.8). In this case T_{int} was assumed to be 110°C because the rendering plant, at which test data were collected, used this value as an ideal set point.

(ii) Values of the overall heat transfer, U_l in Table 5.4 were calculated using equation (5.17). Values for h_l and h_2 were corrected for steam at 7 bars absolute.

(iii) Observation of a number of Stord driers in operation indicated that at startup, the initial internal temperature, T_{int} would normally be approximately 60°C and moisture content would be about 0.05 kg moisture/kg fat-free solids. This is the expected finishing value from the previous day.

(iv) The specific heat capacity value of solids, c_s and fat, c_{fat} were taken from Caddigan and Swan (1985).

Table 5.3

Effect of fat content on meal exit temperature (°C) at three moisture content endpoints. (Mean of eight results for each fat content). Data from Brown *et al.* (1988).

Moisture Content (% drybasis)	Low Fat (5%)	Medium Fat (20%)	High Fat (50%)
8	116.7	116.7	125.9
10	114.3	114.2	124.1
12	112.1	112.0	122.3

Table 5.4

Data for the performance of Stord dryers

Stord Bartz Rotodisc dryer model	TST 30	TST 60	TST 100
A. Stord Specifications			
Heating surface A_l (m^2)	121.0	202.0	410.0
Shell mass (kg)	21250.0	44000.0	82000.0
Load mass (kg)	3750.0	5870.0	12000.0
Steam pressure (bar abs)	7.0	7.0	7.0
Steam usage Q_d (kg/s)	0.35	0.58	1.18
Water evaporated W (kg/s)	0.27	0.45	0.91
B. Derived Data			
$k_g A$ (s/m)	0.0032	0.0054	0.011
Shell Htc. U_l (W/m^2K)	121.0	121.0	121.0
Dry solids feed F_d (kg/s)	0.27	0.45	0.91

(v) Because the dryer was divided into two compartments the following data were half the total for the dryer as a whole:

M_{st}	=	dryer steel mass (kg)
M	=	mass of dry solids in each dryer compartment (kg fat-free dry solids)
k_g	=	mass transfer coefficient (s/m)
A	=	surface area of material in the dryer (m^2)
A_l	=	Heating surface of dryer (m^2)

5.3.5.2 Iwell batch dryer

The Iwell batch drying system model is effectively identical to that for batch dry rendering other than expressing solids contents on a fat-free basis. There are three parameters which would be expected to be different to those used in the batch dry rendering process.

(1) a_w, this has already been discussed,

(2) U, the absence of fat would be expected to make U values lower, and

(3) k_gA, the absence of fat and the different a_w values may change k_gA.

Due to time constraints it was not possible to test all rendering system models, and the Iwell batch dryer was the one chosen to be omitted on the basis of the detailed testing of the batch dry rendering model. Thus no attempts were made to determine U and k_gA values. No data from which they could be determined was found in the literature so implementation of this model in the future will require experimental determination of U and k_gA values.

5.3.5.3 Rotary dryer

The data shown in Table 5.5 were stated by Langrish *et al.* (1990). As previously discussed, the proposed model for the rotary dryer is algebraic and describes steady state conditions. The model only predicts certain output conditions and does not attempt to predict any intermediate conditions. Data such as mass and heat transfer coefficients and heating surface areas are therefore not required.

Table 5.5

Data for the performance of a Flo Dry dryer from Langrish *et al.* (1990)

Diameter (m)	1.8
Length (m)	13.2
Dry gas flow (kg/s)	1.6
Inlet gas moisture content (kg water/kg dry gas)	0.112
Inlet gas temperature (°C)	800
Inlet moisture content (kg water/kg fat free solids)	0.112
Fat free solids feed F_d (kg/s)	0.37
Fat free solids inlet temperature (°C)	30
Fat free solids moisture content (kg water/kg fat free solids)	1.5

5.3.6 Model Implementation for the LTR

The mass and energy balances equations were incorporated into an advanced continuous system simulation language software package (Hay *et al.* 1988). Logical statements were included for changing variables such as feed flow rate in and product flow rate out as functions of time, for modulating temperature and for modulating mass of material in the cooker. An example programme listing for the continuous heating and rotary dryers is shown in Appendix B3 and B4.

5.3.7 Model Testing

Initial model tests taken were mathematical e.g. overall mass and energy balances on simulated behaviour. The model was run until steady state was achieved at which point mass and energy balances were carried out manually to mathematically validate the model.

5.3.7.1 Plant using Continuous Conduction Heating dryer

An attempt was made to collect data from a plant using this type of system. Although the plant had no means of steam flow rate recording, the only other major steam user was the hot water generation unit. Hot water flow rate through the generation unit was well metered and entry and exit water temperatures were available. It was hoped that if the coal usage was recorded and converted to gross thermal kW hot water, thermal energy requirements could be subtracted to give a clear indication of rendering steam usage.

This system relied on accurate knowledge of boiler thermal efficiency. The boiler was equipped with an O_2 meter but the lack of a back end thermometer to measure combustion flue gas temperatures meant that overall thermal efficiency checks could not be made. The thermal efficiency could be expected to alter 15% over the firing downturn range, and although the boiler generally had a good load factor, firing modulated frequently during the measurement period. A constant overall thermal efficiency had to be assumed, and this proved unsatisfactory.

Inspection of raw data showed the total rendering steam requirements ranged from a small part of the overall steam requirements to about 50%. This coupled with uncertainties in overall thermal efficiency meant that the measured steam flow rate data for rendering alone had a very large percentage error, and fluctuated wildly. This meant that a realistic comparison of the model results and measured data could not be made. It was therefore decided to carry out a comparison against previously published data.

Caddigan and Swan (1985) surveyed energy use for a Stord TST 30 continuous conduction heating dryer and within their report data which represent the overall average of a number of runs are reported. They recorded raw material feed rate details as follows: fat-free dry solids rate G = 0.255 kg/s, moisture content x_g =1.87 kg water/kg fat-free dry solids and fat content y_g = 1.48 kg fat/kg fat-free dry solids. The steam pressure was 6.5 bars absolute. The raw material temperature T_f reported was 10°C.

These data were input to the simulation, and changes made to the model to alter the makeup water flow rate prior to the reactor to simulate the use of tallow recycled at 93°C rather than water. Results of the simulation are shown in Figure 5.23 and 5.24.

Predictions for when stable conditions were reached are as follows:

(i) x = 0.354 kg water/kg fat free dry solids

x_q = 0.051 kg water/kg fat free dry solids

(ii) W = 0.165 kg/s

W_2 = 0.077 kg/s

W_t = 0.242 kg/s

(iii) Q_{dt} = 0.278 kg/s

Q_r = 0.131 kg/s

Q_t = 0.409 kg/s

(iv) T_{ini} = 108.7 °C

T_{2ini} = 136.4 °C

The predicted ratio between total dryer steam consumption and water evaporated within the dryer is 1.15. This is 13% lower than 1.3 specified by the manufacturers and 3% lower than the ratio of 1.18 reported by Caddigan and Swan (1985) which is considered more accurate. Their value corresponds to an efficiency of 94%. The heat loss from the outer shell of each compartment to ambient had been estimated as approximately 10 kW, and this allowance had been included in the model. Any inaccuracy would affect the steam to evaporation ratio.

Caddigan and Swan (1985) report a ratio of steam use for the reactor to the total steam used of about 35%. The reactor system they studied included some heating requirements for minor buffer tanks. The model predicted a ratio of 32% without including any allowance for heat losses from the ancillary tanks and the reactor vessel.

A total rendering system steam usage of about 0.4 tonne/tonne raw material was reported by Caddigan and Swan (1985). The model predicts a steady state condition usage of 0.37 tonne/tonne (8% less) for raw material of the same composition. The measurements of raw material composition reported by Caddigan and Swan (1985) were obtained by mass balance and may have contained some errors. Further, heat losses to ambient may be greater than allowed for, so the disagreement was not considered significant.

The predicted amount of moisture remaining in the meal emerging from the second compartment is within 0.9% of the actual content reported by Caddigan and Swan (1985).

The main disagreement with the results of Caddigan and Swan (1985) is that the predicted meal temperature emerging from the second compartment is much higher than their results. Brown *et al.* (1988) carried out laboratory trials and surveyed two Stord TST 30 continuous conduction heating dryers within actual rendering plants to establish relationships between endpoint moisture and temperature.

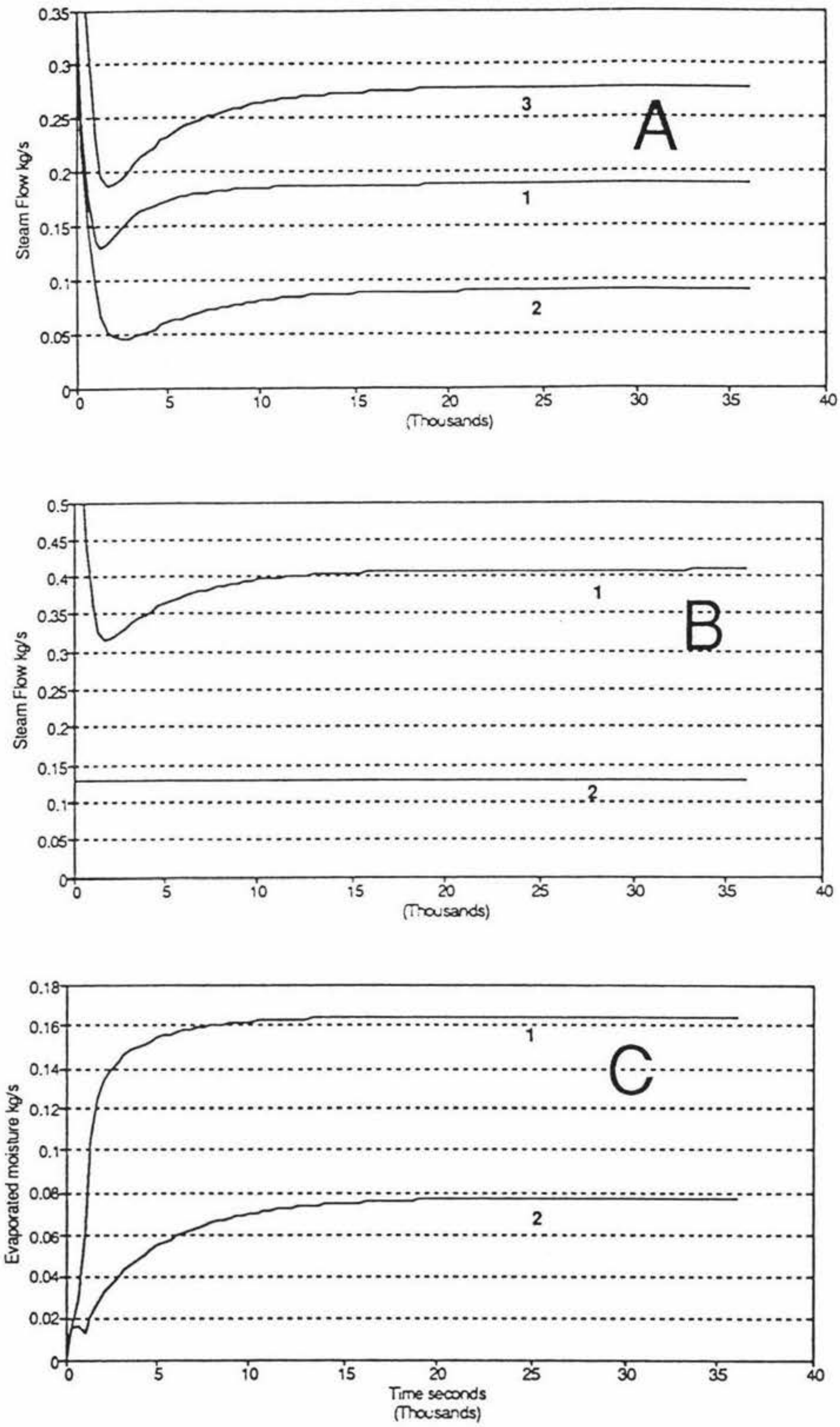


Figure 5.23 Plot of simulated results vs time for a LTR system using a continuous conduction heating dryer. A: Dryer steam consumption (kg/s); (1) indicates 1st dryer compartment Q_d, (2) 2nd compartment Q_{d2} and (3) total dryer Q_{dt}, B: Steam flow (kg/s); (1) indicates the total rendering Q_t, (2) indicates the reactor flow Q_r, C: Evaporated water (kg/s); (1) indicates 1st dryer compartment *W* and (2) 2nd dryer compartment *W2*.

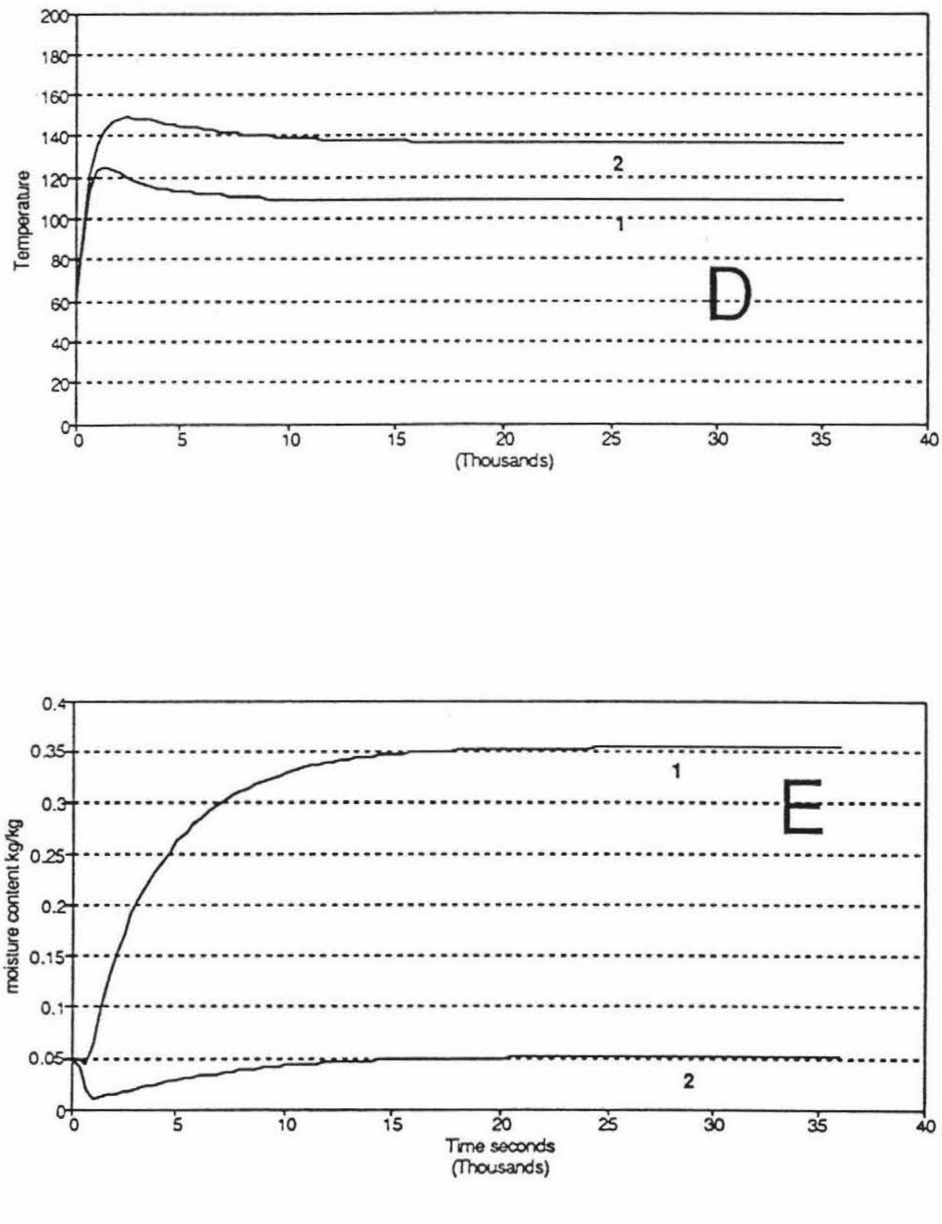


Figure 5.24 Plot of simulated results vs time for a LTR system using a continuous conduction heating dryer. D: Dryer meal temperatures (°C); (1) indicates the meal temperature within the 1st dryer compartment T_{int}, and (2) represents the meal temperature within the 2nd compartment T_{int2}, E: Moisture content of the meat meal (kg water/kg fat free dry solids); (1) indicates the moisture content in the 1st dryer compartment x, and (2) indicates the moisture content in the 2nd dryer compartment x_q.

Laboratory trials and results from one of the dryers surveyed indicate that the endpoint temperature associated with an endpoint moisture content of 6% may be nearer to 120°C than the 110°C found by Caddigan and Swan (1985). Nevertheless the model prediction is still too high. Because of the lack of better data the mean heat transfer coefficient for the dryer as a whole was used in each compartment. Investigation within Section 5.2 for batch dry rendering showed that heat transfer coefficients diminish with meal moisture content. The heat transfer coefficient might reasonably be expected to be lower in the second compartment than the first because of the lower meal moisture content. If a higher U values was used in the first compartment, and a lower U value in the second this would have the effect of lowering the predicted meat meal temperature within the second compartment. No measured data for the temperature early in the dryer were available to check the first compartment meal temperature. The amount of heat to raise the outlet meal from 110°C to 136°C is only 8.6 kW, which is small in comparison to the energy used for evaporation, so the lack of fit of meal temperature is not a good indication of the difference in energy flows which is in fact quite small.

5.3.7.2 Iwell batch dryer

As has been stated time constraints prevented this model being tested. Its similarity to the batch dry rendering model, and the successful testing of the latter, suggest that there is no reason to expect poor predictions.

5.3.7.3 Rotary dryer

The results of Langrish *et al.* (1990) were used to verify the model. The measured and predicted results are summarised in Table 5.6. In their work the fat-free solids feed rate and moisture content of the feed were not stated so it was assumed that the values of Table 5.5 applied. That is, the fat-free solids feed rate was 0.37 kg/s, the moisture content was 1.5 kg water/kg fat-free dry solids, and the ratio between fat-free solids and the inlet dry gas was 1.6. Predicted results from the model are in close agreement with the data of Langrish *et al.* (1990).

5.3.8 Discussion and Conclusion

This section focuses on whether the models projected in Section 5.3.2 are a sufficiently accurate predictors of energy use by low temperature rendering systems to be adopted into the overall meat plant energy model. For the system using the continuous conduction heating dryer the unsatisfactory measured plant data meant that a comparison between model predictions and measured data could not be carried out. The model predictions generally agree well with the averaged data of Caddigan and Swan (1985). The major weaknesses within the prediction system appear to lie more with the quality of data than the assumptions made in model derivation. In particular, there is uncertainty over the heat transfer coefficients and product water activity which can only be overcome by more experimental work. The overall function of the model is to predict energy usage required for the process to within about $\pm 10\%$, and in this respect the model of the system incorporating the continuous conduction heating dryer appears to be adequate for adoption in the overall meat plant energy model.

The model for the system incorporating a Iwell batch dyer was not tested, but it is expected to be accurate due to its similarity to the successful batch dry rendering model. Experimental work to estimate heat transfer coefficients and k_gA values is required.

The model incorporating the rotary dryer is very simple, and predicted measured data accurately. It was therefore adopted for the meat plant energy model.

Table 5.6

Comparison of predicted results with measured data from Langrish *et al.* (1990)

	Langrish *et al.* (1990)	Predicted results
Energy requirement (MW)	Not available	2.56
I(kg/kg)	0.42	0.44
T_{po} (°C)	116	113

6.0 HOT WATER SYSTEMS

6.1 HOT WATER USAGE

6.1.1 Mechanistic Description

Hot and warm water are used for a variety of purposes in the meat industry. The water use may be conveniently divided into three streams on the basis of temperatures: sterilising and hosing, hand and apron washes, and carcass washes. Ministry of Agriculture (MAF) regulations define sterilising water as water at a temperature of not less than 82°C, recommend hand wash water at 38°C to 44°C and have no recommendations for carcass wash water temperature whatsoever. Hot water at 82°C is used for knife and hand tool sterilising, and is also commonly used for production department cleanups. At this temperature, and in conjunction with detergents and sanitisers the hot water breaks down fat on surfaces that have been in contact with meat and also provides an environment in which pathogenic bacteria cannot survive. Comprehensive cleanups are carried out at the end of the day when production has ceased and likewise the next morning a light cleanup is sometimes carried out. The specific methods used for the cleanup will vary from plant to plant depending on the hygiene regime and actual surfaces being cleaned.

Warm water, typically at 43°C, is used for hand and apron washes during production, and showers for workers after production has ceased. Some offal product such as headmeat and tongues may be washed in warm water and it is sometimes also used to assist in moving product in chutes from one position to another.

MAF require that the water is reticulated in so-called ring mains which ensure that water is continuously being circulated out to the production departments, back to a storage tank and then reheated if necessary before being passed out to the production departments again. Because the distance between the ring main take off point and the point of use is usually short, this ensures that the water is at the required minimum temperature at the point of use. The use of a ring main also minimises the possibility of mesophilic bacteria proliferation so that conditions that lead to the presence of legionnaires disease are unlikely to arise within the pipework system. However the use of ring mains mean that long runs of pipe are common within the New Zealand meat industry and heat loss can be considerable if pipe insulation is incomplete or if insulation breakdown occurs.

6.1.2 Design Philosophy

The model for hot water usage should be able to accurately predict usage against time with minimum mathematical complexity and minimum requirements for data input by the user. The purpose of the model is to assist the user in determining the minimum usage rates possible when designing a plant or evaluating current flows. Therefore the actual flows built into the model should reflect "good practice" washing and sterilising equipment and good water management.

The selection of the number of production departments to be individually modelled should be kept to a minimum yet should still preserve accuracy. To this end it is proposed that the production departments are grouped as follows:

(1) Beef kill including:

- slaughter chain, (sterilisers, cleanup, apron and hand wash, carcass wash)
- chillers, (hosing walls, floors)
- edible offal, (sterilisers, daily cleanups)
- hides, (daily cleanups).

(ii) Beef boning and trimming/cutting (sterilisers, daily cleanups).

(iii) Lamb kill including:

- slaughter chains, (sterilisers, cleanup, apron and hand wash, carcass wash)
- cooling floor, (daily cleanups)

- edible offal, (sterilisers, daily cleanups)
- casings, (daily cleanups)
- fellmongery, (daily cleanups)
- pelts, (daily cleanups).

(iv) Lamb boning and cutting/trimming, (sterilisers, daily cleanups).

(v) Rendering, blood and effluent, (daily cleanups).

Any hot water used during the receiving of outside material or effluent disposal can be included in the rendering usage.

There are three distinct modes of water usage within departments which occur during and outside production runs. These are:

(1) production usage,

(2) complete shutdown during tea break and lunch breaks, and

(3) end of day cleanups and showers.

In the design of the model it was desirable to incorporate means which would allow departmental usage of both hot and warm water to switch from one mode to another easily as simulation progressed through the day.

The resulting model configuration is shown in Figures 6.1, 6.2 and 6.3. The philosophy adopted was to determine starting and stopping times for each flow, and to assume that the flow was constant between these times. This meant that the model was entirely algebraic.

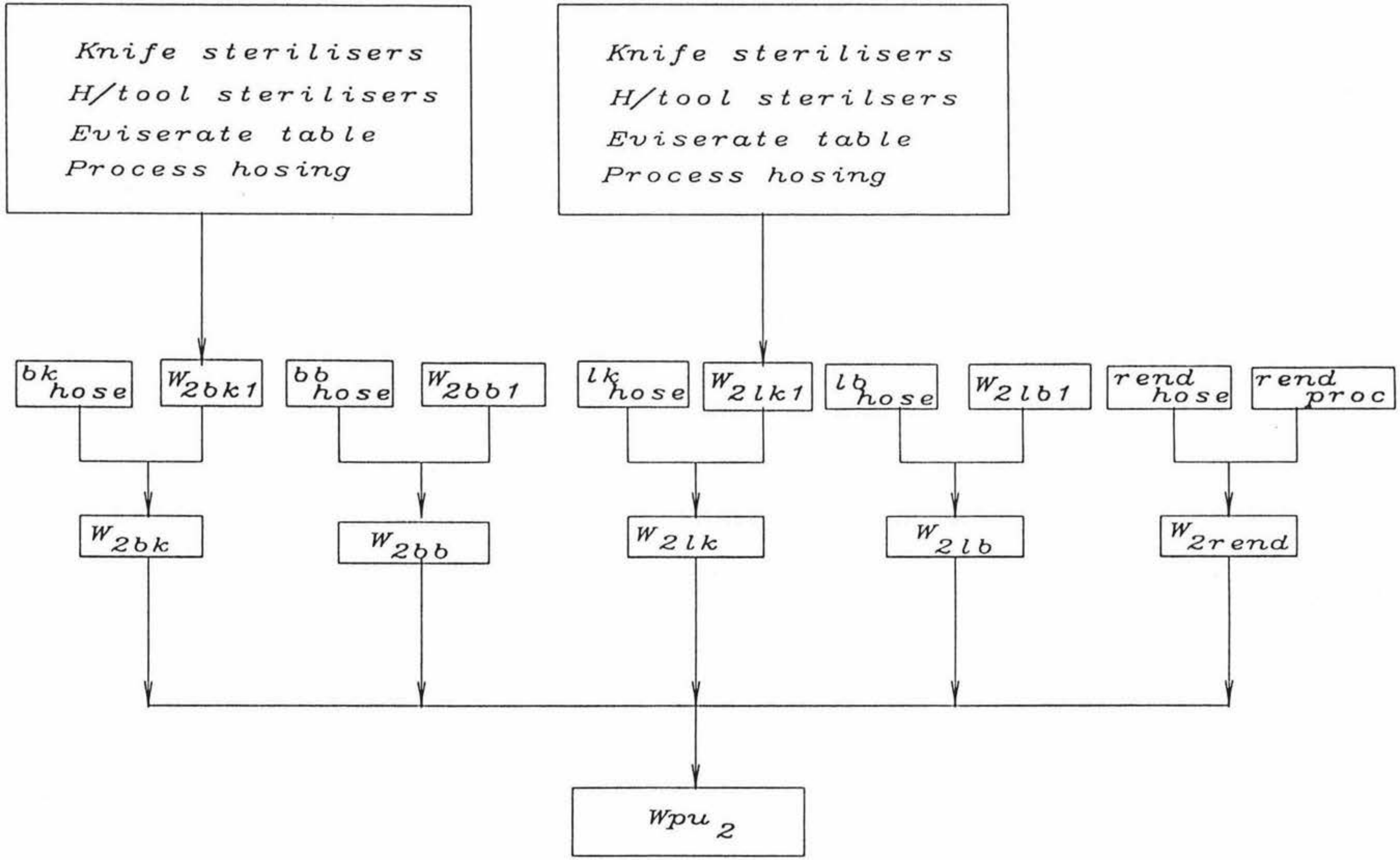


Figure 6.1 Schematic diagram of steriliser and hosing flows

6.1.3 Model Development

6.1.3.1 Sterilisers and hosing (Figure 6.1)

The total demand (at flow rate Wpu_2) consists of that used for hosing before and after production, and that used during production, by equipment such as sterilisers for knives, hand tools, eviscerate tables or gut buggies and rotary washers where present.

To maintain simplicity of operation the model was structured so that the steriliser and cleanup hosing water flow to each department is either in a steriliser mode to represent normal production, switched off during breaks or a cleanup hosing mode after production has ceased as discussed in Section 6.1.2. The steriliser and hosing flow is switched off after cleanup hosing has ceased. This structure introduces several anomalies.

(i) There will be a short period towards the end of the morning cleanup where overflow type sterilisers are on at the same time as the hoses. This will mean that both flows operate together in practice, but as this should only be for 600 seconds or less the effect can be neglected.

(ii) Some processes within departments such as chillers, hides, casings, fellmongery, rendering and blood require intermittent hosing and washing during normal production runs. Modelling of every single usage period would require a great deal of effort in relation to the size of the water flows involved. Further the flows will occur at different times on different days. Flows of this nature were therefore not modelled in detail, but rather represented by a mean flow rate over the full production period. The model could not, therefore, be used in its present form to model departmental peak flows unless the user input values which represented those present at peak times.

6.1.3.2 Mass balances for sterilisers and hosing

A mass balance for the steriliser and hosing flow across a plant may be described as:

$$Wpu_2 = W_{2bk} + W_{2bb} + W_{2lk} + W_{2lb} + W_{2rend} \tag{6.1}$$

where Wpu_2 = total plant steriliser and hosing flow rate (kg/s)

W_{2bk} = total grouped beef kill steriliser and hosing flow rate (kg/s)

W_{2bb} = total grouped beef boning steriliser and hosing flow rate (kg/s)

W_{2lk} = total grouped lamb kill steriliser and hosing flow rate (kg/s)

W_{2lb} = total grouped lamb boning steriliser and hosing flow rate (kg/s)

W_{2rend} = total grouped rendering hosing and processing flow rate (kg/s)

A mass balance for the sterilising and hosing flow within the beef kill group is:

$$W_{2bk} = W_{2bkl} + bk_{hose} \tag{6.2}$$

$$W_{2bkl} = bk_{wr} + bk_{dho} + bk_{dhi} + bk_{hk} + bk_{e} + bk_{bs} + bk_{ss} + bk_{et} + bk_{gb} + bk_{hh} + bk_{t} + bk_{wash} + bk_{ks} N_{bk} + bkp_{hose} \tag{6.3}$$

where W_{2bkl} = total grouped beef kill steriliser flow rate (kg/s)

bk_{hose} = total grouped beef kill cleanup hose flow rate (kg/s)

bk_{wr} = weasand steriliser flow rate (kg/s)

bk_{dho} = dehorner steriliser flow rate (kg/s)

bk_{dhi} = total dehider steriliser flow rate (kg/s)

bk_{hk} = total hockcutter steriliser flow rate (kg/s)

bk_{e} = elastorator steriliser flow rate (kg/s)

bk_{bs} = brisket saw steriliser flow rate (kg/s)

bk_{ss} = side saw steriliser flow rate (kg/s)

bk_{et} = eviscerate table flow rate (kg/s)

bk_{gb} = gut buggy steriliser flow rate (kg/s)

bk_{hh} = head hook steriliser flow rate (kg/s)

bk_t = trolley steriliser flow rate (kg/s)

bk_{wash} = rotary washers etc, (if any) flow rate (kg/s)

bk_{ks} = mean group knife steriliser flow rate (kg/s)

N_{bk} = number of knife sterilisers within the beef house

bkp_{hose} = total grouped beef kill production hose flow rate (kg/s)

A mass balance for sterilising and hosing flow within the beef boning group is:

$$W_{2bb} = W_{2bbl} + bb_{hose} \tag{6.4}$$

$$W_{2bbl} = bb_{ks} N_{bb} \tag{6.5}$$

where W_{2bbl} = total grouped beef boning steriliser flow rate (kg/s)

bb_{hose} = total grouped beef boning cleanup hose flow rate (kg/s)

bb_{ks} = mean beef boning group knife steriliser flow rate (kg/s)

N_{bb} = number of knife sterilisers within the boning room

A mass balance for the sterilising and hosing flow within the lamb kill group is:

$$W_{2lk} = W_{2lkl} + lk_{hose} \tag{6.6}$$

$$\begin{aligned} W_{2lkl} = \; & lk_{wr} + lk_{rhc} + lk_{nb} + lk_{nr} + lk_{dp} + lk_{bd} + lk_{fhc} + lk_{bc} + lk_{e} + \\ & lk_{et} + lk_{wash} + lk_{ks} N_{lk} + lkp_{hose} \end{aligned} \tag{6.7}$$

where W_{2lkl} = total grouped lamb kill steriliser flow rate (kg/s)

lk_{hose} = total grouped lamb kill cleanup hose flow rate (kg/s)

lk_{wr} = lamb weasand rod steriliser flow rate (kg/s)

lk_{rhc} = rear hock cutter steriliser flow rate (kg/s)

lk_{nb} = neck breaker steriliser flow rate(kg/s)

lk_{nr} = nose roller steriliser flow rate (kg/s)

lk_{dp} = total depelter steriliser flow rate (kg/s)

lk_{bd} = brisket drill steriliser flow rate (kg/s)

lk_{fhc}	=	fore leg hock cutter steriliser flow rate (kg/s)
lk_{bc}	=	brisket cutter steriliser flow rate (kg/s)
lk_{e}	=	eviscerator steriliser flow rate (kg/s)
lk_{et}	=	eviscerate table steriliser flow rate (kg/s)
lk_{wash}	=	rotary washers etc (if any) flow rate (kg/s)
lk_{ks}	=	mean lamb kill knife steriliser flow rate (kg/s)
N_{lk}	=	number of knife sterilisers within the lamb kill
lkp_{hose}	=	total grouped lamb kill production hose flow rate (kg/s)

A mass balance for the sterilising and hosing flow within the lamb boning group is:

$$W_{2lb} = W_{2lbl} + lb_{hose} \tag{6.8}$$

$$W_{2lbl} = lb_{ks} N_{lb} \tag{6.9}$$

where W_{2lbl}	=	total grouped lamb boning steriliser flow rate (kg/s)
lb_{hose}	=	total grouped lamb boning cleanup hosing consumption (kg/s)
lb_{ks}	=	mean lamb boning knife steriliser flow rate (kg/s)
N_{lb}	=	number of knife sterilisers within lamb boning

A mass balance for hosing and process water flow within the rendering group is:

$$W_{2rend} = rend_{hose} + rend_{proc} \tag{6.10}$$

where $rend_{hose}$	=	total rendering hose flow rate (kg/s)
$rend_{proc}$	=	total rendering process flow rate (kg/s)

Hot water is used in low temperature rendering prior to the reactor. This is conveniently included in $rend_{proc}$.

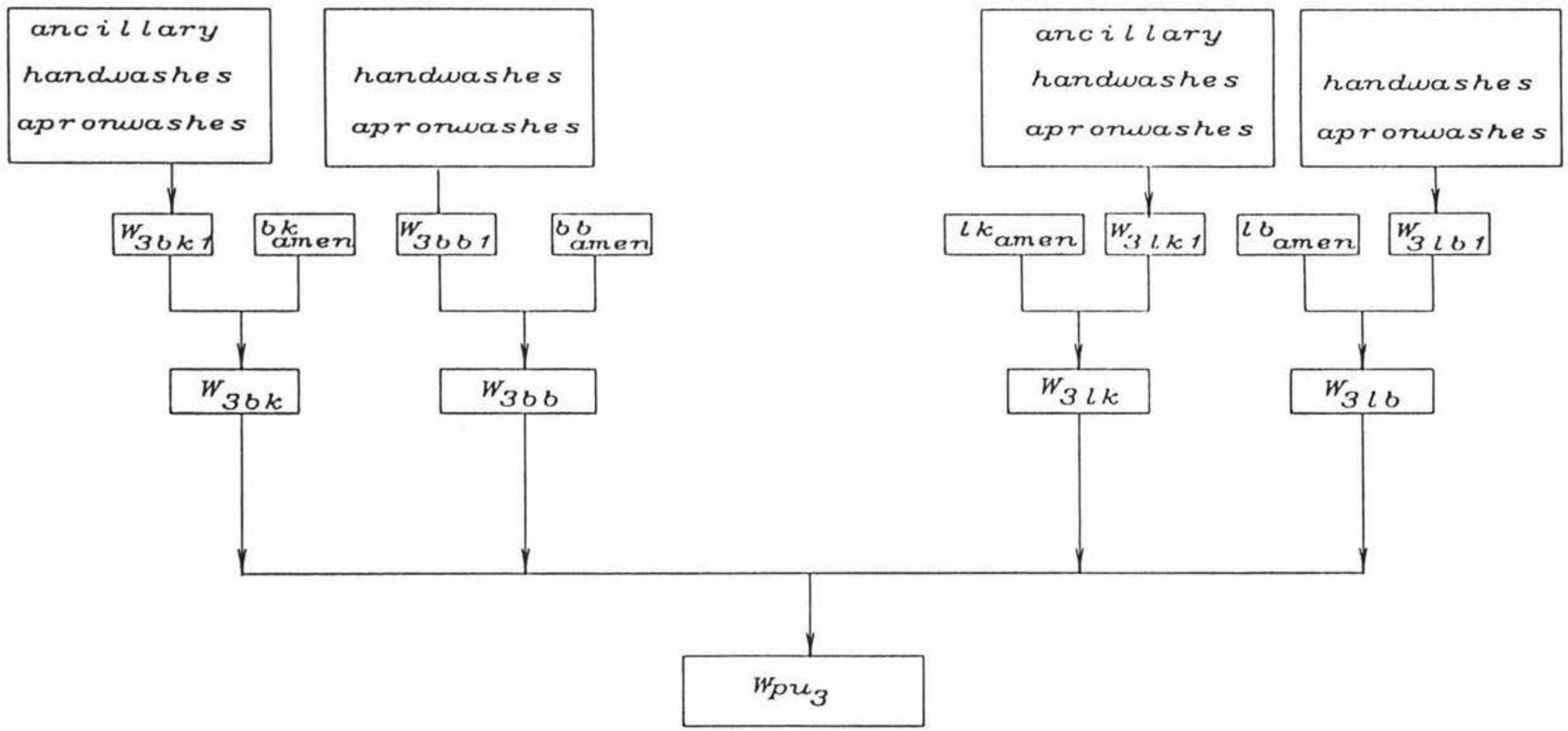


Figure 6.2 Schematic diagram of hand, apron and shower flows

6.1.3.3 Hand, apron wash and showers (Figure 6.2)

The total plant hand, apron wash and shower water flow Wpu_3 is divided up into departmental groups as discussed in Section 6.1.2.

As mentioned in Section 6.1.1 there are some ancillary user devices such as product washes and chute water. The use of warm water for these purposes is not recommended, but, because it is common practice provision should be made for their inclusion in the model. Ancillary user devices should only occur in the beef and lamb kill areas. The number of ancillary user devices will be small so they will be summed before inclusion into the two departmental mass balances. The warm water flow within the rendering group is so small it may be neglected.

As discussed earlier, to maintain simplicity of operation the model was structured so that the hand, apron wash and shower water flow to each department may be switched through three separate flow modes as follows:

(1) during normal production (through hand and apron washes)
(2) a nil flow at tea breaks
(3) at the end of production the use of showers and further washbasins as the butchers clean up prior to going home.

6.1.3.4 Mass balances for hand, apron wash and showers

A mass balance for the plant hand, apron wash and shower flow is described by:

$$Wpu_3 = W_{3bk} + W_{3bb} + W_{3lk} + W_{3lb} \tag{6.11}$$

where Wpu_3 = total plant hand, apron wash and shower water flow rate (kg/s)

W_{3bk} = total grouped beef kill hand, apron wash and shower flow rate (kg/s)

W_{3bb} = total grouped beef boning hand, apron wash and shower flow rate (kg/s)

W_{3lk} = total grouped lamb kill hand, apron wash and shower flow rate (kg/s)

W_{3lb} = total grouped lamb boning hand, apron wash and shower flow rate (kg/s)

A mass balance for the hand, apron wash and shower flow within the beef kill group is:

$$W_{3bk} = W_{3bkl} + bk_{amen} \tag{6.12}$$

$$W_{3bkl} = bk_{hand} N_{bkh} + bk_{apron} N_{bka} + bk_{anc} \tag{6.13}$$

where W_{3bkl} = total beef kill grouped hand and apron wash flow rate (kg/s)

bk_{hand} = mean beef kill hand wash flow rate (kg/s)

N_{bkh} = number of hand washes within the beef house

bk_{apron} = mean beef kill apron wash flow rate (kg/s)

N_{bka} = number of apron washes within the beef house

bk_{anc} = total beef kill ancillaries flow rate (kg/s)

bk_{amen} = total grouped beef kill shower flow rate (kg/s)

A mass balance for the hand, apron wash and shower flow within the beef boning room group is:

$$W_{3bb} = W_{3bbl} + bb_{amen} \tag{6.14}$$

$$W_{3bbl} = bb_{hand} N_{bbh} + bb_{apron} N_{bba} \tag{6.15}$$

where W_{3bbl} = total grouped beef boning hand and apron wash flow rate (kg/s)

bb_{hand} = mean beef boning hand wash flow rate (kg/s)

N_{bbh} = number of hand washes within the beef boning

bb_{apron}	=	mean beef boning apron wash flow rate (kg/s)
N_{bba}	=	number of apron washes within the beef boning
bb_{amen}	=	total grouped beef boning shower flow rate (kg/s)

A mass balance for the hand, apron wash and shower flow within the lamb chain group is:

$$W_{3lk} = W_{3lkl} + lk_{amen} \tag{6.16}$$

$$W_{3lk} = lk_{hand} N_{lkh} + lk_{apron} N_{lka} + lk_{anc} \tag{6.17}$$

where W_{3lkl}	=	total grouped lamb kill hand and apron wash flow rate (kg/s)
lk_{amen}	=	total grouped lamb kill shower flow rate (kg/s)
lk_{hand}	=	mean lamb kill hand wash flow rate (kg/s)
N_{lkh}	=	number of hand washes within the lamb kill
lk_{apron}	=	mean lamb kill apron wash flow rate (kg/s)
N_{lka}	=	number of apron washes within the lamb kill
lk_{anc}	=	total lamb kill ancillaries flow rate (kg/s)

A mass balance for the hand, apron wash and shower flow rate within the lamb boning group is:

$$W_{3lb} = W_{3lbl} + lb_{amen} \tag{6.18}$$

$$W_{3lb} = lb_{hand} N_{lbh} + lb_{apron} N_{lba} + lb_{amen} N_{lba} \tag{6.19}$$

where W_{3lbl}	=	total grouped lamb boning hand and apron wash flow rate (kg/s)
lb_{amen}	=	total grouped lamb boning shower flow rate (kg/s)

lb_{hand}	=	mean lamb boning hand wash flow rate (kg/s)
N_{lbh}	=	number of hand washes within the lamb boning
lb_{apron}	=	mean apron wash flow rate (kg/s)
N_{lba}	=	number of apron washes within the lamb boning

6.1.3.5 Carcass wash (Figure 6.3)

The beef and lamb kill areas will be the only departments which will use this flow system. This flow only operates during production runs and should be actuated on and off by sensor so as to conserve water.

A mass balance for the carcass wash flow across a total plant is:

$$Wpu_4 = W_{4bk} + W_{4lk} \tag{6.20}$$

where W_{4bk} = beef kill carcass wash consumption rate (kg/s)

W_{4lk} = lamb kill carcass wash consumption rate (kg/s)

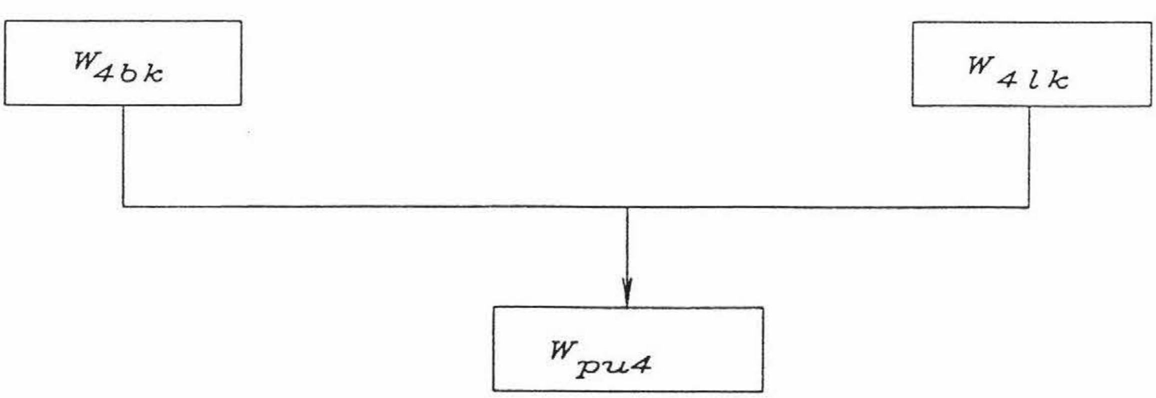


Figure 6.3 Schematic diagram illustrating carcass wash flows

6.1.4 Energy Balances

Any heat losses in the ring main system will be accounted for in the hot water generation and storage model which is described in Section 6.2. Energy balances are thus not required within the hot water use model. Refrigeration heat load generated by cleanup hot hoses will be dealt with Section 7.

6.1.5 Data Required to Use the Model

To use the model as proposed there are substantial data requirements; specifically the water flows for each of the various operations. These will vary widely from plant to plant, but the philosophy used in determining data was to seek "good practice" values. Initially these were sought from published data, but it was found necessary to augment these data by measured data collected at a modern plant. A beef-only plant designed for two shifts was selected. The plant had been constructed less than twelve months before and was representative of at least three other plants which were in the process of being built. Care had been taken to use modern designs and so the consumption of hot and warm water should reflect "good practice", although this was not guaranteed for any particular water user.

There are two basic philosophies used in designing water using devices. The modern trend is intermittent flow devices, but where usage is very frequent continuous flow can be justified. The general model form was:

$$D_{flow} = D_{inst}\, t_a\, Op_{rate} \tag{6.21}$$

where D_{flow} = mean device flow rate (kg/hr)

D_{inst} = instantaneous device flow rate (kg/s)

t_a = mean activation time (s)

Op_{rate} = frequency of use (operations per hour)

However if the product (t_a Op_{rate}) $\geq$ 3600s then D_{flow} = D_{inst} and the unit operates continuously. One complication (which will be illustrated in Section 6.1.5.1) is that once a move is made to continuous operation a change in technology may occur and the value of D_{inst} for the continuous operation may be different to that for an intermittent device. Thus to define "good practice" water usage rates for an operation the following data are required:

Intermittent	-	good practice D_{inst}
	-	good practice t_a
Continuous	-	good practice D_{inst} (t_a = 3600s, Op_{rate} = 1 hr^{-1})

The actual data input to the model in the case of intermittent use devices can be the product (D_{inst} t_a), so the model user need only specify frequency of use. Values of Op_{rate} will be determined from the nature of the operation and ultimately will be determined from the generic model of Section 4.

Within the model, irrespective of whether the device is continuous or intermittent the resulting D_{flow} was treated as a continuous flow during the full production period. This was because time steps to simulate each device actuation would have made the model unreasonably complicated, and because the summations of a number of intermittent users would closely resemble a smooth continuous profile.

Whilst this approach was considered valid for regular operations it may be inappropriate for less regular ones. The use of hoses during production is particularly difficult in this respect. Nevertheless in the interests of simplicity equation (6.21) was also applied for less regular operations using typical values for t_a and Op_{rate}, to arrive at values for D_{flow}.

At the plant where measurements were taken by the author, values of t_a were measured directly by bucket and stopwatch. The activation time, t_a had been recommended by the equipment manufacturers as 7s in most instances (although there was one major exception). The operational frequency (Op_{rate}) was equal to the chain speed in most beef kill area water use operations, other than the detain rail, where Op_{rate} was arbitrarily set to (0.16 * chain speed) to represent a mean of about 1 in 6 bodies going there. The beef boning room operational frequency was twice the beef kill chain speed because sides were handled there rather than carcasses.

Where published data for water use exists, meaningful comparisons can only be made if all data can be expressed on the same basis. The best basis is to consider values of D_{inst} and t_a for intermittent use devices, and values of D_{flow} for continuous operation devices.

6.1.5.1 "Good Practice" flow rates for knife sterilisers

Knife steriliser flows vary widely depending on the design and management practice. Some typical types are:

(a) single skin overflow type (continuous)
(b) double skin overflow type (continuous)
(c) spray type foot control (intermittent)
(d) spray type sensor control (intermittent)

Measured flows recorded by Peacham (1993) for three of these types are tabulated in Table 6.1. Cornelius and Cleland (1990) report usages for overflow sterilisers ranging from 30 to 150 kg/hr in one plant and averaging 48 kg/hr in another. Pearson (1981) found that usage rates as low as 30 kg/hr were possible with the ring main temperature (Tpu_2) as high as 93°C. While this has been confirmed as possible by Shaw (1992) temperatures as high as this are still not common within the NZ Meat Industry.

On the plant at which the author collected data there are two basic designs of knife steriliser fitted. The first, the so-called apron wash steriliser, is mounted on the side of the apron wash and is activated by the same sensor as the apron wash. The second type is the so-called hand wash steriliser, and is an integral part of the hand wash device, which again, is triggered by the sensor which controls the flow to the hand wash unit. Both types are shown in Figure 6.4 and measured flows for each are shown in Table 6.2. Table 6.3 gives measured flows for sterilisers in the beef boning room.

Table 6.1

Knife steriliser flows (D_{inst}) measured at three plants by Peacham (1993)

Type	Operation	Range of D_{inst} (kg/s)	Mean D_{inst} (kg/s)
Double skin	Continuous	0.010 - 0.052	0.027
Ring Spray	Foot Op.	0.10 - 0.30	0.25
Rose	Sensor	N/A	0.05

Table 6.2

Knife steriliser flows measured by the author in the beef kill area of the test plant

Beef kill area	Number	D_{inst} (kg/s)	D_{flow} (kg/hr)	Total (kg/hr)
Apron wash type	18	0.076	16.6	300
Hand wash type	4	0.266	58.2	232

Table 6.3

Beef boning room steriliser flows measured by the author

Boning/Trimming	Number	D_{inst} (kg/s)	D_{flow} (kg/hr)	Total(kg/hr)
Apron wash type	4	0.076	16.6	133
Scribe saw	1	0.210	66.0	66

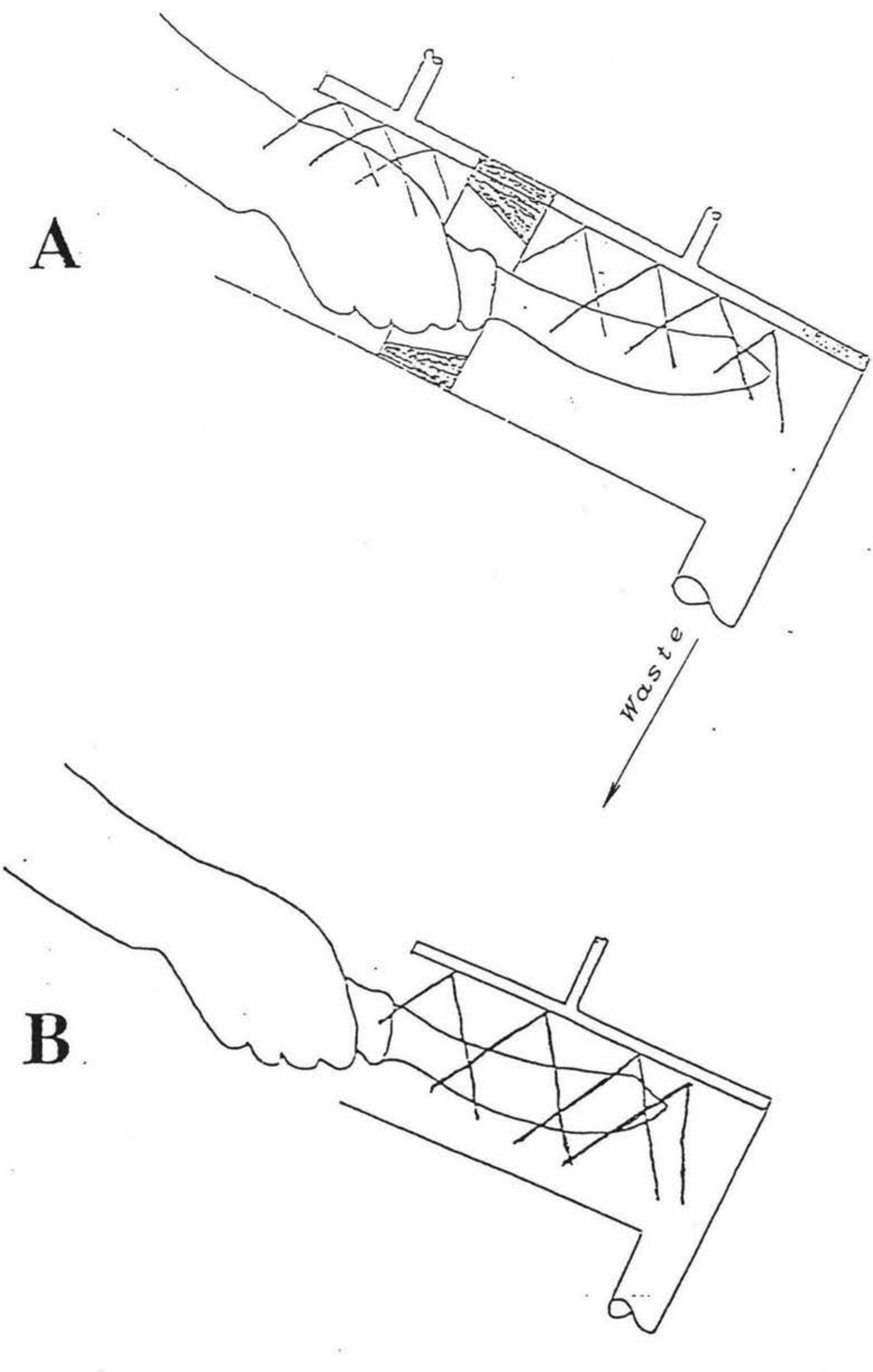


Figure 6.4 Sectioned view of A: Hand wash steriliser and B: Apron wash steriliser

While the double skin continuous type of Table 6.1 apparently compares unfavourably with the apron wash knife steriliser of Table 6.2 it should be noted that the 7s activation time measured by the author at a modern beef plant would normally be entirely unsuitable for a lamb kill where a butcher must sterilise his knife and complete a dressing operation all within about 6s.

The foot operation required to operate a spray steriliser and the length of time needed to bring the water in the drop pipe to the steriliser from the ring main up to the required temperature means that the spray type of knife steriliser is currently unsuitable for high frequency of use. The continuous type is probably the only design which provides water at a constant temperature greater than 82°C and allows sterilisation in 2 seconds.

The steriliser design fitted at the beef-only plant measured by the author has a ring main which runs right to the steriliser, thus providing instant hot water and negating one of the objections which originally precluded the use of the spray type in lamb kill operations.

Activation by automatic sensor means that the butcher is not required to manually operate the spray steriliser. Provided the instantaneous flow rate and activation time were decreased by better equipment design this type could possibly be used successfully in lamb kill operations with a flow rate less than that of the continuous overflow type.

In the opinion of the present author, based on industry observations, the instantaneous flow rate in a good quality spray steriliser is about 0.076 kg/sec (270 kg/hr). A good quality overflow steriliser operates at 0.0083 kg/sec (30 kg/hr). Therefore, if a spray steriliser operates for more than 400 seconds per hour an overflow steriliser is more economic. On the plant measured by the author there were 31.25 activations per hour, each of 7s duration, or 219 seconds per hour in total so a spray steriliser is the preferred choice. However on a lamb kill chain with the possibility of about 500 activations per hour the activation time for each operation must be very short for a spray steriliser to be preferred and no present equipment achieves this.

"Good practice" values were defined as:

Intermittent:	D_{inst}	=	0.076 kg/s
	t_a	=	7 s
Continuous:	D_{inst}	=	0.0083 kg/s
			(t_a = 3600 s, Op_{rate} = 1 hr^{-1})
	D_{flow}	=	30 kg/hour

Inspection of Table 6.2 suggests that the combined hand wash steriliser could benefit from further design, eg. the sparge pipe holes possibly need reducing in diameter. With suitable improvements the above "good practice" flows should be achievable in this device.

6.1.5.2 "Good Practice" flow rates for hand tool sterilisers

Such sterilisers are mainly found within the beef and lamb kill areas, and flows measured by the author are listed in Table 6.4. Table 6.3 contains some data for hand tool sterilisation in the beef boning room. No published data were found.

As well as requiring that hand tools are adequately sterilised, MAF also expect:

(i) Visual cleanliness of the sterilised hand tool which is used as an indicator that the tool had been sterilised.

(ii) Prevention of back splash from the steriliser through the entry aperture.

(iii) Waste water ducted in an enclosed wastepipe to the floor drain.

Table 6.4

Data measured by the author for beef kill area hand tool sterilisers and hoses.

Beef kill area Description	No	D_{inst} (kg/s)	D_{flow} (kg/hr)	Comment
Weasand rod	1	0.25	55	Adequate
Dehorner	0	N/A	N/A	N/A
Dehiders	**	N/A	N/A	N/A
Hockcutter	3	0.25	55*3	Adequate
Elastorator	1	0.25	55	Adequate
Brisket saw	1	0.32	70	Fair
Side saw	1	1.00	563	Poor
Eviscerate table	1	3.00	1690	Poor
Gut buggies	0	N/A	N/A	N/A
Head hooks	1	0.050	180	Poor
Trolleys	0	N/A	N/A	N/A
Scribe saw	1	0.25	8.75	Adequate
Inedible hose	1	0.66	800	Good
Rotary washes	0	N/A	N/A	N/A

* * The dehiders are sterilised in the wash basin/knife sterilisers on this plant.

A sheetmetal worker normally constructs the hand tool sterilisers to the above requirements with little thought given to water consumption. The hot water is usually directed onto the tool within the steriliser through a sparge pipe which tends to follow the longitudinal axis of the tool on either side. The sparge pipe has a series of small diameter holes drilled into it through which the water cascades over the tool. The water flow is expected to remove hair, fat and small pieces of meat as well as providing a sterilising effect over a fairly large surface area. Because sparge pipes with drilled holes are used rather than properly designed spray nozzles there is a tendency to rely on high volumetric flow rather than increased nozzle velocity (and therefore increased kinetic energy to assist in flushing away pieces of waste material.) This has resulted in disproportionate amounts of hot water being used and indicates a real design need whilst still carrying out sterilisation to MAF satisfaction. The lowest D_{inst} recorded in the beef kill area was 0.25 kg/s and in the beef boning room was 0.21 kg/s. Usage rates over all the plant, at least as low as the latter, should be possible.

Overflow or continuous flow sterilisers are generally impractical for hand tools because of the greater mass to be sterilised which would result in a large displacement of the heated water and the subsequent replacement flow would result in a greater consumption. The displaced water would also tend to spill out onto the work area raising concerns from the MAF. Foreign bodies as discussed earlier would transfer to the heated volume of water and quickly form a "soup" which would be unacceptable.

Head chain hook sterilisers are an exception to this rule because the hook is approximately the same size as a knife and has no more contamination on it than a knife would have. Because the head hook is travelling along on a chain as it is sterilised, the steriliser must by necessity be at least a metre in length. It must also be wide enough to allow occasional hand cleaning and be deep enough to accommodate the hook, (about 200mm). The steriliser on the measured plant, is single skinned and the heat losses from both the open top and the skin surface are considerable. The measured head hook steriliser flow rate (D_{flow}) was 180 kg/hr which is considered excessive when compared with an overflow type knife steriliser flow rate of 30 kg/hr. There is no reason why a properly designed steriliser could not cut the consumption down considerably.

Eviscerate tables pose special problems with long fibrous or "stringy" pieces of trim becoming lodged between the table slats when they are spread round the end sprocket at the feed-off end of the table. The only opportunity to dislodge this trim is at the ends of the table and so considerable effort is concentrated at these points. This effort is usually in the form of water which is sometimes hot. Considerable ingenuity is required in the placement of the spray nozzles or sparge pipes to find a correct "angle of attack" which will ensure removal of the trim. MAF personnel use the presence of trim as an indication of whether adequate sterilisation has taken place.

It is essential to separate efforts to sterilise from efforts to dislodge macro pieces of trim and ingesta if hot water consumption rates are to be reduced to a minimum. Efforts to remove ingesta and trim should be at the feed-off end of the table utilising cold water, possibly boosting the water pressure at this point considerably. A two stage centrifugal pump could develop sufficient pressure. Sterilisation can be carried out under the table or at the feed-on end and should only be concerned with raising the table slat temperature sufficiently to destroy pathogenic bacteria. The spray configuration at the measured plant was unsophisticated resulting in a very high measured flow rate (D_{inst}) of 3.0 kg/s. Activation time (t_a = 18 s) was also very long.

Similarly the measured side saw steriliser flow rate (D_{inst} = 1.00 kg/s) was considered high thus failing to achieve a "good practice" standard.

Due to the lack of published data, only the flows presented in Table 6.3 and 6.4 were considered in an attempt to define "good practice" flows. The best that can be said about the lowest flow recorded, (D_{inst} = 0.21 kg/s), is that the steriliser produces a hand tool which is adequately clean when operated. Further work is required to investigate whether lower flows, better directed onto the tool can produce a result which is satisfactory to the MAF and thus can be adopted as "good practice".

The activation time could also be included in further investigation.

In summary because of the lack of information the lowest flows in Table 6.3 and 6.4 were adopted in the model even though they do not really represent "good practice".

These data are:

Most intermittent devices	D_{inst}	=	0.21 kg/s
	t_a	=	5 - 7 s (depending on level of soiling)
Eviscerate table	D_{inst}	=	3.0 kg/s
	t_a	=	18s
Head hook steriliser			
Continuous	D_{flow}	=	180 kg/hour

In the author's view, the real concern for steriliser hot water usage rates lies with hand tool steriliser designs. Various workers have investigated knife steriliser usage rates, (Pearson 1981, Shaw 1991), but hand tool sterilisers have apparently been ignored. On the measured plant the steriliser hot water usage in the beef kill area is 2787 kg/hr for 10 so-called hand tools compared to 532 kg/hr for 22 knife sterilisers. A 20% reduction in hand tool steriliser use would equate to the total knife steriliser use. Further investigation could result in substantial savings.

6.1.5.3 "Good Practice" production run hosing regimes

Separate model consideration of production run hosing would involve unnecessary model complications and there is no valid reason why the hosing could not be considered as part of the overall beef kill group as discussed in Section 6.1.2. Hosing is prohibited in edible areas during production because of the "aerosol effect" which MAF perceives to allow water vapour to transport contaminants onto meat surfaces. Support areas, however, such as the inedible offal, rendering and effluent require periodic cleaning during production runs with hot water which is permissible. This involves spills of trim, fat and ingesta from chutes, trommel washers and hashers being moved by hosing to floor drains. The rotary screens on trommel washers also "blind" with fat periodically and require hot water to move the congealed fat away.

Because workers tend to remove pieces of trim etc, by "hose power" rather than scraping or sweeping, the choice of hose nozzle, (which largely decides D_{inst}) requires careful attention to ensure that maximum nozzle velocity is attained. Published data concentrates on departmental use rather than individual "good practice" hose usage rates.

The individual hose usage rates produced by nozzles fitted to the hoses at the plant measured by the author and shown in Table 6.4, were in his opinion, representative of "good practice" instantaneous rates, as was the hose line pressure of 4 bars. This flow rate was therefore adopted as "good practice" for production run hosing.

The activation time will depend largely on the local plant conditions, particularly the design of the equipment. The plant measured was somewhat unusual in terms of modern design in that it utilised blowpots to transport inedible material to rendering storage rather than auger screws. This meant hosing normally done at cleanups would be done from time to time during production runs. The author's observation was that the usage rate of 1200 s/hr was not excessive in the circumstances. On other plants the demand may be different. In the lack of better information the 1200 s was selected.

"Good practice" values were defined as:

Intermittent: D_{inst} = 0.66 kg/s

t_a = 1200 s

6.1.5.4 "Good Practice" cleanup hosing regimes

Edible production areas have traditionally been cleaned by using large volumes of 82°C water at relatively low pressures. Sanitizers in the form of powder have been added sporadically to control microbial growth. While the benefits of dry scraping up macro pieces of trim and fat, (floor trim) have long been advocated by agencies such as MIRINZ, the practical tendency has been to move floor trim with the relatively weak kinetic energy generated by low pressure hot water. The consequence has been a large consumption of hot water. (Graham 1972).

Current hygiene practices utilise minimisation of floor trim thereby increasing the yield of edible product. A reduced amount of 82°C water is then used to break down intermediate fat deposits and then foam sanitizers are applied to surfaces and left on overnight. A brief rinse with cold water the next morning prior to production washes away the sanitized soil and leaves a surface which meets hygiene microbiological standards.

The governing factor for cleanup water usage is the total surface to be cleaned (which can be roughly indexed to an area which consists of the floor and walls to a height of 3m), but the degree of soiling, equipment, floor and wall design are also important. For simplicity and because of a lack of better information only the floor and wall area were considered in the model. There should be a minimum amount of water required to clean an area, (and equipment in this area) and this could be defined in units of kg water/m^2 cleaned surface area.

This parameter does not appear to have been defined or measured previously. On the plant measured by the author 10800 kg water were used to clean about 918 m^2 in the beef kill area (11.8 kg/m^2) and 10800 kg water for 838 m^2 in the beef boning room (12.9 kg/m^2). This plant used low pressure wate: (4 bars) and in spite of good nozzle designs the measured individual hose flow rate was 0.66 kg/s (2400 kg/hr). Lively (1975) reports that at higher pressures (34 bars) an individual hose flow rate could be reduced to 680-1140 kg/hr. Thus if a high pressure system was adopted the water use might reduce significantly, and almost certainly would halve to about 6.0 kg/m^2.

Because so few data exist "good practice" was assumed to match the above data, that is:

(i)	Low Pressure	12.3 kg/m^2
(ii)	High Pressure	6.0 kg/m^2

Having defined the total water use required from the floor and wall area, the cleanup time is determined from local considerations, and D_{flow} for the cleaning system as a whole determined as follows:

Low pressure system:

$$Total\ cleanup\ water\ use\ (kg) = floor\ area\ *\ 12.3\ kg/m^2 \tag{6.22}$$

$$D_{flow} = \frac{Total\ cleanup\ water\ use}{cleanup\ time} \tag{6.23}$$

High pressure system:

$$Total\ cleanup\ water\ use\ (kg) = floor\ area * 6.0\ kg/m^2 \tag{6.24}$$

$$D_{flow} = \frac{Total\ cleanup\ water\ use}{cleanup\ time} \tag{6.25}$$

Further investigation is required, to establish better "good practice" data taking into account differences in departmental work surfaces and different cleaning systems. Important factors may include:

(i) Degree of difficulty in cleaning process equipment.

(ii) Soiling effect.

(iii) Floor and wall design

Current hygiene control methods relying on the use of 82°C water alone have been shown to be inadequate microbiologically. (Husband and McPhail 1978). D'Souza and Scriven (1983) have shown that a cleaning regime which utilises warm water at 40°C and specially formulated sanitizers can provide satisfactory microbiological control. Adoption of this regime could result in substantial reductions in energy consumption by dropping the required hosing temperature from 82°C to approximately 40°C, but this has not been proven to MAF satisfaction. Heat recovery technologies for hot water production which are available at present but which cannot achieve a temperature of 82°C may then become applicable.

6.1.5.5 "Good practice" hand, apron wash and shower flow rates

(i) Hand washes

Traditionally, hand washes have consisted of a commercially available sink or basin with a fixed shower rose or "swan neck" nozzle fitted above them as shown in Figure 6.5.A. The valve operation is never by hand but always by foot, hip or sensor to avoid cross contamination with soiled hands.

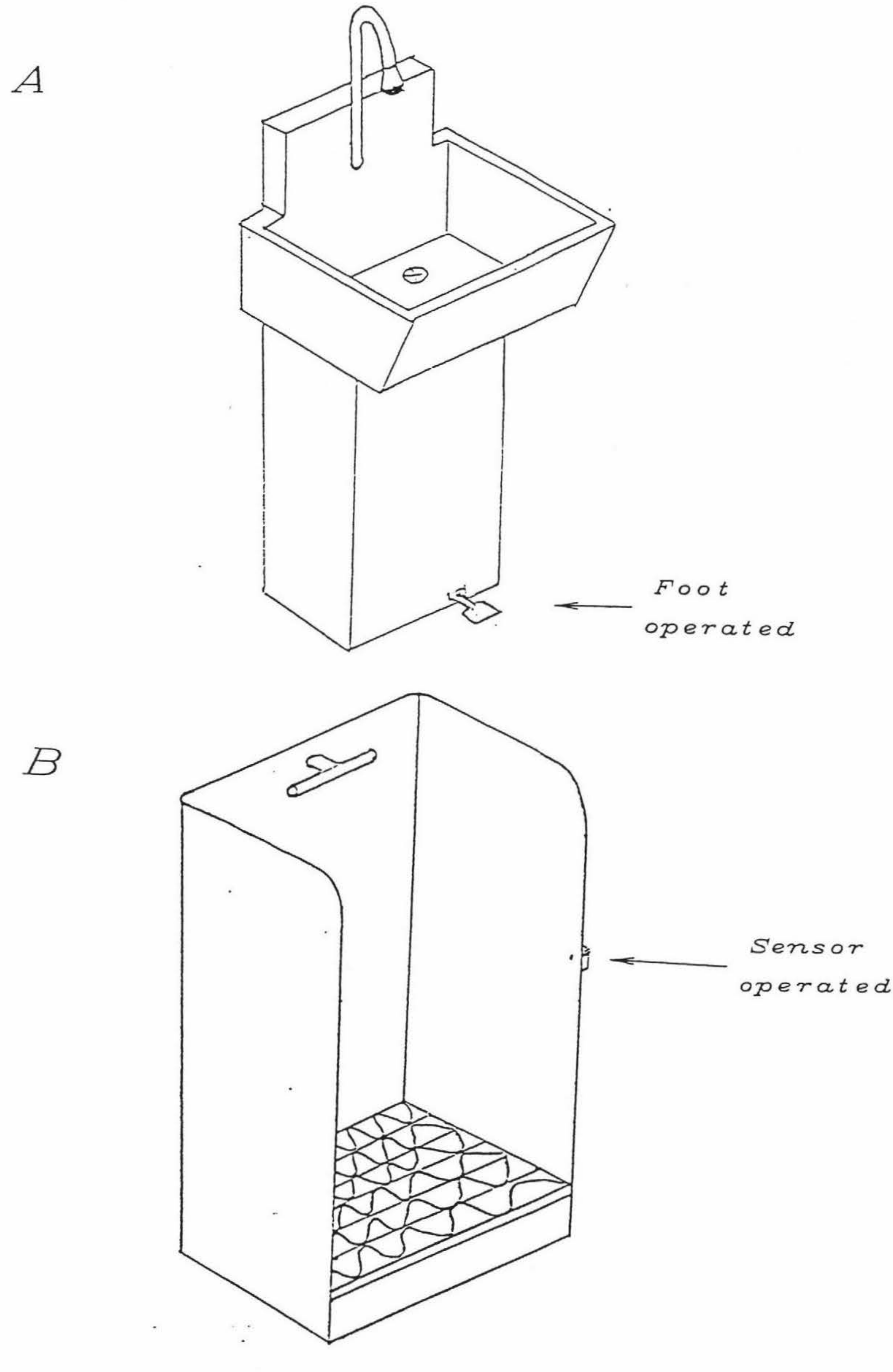


Figure 6.5 A: Traditional hand wash basin. B: Apron wash

The wash basin is mounted on a pedestal so the top of the basin is approximately at waist height.

A more modern design was used in the plant at which the author took measurements as illustrated in Fig 6.4. This was a combination of hand wash/steriliser so that the hand used by the butcher to carry out a dressing operation is washed at the same time as his knife is sterilised.

Hand wash data measured by Peacham (1993) are stated in Tables 6.5 and data measured by the present author are presented in Table 6.6 and 6.7. The variations between data supplied by Peacham (1993) and data measured by the author is substantial. All plants apparently had adequate water flows so that the lowest mean flow rate measured on any plant (0.11 kg/s) was chosen to represent "good practice".

The activation time measured by the author was 7 s. It would be expected that the necessary time may increase as flow rate decreases, yet the time must of necessity be modest. Therefore an activation time of more than 7 s is unlikely. On sheep plants with frequent activation continuous operation is possibly justified.

"Good practice" hand wash rates were defined as:

Intermittent:	D_{inst}	=	0.11 kg/s
	t_a	=	7 s
Continuous:	D_{flow}	=	396 kg/hr

(ii) Apron washes

Apron washes consist of a 3 sided cabinet wide enough to allow the butcher to walk into, and approximately breast high as shown in Figure 6.5.B. A shower rose or horizontal sparge pipe is fixed at a height which allows warm water to be directed over the butchers apron and carry away all the matter which may have collected there. The apron washes may be foot or sensor operated. The floor consists of grating so that the waste water does not pool around the workers boots and thus cause recontamination.

Table 6.5

Hand wash flow rates as measured on three plants by Peacham (1993)

Type	Operation	D_{inst} (kg/s)	Mean D_{inst} (kg/s)
Rose head	Foot Op.	0.08 - 0.22	0.11
Rose head	Foot Op.	0.18 - 0.55	0.36
None	Part of Ap. Wash	N/A	0.2

Table 6.6

Beef kill area data for apron, hand wash and showers measured by the author

Description	Action	Number	D_{inst} (kg/s)	D_{flow} (kg/hr)
Hand wash	Sensor	4	0.33	290
Apron wash	Sensor	18	0.18	710
Showers	Manual	15	0.15	3420
Tongue wash	Manual	1	0.30	1080
Paunch chute	Continuous	1	0.36	1296

Data measured by Peacham (1993) are stated in Table 6.8. Data measured by the present author are presented in Table 6.6 and 6.7. Inspection of the tables shows that the data measured by the author fell within the ranges measured by Peacham (1993) at three plants. It is suspected that some of the apron wash D_{inst} flows recorded by Peacham (1993) were coupled with quite long activation on foot operated apron washes to obtain satisfactory results. Hence D_{inst} and t_a must be chosen in conjunction. A low to mid-range value of D_{inst} = 0.15 kg/s was selected so that the activation time could be kept short. An activation time of 7 s was chosen. Again where operation is very frequent continuous operation may occur.

"Good practice" apron wash rates were defined as:

Intermittent:	D_{inst}	=	0.15 kg/s
	t_a	=	7 s
Continuous:	D_{flow}	=	540 kg/hr

(iii) Ancillary users

As discussed in Section 6.1.3.3, there are several such users including some edible offal and chute washers. The use of warm water for these purposes is not necessary.

"Good practice" ancillary user flow rates were therefore defined as:

Intermittent:	D_{inst}	=	0.0 kg/s
	t_a	=	0 s
Continuous:	D_{flow}	=	0 kg/hr

(iv) Showers

The length of time butchers take to shower varies widely as does the number of workers who actually have a shower at work. This depends on the operation they fulfil on the chain and thus how soiled they may become over the day, and also personal preference. No published data were available, so data were measured by the author. (Table 6.6 and 6.7)

An arbitrary decision was required to select the activation time t_a. It was decided that each shower would take an average of 10 minutes or 600 s. This also includes an allowance for amenity basin use.

"Good practice" shower rates were defined as:

Intermittent: $D_{inst} = 0.15$ kg/s

$t_a = 600$ s

The number of shower stalls that a plant is required to provide has been regulated in the past by the Labour Department requirement of 1 shower per 7 workers. This may be further complicated by the number of males and females. Recent legislation has meant that local body building regulations now govern this ratio. Because this will vary from region to region it is suggested that the model user inputs shower numbers which comply with local regulations.

As an example, on the measured plant it was estimated that 76 people could have a shower per shift. This would be divided in half between the beef kill area and the beef boning area. Thus if 38 people had a shower within a one hour period and 15 showers were available, the Op_{rate} for each shower would be:

$$Op_{rate} = 38/15 = 2.53 \text{ hr}^{-1}$$

If estimates of shower water use are in error it is thought that better data would either reduce activation time t_a or Op_{rate}.

Table 6.7

Beef boning area data for apron washes and showers measured by the author

Description	Action	Number	D_{inst} (kg/s)	D_{flow} (kg/hr)
Apron wash	Sensor	4	0.18	315
Showers	Manual	15	0.15	3420

Table 6.8

Apron wash flows as measured on three plants by Peacham (1993)

Type	Operation	D_{inst} (kg/s)	Mean D_{inst} (kg/s)
Shower rose	Foot Op.	0.10 - 0.21	0.15
Shower rose	Foot Op.	0.11 - 0.35	0.25
Includes W/basin	Sensor	N/A	0.05

6.1.5.6 "Good Practice" carcass wash flows

The carcass wash is generally used for removing bone dust on beef sides and small amounts of wool on sheep carcasses. Should any faecal matter or foreign bodies be present at this stage the carcass wash merely spreads the contamination over a wider body surface. The carcass wash was not used on the plant the author measured and this is a very satisfactory arrangement if it can be managed.

There is strong pressure from several client countries to abolish pre-evisceration carcass washes from lamb kill chains and final carcass washes from beef chains.

The data supplied by Peacham (1993) are presented in Table 6.9 and are all cold water flows. However some plants do use water at about 31°C. Inspection of Table 6.9 illustrates the huge variations in flows from plant to plant.

Because the washes are no longer needed "good practice" flows were defined accordingly:

Intermittent:	D_{inst}	=	0.0 kg/s
	t_a	=	0 s
Continuous:	D_{flow}	=	0 kg/hr

6.1.6 Model Implementation

The algebraic equations were incorporated into an advanced continuous system simulation language software package, (ESL) described earlier in this work. Logical statements were included for changing variables such as flow rates as a function of time. A programme listing is shown in Appendix C1.

6.1.7 Model Testing

The model is entirely algebraic which meant that initial checks could be made at different times through a simulation by hand calculations. All such hand calculations were found to return summations in agreement with the model.

Table 6.9

Measured data for carcass washes. (Peacham 1993)

Description	Operation	Daily kill	D_{inst} Flow (kg/s)	D_{flow} (kg/hr)
Beef kill	Continuous	400	1.93	6937
Lamb Kill	Manual gun	2220	0.48	1725
Lamb Kill	Continuous	2951	5.8	20875

In the second stage of testing it was decided that model simulations would be carried out to compare measured flows from a modern designed plant to the "good practice" flows postulated in this work. The first model simulation would use data measured by the author and presented in Tables 6.2 - 6.7. This simulation should predict the total measured daily water use accurately. In the second run the "good practice" flow rates stated in Section 6.1.5 were adopted with three exceptions. As has been discussed there was some uncertainty over handtool steriliser flow rates so the following reductions on the values in Section 6.1.5 were postulated as possible for hand tool sterilisers:

(i) Side saw and eviscerate table - 50%.
(ii) Head hook - 83.4% (to match an overflow knife steriliser flow rate)
(iii) Production hosing - 51.6%

The postulated data for handtool sterilisers are presented in Table 6.10. The second simulation would give an indication of what target water usage rates should be for this plant.

Each simulation was carried out for a typical single shift, commencing at time 0, with tea or lunch breaks at times 8100s, 14400s, and 23400s, and then final cleanup from 32400s to 37800s. The simulation was then terminated.

6.1.7.1 Model customisation

In order to simulate the specific plant some small changes to the general model were required. The plant water users that could be handled by the general model "as is" were 26 knife sterilisers, 11 hand tool sterilisers, 1 production hose and 6 cleanup hoses, 4 hand washes, 22 apron washes and 15 showers.

Table 6.10

Postulated possible beef kill area hand tool steriliser and hose flows

Beef kill area Description	D_{inst} (kg/s)	D_{flow} (kg/hr)
Weasand rod	0.21	6
Dehorner	N/A	N/A
Dehiders	N/A	N/A
Hockcutter	0.21	46*3
Elastorator	0.21	46
Brisket saw	0.21	46
Side saw	0.5	297
Eviscerate table	1.5	845
Gut buggies	N/A	N/A
Head hooks	0.0083	30
Trolleys	N/A	N/A
Scribe saw	0.21	8.75
Inedible hose	0.32	384
Rotary washes	0.0	0.0

In the "as measured" simulation special provision had to be made to include warm water use for the tongue wash and paunch chute. Neither of these uses is considered in the "good practice" model. The net result of accumulation of water flows from the various users at various times could be represented by three "modes":

- during production
- during breaks
- during cleanup.

Within each type of period both hot and warm water flows were constant, but there were major differences between periods.

6.1.7.2 Model verification

The "as measured" simulation provided a means to check correct implementation of equation (6.1) to (6.25) in the model. The predicted and measured cumulative water flows per shift are shown in Table 6.11, which verifies correct model implementation.

6.1.7.3 Results

The results of both the "measured" and "good practice" simulations are shown in Figure 6.6. The small plateaus at 8100s and 14400s represent tea breaks and the larger one at 23400s indicates the lunch break. The sharp increase in hot water usage at 32400s represents cleanups in both departments which continue to 37800s. Warm water usage for showers commences at 32400s and ceases at 33900s.

Table 6.11

Predicted and measured cumulative water flows per shift.

Stream/mode	Measured	Predicted
Hot		
- Production	1.19 kg/s	1.19 kg/s
- Breaks	0.0 kg/s	0.0 kg/s
- Cleanup	4.0 kg/s	4.0 kg/s
Warm		
- Production	1.02 kg/s	1.02 kg/s
- Breaks	0.0 kg/s	0.0 kg/s
- Cleanup	4.5 kg/s	4.5 kg/s
Cumulative per shift		
- Hot	56120 kg	56120 kg
- Warm	36300 kg	36300 kg

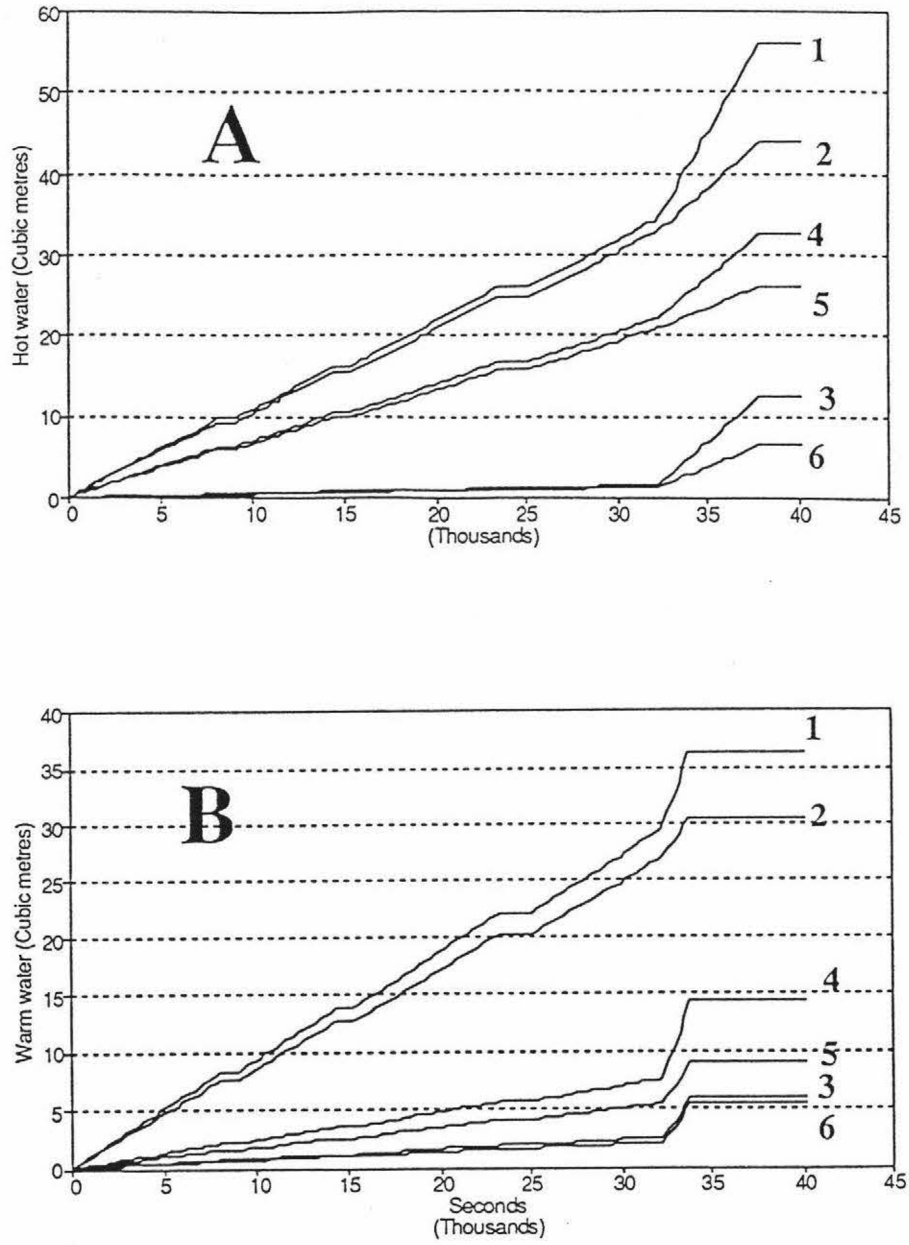


Figure 6.6 A: Plot of cumulative daily hot water usage (m^3) vs time (s)

B: Plot of cumulative daily warm water usage (m^3) vs time (s)

(1) measured total plant usage, (2) measured beef kill area usage, (3) measured beef boning usage, (4) "good practice" total plant usage, (5) "good practice" beef kill area usage and (6) "good practice" boning room usage.

The value of improved hot water using equipment is seen by comparing the "good practice" simulation to the "as measured":

	"as measured"	"good practice"	
hot water	56 m^3/day	32 m^3/day	(-43%)
warm water	36 m^3/day	14 m^3/day	(-61%)

6.1.8 Discussion and Conclusions

Peacham (1993) measured hot water usage on a small modern beef-only plant and found a usage rate of 0.27 m^3/carcass. The "good practice" simulation predicts a usage rate of 0.128 m^3/carcass and addition of warm water usage gives a total "good practice" heated water usage of 0.192 m^3/carcass. Achievement of postulated reduced usage rates in practice will still require significant research and development and technology transfer; for example:

(i) Hand tool steriliser designs are rudimentary and urgently require rework.

(ii) Introduction of high pressure hosing for cleanups could result in savings of at least 50% during cleanups. Demonstration projects under New Zealand conditions are needed for there to be rapid uptake of modern cleaning techniques by the Meat Industry.

(iii) The use of unnecessary warm water (eg. for carcass, offal and chute washes) should be discontinued. Little research seems necessary in this area.

Departmental divisions within the model have been kept as low as possible to simplify data input yet retain reasonable accuracy of model predictions.

Various user device flows measured by other workers and the author have been discussed. "Good practice" flows have been suggested in Section 6.1.5. Sheep plant operations can also be expected to have specialist user devices, but because of time constraints it was not possible to survey these within this work. Further investigation is recommended so that "good practice" flows may be determined for user devices within sheep plants.

Two simulations were run which showed that the use of "good practice" flows postulated with this work reduced overall plant daily hot water use by 40% and warm water by 47%. Results for hot water may be questioned because some hand tool steriliser flows were supposition, nevertheless substantial savings have been demonstrated indicating that further investigation by the Meat Industry in this area could result in useful savings in heated water use and therefore thermal energy.

Reductions in heated water use would allow the use of smaller heat generation and exchanger units thereby reducing initial capital expenditure for new plants.

The model could also be used to:

- (i) predict reticulation equipment sizes by new plant designers bringing about a further reduction in capital expenditure by the use of
  - (a) smaller pump and motor sets.
  - (b) smaller pipe and insulation diameters.
- (ii) provide accurate flow information for correct sizing of control valves and flow metering which is often difficult at the present time.

The model can be used to provide both hot and warm water usage requirements for the model of hot water storage and generation systems.

The model has been shown to provide reasonably accurate predictions with low user input and provide useful benchmarks for "good practice" flows. It was therefore adopted into the overall model.

6.2 HOT WATER GENERATION AND STORAGE SYSTEMS

6.2.1 Mechanistic Description

Hot water generation and storage for a meat plant is driven by the anticipated demand within production departments which was discussed in Section 6.1. A balance has to be struck between practical storage volumes in terms of capital cost on the one hand, and continuing heat recovery after production has finished from such sources as rendering and refrigeration on the other. Some plants have heat generation units which are capable of handling any instantaneous demands which may arise during the day. It could be argued that the capital cost of a larger thermal heating unit is more economical than extra hot water storage which is necessary when smaller heating units are employed through a 24 hour day, plus the subsequent additional heat losses associated with ring mains and greater hot water tank surface areas. Others argue that a cluster or series of heating units may be more efficient so that they may be loaded in parallel as required.

Hot water generation will always use some form of indirect heat exchanger to ensure that the water used in production departments remains potable. Having noted this however, the heating method used may range from steam coils in hot water tanks, to steam or hot water on the primary side of a heat exchanger.

Although hot water generation capabilities must be sufficient to provide the entire production demand for hot water when required, all plants have some form of heat recovery. The percentage of total hot water demand that the heat recovery units will be able to supply depends on whether the plant processes beef and/or sheep and the types of heat recovery mechanisms installed. In the authors own industrial experience a modern beef plant for example, with good management practices for cleanups and an efficient steriliser design should be able to supply the entire hot water demand from heat recovery. Section 6.3 deals with heat recovery. Integration of the various overall hot water models (demand, supply and recovery) will require an inter-relationship between the hot water recovery and generation with a preference to use recovered heat first. This must be built into the decision hierarchy within the model.

6.2.2 Design Philosophy

The model should be able to accurately predict performance of various system designs that users may wish to test. The core model should be able to describe as simply as possible a minimum basic layout for any new plant but also be able to be expanded or modified to suit other conditions which may be required for a particular plant situation. The model should be structured to not only recognise that recovered heat should be used first, but also be intelligent enough to utilise this heat in the most efficient way, i.e. with the minimum mixing with cold water. Variations in tank capacities should be easily accommodated, as should maximum and minimum levels for controlling flows in and out of tanks. Modelling of time variable changes in tank operating levels should be included to represent tank filling, especially at night when production has ceased but recovery from refrigeration and rendering may continue.

The generalised model shown in Figure 6.7 was adopted and from this it was seen that the Tanks 3 and 4 which might operate to satisfy demands for hand and apron wash, (43°C) and carcass wash, (31°C) are the "end of the line" in terms of mixing and demand. It is common to mix various streams of water to generate these streams and it was therefore reasoned that any higher temperature water demand would be influenced by the required usage from these streams.

There are several common configurations regarding holding tanks and heat exchangers. It would be possible to fit heat exchangers upstream of holding tanks, but the advantage of fitting a heat exchanger downstream is that any heat losses are made up prior to the water being passed out to the production plant. A recirculation flow occurs back to the tank from the main. In symbolic terms Wr_β represents an outgoing flow rate entering the ring main from Tanks 2, 3 and 4. (The symbol β represents the tank number.) Some of the flow is lost to plant usage at a rate of Wpu_β so the return flow to the tank is $(Wr_\beta - Wpu_\beta)$. Tank 2 is somewhat different from the others as it may also feed Tanks 3 and 4 through flow Wt_2. The ring main pump-round rate may be unknown to the user, and in these circumstances it is nominally set at twice the plant usage for each temperature system.

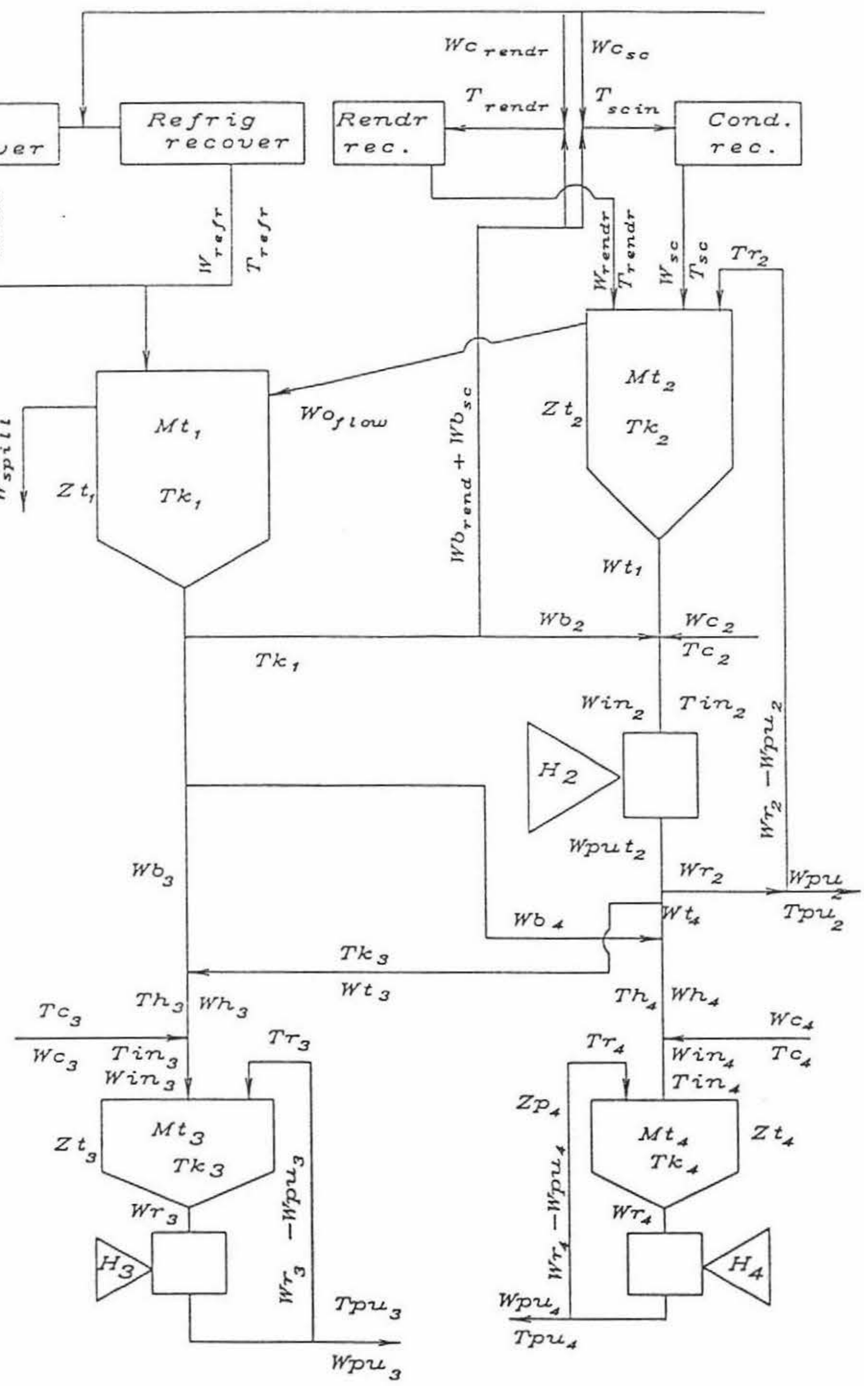


Figure 6.7 Schematic diagram of hot water storage and generation

6.2.2.1 Tank 1

A collection tank, Tank 1 is provided to collect water from:

(i) A heat recovery unit fitted on production department hot water wastes at flow rate W_{drain} and temperature T_{drain}.

(ii) A refrigeration heat recovery source at flow rate W_{refr} and temperature T_{refr}.

It is envisaged that both these sources will collect water in a temperature range of 25-50°C. The mass of water in the tank, (Mt_1) will vary throughout the day in response to the various demands, and the flow rates from heat recovery. Modelling of both water mass present and its temperature, is therefore required.

6.2.2.2 Tank 2

A buffer or collection tank, Tank 2 upstream of the mixing area for steriliser and hosing water, (82°C) would collect recovered water from the rendering at flow rate W_{rendr}, temperature T_{rendr} and from the steam condensate undercooling area at flow rate W_{sc} and temperature T_{sc}. These systems usually recover water at a temperature of at least 70°C. Both the temperature and mass present must be dynamically modelled.

6.2.2.3 Spillover arrangements

In Tank 2 when the mass present (Mt_2) becomes greater than a predetermined full level $max2_{level}$ then an overflow Wo_{flow} is fed to Tank 1. A potential problem can arise if an overflow is occurring from Tank 2 to Tank 1 whilst Tank 1 is still supplying water to the rendering and steam condensate heat recovery, thus arriving back at Tank 2. The net result is that the temperature can build up to a point where the necessary process cooling in the rendering and condensate area will not occur. To prevent this situation, water use for rendering and condensate heat recovery from Tank 1 was limited to only occur when the Tank 1 temperature was below 50°C (a temperature which exceeded the set point temperatures in Tanks 3 and 4 Tk_{3set} and Tk_{4set}). Once Mt_1 becomes greater than $maxl_{level}$ then flow to waste W_{spill} is activated. The destination of this flow is not considered important within the model but rather the flow rate. This hierarchy ensures maximum possible retention of recovered heat.

6.2.2.4 Tank 3 and Tank 4

These tanks are usually provided to act as a buffer against sudden demands in the lower temperature systems. These tanks should be as small as possible to reduce capital costs; storage should be utilised for high temperature water because of its higher energy content. Satisfactory holding capacities for Tanks 3 & 4 may be as low as 1-2 m^3. Only their temperature need be modelled.

The distribution tanks have set-point temperatures, (Tk_{3set} and Tk_{4set}) to which the incoming water temperatures are compared. If the incoming temperature Tin_β is warmer than the set point, then mixing of hot and cold flow rates as discussed below, is initiated.

6.2.2.5 Mixing options associated with water supply at temperature Tpu_2

The total supply flow rate ($Wput_2$)is the sum of Wr_2, Wt_3 and Wt_4.

Mixing options to supply this water at temperature Tpu_2 assuming availability in descending preference would be:

(i) Single flow rate from Tank 2, at flow rate Wt_1:

- if it is cooler than Tpu_2 then a positive heat requirement (H_2) arises in the heat exchanger.
- if it is hotter than Tpu_2 it is mixed with cold water at flow rate Wc_2 to achieve a mix temperature of Tpu_2.

(ii) Water from Tank 1, at flow rate Wb_2. Because this is only partially heated, final heating to Tpu_2 creates a positive heat demand H_2.

(iii) If water was not available from either of the above sources then cold water at flow rate Wc_2 is used. The heat demand H_2 to reach Tpu_2 is at its maximum.

6.2.2.6 Mixing options associated with Tanks 3 & 4

Mixing options to create water at $Tk_{\beta set}$ assuming availability in descending preference would be:

(i) Flow rates Wb_3 and Wb_4 occur from Tank 1:

- if Tk_1 is lower than the desired Tanks 3 and 4 temperatures Tk_{3set} or Tk_{4set} respectively, no mixing with cold occurs.
- Flow rates from Tank 1 are mixed with the appropriate cold water stream (either Wc_3 or Wc_4 respectively) if Tk_1 is higher than the desired Tanks 3 and 4 temperatures to achieve a water inlet temperature of $Tk_{\beta set}$.

(ii) Flow rates downstream of heat exchanger H_2 are assumed to be at Tpu_2 and thus require mixing with the appropriate cold streams.

(iii) Cold water at flow rate Wc_β and temperature Tc_β is used.

Independent inlet cold water temperatures have been specified so that any alternative heat recovery stream, even at modest temperature, could be substituted for one or more of the cold water flow rates.

6.2.2.7 Heat exchangers

There is no real need in this work to model the detail of various heating methods as the primary role of the overall model is to predict the energy requirements not how they are applied. The optimum thermal heating method will vary between plants according to locality and conditions peculiar to that company. A configuration which may suit one plant may well be unsuitable in another.

6.2.2.8 Recovered heat flows

Heat is available to be recovered from four broad areas:

(1) Hot water in drains leaving production departments. This is virtually impossible to recover on most plants at present.

(2) Refrigeration sources such as desuperheating of high pressure refrigerant, and use of water passed through oil coolers, or direct compressor cooling systems.

(3) Condensing of water evaporated from the rendering system.

(4) Cooling of steam condensate to less than 100°C prior to pumping it back to the boiler.

These flow rates are represented within the model as follows. It is recognised that the heated flow rate of water recovered from refrigeration areas W_{refr} or production departments, W_{drain} will fall into a temperature range of between 25 and 50°C. As mentioned in Section 6.2.2.1, recovery of water from production departments is probably not economic for existing plants. A recovery system could, however be economically installed in a new plant which would pick up the waste streams downstream from the steriliser and washbasin drains and pass them through a common heat exchanger which would heat cold incoming water to be passed to storage. Because a new plant should also install efficient sterilisers with low flow rates the ratio of waste steriliser water in relation to waste wash water should be low and the subsequent mixed flow rate to the heat exchanger would probably lie in a temperature range similar to that recovered from the refrigeration heat recovery system. Thus the recovered flow rate W_{drain} would be directed to Tank 1.

It is more energy efficient to direct a flow of partially heated water from Tank 1, to the inlet of the rendering heat exchanger at flow rate Wb_{rendr} and the condensate desuperheater at flow rate Wb_{sc}, than use cold water at flow rates, Wc_{rendr} and Wc_{sc}. Thus if the Tank 1 level is sufficiently high and Tk_1 is less than 50°C, then Wb_{rendr} is made available as cooling source rather than the cold water supply Wc_{rendr}. Similarly Wb_{sc} is made available to the steam condensate desuperheater in preference to Wc_{sc}.

There is no advantage in supplying the drain or refrigeration desuperheater units with cooling water from their own outlet thus the only available cooling source for these units are Wc_{drain} and Wc_{refr} respectively.

6.2.2.9 Model control

When fully integrated the hot water demand and hot water recovery models will provide the necessary water demand data, but for initial model testing realistic but arbitrary flow rates and timing of those flow rates were used to test the supply model in isolation. In this situation the model control system should allow different inputs and outputs to the model to be set by time, e.g. recovered heat flow rates and demands for flow rates of heated water to the plant. The control system then uses defined timesteps and allows the user to specify what time of day different heat recoveries are operational.

6.2.3 Model Development - Mass Balances

A mass balance for Tank 1 is:

$$\frac{dMt_1}{dt} = W_{drain} + W_{refr} + Wo_{flow} - Wb_{rendr} - Wb_{sc} - Wb_2 - Wb_3 - Wb_4 - W_{spill} \tag{6.26}$$

where

Mt_1	=	mass of water in Tank 1 (kg)
W_{drain}	=	water flow rate through drain recovery heat exchanger (kg/s)
W_{refr}	=	water flow rate through refrigeration heat exchanger (kg/s)
Wo_{flow}	=	overspill flow rate from Tank 2 to Tank 1
Wb_{rendr}	=	cooling water flow rate to rendering heat exchanger (kg/s)
Wb_{sc}	=	cooling water flow rate to steam condensate desuperheater (kg/s)
Wb_2	=	warm water flow rate to Tank 2 (kg/s)

Wb_3	=	warm water flow rate to Tank 3 (kg/s)
Wb_4	=	warm water flow rate to Tank 4 (kg/s)
W_{spill}	=	overflow rate from Tank 1 to waste (kg/s)

A mass balance for Tank 2 may be described by:

$$\frac{dMt_2}{dt} = W_{rendr} + W_{sc} + (Wr_2 - Wpu_2) - Wt_1 - Wo_{flow} \tag{6.27}$$

where

Mt_2	=	mass of water in Tank 2 (kg)
W_{rendr}	=	water flow rate through rendering heat exchanger (kg/s)
W_{sc}	=	water flow rate through steam condensate heat exchanger (kg/s)
Wr_2	=	combined flow rate of hot water to plant and return to Tank 2 (kg/s)
Wpu_2	=	hot water flow rate to the plant (kg/s)
Wt_1	=	total flow rate out of Tank 2 (kg/s)

Tanks 3 and 4 are assumed to be full all the time and merely used as mixing or buffer tanks. It was thus unnecessary to develop differential equations to describe their masses.

6.2.4 Model Development - Energy Balances

Heat losses from tank walls should be small because those tanks containing higher internal temperatures are usually lagged while those which are not, are usually run at lower temperatures and have smaller surface areas. Nevertheless the model should be able to calculate the overall heat loss from each tank and adjust the energy balance accordingly. An overall heat transfer coefficient for losses of 0.5 W/m^2K (representing an insulated condition) was assumed for all tanks.

The calculation methodology for heat losses from the Tanks is:

$$Zt_{\beta} = U_{\beta} A_{\beta} (Tk_{\beta} - T_{amb}) \tag{6.28}$$

where	Zt_{β}	=	heat loss from Tank β (W)
	U_{β}	=	heat transfer coefficient for losses from the tank surfaces (W/m^2K)
	A_{β}	=	surface area of the tank (m^2)
	Tk_{β}	=	temperature of the tank contents (°C)
	T_{amb}	=	temperature of the ambient air (°C)

Heat losses from the ring main systems associated with Tanks 2, 3 and 4 that must be replaced by the heating system, may be estimated using

$$Zp_{\beta} = (Wr_{\beta} - Wpu_{\beta})\ c_w\ (Tpu_{\beta} - Tr_{\beta}) \tag{6.29}$$

where	Zp_{β}	=	heat losses from ring main associated with Tank β (W)
	Wr_{β}	=	flow rate into the ring main (kg/s)
	Wpu_{β}	=	plant consumption flow rate (kg/s)
	Tr_{β}	=	temperature of ring main return (°C)

Because the mass and temperature are both changing with time in Tanks 1 and 2 it is necessary to use an intermediate variable, $(Mt_{\beta}Tk\beta)$ which is then divided by Mt_{β} to determine the temperature of each Tank Tk_{β}.

An energy balance for Tank 1 may thus be described by:

$$\frac{d(Mt_1 Tk_1)}{dt} = (W_{drain}\ T_{drain}) + (W_{refr}\ T_{refr}) + (Wo_{flow}\ Tk_2) - (Wb_t + W_{spill})\ Tk_1 - \frac{Zt_1}{c_w} \tag{6.30}$$

$$Wb_t = (Wb_2 + Wb_3 + Wb_4 + Wb_{rendr} + Wb_{sc}) \tag{6.31}$$

$$Tk_1 = \frac{Mt_1\ Tk_1}{Mt_1} \tag{6.32}$$

where	T_{drain}	=	temperature of the flow rate from the drain heat recovery system (°C)
	T_{refr}	=	temperature of the flow rate from the refrigeration heat recovery system (°C)
	Tk_2	=	temperature of water in Tank 2 (°C)
	Wb_t	=	total supply flow rate from Tank 1 (kg/s)

An energy balance for Tank 2 is:

$$\frac{d(Mt_2 Tk_2)}{dt} = (W_{rendr}\ T_{rendr}) + (W_{sc}\ T_{sc}) + (Wr_2 - Wpu_2)\ T_{r2} - (Wo_{flow} + Wt_1\ )Tk_2 - \frac{Zt_2}{c_w} \tag{6.33}$$

where	T_{rendr}	=	temperature of flow rate from the rendering recovery system (°C)
	T_{sc}	=	temperature of the flow rate from the steam condensate heat recovery system (°C)
	T_{r2}	=	temperature of the hosing and steriliser ring main return flow rate from the plant (°C)

Although Tanks 3 and 4 were considered as holding a stable mass, the temperature could change with time.

The energy balance below for Tank 3 is effectively identical to that for Tank 4:

$$Mt_{\beta} \frac{dTk_{\beta}}{dt} = (Wpu_{\beta}Tin_{\beta}) + (Wr_{\beta} - Wpu_{\beta})\, Tr_{\beta} - \frac{Zt_{\beta}}{c_w} \tag{6.34}$$

Heat exchangers will require a flow rate of heat defined by:

$$H_{\beta} = Win_{\beta}\, c_w\, (Tpu_{\beta} - Tin_{\beta}) \tag{6.35}$$

where	H_{β}	=	energy required by any heat exchanger (W)
	Win_{β}	=	flow rate of water to heat exchanger (kg/s)
	Tpu_{β}	=	required temperature of outlet water (°C)
	Tin_{β}	=	temperature of flow rate to heat exchanger (°C)

6.2.5. Proportional Mixing Controls

Because the supply temperatures of flow rates to be mixed may change with time, the mixing proportions must also change, so that the required temperature downstream is maintained. In the case of hot water to be delivered at temperature Tpu_2 this involved two flow rates only, Wt_1 and Wc_2 which when combined created flow rate Win_2. Energy balances were used to derive two algebraic equations which describe the required flow rates Wt_1 and Wc_2.

When $Tk_2 > Tin_2$ then:

$$Wt_1 = Win_2 \frac{(Tin_2 - Tc_2)}{(Tk_2 - Tc_2)} \tag{6.36}$$

$$Wc_2 = Win_2 - Wt_1 \tag{6.37}$$

where

Wt_1	=	flow rate from Tank 2 (kg/s)
Win_2	=	total required flow rate (kg/s)
Tin_2	=	required final temperature to plant (°C)
Tc_2	=	temperature of cold water supply (°C)
Tk_2	=	temperature of water in Tank 2 (°C)
Wc_2	=	cold water flow rate (kg/s)

The distribution tanks could use either of two hot water flow rates. The source of heated water was determined by the descending order of preference described earlier. Once the flow rate source had been selected, the flow rate from this source is either designated Wh_3 or Wh_4 and its temperature is Th_3 or Th_4. Then equations 6.38 and 6.39 can be solved for the unknown required flow rates Wh_β and Wc_β.

$$Wh_\beta = Win_\beta \left[\frac{Tin_\beta - Tc_\beta}{Th_\beta - Tc_\beta}\right] \tag{6.38}$$

$$Wc_\beta = Win_\beta - Wh_\beta \tag{6.39}$$

If Tank 1 is the source then $Wb_\beta = Wh_\beta$ and $Wt_\beta = 0$, otherwise $Wb_\beta = 0$ and $Wt_\beta = Wh_\beta$.

6.2.6 Model Implementation

The algebraic equations were incorporated into an advanced continuous system simulation language software package, (ESL) already described earlier in this work. Logical statements were included for changing variables such as flow rates as a function of time. A programme listing is shown in Appendix C2.

Because of the number of checks required for the logic to operate in a satisfactory manner it was found necessary to place the time step instructions and conditional codes for tank levels, spillover conditions and heat recovery units in the part of the program where the model would only look at them at the end of each time step.

This meant that the calculation of ordinary differential equations would not have to cope with a so called "step" change of input during a time step.

Mixing of cold water with heated water also appears to occur when the streams at flow rates Wc_{rendr} and Wb_{rendr} are combined to form a stream at flow rate W_{rendr}, and when streams at flow rates Wc_{sc} and Wb_{sc} are combined to generate a flow rate W_{sc}. In practice no mixing occurs because at any time one of each pair is zero. For example, if water is available in Tank 1 then Wc_{rendr} and Wc_{sc} are set to zero, and $Wb_{rendr} = W_{rendr}$, and $Wb_{sc} = W_{sc,}$ T_{renin} takes the appropriate value of T_{rec} or Tk_1.

6.2.7 Model Testing

To run the model with heat recovery systems in place required data defining the available heat. Heat recovery will be covered in Section 6.3 so only a simplified description of the heat recovery was used in the hot water supply model testing. For example, by defining W_{rendr}, T_{rendr} and T_{renin} the rate of heat recovery from the rendering is defined. As will be discussed in Section 6.3 the heat recovery model will determine T_{rendr}, and the total heat available at this temperature, thus allowing W_{rendr} to be found by energy balance.

Having adopted simplified recovery system description, testing was carried out in three parts:

(1) Testing of the overall mass and energy balance for the system, thus verifying implementation of algebraic and differential equations.

(2) Mass and energy balancing around each tank and associated heat exchangers and piping.

(3) Testing of logic controls. Various actions depended on preconditions such as whether heat recovery units were working at the time of model interrogation and whether Tanks 1 and 2 were over a predetermined level and/or filling or emptying. Switchover of codes controlling these functions were tested manually by running the model and checking code outputs.

In the interests of brevity only the first of the tests is described here. A mass balance that describes all the inputs and outputs is:

$$\frac{dM_{tot}}{dt} = Wc_2 + Wc_3 + Wc_4 + Wc_{drain} + Wc_{refr} + Wc_{rendr} + Wc_{sc} - Wpu_2 - Wpu_3 - Wpu_4 - W_{spill} \tag{6.40}$$

where M_{tot} = total mass within the system (kg)

This was compared with the mass held in the tanks:

$$M_{trial} = Mt_1 + Mt_2 + Mt_3 + Mt_4 \tag{6.41}$$

where M_{trial} = total mass held within system (kg)

A summation of the total thermal energy held within the system is:

$$T_{trial} = ((Mt_1\ Tk_1) + (Mt_2\ Tk_2) + (Mt_3\ Tk_3) + (Mt_4\ Tk_4))\ c_w \tag{6.42}$$

where T_{trial} = total heat held within system (J)

This was compared to the result of an energy balance that describes all the inputs and outputs to the system:

$$\frac{(dM_{tot}T_z)}{dt} = (Wc_2\ Tc_2) + (Wc_3\ Tc_3) + (Wc_4\ Tc_4) + \\ (Wc_{drain} + Wc_{refr} + Wc_{rendr} + Wc_{sc})\ Tc_{rec} + \\ \frac{(H_2 + H_3 + H_4)}{c_w} + \\ W_{drain}\ (T_{drain} - T_{rec}) + W_{refr}\ (T_{refr} - T_{rec}) + \\ W_{rendr}\ (T_{rend} - T_{renin}) + W_{sc}\ (T_{sc} - T_{scin}) - \\ \frac{(Zt_1 + Zt_2 + Zt_3 + Zt_4)}{c_w} - \\ \frac{(Zp_2 + Zp_3 + Zp_4)}{c_w} - \\ (Wpu_2\ Tpu_2) - (Wpu_3\ Tpu_3) - (Wpu_4\ Tpu_4) - W_{spill}\ Tk_1 \qquad (6.43)$$

where $(M_{tot}T_z)\ c_w =$ total embodied energy in system (J)

In all tests performed agreement of both the mass and the energy balances was within 0.5%, indicating that there were unlikely to be program errors. The mass and energy balances around smaller parts of the system were more accurate (within 0.1%). All desired switching seemed to occur, thus indicating that the likelihood of undetected program errors was small. The model and program were therefore considered sufficiently tested.

6.2.8 Model Application

To illustrate the value of the model the plant discussed in Section 6.1 was modelled. This was a beef-only plant which had a beef kill area and beef boning room operating for one shift a day. The water usage rates were the "as measured" set of data.

Three different scenarios were simulated as follows:

(1) No heat recovery whatsoever.

(2) Heat recovery from rendering and steam condensate (6 a.m. - 5.40 p.m.).

(3) Heat recovery also including drain and refrigeration heat recovery (6 a.m. - 5.40 p.m.).

The plant which was simulated in Section 6.1.7 had no carcass wash flow rate, and so Tank 4 was disabled in all three scenarios. The hot water supply model determined values for Wpu_2 and Wpu_3.

Because heat recovery modules had not been developed, the nominal flow rates returning from the various heat recovery sources presented in Table 6.12 were used. The day modelled would be any week day except Monday so in the cases of scenarios which included heat recovery, initial levels of Tanks 1 and 2 would tend to reflect tank levels from the day before when production usage and heat recovery had ceased.

Table 6.12

Flow rates to various heat exchangers and temperature of flows out

Source	Flow rate (kg/s)	Temp. out (°C)
Wb_{rendr}	1.25	95
Wc_{rendr}	0.75	95
Wb_{sc}	0.4	95
Wc_{sc}	0.3	95
W_{refr}	1.0	50
W_{drain}	0.75	50

To ensure that a repeating cycle of behaviour would arise, it was necessary for the initial and final daily tank levels to match each other. It was also necessary to determine necessary tank sizes. A series of simulations was carried out for scenarios 2 and 3 to determine initial tank starting levels and tank volumes on a trial and error basis.

Scenario 1 Because no heat recovery was simulated Tanks 1 and 2 were disabled.

Scenario 2 The initial level in Tank 1 was set to zero as the only inflow that might be expected into this tank in this scenario would be a spillover from Tank 2 if that tank became overfull. Because the rendering and steam condensate recovery were operating after water use ceased, Tank 2 would be expected to have a level of at least 5.5 m^3, this being the predicted amount that would have accumulated during the previous day after water use ceased.

Scenario 3 Tank 1 was enabled with a starting volume of 18 m^3 as both the drain and refrigeration recovery were operating in this scenario as well as rendering and steam condensate recovery. Tank 2 had an initial level of 16 m^3.

To provide a meaningful comparison between simulations of the three scenarios the daily cold water usage and heat requirements for each were summed.

A: total cold water makeup to the system for the three runs:

$$\frac{d(Wc_{tot})}{dt} = Wc_{rec} + Wc_2 + Wc_3 + Wc_4 \qquad (6.44)$$

$$Wc_{rec} = Wc_{drain} + Wc_{refr} + Wc_{rendr} + Wc_{sc} \quad (6.45)$$

where Wc_{tot} = total cold water requirement (kg)

B: total heat input required also for the three runs:

$$\frac{d(H_{tot})}{dt} = H_2 + H_3 + H_4 \quad (6.46)$$

where H_{tot} = total daily heat requirement (J)

6.2.9 Results and Discussion

Predictions for daily cold water and heat requirements are shown in Table 6.13 and Figure 6.8. Predicted tank levels and capacities are presented in Table 6.14.

Figure 6.8(A) shows that the three scenarios use similar amounts of water for the day's production. Only Scenario 1 displays the plateaus discussed in Section 6.1.7.3 representing various rest breaks. This may be expected because with both Tanks 1 and 2 disabled the cold water demand flow rate follows production flow rate requirements exactly.

Table 6.13

Daily requirements for cold water and heat

Scenario	Total cold water Reqd. (m^3)	Total heat reqd. (GJ)
1	93.46	22.15
2	93.05	7.46
3	94.27	0.45

Table 6.14

Tank levels and sizing (m^3).

Scenario	Tank 1			Tank 2		
	Start Level	Finish Level	Reqd. Size	Start Level	Finish Level	Reqd. Size
1	Nil	Nil	Nil	Nil	0.37	28.00
2	Nil	Nil	Nil	5.50	5.46	6.00
3	18.00	18.00	18.00	16.00	15.90	16.0

Scenario 2 shows a somewhat more smoothed demand profile but begins to exhibit real time cleanup demand characteristics when hosing and showers commence at 32400s. This is because Tank 1 has been disabled and while hot water makeup through Wt_1 has been sufficient in the production mode, Tank 2 is unable to supply hot water for both Wt_3 and Wpu_2 during the cleanup mode. The level has temporarily fallen below the minimum level and the tank is unable to supply until the minimum operating level of $4.0m^3$ is reached.

Scenario 3 exhibits the smoothing effect of ample storage in Tanks 1 and 2. The cold water supply here is directed to heat recovery systems which are quite independent of production or cleanup demands. Thus if tank levels are kept above minimum levels the line rises smoothly throughout the day.

Figure 6.8(B) shows daily total heat requirements. Scenario 1 represents a case where no heat recovery is practical and gives an indication of the worst case energy consumption a plant might encounter in terms of hot water generation. Plateaus representing rest breaks are again evident because of the lack of stored water and heat requirements therefore matching production and cleanup mode demand.

Scenario 2 shows the benefit of heat recovery from the rendering and steam condensate. Cleanup mode demand depletes the reservoir of heat built up in Tank 2 and the energy requirement can be seen to rise quite steeply from 33000s to 37000s.

Energy use in Scenario 3 is small and represents only heat losses from both tanks and pipework. Energy recovery is sufficient to meet all other demands.

Figure 6.9(A) shows the level in Tank 1 (which is disabled in scenarios 1 and 2). Results from the trial and error simulations with various initial tank levels suggest that 18 m^3 is probably the most effective initial level and tank volume in Scenario 3 to avoid overflow yet provide sufficient storage of recovered heat so that cold water makeup is kept to a minimum.

Figure 6.9(B) shows various levels for Tank 2. Scenario 1 utilises this tank purely as a means of returning the ring main return, (Wr_2-Wpu_2) to the heat exchanger. The tank level does not return to exactly zero at the end of day, but this is not of practical importance.

Scenario 2 is the situation where the heat recovery is tuned reasonably closely to production demand and the tank is replenished in the period between cleanup hosing finishes and the rendering and steam condensate heat recovery ceases.

Scenario 3 is characterised by a slow buildup in Tank 2 during production. This is affected by levels in Tank 1 which drop below the minimum level and cause Wb_{rendr} and Wb_{sc} to shut off at 20000s thus involving Wc_{rendr} and Wc_{sc} as the flows to heat recovery and thence to Tank 2. This maintains a balance, apart from a small overflow from Tank 2 to Tank 1 during the lunch break. Stable operation continues until the cleanup mode demand flow rates reduce the level in Tank 2 between 32400s and 37800s. The tank level reaches 15.9 m^3 by the cessation of rendering.

Agreement between the mass and heat balances discussed above in all scenarios was better than 99.5% and so the model can be considered to be satisfactorily implemented.

Whilst the example used was to some extent hypothetical (because nominal flow rates from heat recovery were used) the benefits of having such a model include the ability to predict:

(i) Instantaneous cold water demands allowing sizing of various pipelines.

(ii) Total required cold water makeup for the hot water system, given differing heat recovery scenarios.

(iii) Instantaneous heat requirements at various heat generators.

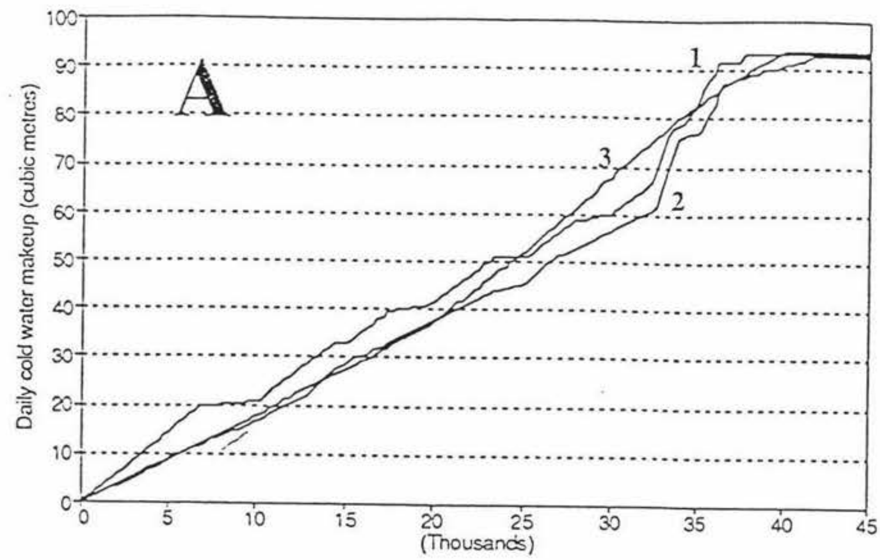
(iv) Total heat input requirements for heat exchangers.

(v) Reserves held in either Tank 1 or Tank 2 at any time of the day.

(vi) Minimum size required for storage tanks for various operating scenarios.

Various heat recovery systems are simply enabled or disabled by alteration of time steps. The model recognises that recovered heat should be used first and is intelligent enough to utilise this heat in the most efficient way with minimum mixing with hot water. Variations in tank capacities and Tank 1 and 2 operating levels are easily adjusted within the programme. Time variations of operating levels can also be manipulated within the time step section of the program.

The model was therefore considered to have complied with all the requirements outlined in section 6.2.2 and was adopted into the overall hot water model.



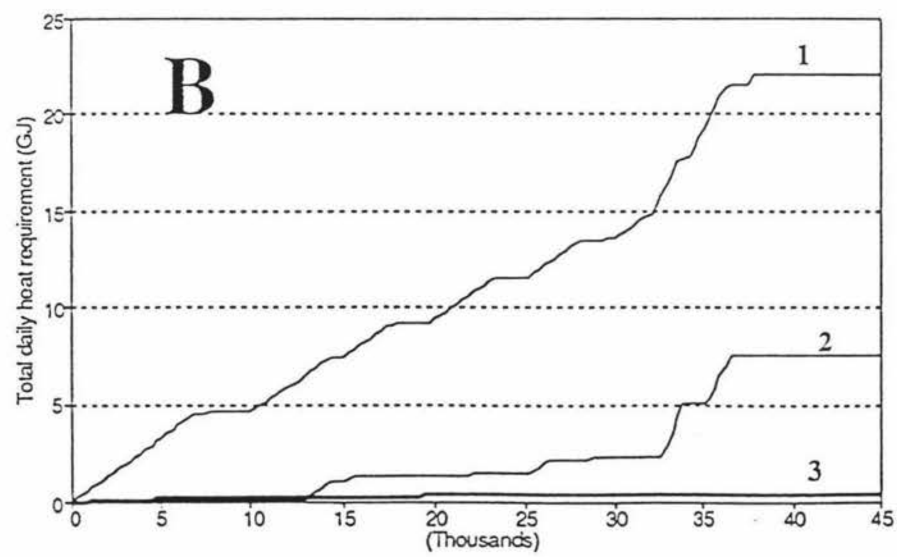
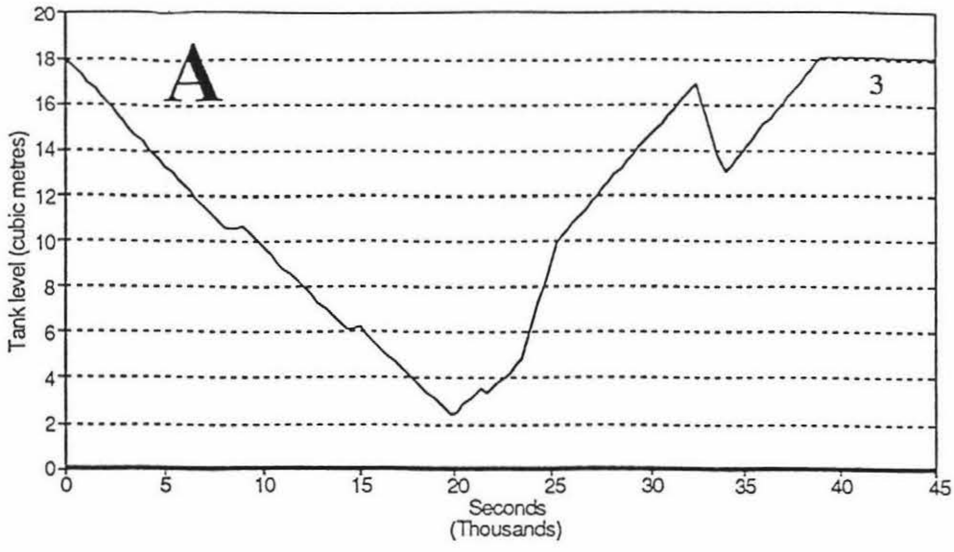


Figure 6.8 A: Plot of daily cold water makeup requirement (m^3) vs time (s)

B: Plot of daily total heat requirement H_{tot} (GJ) vs time (s)

Numbers indicate scenario number.



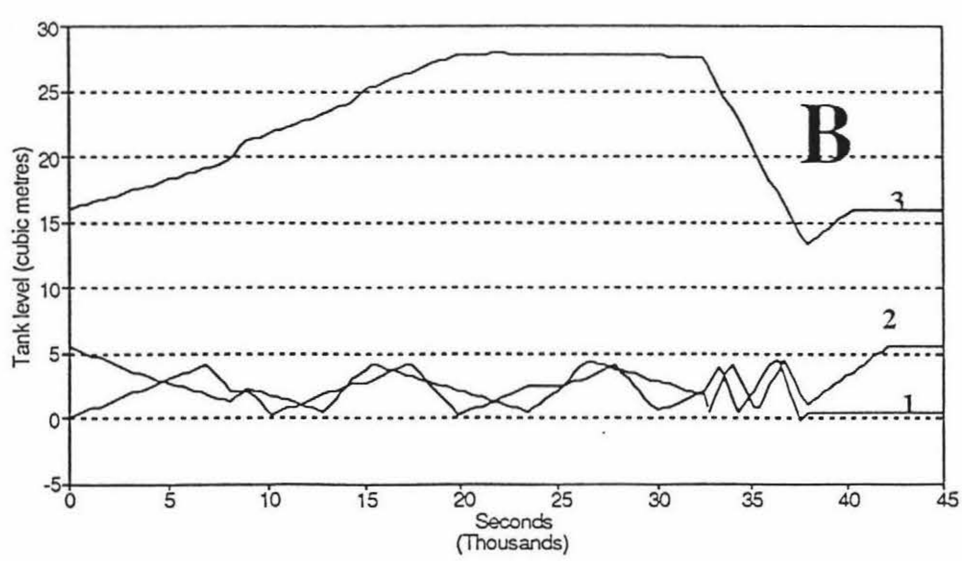


Figure 6.9 A: Plot of Tank 1 contents Mt_1 (m^3) vs time (s). Line 3 indicates scenario 3.

B: Plot of Tank 2 contents Mt_2 (m^3) vs time (s).

Numbers represent scenario number.

6.3 HEAT RECOVERY SYSTEMS

6.3.1 Mechanistic Process Description

Models are required for four types of heat recovery systems, each of which will be examined in turn. Each of these models requires interfacing to the heat supply model so that the recovered heat can be used. Other interfaces also exist - the refrigeration heat recovery model will interface to the refrigeration model, the steam condensate heat recovery model to all the models of steam users (e.g. hot water and rendering), the drain heat recovery model to the hot water demand model and the rendering heat recovery model to the rendering model. Only one heat recovery model has been implemented in software, but there should be no problems in implementing others because they are purely algebraic.

6.3.2 Rendering Recovery

The rendering systems investigated in this work all have heat recovery units capable of producing potable hot water. These units condense the vapour driven off the drying meat meal and heat potable water which is then passed to the hot water supply system. The heat exchanger usually consists of a vertical shell and tube condenser with the heated vapour entering the tubes at the top and non-condensible gases and water vapour condensate being led away from the bottom. The non-condensibles are usually scrubbed or burnt to comply with regulatory requirements. Cooling water enters the shell at the bottom and the flow rate is usually controlled by an automatic valve driven by a controller operating to a pre-determined outlet water temperature set point.

There are alternative methods of heat recovery to such a heat exchanger:

(i) recompression of vapour can in theory be used to provide the heat source for rendering, but then minimal hot water is recovered.

(ii) heat could be recovered from stick water.

In practice neither of these appears likely to be implemented in the near future, the former limited by the air content of the vapour, and the latter by heat exchanger fouling. What may be seen instead for stick water are ultrafiltration or evaporation systems (possibly with mechanical vapour recompression) to reduce pollution loads. None of these possibilities has been modelled within this work.

The amount of air present with the water vapour leaving the dryer has a significant effect on the temperature at which the water vapour will condense. This effect is relatively small for the indirectly heated rendering dryers provided reasonable efforts are made to prevent air ingress, but will affect the direct fired rotary drier which uses air as a heat and mass transport medium. This type of dryer typically has a ratio of air to water vapour of about 2:1, lowering the maximum possible condensation temperature to about 70-80°C . Figure 6.10 shows a schematic diagram of a typical heat recovery unit, and defines nomenclature.

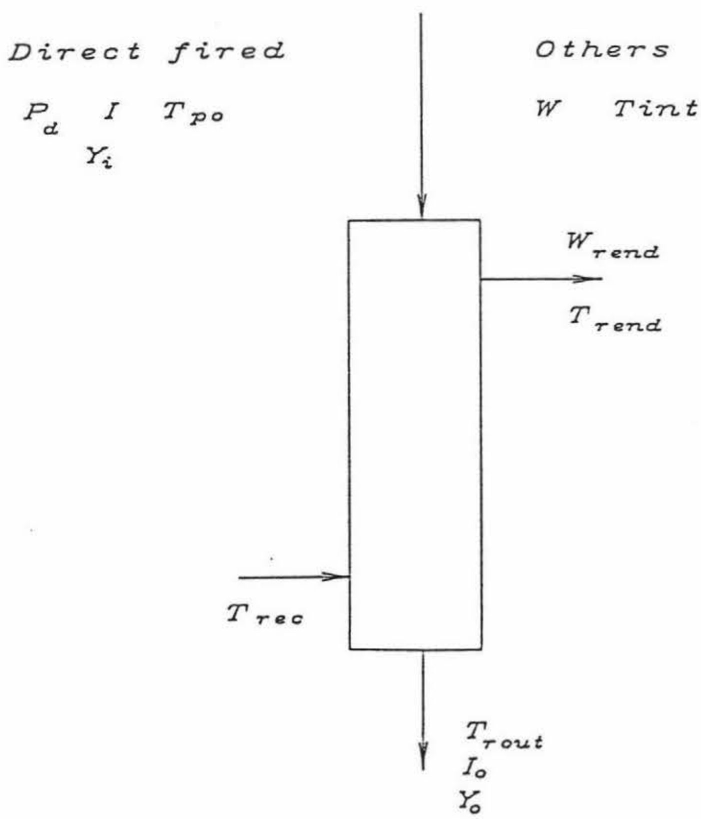


Figure 6.10 Schematic diagram of a rendering heat recovery system

As the thermal capacity of the unit is relatively small, heat storage within the metal etc. is ignored, as is start-up. This means the model is algebraic, and assumes instantaneous energy transfer from the gas stream leaving the dryer to the cooling water in the heat exchanger.

6.3.2.1 Direct fired dryer

The incoming waste heat stream from a direct fired rotary dryer contains a mixture of heated air and water vapour. The direct fired rotary dryer model described in Section 5.4.2 will supply the following data:

(i) P_d, flow rate of dry gas (kg dry gas/s),

(ii) I, moisture content of the outlet gas from the dryer (kg water vapour/kg dry gas),

(iii) T_{po}, temperature of the outlet gas from the dryer (°C).

The first step in the model is to calculate the maximum possible condensation temperature of the vapour from psychometric relationships, using the Antoine equation to relate water vapour pressure to temperature. The resultant equation is:

$$T_{sat} = \left[\frac{3990.56}{23.4795 - \ln\left[\frac{2937700\, I}{18 + 29\, I}\right]} \right] - 233.833 \qquad (6.47)$$

where T_{sat} = maximum possible condensation temperature of the moisture in the gas outlet stream (°C)

The outlet temperature of the water flow is defined by an approach factor to this temperature:

$$T_{rendr} = T_{sat} - \Delta T_a \qquad (6.48)$$

where T_{rendr} = temperature of the water flow leaving the heat recovery unit (°C)

ΔT_a = approach to maximum possible condensation temperature in heat recovery unit (°C)

The enthalpy of the incoming gas stream may be determined by the following approximate equation for the gas stream:

$$Y_i = 1.01\ T_{po} + I\ (2500 + 1.88\ T_{po}) \tag{6.49}$$

where Y_i = enthalpy of the gas stream into the heat exchanger (kJ/kg)

The outlet waste stream from the heat recovery unit is assumed to be at temperature T_{rout}, calculated by the approach to T_{renin}:

$$T_{rout} = T_{renin} + \Delta T_b \tag{6.50}$$

where T_{rout} = temperature of the outlet waste stream (°C)

T_{renin} = inlet temperature of the cooling water (°C)

ΔT_b = approach to the water inlet temperature (°C)

It is then assumed that the outlet humidity I_o corresponds to saturation at T_{rout}:

$$I_o = \frac{18\ P_v}{29\ (101325 - P_v)} \tag{6.51}$$

where P_v, the vapour pressure of water at temperature T_{rout} is found from the Antoine equation:

$$P_v = \exp\left(23.4795 - \frac{3090.56}{T_{rout} + 233.83}\right) \tag{6.52}$$

where I_o = outlet gas stream humidity (kg water/kg dry gas)

The outgoing air enthalpy is then calculated by the approximate gas stream enthalpy equation:

$$Y_o = 1.01\ T_{rout} + I_o\ (2500 + 1.88\ T_{rout}) \qquad (6.53)$$

where Y_o = enthalpy of the outgoing gas stream (kJ/kg)

There is also an outgoing condensed liquid stream, carrying with it embodied energy:

$$Y_l = (I - I_o)\ c_w(T_{rout} - 0) \qquad (6.54)$$

where Y_l = enthalpy of the outgoing condensed liquid stream (kJ/kg)

c_w = specific heat capacity of water (kJ/kgK)

Thus the total recovered heat is:

$$Y_{rend} = Y_i - Y_o - Y_l \qquad (6.55)$$

where Y_{rend} = enthalpy change across the rendering heat exchanger on the condensing vapour side (kJ/kg)

The water flow rate is then calculated by energy balance as:

$$W_{rend} = \frac{Y_{rend}\ P_d}{(T_{rendr} - T_{renin})\ c_w} \qquad (6.56)$$

The user must specify values of ΔT_a and ΔT_b (which are functions of heat exchanger size). Typical values might be 5-10°C.

6.3.2.2 Other rendering heat recovery units

It is assumed that all other forms of rendering waste heat streams have air contents so low as to be ignored so T_{sat} is assumed to be 100°C.

The energy recovered has three components:

(1) cooling of the vapour from the cooker exit temperature of 120-135°C to the condensation temperature of 100°C.

(2) latent heat released at the phase change from a gas to a liquid at 100°C.

(3) temperature drop of the liquid from condensation temperature to the heat exchanger exit temperature.

The exit temperature of the condensed waste stream T_{rout} is derived by use of equation (6.50). The energy available in the heat exchanger is then:

$$Y_{rend} = c_v \, (T_{int} - 100) + h_{fg} + c_w \, (100 - T_{rout}) \qquad (6.57)$$

where c_v = mean specific heat of vapour (kJ/kgK)

T_{int} = vapour temperature leaving the cooker (°C)

h_{fg} = latent heat of condensation at 100°C (kJ/kg)

The outlet temperature of the water is derived by use of equation (6.48). The water flow rate is then calculated using an energy balance:

$$W_{rend} = \frac{W \, Y_{rend}}{c_w(T_{rendr} - T_{renin})} \qquad (6.58)$$

The user must again specify values of ΔT_a and ΔT_b which are functions of heat exchanger size. Typical values might be 5-10°C.

6.3.2.3 Steam condensate heat recovery

Steam condensate should be returned whenever possible, and at the very least should come back from the rendering cooker or dryer and reactor (in LTR plants), and from the hot water supply system.

It is common to undercool the steam condensate returning to the hotwell to below 100°C to avoid flashing of steam if the hotwell is open to atmosphere (which is often the case). Pressurised systems may also sometimes have to be undercooled to avoid vapour lock in the boiler feed water pumps caused by temperatures above 100°C unless some static head is provided. Figure 6.11 illustrates the arrangement for this heat recovery unit which usually consists of a shell and tube or plate heat exchanger.

As was the case for rendering heat recovery the thermal capacity of the heat recovery unit was ignored, and an algebraic model used.

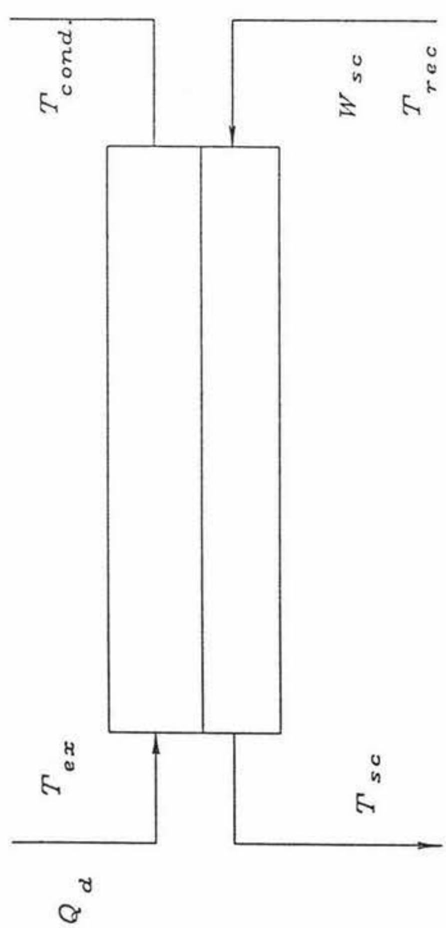


Figure 6.11 Schematic diagram of a steam condensate heat recovery system

A mass balance across the steam condensate heat exchanger is:

$$W_{sc} = \frac{Q_d\ (T_{ex} - T_{cond})}{(T_{sc} - T_{scin})} \tag{6.59}$$

$$T_{cond} = T_{scin} + \Delta\ T_c \tag{6.60}$$

$$T_{sc} = 100.0 - \Delta\ T_d \tag{6.61}$$

where W_{sc} = flow rate of water through the heat recovery unit (kg/s)

Q_d = steam condensate flow rate through the heat recovery unit (kg/s)

T_{ex} = condensate entry temperature (°C) (is always assumed to be >100°C)

T_{cond} = temperature of the cooled steam condensate leaving the heat recovery unit (°C)

T_{sc} = temperature of the heated water leaving the heat recovery unit (°C)

T_{scin} = temperature of cooling water to the heat recovery unit (°C)

ΔT_c = approach to the inlet cooling water temperature (°C)

ΔT_d = approach to 100°C of water leaving the heat recovery unit (°C)

Users must specify ΔT_c and ΔT_d which are both functions of heat exchanger design. Typical values might again be 5-10°C.

6.3.2.4 Drain heat recovery

The practice of recovering heat from waste water downstream of sterilisers and washbasins through some form of heat exchanger as described in Section 6.2.2 does not appear to exist at present in New Zealand. Used steriliser and hand and apron wash water would gravitate through closed pipe drains to a collection tank placed below floor level. A small lift pump would pass the waste water at a temperature of about 50°C through a suitable heat exchanger and then to waste. Cold water would be introduced to the other side of the heat exchanger and be heated to about 45°C before being passed to the heat supply system.

The model of the system simulates a balance tank and heat exchanger as shown in Figure 6.12. Water will probably be recovered from various user-selected departmental sterilisers and hand and apron washes wastes when the plant is operating in production run mode only. At other times when hosing and showers are taking place there will be no recovery because the recovered temperature will be so low that recovery is not warranted.

The thermal storage capacity of the tank and heat exchanger are assumed to be small and so heat storage is ignored. This meant that the model could be developed using algebraic equations.

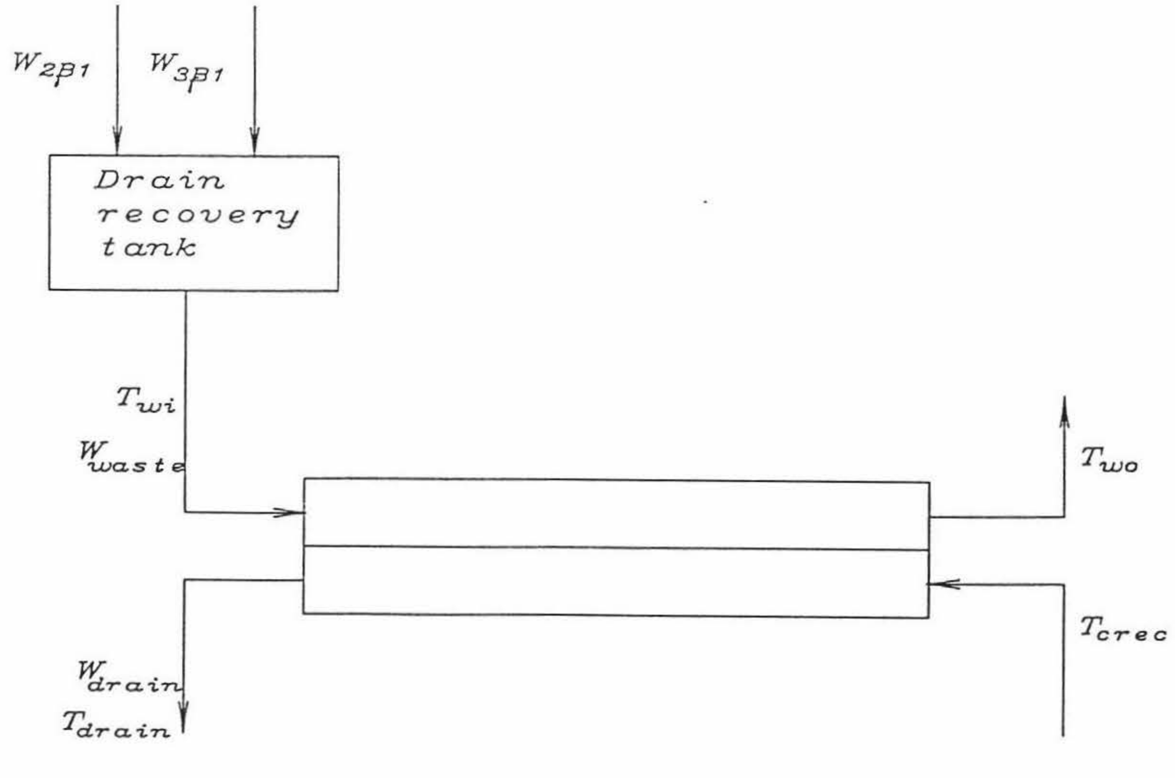


Figure 6.12 Schematic diagram of a drain heat recovery system

A mass balance across the drain recovery tank is:

$$W_{waste} = W_{2\beta 1} + W_{3\beta 1} \tag{6.62}$$

where W_{waste} = total flow rate of drain water (kg/s)

$W_{2\beta 1}$ = recovered steriliser waste water flow rate from user selected departments (kg/s)

$W_{3\beta 1}$ = recovered hand and apron wash water flow rate from user selected departments (kg/s)

Steriliser water is supplied to departments at temperature Tpu_2, but is assumed to arrive at the heat recovery unit at temperature (Tpu_2 - ΔT_e) thus taking account of heat loss. Similarly, hand and apron wash water supplied at temperature Tpu_3, returns to the heat recovery unit at temperature (Tpu_3 - ΔT_f). The temperature of the mixed flow, determined by energy balance is:

$$T_{wi} = \frac{W_{2\beta 1}\ (Tpu_2 - \Delta T_e\ ) + W_{3\beta 1}\ (Tpu_3 - \Delta T_f\ )}{W_{waste}} \tag{6.63}$$

where T_{wi} = mean temperature of recovered waste water (°C)

Tpu_2 = temperature of steriliser water (°C)

Tpu_3 = temperature of hand and apron wash water (°C)

ΔT_e = drop in steriliser water temperature from point of use to heat recovery unit (°C)

ΔT_f = drop in hand and apron wash water temperature from point of use to heat recovery unit (°C)

Users must specify values for ΔT_e and ΔT_f. These values may change from plant to plant and it is suggested that the user choose values which best reflect local conditions.

An energy balance across the drain heat exchanger then yields W_{drain}, the water flow rate:

$$W_{drain} = \frac{W_{waste}\ (T_{wi} - T_{wo})}{(T_{drain} - T_{crec})} \tag{6.64}$$

$$T_{wo} = (T_{crec} + \Delta T_g) \tag{6.65}$$

$$T_{drain} = (T_{wi} - \Delta T_h) \tag{6.66}$$

where T_{wo} = temperature of the waste water leaving the heat recovery unit °C

W_{drain} = water flow rate through heat recovery unit (kg/s)

T_{crec} = temperature of cold water entering the heat recovery unit (°C)

ΔT_g = approach to cold water inlet temperature (°C)

ΔT_h = approach to the waste water temperature (°C)

The user must specify values for ΔT_g and ΔT_h which are functions of heat exchanger design. Typical values again might be 5-10°C.

6.3.2.5 Refrigeration heat recovery

In a typical meat plant refrigeration system compressor discharge gas is passed through refrigeration oil separators, desuperheaters (where fitted) and then condensers. There are also oil coolers associated with many screw compressors. The heat exchangers traditionally consist of shell and tube heat exchangers with the refrigerant passing through the shell and the cooling water through the tubes but plate heat exchangers are being used occasionally. Condensers may be air cooled but this type will not be considered in this work. Direct compressor cooling (e.g. of reciprocating compressors) could provide some hot water, but because screw compressors are becoming increasingly dominant direct compressor cooling was not modelled.

While the discharge gas from the refrigeration compressors may be as hot as 70-100°C the maximum recoverable condenser water temperature from condensers is usually lower than the refrigerant condensing temperature, (typically 25-30°C). This is because the bulk of the energy available is latent heat and thus the maximum water outlet temperature can only approach the condensing temperature.

Both the lubricating oil and superheated vapour are considered to have a high enough temperature to allow economic heat recovery for the hot water supply system. It is recognised that at least one meat plant in New Zealand is recovering heat from condensers for potable hot water by deliberately allowing the compressor discharge pressure (and thus the temperature) to increase the water outlet temperature. This increases the required compressor shaft power to some extent. This is effectively a heat pumping operation, and the rules of pinch technology state that such options should not be considered until a full pinch analysis has been done. Therefore, it was decided to construct the model in such a way that simulation of deliberate elevation of the condensation temperature in one or more of a bank of condensers, could be added with relative ease at a later stage, but not to directly include this option in the present model. In practice, the condenser bank has to be broken into two parts, the first still using non-potable water and in which the condensate temperature is kept as low as possible, and the second in which the condensation temperature may or may not be elevated, but potable water is used. The feed of water to oil coolers and desuperheaters would then come from the outlet of the second bank of condensers.

The model of the superheated gas and oil cooling is illustrated in Figure 6.13, with the desuperheater being an optional addition.

It was decided that the only refrigerant that required modelling was ammonia (R717). Figure 6.14 shows a typical high-stage compression from a suction pressure of 3 bars absolute (saturated suction temperature of -9°C) to a discharge pressure of 11 bars absolute (saturated discharge temperature of 30°C). The various points marked are as follows:

A Isentropic compression discharge point. This represents the theoretical discharge temperature and enthalpy value of the gas leaving the compressor.

It is found by calculating the theoretical energy requirement for compression and adding this to the suction vapour enthalpy.

B Real compression discharge point without cooling. The compressor cannot compress the gas with 100% efficiency. Point B is determined by adding the real energy required for compression (theoretical/isentropic efficiency) to the suction vapour enthalpy.

C Real discharge point with cooling during compression. The compressor manufacturer usually decides the desirable discharge temperature. This temperature is maintained by the presence of oil which lubricates the compressor working parts, provides a vapour seal in the compression area, and absorbs heat. This oil flows out of the compressor in suspension with the discharge gas. The discharge gas is passed through an oil separator and the separated oil is then pumped through an oil cooler where heat is given up to cooling water and the oil returned to the compressor at a temperature of about 45°C. Point C is located from thermodynamic data for the refrigerant using the discharge pressure and desired discharge temperature as input.

The energy lost to the oil is determined by subtracting the enthalpy at point C from point B.

D Desired temperature of gas leaving the desuperheater. This is nominated by the user and is assumed to be in the superheated vapour region. The enthalpy at D is determined from the input temperature and discharge pressure. The energy available in the desuperheater is the enthalpy difference between C and D.

A later model refinement could allow the gas within the desuperheater to partially condense thus bringing the point D to within the wet region on the Mollier diagram. Increased recovered energy would be traded off against a lower temperature difference. This possibility would require a specialist design of both the desuperheater and the condenser and was not considered in the present model.

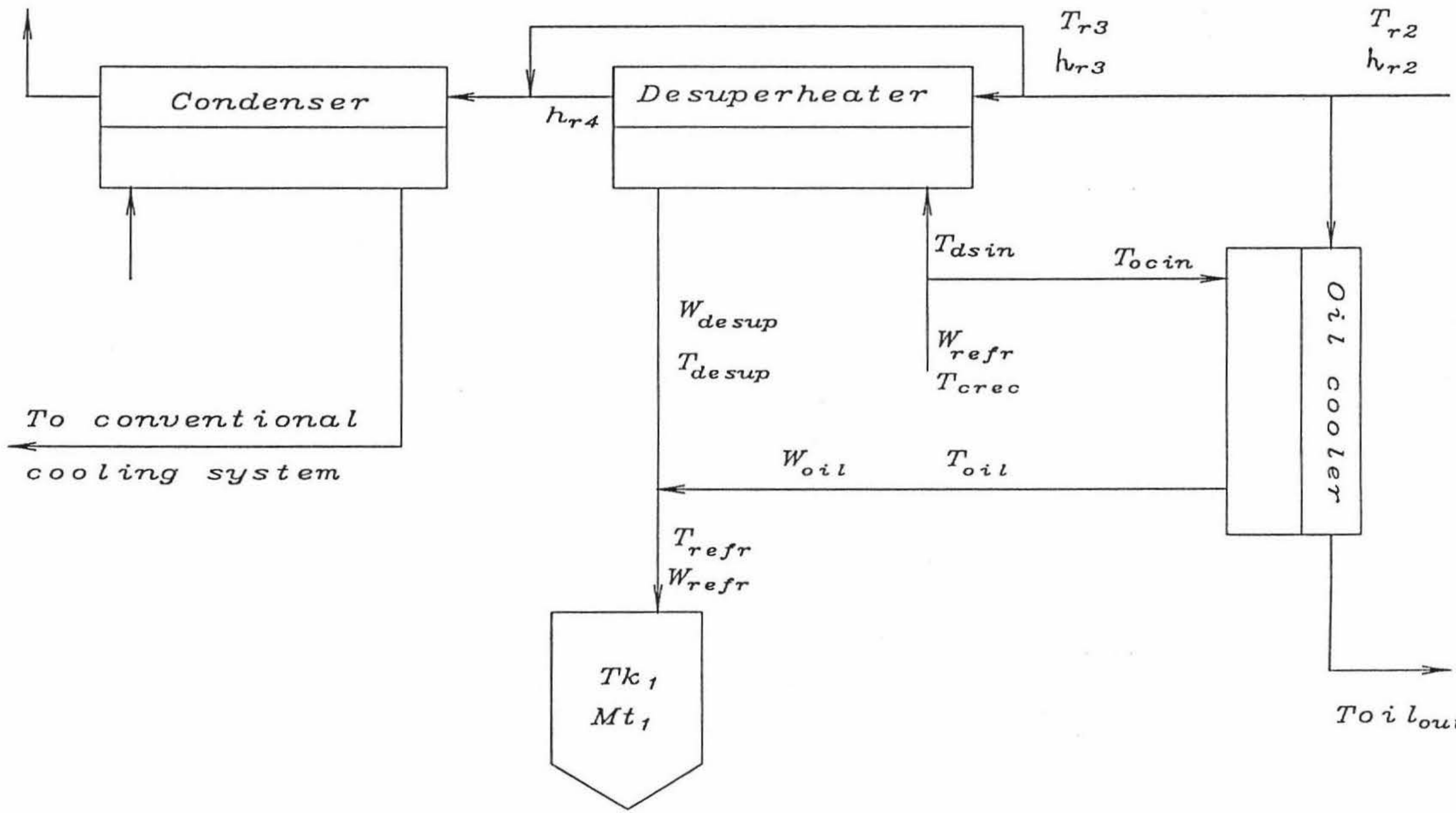


Figure 6.13 Schematic diagram of a refrigeration heat recovery system.

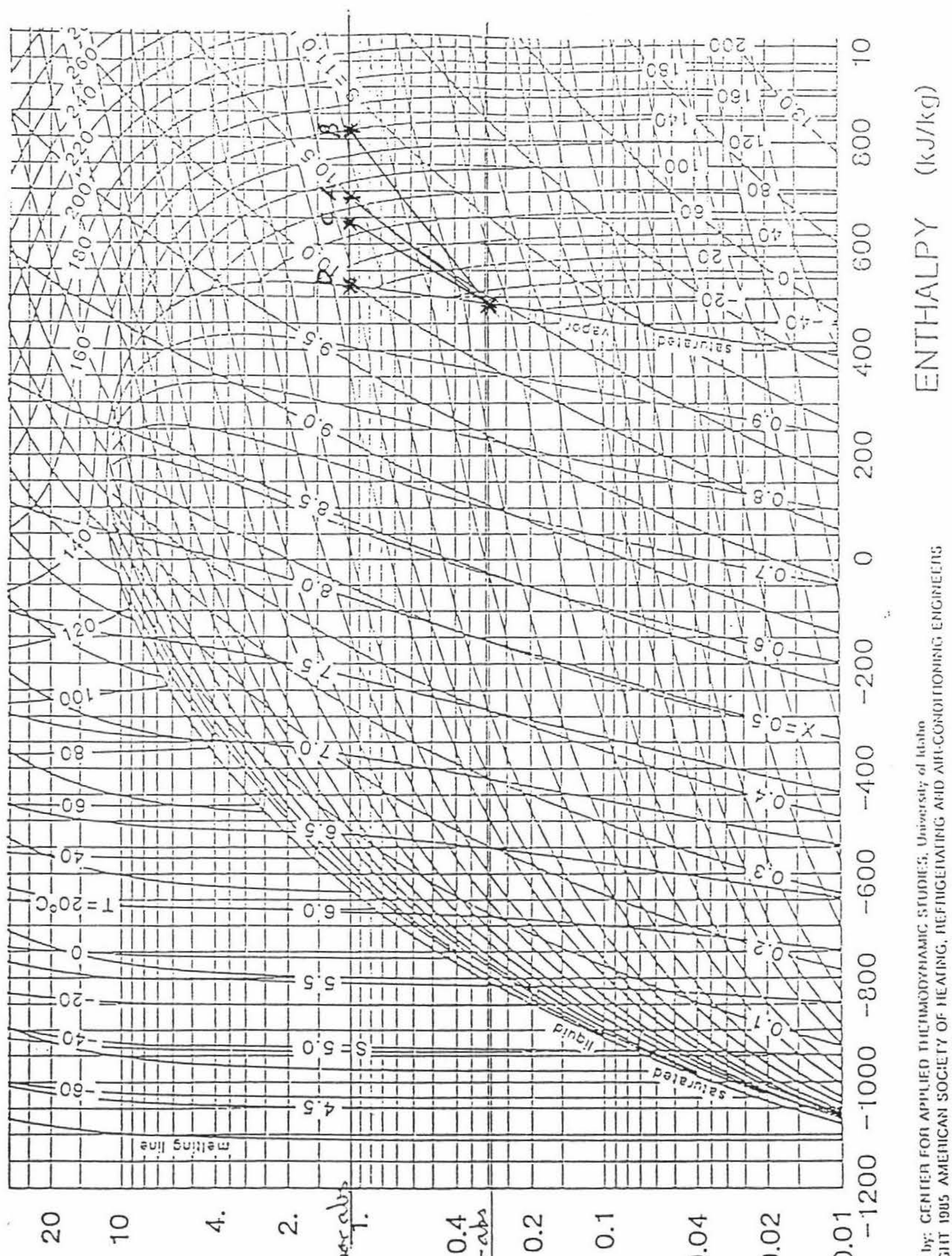


Figure 6.14 Mollier diagram for Ammonia (R717) showing various enthalpy points for refrigeration heat recovery.

The refrigeration section of the model will require the following data from the user:

(i) suction pressure P_s,

(ii) discharge pressure P_d,

(iii) mass flow rate of refrigerant R (which will be determined from the refrigeration system model),

(iv) design discharge gas temperature exiting the oil cooler T_{r3},

(v) a parameter to specify whether desuperheating is to be modelled,

(vi) design discharge gas temperature exiting the desuperheater (if specified) T_{r4}.

Note that saturated suction vapour is assumed.

The model will then calculate a number of intermediaries:

(i) saturated vapour specific volume (suction),

(ii) saturated vapour enthalpy (suction),

(iii) enthalpy change in isentropic compression,

(iv) compressor isentropic efficiency,

to finally determine:

(v) enthalpy at the end of compression assuming no cooling (point B),

(vi) enthalpy at the end of oil cooling (point C),

(vii) enthalpy at the end of desuperheating (if specified) (point D).

6.3.2.6 Thermodynamic variables

Cleland (1986) developed empirical constants ($a_{\#}$, $b_{\#}$ & $c_{\#}$) and subroutines for rapid evaluation of refrigerant thermodynamic properties. These routines were used, but any other accurate thermodynamic data could be substituted.

(i) Saturated vapour specific volume. Because the suction superheat would be small the specific volume is calculated only for saturated vapour conditions thus:

$$\mathrm{v}_v = e^{\frac{(a_{19} + a_{20})}{(T_{satr} + 273.15)}} (a_{21} + a_{22}T_{satr} + a_{23}T_{satr}^2 + a_{24}T_{satr}^3) \tag{6.67}$$

where v_v = saturated suction vapour specific volume (m^3/kg)

T_{satr} = temperature of saturated refrigerant vapour (°C)

(ii) Saturated suction vapour enthalpy:

$$h_{vs} = h_{il} + a_{12} \tag{6.68}$$

$$h_{il} = a_8 + a_9T_{sat} + a_{10}T_{sat}^2 + a_{11}T_{sat}^3 \tag{6.69}$$

where h_{vs} = saturated suction vapour enthalpy (J/kg

h_{il} = enthalpy intermediate value (J/kg)

a_β = coefficient from Cleland (1986)

(iii) Enthalpy change in isentropic compression may be determined by:

$$\Delta h = \frac{c}{c-1} P_s \mathrm{v}_v \left(\left(\frac{P_d}{P_s} \right)^{\frac{c-1}{c}} - 1 \right) \tag{6.70}$$

where Δh = enthalpy change in isentropic compression (J/kg)

c = empirical coefficient determined by Cleland (1986)

P_s = absolute suction pressure (Pa)

P_d = absolute discharge pressure (Pa)

(iv) Compressor isentropic efficiency (η_i):

The compressor pressure ratio is:

$$PR = \frac{P_d}{P_s} \tag{6.71}$$

where PR = compressor pressure ratio

Cleland (1988) presents "good practice" data for isentropic efficiency vs pressure ratio. In the manner of Section 7.6.2 these have been curve-fitted and a part-load factor of 0.9 added to yeild:

$$\eta_i = 0.90\ (0.753\ -\ 0.000948\ (PR)^2) \qquad (6.72)$$

where η_i = compressor isentropic efficiency

(v) Enthalpy at point B.

The compressor uncooled discharge enthalpy may now be calculated:

$$h_{r2} = h_{vs} + \frac{\Delta h}{\eta_i} \qquad (6.73)$$

where h_{r2} = uncooled compressor discharge enthalpy (J/kg)

(vi) and (vii) Enthalpy at points C and D.

The following equations may now be used to calculate superheated vapour enthalpies h_{r3} and h_{r4}:

$$h_{r\beta} = h_{i2} + a_{12} \qquad (6.74)$$

$$h_{i2} = h_{il}\ (1 + a_{13}\ \Delta T_s + a_{14}(\Delta T)^2 + a_{15}(\Delta T_s)\ (T_{satd}) + a_{16}\ (\Delta T_s)^2\ (T_{satd}) + a_{17}(\Delta T_s)\ (T_{satd})^2 + a_{18}(\Delta T_s)^2\ (T_{satd})^2) \qquad (6.75)$$

The Antoine equation for T_c is as follows:

$$T_c = \left[\frac{a_2}{\ln\ (P_d) - a_1} \right] - a_3 \qquad (6.76)$$

where $h_{r\beta}$ = superheated vapour enthalpy (J/kg)

h_{i2} = intermediate enthalpy value (J/kg)

T_c = saturated discharge temperature calculated from P_d

ΔT_s = temperature difference between saturation and superheat (°C). (ΔT_s takes different values at points C and D.)

6.3.2.7 Mass and energy balances

A mass balance across the entire refrigeration recovery system is:

$$W_{refr} = W_{oil} + W_{desup} \tag{6.77}$$

where W_{refr} = total water flow rate leaving the refrigeration heat recovery system (kg/s)

W_{oil} = flow rate of water through the oil cooler (kg/s)

W_{desup} = flow rate of water through the desuperheater (kg/s)

An energy balance across the entire refrigeration heat recovery unit is:

$$T_{refr} = \frac{(W_{oil}\ T_{oil}) + (W_{desup}\ T_{desup})}{W_{refr}} \tag{6.78}$$

$$T_{oil} = T_{r2} - \Delta T_i \tag{6.79}$$

$$T_{desup} = T_{r3} - \Delta\ T_j \tag{6.80}$$

where T_{refr} = temperature of the water flow leaving the total refrigeration heat recovery unit (°C)

T_{oil} = temperature of the water flow leaving the oil cooler (°C)

T_{desup} = temperature of the water flow leaving the desuperheater (°C)

T_{r2} = temperature of the oil at the oil cooler inlet (equal to discharge gas temperature) (°C)

ΔT_i	=	approach of oil cooler water outlet temperature to the oil inlet temperature (°C)
T_{r3}	=	temperature of the discharge gas flow at the inlet of the desuperheater (°C) (equal to Tr_2)
ΔT_j	=	approach of the desuperheater water outlet temperature of the discharge gas at the inlet of the desuperheater (°C)

The user must specify values of ΔT_i and ΔT_j (which are functions of heat exchanger size). Typical values might be 5-20°C.

The water flow rate through the oil cooler may now be derived by:

$$W_{oil} = \frac{R\ (h_{r2} - h_{r3})}{c_w\ (T_{oil} - T_{ocin})} \tag{6.81}$$

where R	=	the discharge gas flow rate (kg/s)
h_{r2}	=	enthalpy of the discharge gas flow at the oil cooler inlet (J/kg)
h_{r3}	=	enthalpy of the discharge gas flow at the desired oil cooler exit temperature (J/kg)
T_{ocin}	=	temperature of cooling water to the oil cooler (°C) (equal to T_{crec})
c_w	=	specific heat capacity of the cooling water (J/kgK)

The water flow rate through the desuperheater may now be calculated by:

$$W_{desup} = \frac{R\ (h_{r3} - h_{r4})}{c_w\ (T_{desup} - T_{dsin})} \tag{6.82}$$

where h_{r4}	=	enthalpy of the discharge gas flow at the desuperheater exit (point D) (J/kg)
T_{dsin}	=	temperature of the cooling water to the desuperheater (°C) (equal to T_{crec})

To model use of the outlet water from a condenser as cooling water for the

(°C) (equal to T_{crec})

To model use of the outlet water from a condenser as cooling water for the desuperheater and oil cooler, the user would set T_{crec}, T_{ocin} and T_{dsin} equal to the estimated condenser outlet water temperature.

6.3.3 Model Implementation and Testing

Time did not permit implementation and testing of all the heat recovery models. As an example it was decided that the rendering heat recovery model of Section 6.3.1.3 would be coupled to the model developed in Section 5.1.2 for a continuous conduction dryer (Keith Cooker) plus a steam condensate heat recovery unit for the dryer only. The continuous dry rendering model listing in Appendix B1 contains the steam condensate heat recovery unit programme addition.

The mass and energy balances equations were incorporated into an advanced continuous system simulation language software package but made part of the earlier rendering program (Hay *et al.* 1988).

The combined model would again use data and conditions stated in Section 5.1.7.2.

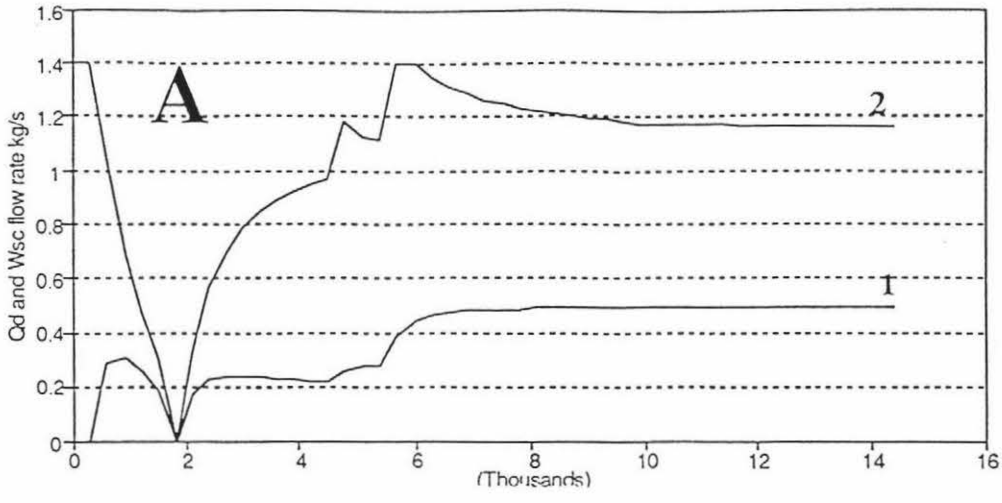
Hand calculations were carried out to ensure that predictions for flow rates leaving the rendering and steam condensate heat recovery units were accurate at different times during simulation.

6.3.4 Results and Conclusions

Figure 6.15 (A) shows the steam usage rate predicted in Section 5.1.7.4, with the predicted hot water flow rates from the steam condensate heat exchanger model. Both flow rates are reasonably consistent showing that the recovered hot water flow rate varies in response to process demands for steam.

Figure 6.15 (B) shows the predicted evaporated moisture flow rates predicted in Section 5.1.7.4 and the predicted hot water flow rate from the rendering heat recovery model developed in this Section. Line 2, the predicted recovered hot water, appears to fluctuate much more than line 1, the evaporated water from the Keith cooker. This is not real, but a visual effect arising from the scales used.

Time did not permit all the heat recovery models developed to be tested within ESL. Nevertheless the two models that were tested at various time intervals by hand calculations were found to be accurate. The models were judged to be sufficiently accurate to be adopted into the overall meat plant energy model.



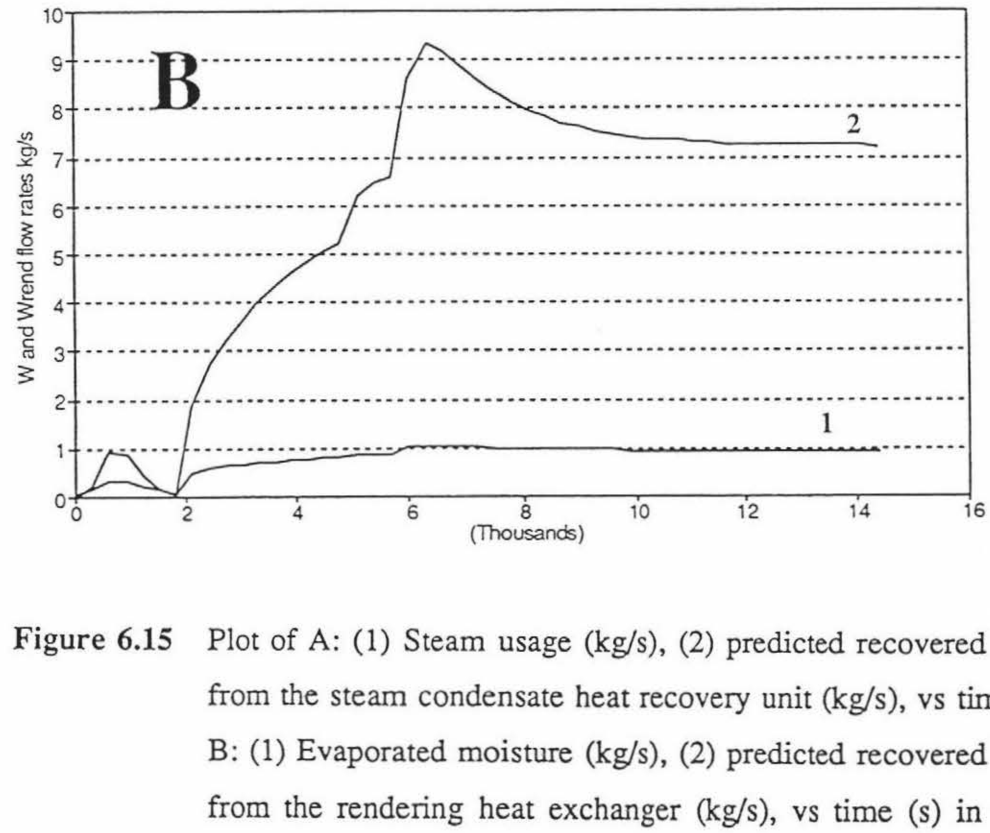


Figure 6.15 Plot of A: (1) Steam usage (kg/s), (2) predicted recovered hot water from the steam condensate heat recovery unit (kg/s), vs time (s). B: (1) Evaporated moisture (kg/s), (2) predicted recovered hot water from the rendering heat exchanger (kg/s), vs time (s) in the Keith cooker at AFFCO Rangiuru. Simulations used final values defined in Figure 5.8, Section 5.1.8, i.e. U_1 = 750 W/m^{2}K, x_f =1.242 kg water/kg dry solids.

7 REFRIGERATION

7.1 MECHANISTIC DESCRIPTION

Refrigeration processes within a meat plant may be considered to have five distinct purposes.

(1) Air conditioning of process rooms to below 10°C to meet process regulations, or at higher air temperatures to provide worker comfort.

(2) Chilling of carcasses or sides using air temperatures of 0-15°C.

(3) Chilling and subsequent storage of cartons of meat cuts using air at about 0°C.

(4) Freezing of product using a cooling medium at below -20°C and sometimes as low as -40°C.

(5) Cold storage of frozen product at less than -12°C.

Figure 7.1 shows a schematic diagram of product flow through a meat plant illustrating the various ways in which these five types of operation can combine.

It is common to operate at least two suction pressure vessels (pots) within the refrigeration system in order to maintain an economical coefficient of performance (COP, defined as the ratio of cooling achieved/energy used). The COP drops sharply as the ratio refrigeration system widens.

Process requirements dictate that the low pressure (LP) system should run at -30 to -40°C, and the intermediate pressure (IP) system at -5 to -10°C. The discharge pressure (HP) should be as low as possible although this will depend on the temperature of the condenser coolant. Figure 7.2 shows a typical meat plant engineroom layout incorporating a two stage system; two stage compression of the LP vapour is necessary for energy efficient operation.

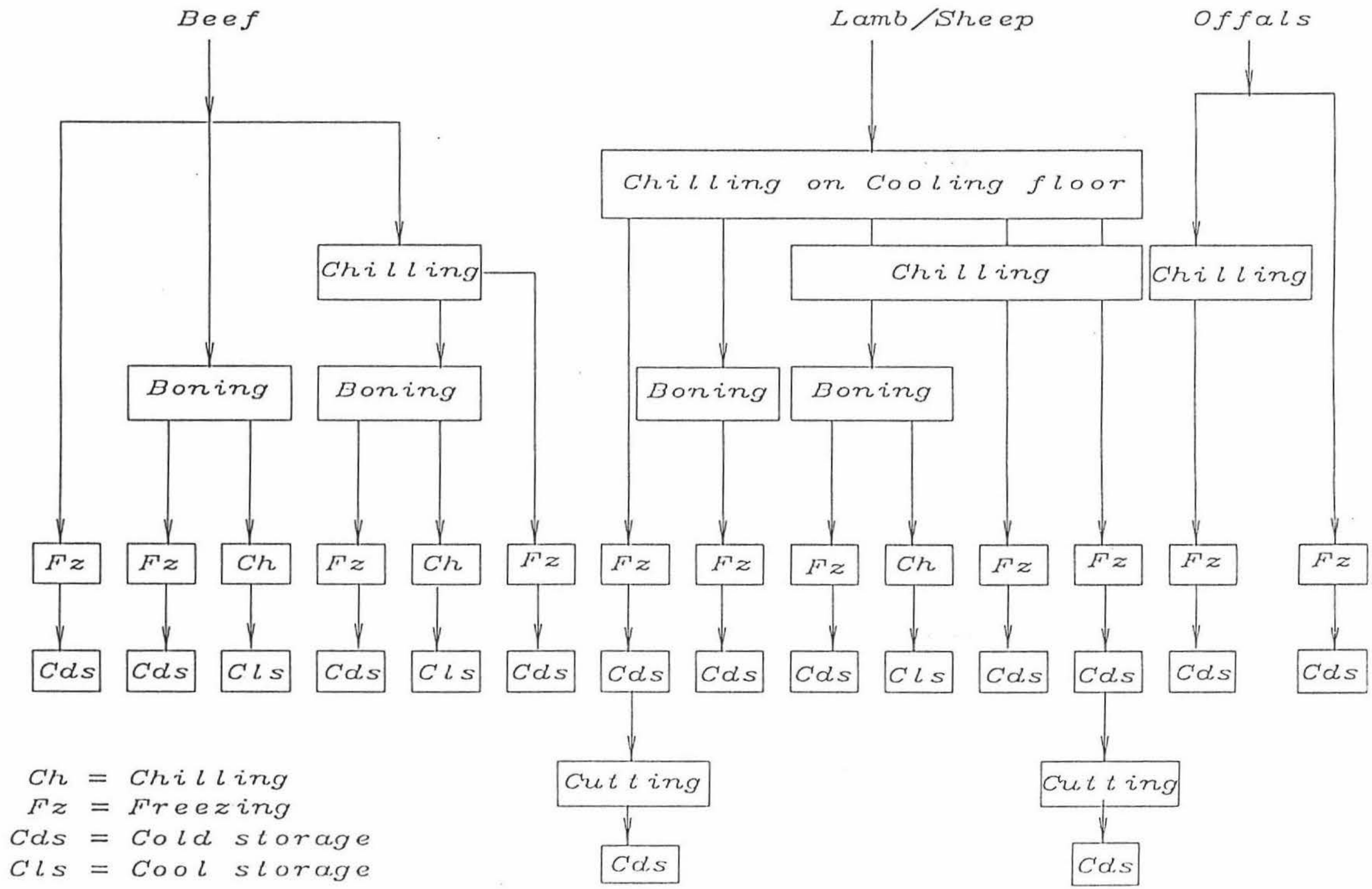


Figure 7.1 Schematic diagram of possible product flow pathways through a meat plant cold chain.

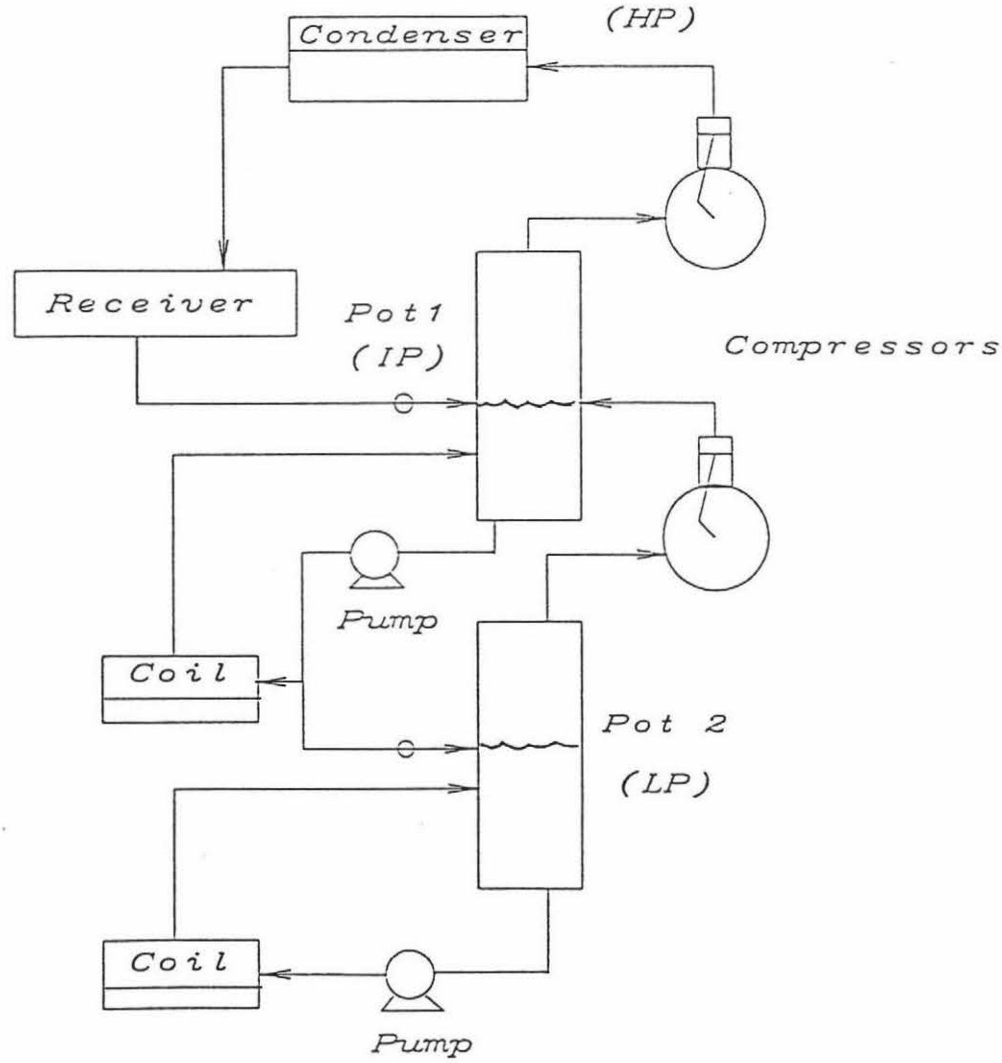


Figure 7.2 Schematic diagram of a two stage compression refrigeration system

7.2 DESIGN PHILOSOPHY

7.2.1 General Philosophy

The approach taken in the design of a refrigeration system model was quite different to that used to develop models for rendering and hot water. In the latter two cases, no models existed, or else existing models were inadequate, so new, and in some cases more complex models, were developed.

For refrigeration systems, models have been extensively developed; the work of Lovatt (1992) and Pham (1991) represents the present state of the art. Such models focus entirely on a room by room approach - Lovatt (1992) used dynamic models for a large number of parameters including air, product and structures, as had Marshall and James (1975), and Cleland (1983,1985). Pham (1991) used a dynamic model for the product only; algebraic models were used for all other parameters. He achieved a major reduction in computation time and some reduction in data requirements but at the expense of some loss of accuracy. However, it was still necessary to have detailed data on a room by room basis, and for the engineroom.

A refrigeration model that will form part of an overall meat plant energy model does not have to get the detail of each room right. Rather, it need only predict the overall electricity use vs time profile accurately. The very substantial data inputs required by earlier methods are a concern. If the room by room approach could be abandoned in favour of an alternative method that significantly reduced input data needs, this would be a major advantage. The basis of the new model design was chosen taking these factors into account.

A key question is whether the model should represent both existing practices and good practice. There are very different designs of freezers, chillers etc. within the meat industry so a general model capable of covering existing practice would need substantial data inputs. It would inevitably return to a room by room analysis. In contrast, a good practice model would consider room design in a more abstract sense. For example, if all chillers were designed to good practice the overall plant electricity would be effectively the same at any time, irrespective of which chiller was used. Thus, development of a good practice model can be carried out in a manner that does not require specific knowledge of each room. Instead it uses data for room types, but these data are fewer, and presented in more generalised form. Should it be necessary to model existing practice the models of Lovatt (1992) can be applied on a room by room basis via software products such as RADS, (Cornelius 1991); REFSIM, (Lovatt 1992) or LOADS, (Pham 1991).

Figure 7.3 illustrates the model philosophy for the good practice model. As was discussed in Section 4.5.2, the refrigeration model will respond primarily to flows of product originating in the generic model. Chillers and freezers are only operated in response to product flow so these operations must be modelled in a product related manner. In contrast, cold and cool stores operate with relative independence of the product flows from the generic model so they were modelled independently. Boning and cutting rooms respond to the need to operate arising from product flows, but their refrigeration demand is not significantly affected by product heat load.

The refrigeration load for chillers and freezers may be considered in two groups:

(1) product load,

(2) product-related loads consisting primarily of:

- (i) fans,
- (ii) wall, floor and ceiling surface gains, and
- (iii) doors.

The product and product-related heat loads are driven by product movement through the plant refrigerated environment rather than the demand generated by existing structures or management practices. A general, but realistic relationship between product and product-related loads was sought so that the model delivers good practice estimates of the latter rather than requiring the user to input data for doors, surfaces, fans, etc.

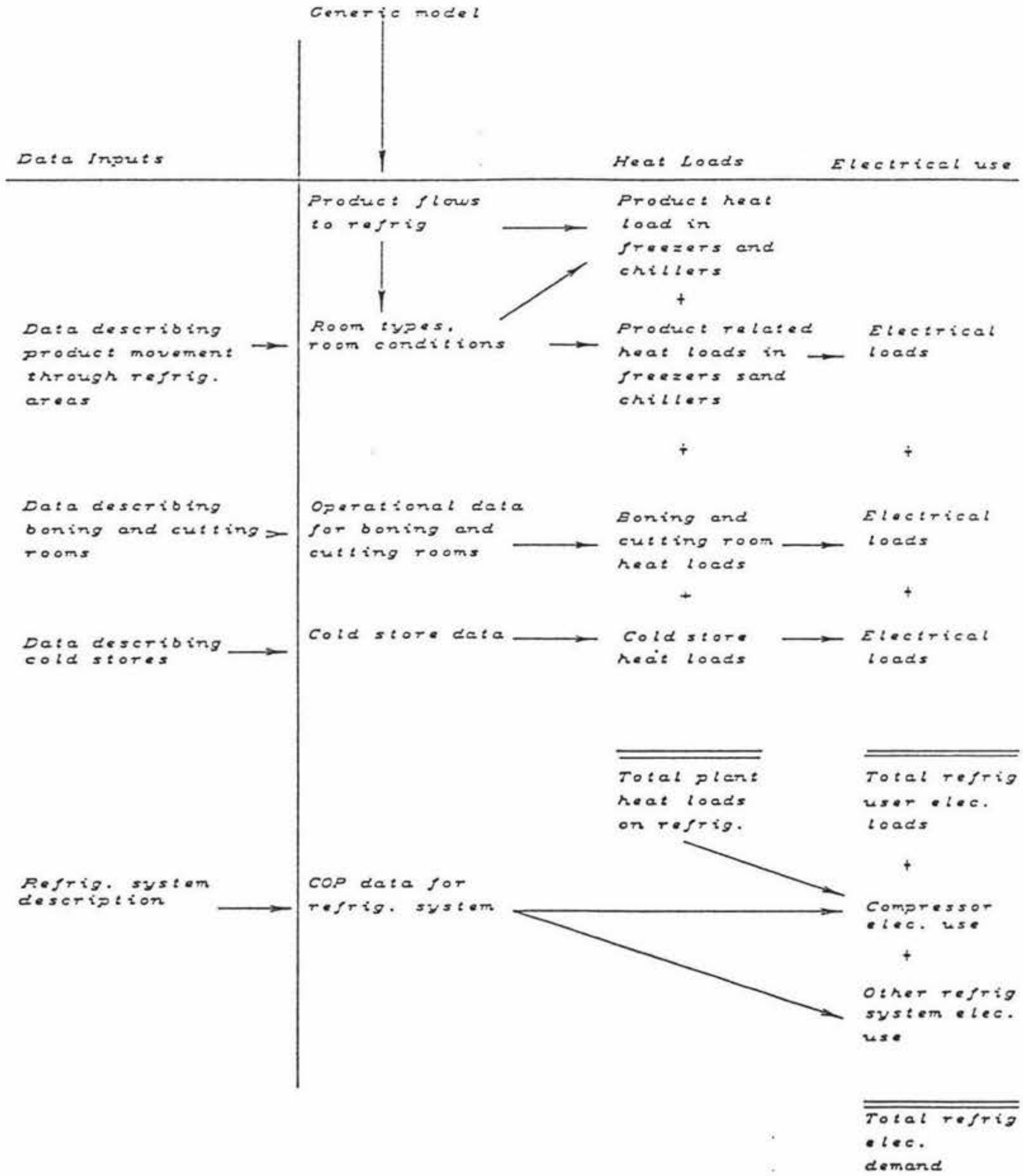


Figure 7.3 Schematic diagram of good practice refrigeration system model philosophy.

As well as product and product-related loads, there are base loads consisting of:

(i) cold stores,

(ii) cool stores,

(iii) boning and cutting rooms.

The good practice model will estimate these loads from a small number of user inputs e.g. total cold store volume, without reference to any specific room.

All refrigeration loads are summed at each evaporation temperature level and passed to an engineroom submodel which will use inputs of saturated suction temperatures to estimate good practice COPs. From COP's, compressor energy use can be calculated using generalised expressions for good practice compressor efficiencies. Ancillary equipment electrical loads such as condenser and oil pumps, and cooling tower fans will be added to arrive at the predicted good practice engineroom dynamic electrical energy requirements. To determine the total refrigeration related electrical use, that used for fans, lights and machines in rooms must also be added.

To demonstrate the model validity, the predicted time-variable refrigeration electricity usage should agree with measured data collected at a plant considered to be operating close to good practice.

7.2.2 Modelling Periods

The product flow is subdivided into batches as described in Section 4.5.2 and the model monitors the passage of each batch through the refrigerated environment. Examination of product flows through various refrigeration regimes employed in the New Zealand meat industry indicate that, (unless a non-working day interferes), the usual maximum period during which heat might be abstracted from a product would be three days. After that time, the product would have reached some sort of refrigerated storage at constant product temperature. However, four working days must be modelled as the following example shows.

Consider a typical cold-boning beef operation: Product killed on a Monday would be boned on Tuesday and would complete the freezing cycle on Thursday. Thus engine room electrical demand predictions for Thursday would need to consider heat loads arising from:

(i) product killed on Monday (finishing freezing),
(ii) product killed on Tuesday (midway through freezing),
(iii) product killed on Wednesday (finished chilling, boned and starting freezing),
(iv) product killed on Thursday (loaded into chiller and commencing chilling).

If the product throughput, and hence the size, is the same for each day, then the heat load from the four sources can be determined from a single batch monitored for four days. The 4th day predictions by the simulation could be used to generate (i), the 3rd day (ii), the 2nd day (iii), and the 1st day (iv). Figures 7.4, 7.5 and 7.6 illustrate this summation carried out to obtain a typical daily operating cycle for a Thursday, Friday or Saturday, (if worked).

It is recognised that scenarios to describe refrigeration requirements on a Monday, Tuesday and Wednesday would differ in some respects to that discussed above. In such a case, the surveillance period may need to extend to 5 or 6 days because of intervention of non-working days. The modelling system was sufficiently flexible that the modelled period could easily be extended to 6 days, but because a Thursday or Friday would likely have the highest heat loads, the existing implementation was restricted to 4 day cycles.

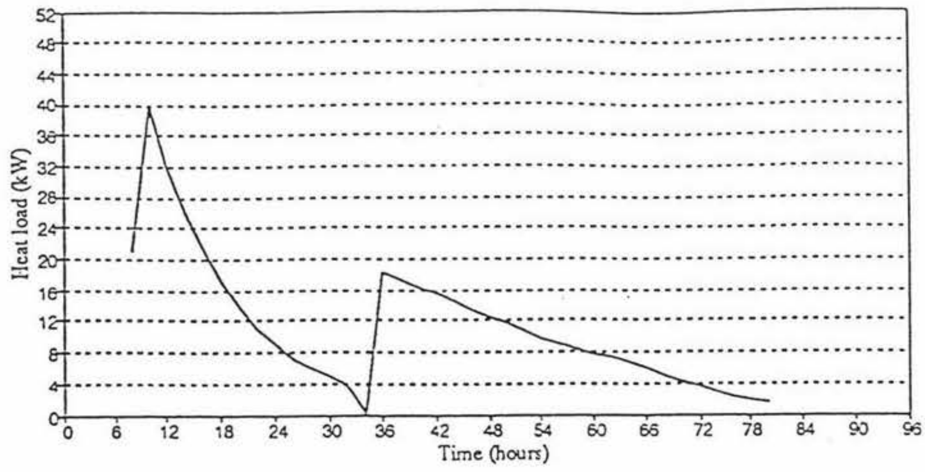


Figure 7.4 Typical beef batch product load over 96 hours.

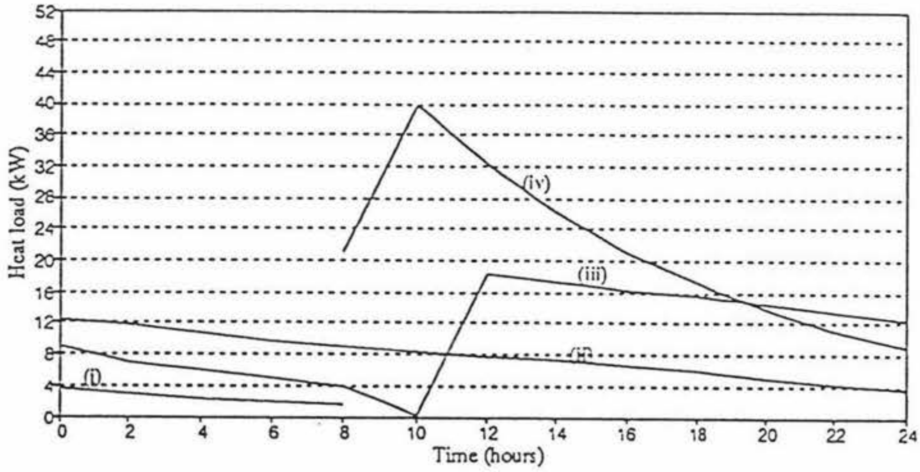


Figure 7.5 Batch product load divided into four daily loads

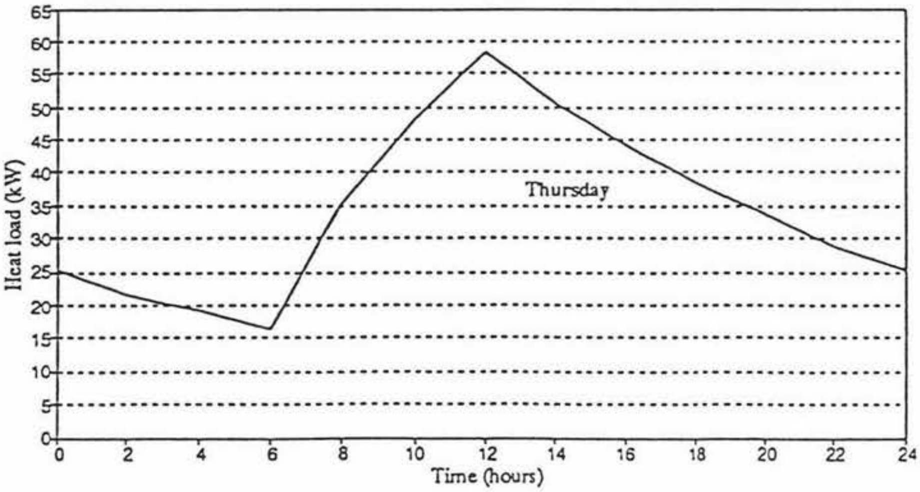


Figure 7.6 Batch product load summed to give Thursday's load arising from periods (i) to (iv).

7.3 MODEL DEVELOPMENT - PRODUCT HEAT LOAD

7.3.1 Algorithms for Cooling, Freezing and Subcooling of Product

The present model will require a method describing the cooling, freezing and subcooling of the products being cooled. The model proposed by Lovatt (1992) is capable of providing heat load prediction of more than sufficient accuracy for this work.

7.3.2 Data Required by the Model for Each Batch

As has been discussed, the batches progress through various refrigerated rooms or environments until finally being stored in a chilled or frozen form. At each environment change or (step change) the model requires data describing the next set of environmental conditions in order to simulate the product heat load.

7.3.2.1 Batch control data

The model user is required to input data into a spreadsheet block such as that presented in Table 7.1.

Table 7.1

Typical batch data for five step changes.

N_{batch}	t_{start}	Ta	$Airvel$	Rel_{sp}	Pot	$Yield$	M_{avg}	M_{batch}	Rm	Pk	Pr
1	8	10.0	0.2	1.0	1	1.0	143.0	15000	A	N	B
1	9	6.0	1.0	1.0	1	1.0	143.0	15000	S	N	B
1	34	10.0	0.2	0.5	1	0.63	27.2	9450	A	C	B
1	36	-30.0	3.0	1.0	2	0.63	27.2	9450	C	C	B
1	84	-30.0	3.0	1.0	2	0.63	27.2	9450	C	C	B

Data that the model user will be required to input for each change of batch refrigerated environments are:

(i) N_{batch}, batch number,

(ii) t_{start} (s), time that this line of data becomes "current",

(iii) T_a ambient air temperature (°C),

(iv) *Airvel* air velocity over product (m/s),

(v) Rel_{sp}, this is the fraction of available fan speed. Note that the air velocity at full fan speed will be approximately $airvel/rel_{sp}$. (This calculated value is designated v_{full}).

(vi) *Pot*, represents the suction pressure level to which the heat load is assigned,

(vii) *Yield*, as the batch progresses through time and thus through the simulated plant the meat may be further processed. It is common for both beef and lamb carcasses to be boned out, with only the meat progressing further down the cold chain. The total mass within the batch will alter and the model user must signal this change to the model through an alteration in yield fraction,

(viii) $M_{average}$, average unit weight, (kg)

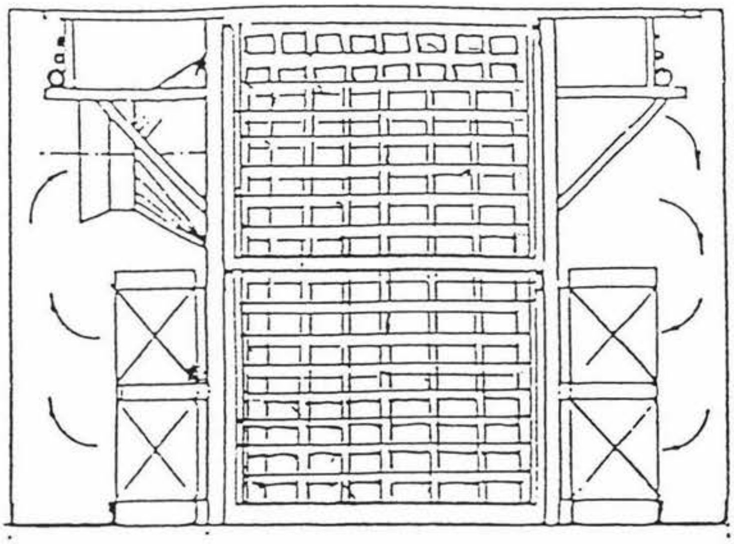
(ix) M_{batch}, total mass of product in the batch, (kg)

(x) *Rm*, the Room type definition for each batch. These were selected as follows:

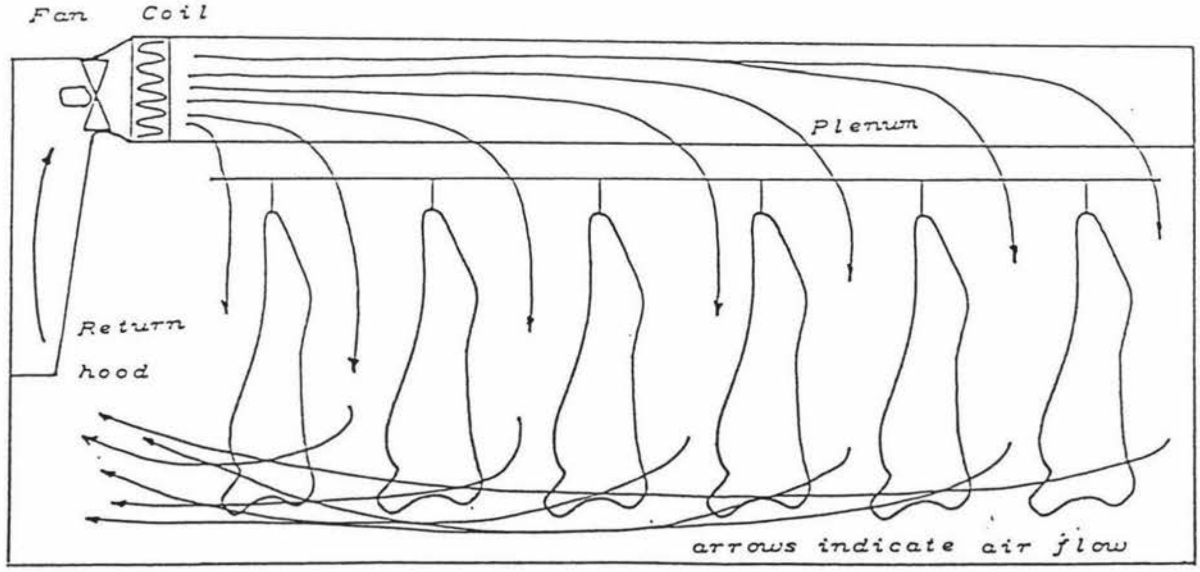
- *C* air passes over rows of cartons, (several cartons per air pass) e.g. Figure 7.7a,
- *S* air passes over single sides or carcasses per air pass e.g. Figure 7.7b,
- *M* air passes over multiple sides or carcasses per air pass,
- *P* plate freezer, no air movement whatever,
- *A* air-conditioning, (partly handled under base-loads).

(xi) *Pk*, the packaging type. These were:

- *N* (None) or stockinet only,
- *P* (Polywrap) and stockinet,
- *C* (Cartons).



A



B

Figure 7.7 A: details of air flow and stow in a typical carton chiller or freezer. (RoomType = *C*) and B: details of air flow and stow in a typical carcass chiller or freezer (RoomType = *S*)

(xii) Pr, product type,

The following three definitions describe the different product types:

(1) B: beef,

(2) S: sheep,

(3) O: offals (sheep and beef).

Categories within each species were not considered to be sufficiently different to warrant separate definitions.

The data presented in the example of Table 7.1 are representative of prime beef moving through an air conditioned beefkill area (line 1) and side chiller (line 2). Data on line 3 describes conditions in an air conditioned boning room, line 4 represents a carton freezer and line 5 is where the batch terminates at carton freezer exit. The model compares t_{start} for the current data line of each batch to the model real time (t). If $t < t_{start}$ then the data on the previous line is used by the model. However, if $t > t_{start}$ then the model moves to the present line of data. This process continues until the final batch line is reached at which calculations for the batch cease.

Yield changes as the batch progresses through the refrigeration system as discussed earlier. An example of this may be seen on line 3 of Table 7.1. The meat is now in cartoned form with the *Yield* and M_{batch} reduced accordingly. Product thermal properties and geometry change simultaneously.

7.3.2.2 Product thermal and geometric properties

Product thermal and geometric properties are chosen by a combination of product and packaging type. Data used within the model were obtained from the following sources: Fleming (1969), Pham and Willix (1989), Hossain *et al.* (1992a,b), Lovatt (1992), Pham *et al.* (1993). Values used in the model are presented in Table 7.2.

Table 7.2

Product thermal and geometric properties.

Property	Beef		Lamb		Offal
	Carcass	Carton	Carcass	Carton	Cartons
cs	1.9E6	1.96E6	1.85E6	2.1E6	2.25E6
cl	3.4E6	3.6E6	3.2E6	3.5E6	3.6E6
L	2.0E8	2.15E8	1.7E8	2.2E8	2.1E8
ks	1.43	1.5	1.35	1.45	1.5
kl	0.46	0.48	0.45	0.46	0.5
ρ	1025	1060	1025	1060	1060
T_f	-1.0	-1.0	-1.0	-1.0	-1.0
E	1.3	1.3	2.1	1.3	1.3
N	E+0.5	E+0.5	E+0.5	E+0.5	E+0.5

where	cs	=	frozen material specific heat capacity (J/m^{3}K)
	cl	=	unfrozen material specific heat capacity (J/m^{3}K)
	L	=	enthalpy change in freezing (J/m^3)
	ks	=	frozen material thermal conductivity (W/mK)
	kl	=	unfrozen material thermal conductivity (W/mK)
	ρ	=	density (kg/m^3)
	T_f	=	product initial freezing temperature (°C)
	E	=	equivalent heat transfer dimensionality
	N	=	shape factor (Lovatt *et al.* 1993)

Also required, but not included in Table 7.2 are values of the product critical dimension X. This is the "radius" at the slowest cooling point. For cartons this can be directly measured:

Full carton	X	=	0.080m
Half carton	X	=	0.040m

For lamb and sheep carcasses, the leg position was used as the index and X related to product dressed weight, $M_{average}$, using the following relationship which approximates measured data:

$$X = 0.023\ M_{average}^{\ 0.33} \tag{7.1}$$

For beef carcasses a similar analysis suggests:

$$X = 0.0154\ M_{average}^{\ 0.33} \tag{7.2}$$

where X = critical dimension (m)

7.3.2.3 Product surface heat transfer coefficients

The product heat transfer coefficient is chosen according to by the current packaging type within the batch array. The packaging type will have a direct effect on the surface heat transfer coefficient and thus the batch heat load.

Cleland and Cleland (1992) suggests the overall product surface heat transfer coefficient may be calculated by:

$$\frac{1}{h} = \frac{1}{h_a} + \frac{x_p}{k_p} + \frac{x_a}{k_a} \tag{7.3}$$

where h = surface heat transfer coefficient (W/m^{2}K)

h_a = air-side or plate to product heat transfer coefficient (W/m^{2}K)

x_p = thickness of the packaging material (m)

k_p = thermal conductivity of the packaging material (W/mK)

x_a = thickness of air film trapped by packaging (m)

k_a = thermal conductivity of air (W/mK)

They further suggest that values of h_a can be determined using:

$$h_{acarcass} = 12.5\ airvel^{0.6} \tag{7.4}$$

$$h_{acarton} = 7.3\ airvel^{0.8} \tag{7.5}$$

where $h_{acarcass}$ = product heat transfer coefficient for carcasses (W/m^{2}K)

$h_{acarton}$ = product heat transfer coefficient for cartons (W/m^{2}K)

$airvel$ = air velocity over product (m/s)

There are few published data available to enable x_a, x_p, k_p and k_a to be individually evaluated. Rather it has been common to include an allowance for the combined heat transfer resistance:

$$\frac{x_p}{k_p} + \frac{x_a}{k_a} \tag{7.6}$$

The data used need only represent good practice. Values embedded in commonly used meat industry software were adopted:

Stockinet and Polywrap carcasses	0.06 m^{2}K/W
Stockinet wrap or bare carcasses	0.0
Cartons with plastic liners in air blast freezers	0.08 m^{2}K/W

For plate freezing, rather than estimate individual terms in equation (7.6), values of h corresponding to recent unpublished measurements, were adopted:

Horizontal plates, carton
and plastic liners present h = 30 W/m^{2}K

Vertical plates, bare product h = 200 W/m^{2}K

7.4 MODEL DEVELOPMENT - PRODUCT RELATED HEAT LOADS

As discussed in Section 7.2 these heat loads arise as a consequence of the type of environment the product is exposed to at any time. The following major heat loads were identified as directly dependent upon product environment:

(i) fans,

(ii) wall, floor and ceiling surface heat gains,

(iii) doors and associated loads,

(iv) hot water hosing (carcass chillers only).

For plate freezers, loads other than product are very small. Plate freezers were therefore handled as a special case and only the insulation load considered. Air-conditioning has no product-related load as this is handled as a baseload.

7.4.1 Fan Power

The required fan power may be calculated by:

$$Q_{fan} = \frac{airvel\ area\ \Delta\ P_{room}\ NumItem}{\eta_{fan}\ \eta_{motor}} \tag{7.7}$$

where Q_{fan} = required fan power/batch (W)

$area$ = cross-sectional area for air flowassociated with one product item (m^2)

ΔP_{room} = pressure difference across fan (Pa)

$NumItem$ = number of product items

η_{fan} = fan efficiency

η_{motor} = motor efficiency

An investigation was carried out to ascertain how each of the terms on the right-hand side of equation (7.7) could be estimated using a minimum of user input data, and preferably only those available in the user input table (e.g. Table 7.1).

7.4.1.1 Air velocity and pressure drop considerations

The velocity at which air flows over the product surface (*airvel*) is usually different to the air velocity which passes through the refrigeration coil. Irrespective of the desired velocity over the product surface, a coil face air velocity of between 2 and 4 m/s will probably be chosen. Changes to the velocity over the product are then brought about by changes in coil face area rather than an alteration to the coil air velocity. Having fixed the face area the coil depth is determined by the heat load to be removed. The coil depth affects the coil air pressure differential (ΔP_{coil}).

The overall air pressure drop in the room (ΔP_{room}) is the sum of that in the coil (ΔP_{coil}) and that in the product (ΔP_{stow}). Assuming that the airflow is fully developed turbulent flow, each of the two components will change with the square of velocity.

$$\frac{\Delta P_1}{\Delta P_2} = \left(\frac{v_1}{v_2}\right)^2 \tag{7.8}$$

where ΔP_1 = pressure drop at original air velocity (Pa)

ΔP_2 = pressure drop at new air velocity (Pa)

v_1 = original air velocity (m/s)

v_2 = new air velocity (m/s)

However, in design, as has already been indicated, ΔP_{coil} and ΔP_{stow} can be manipulated independently of each other by changing the area and depth of the coil face. The model therefore required to determine good practice values for each ΔP, and for each of the various room types.

Two product stow characteristics can be identified:

(1) In air passing over single product items (code S) the major limitation in coil design should be hydro-dynamic rather than thermal. The air temperature rise over each product item is small, but the airflow is large to achieve the required air velocity. With an upper limit of face velocity for coils not forming frost of about 2.5 m/s (to avoid condensate blow-off), and a commonly used face velocity of about 3 m/s in other circumstances, geometric considerations lead to large face areas, low coil depth, low ΔP_{coil} and relatively low ΔP_{stow} in such circumstances.

(2) Where air passes over a number of product items (codes M and C) the limitation is more often thermal. Large volumetric airflows are not required, face areas can be smaller, but to achieve the required heat removal, the coil depth must be greater. Both ΔP_{coil} and ΔP_{stow} are large.

Whilst these are the most common situations, many practical situations do not exactly fit in either type. For example, carton chillers have air passing over a number of cartons, but heat loads are modest. This means less coil depth and less ΔP_{coil} is required compared to a carton freezer.

There are few data available for pressure drops in various room types. After discussion with a number of equipment suppliers the data in Table 7.3 were postulated. These represent an amalgam of suggestions from the industry, theoretical analysis and judgement by the author, of appropriate good practice values.

In deriving the data for $\Delta P_{refstow}$ in Table 7.3, some assumptions were made about the arrangement of the product stow:

Roomtype C:

It was assumed that there are 6-10 (typically 8) cartons per air pass. Thus if air passes over two sets of cartons per air pass this would be equivalent to 16 cartons, doubling the stow pressure drop. However, coil depth would also have to increase, with a subsequent change in ΔP_{coil}. With 16 cartons the airflow per carton would be halved. The net effect of changing all of the data in equation (7.8) would be to halve the area, and almost double ΔP_{room}. Hence equation (7.8) will give almost the correct results although the intermediary variables used will not be meaningful.

Roomtype S:

It was assumed that there was 1 carcass length plus ceiling plenum system per air pass.

Roomtype M:

It was assumed that there was 4 carcass lengths plus 1 or 2 ceiling plenums per air pass.

Roomtype P:

Pressure drops were set to zero for plate freezer.

Roomtype A:

Fan power included in baseload (Section 7.5).

The reference air velocities quoted in Table 7.3 are velocities over the product. If the air velocity (at full fan speed) over the product is different from that in Table 7.3, it is assumed that this is accomplished without changing coil face velocity as has been discussed.

Table 7.3

Postulated air pressure differentials for various room types and duties.

Room type	T_a	v_{ref} (m/s)	ΔP_{coil} (Pa)	$\Delta P_{refstow}$ (Pa)
C	<-5°C	3.0	150	150
C	>-5°C	0.6	100	50
S	<-5°C	1.0	75	100
S	>-5°C	0.6	75	75
M	<-5°C	1.0	150	125
M	>-5°C	0.6	100	75
P	<-5°C	0	0	0
P	>-5°C	0	0	0
A	>-5°C	N/A	N/A	N/A

Hence the room pressure drop is given by:

$$\Delta P_{room(full)} = \Delta P_{coil} + \Delta P_{refstow} \left(\frac{v_{full}}{v_{ref}} \right)^2 \tag{7.9}$$

where $\Delta P_{room(full)}$ = air pressure differential with fan at full speed

ΔP_{coil} = air pressure differential through coil (Pa)

$\Delta P_{refstow}$ = air pressure differential through product stow (Pa)

v_{full} = velocity of air at full speed (m/s)

v_{ref} = reference velocity of air over product (m/s)

Having determined a good practice pressure drop at velocity v_{full}, adjustment must be made if fan speed control is used. Table 7.1 contains a variable Rel_{sp} to indicate whether fan speed control is in use.

Thus:

$$\Delta P_{room} = \Delta P_{room(full)} \, Rel_{sp}^{2} \tag{7.10}$$

This calculation acknowledges that both the room and coil air velocities are changing as velocity changes once a fixed coil design is included in the model via equation (7.9).

The adequacy of the approach taken depends very much on the quality of the data in Table 7.3. It was decided to make these data "default" values, and to store them in the model in such a way that they may be changed should better information become available. This was accomplished by placing them in a data file known as the standard data file which was kept separate from the user data file. This is discussed in more detail in Section 7.7.

The reference velocities chosen in Table 7.3 were typical mid-range operating values at full fan speed. If a plant uses different velocities the error in extrapolating the data in Table 7.3 via equation (7.9) should not be large provided the actual velocity is close to the reference velocity. The ultimate test of the adequacy of this approach will be data-based testing of the model.

7.4.1.2 Area for air flow over the product

There are two constraints which must be considered:

(1) The free cross-sectional area multiplied by the air velocity over the product should provide a sufficient air flow to carry away the greatest heat load expected from the product.

(2) For carcasses only, hygiene concerns require a minimum rail spacing to ensure that bodies do not touch each other.

(i) Single pass carcass chillers and freezers (Code S)

The recommended rail spacings were examined to see whether they provided sufficient "free space" cross-sectional area to ensure adequate heat transfer at good practice air velocities. For beef chillers such a good practice rail spacing is often taken as 0.9 m/prime carcass, (although the beef is actually in side form it is useful to visualise it as carcasses or pairs of sides). The rails are also commonly spaced 0.9 m apart so that each prime beef body can be considered to have a "body space" in plan view of 0.81 m^2 as shown in Figure 7.8. From this must be subtracted the area occupied by the body. Irregularities in carcass shape may cause some difficulty in calculating this area. Each carcass type was approximated to an equivalent cylinder. The mass, density and approximate length of each product item were used to calculate the cylinder diameter and thus the end area which represented an equivalent cross-sectional area. The free space for prime beef could then be determined by subtracting this area from the body space.

The ratio between the end area and free area for prime beef was assumed to apply to all other beef carcass types to arrive at a theoretical good practice body space for each carcass type. The results were examined to confirm the calculated body space was within guidelines accepted as reasonable by industry standards. This was the case. Further calculations showed that if the air velocities chosen for chillers and freezers were multiplied by the freespace for each carcass type the resulting volumetric flows were more than adequate to carry away the heat load for any of the product items to be modelled.

Similar calculations for lamb and sheep showed that there was typically a two-fold ratio difference between beef and lamb/sheep.

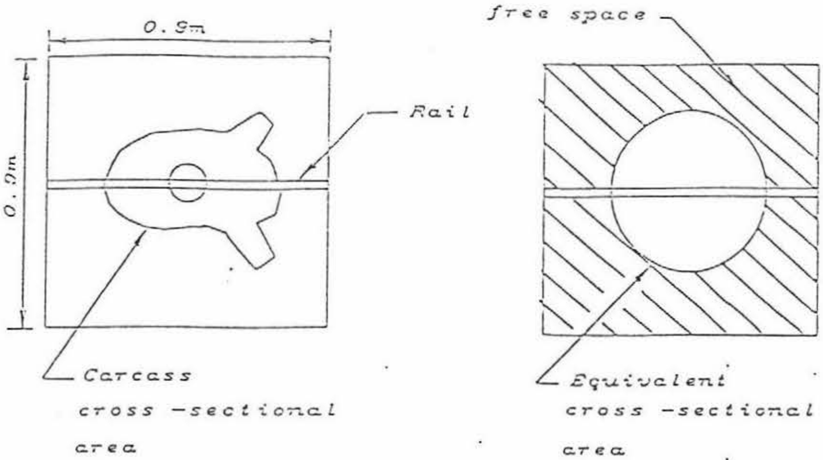


Figure 7.8 Two plan views of a prime beef carcass showing the cross sectional area, equivalent cross-sectional area and free space.

Curve fitting was carried out between product dressed body weight M_{avg}, and free space (*area*), for beef and lamb/sheep groups yielding:

beef:

$$area = 0.00622\ M_{avg}^{\ 0.83} \tag{7.11}$$

lamb and sheep:

$$area = 0.0042\ M_{avg}^{\ 1.16} \tag{7.12}$$

where *area* = free area per product item (m^2)

(ii) Carton chillers and freezers (**Code C**)

There is no hygiene-based spacing requirement in carton freezers and chillers, because of the protective packaging. Allowance need only be made for the net amount of free area required to adequately transport the heat load away. However, some allowance should be made for easy placement of the cartons onto the trays or stillages, which they sit during refrigeration processes. Heat load considerations showed that a minimum free space of 0.011 m^2/carton should be allowed for carton blast freezers operating at an air velocity of 3 m/s.

The physical structure details of the pallets and stillages which support cartons during refrigeration are such that use of half height cartons would cause the freespace to double in area but would lower the velocity. The number of half cartons being used is thought to be low, so it was decided to ignore them in the model.

(iii) **Multi-pass carcass chillers and freezers (Code M)**

These are primarily used for freezing lamb and mutton. Those with vertical air flow typically have air passing over 4 carcasses so that the net area per carcass is 0.25 times that in equation (7.12) thus:

$$area = 0.00105\ M_{avg}^{\ 1.16} \qquad (7.13)$$

Multi-pass horizontal air flow systems for lamb and sheep are not regarded as good practice devices as it is documented that they suffer very bad air velocity distribution. They were therefore not modelled.

7.4.1.3 Other data

To use equation (7.7), three further parameters are required. The number of product items, *NumItem*, is available in the user data file (e.g. Table 7.1). The fan motor efficiency, η_{motor}, was arbitrarily set to 0.9, and the fan efficiency, η_{fan}, to 0.65. These are typical mid-range values and their placement in the standard data file enables them to be changed if required.

7.4.2 Insulation Heat Gains

The following factors affect heat gains through room walls, ceilings and floors:

(i) insulation type,

(ii) insulation thickness,

(iii) age and condition of walls including vapour barrier,

(iv) room temperature,

(v) outside temperature,

(vi) exposure to outdoor elements such as sunshine, and

(vii) total surface area.

A generalised approach is sought which might encompass the above factors yet still require minimum data input from the user. Heat gain through insulation for chillers and freezers is small compared to overall room refrigeration requirements. Cleland and Cornelius (1990) suggest a percentage as low as 5%. This implies that a simple model is appropriate.

The heat transfer through any freezer or chiller exterior surface was modelled using:

$$Q_{ext} = E_i \frac{k_i}{x_i} A_{ext} (T_{ext} - T_a) \tag{7.14}$$

where Q_{ext} = heat gain through wall (W)

E_i = insulation effectiveness factor

k_i = thermal conductivity of insulation (W/mK)

x_i = insulation thickness (m)

A_{ext} = exterior surface area (m^2)

T_{ext} = external temperature (°C)

The good practice model will consider the insulation type as sandwich panel polystyrene, of two thicknesses; chiller 0.15 m and freezer 0.20 m. An insulation effectiveness factor of 1.25, which represents a good workmanship during construction and a well maintained vapour barrier, was adopted. The thermal conductivity for polystyrene foam was assumed to be 0.033 W/mK. All these data were placed in the standard data file so any user could change them if required.

Choice of both T_{ex} and A_{ex} depend on the placement of the chillers or freezers within the overall meat plant buildings, and their values must also reflect only the "contribution" arising from a product batch to the overall insulation load. Meat plant designs are becoming increasingly modular to improve flexibility to handle technology change so the good practice model was based on a modular approach to buildings. This means that there would be free-standing blocks of chillers and freezers. Whilst the underfloor temperature would be below ambient, parts of the walls and ceiling would be influenced by sunlight. For simplicity, these effects were assumed to balance, thus allowing T_{ex} to be set to the mean ambient temperature for the time of year. The user provides an external air temperature which is also used for cold and cool store heat load calculations.

The exposed surface area associated with a batch was determined by considering a chiller/freezer block as a whole. If the block has floor dimensions of R * βR and height Z_h, then the ratio of exposed surface area to floor area is:

$$\frac{2\ (\beta R\ +\ \beta Z_h\ +\ Z_h)}{\beta R} \tag{7.15}$$

Provided $R > Z_h$, which is likely to be true in practice, the ratio changes only slowly as the value of β changes. A constant ratio of 2.6 corresponding to $\beta = 2$, $R = 20$ m and $Z_h = 4$ m was selected as a typical mid-range value. Thus, if the floor area associated with a batch can be determined, the surface area for insulation gains is numerically 2.6 times larger.

7.4.2.1 Determination of floor area and A_{ex} for carcass freezers and chillers

The total body space for each carcass type discussed earlier could be used as the minimum floor area necessary, but to accommodate evaporators, air-turning spaces, etc. a further 20% allowance was included. Because insulation loads were small, the floor area allowances per carcass were not varied with product weight (as had been the case when calculating fan power), but treated as constants, set at typical mid-range values.

Using the factor of 2.6 from above, and the 20% allowance just discussed, the exterior surface area was approximated by:

$$A_{ext} = 3.12\ bodyspace\ NumItem \qquad (7.16)$$

where *bodyspace* = area allowance per carcass (m^2)
= $0.81 m^2$ for beef carcasses
= $0.135 m^2$ for lamb and sheep carcasses

7.4.2.2 Determination of floor area and A_{ext} for carton freezers and chillers.
A similar approach was used. A stowage pattern frequently used within the industry is to stow cartons on stillages which have a "footprint" of 1.44 m^2, and hold 36 cartons. Stillages are usually stowed 2 high, meaning that there are 72 cartons over 1.44 m^2 or 0.020 m^2/carton.

An allowance of 30% floorspace for other equipment in the room is considered realistic for this type of room so on approximation to the exterior surface area is:

$$A_{ext} = 0.068\ NumItem \qquad (7.17)$$

7.4.2.3 Floor area and A_{ext} for plate freezers
Calculations of space needs indicate that a floor area approximately half that for air blast carton freezers would be appropriate for plate freezers. Heat loads in a good practice plate freezer should be almost entirely from product, with the insulation load the next most important. It was arbitrarily assumed that all other heat loads were approximately equal to the insulation load. As these loads are so small a more accurate calculation was not justified. Equation (7.17) was then applied to plate freezers, but the result must be viewed as 50% insulation load and 50% other loads.

7.4.3 Door and Associated Heat Loads

The method used to model heat entry through doors was designed to respond to movement of product from one room type to another. The user data file contains all of the necessary information to detect when this is occurring. For example:

(i) change of room type, or
(ii) change from chiller to freezer conditions, even though room type may not have been altered.

Various types of product transfer may be characterised:

(i) product movement into a chiller or freezer,
(ii) product movement out of a chiller or freezer,
(iii) product movement into a boning room,
(iv) product movement out of a boning room,
(v) product movement into a cold or cool store.

In chillers and freezers, almost all door openings are product flow related, whereas in cold stores and boning rooms a large fraction of door openings do not directly relate to product moving through the batch system. Door heat loads in stores and boning rooms are treated as part of the baseload. Thus only (i) and (ii) are considered here as product-related.

Associated with product movement into and out of chillers there will also be movement of people, and use of lights. These tend to be small loads and so need not be accurately modelled. Lighting levels are typically about 10 W/m^2 of floor area, so to allow for people a further 5 W/m^2 was added. Thus the model for loads associated with product transfers was:

$$Q_{assoc} = 15\ floorarea \qquad (7.18)$$

where Q_{assoc}	=	heat load generated by lights and personnel (W)
floorarea	=	area allowance per batch (m$^{2)}$
	=	0.972 *NumItem*(beef carcasses)
	=	0.162 *NumItem* (lamb and sheep carcasses)
	=	0.026 *NumItem* (Cartons)

This load commences when product transfer starts and ends when product transfer finishes.

The instantaneous door interchange heat load may be calculated by:

$$Q_{door} = W_{air}\ \rho_{ins}\ (h_{out} - h_{ins}) \tag{7.19}$$

where Q_{air} = instantaneous heat load due to air interchange (W)

W_{air} = instantaneous volumetric flow rate through door (m^3/s)

ρ_{ins} = density of the inside air (kg/m^3)

h_{out} = enthalpy of the outside air (J/kg)

h_{ins} = enthalpy of the inside air (J/kg)

There are two types of door usage for loading and unloading of product. The first represents batch loading: the door is large and is open long enough to load batches, but is closed up during the refrigeration cycle. Most carcass freezers and chillers, and cabinet carton freezers match this type. The second type is continuous, for example continuous carton tunnels, and some continuous lamb freezers. This type uses small apertures through which the product enters and exits, so that heat gains through the apertures are small but continuous. It was decided that the batch system was more common (although not necessarily better practice), and could be used to describe all room types within this work with the exception of air conditioning.

The refrigeration model must model door openings in a generalised, rather than room-specific fashion. The requirements for using equation (7.19) are therefore related not just to establishing accurate values for the various parameters in the equation, but also to defining the length of time the door openings would be required. These values need only represent good, rather than existing, practice.

Values of ρ_{ins} and h_{ins} can be determined from psychometric data, provided the inside air, relative humidity and temperature are known. A typical relative humidity of 85% was assumed and temperature found from the user input table. The outside air enthalpy depends on the air conditions outside the door which are not known. The inlet door to a freezer or chiller would be internal to the plant and so in the lack of better information 20°C and 75% relative humidity were adopted. These data were placed in the standard data file so they could be changed if required. Base load cold and cool store heat load calculations, discussed shortly, will also use these data.

This leaves only the air interchange rate, W_{air}, and the timing of the openings to be determined. The data adopted need only reflect good practice. An important aspect to consider in choosing them is the impact on loads if refrigeration systems are off during the loading and unloading. During unloading, in particular, refrigeration may be off, but the inside air is cold and some heating of internal room structures results from air interchange. This heat is removed when refrigeration is turned on. It is increasingly common to operate some refrigeration during loading. Irrespective of whether refrigeration is operated, provided the internal air temperature within the room is cold relative to the outside air, interchange will occur, and hence the heat load may be important.

Air interchange loads in freezers and chillers are normally not large so some inaccuracy can be tolerated. The volume of air in the chillers and freezers associated with any product batch can be determined as will be shown. Because most of the interchange occurs when there is little or no refrigeration it was decided that during each loading and unloading a reasonable (but possibly high) upper limit for air exchanged was one complete volume. Good practice exchange volumes may be less, particularly during unloading. Interchange of one volume for loading and 0.5 volumes for unloading were adopted in the model.

The heat enters the refrigerated air space as a function of time and then leaves as a different function of time according to the refrigeration system design and operation. Rather than try to model the detail, assumptions were made about the rate of heat removal (which is the important value as opposed to the rate of heat entry):

Load in:	50% removed in first 10% of process time,
	50% removed in next 20% of process time,
Load out:	100% removed in last 20% of process time.

Associated heat loads (equation (7.18))are assumed to be present as follows:

Load in: 100% removed in first 10% of process time,

Load out: 100% removed in the last 20% of process time.

For example, for a chilling step lasting 20 hours there would be door heat load from 0 to 6 hours and then from 16 to 20 hours.

Using results from Sections 7.4.2 to determine the floor area, and assuming device heights of 3m for lamb, 5m for beef and 4m for cartons, it then follows that:

beef carcasses:

(i) first 10% of process time

$$W_{air} = \frac{(0.81 * 1.2\ NumItem)\ 5 * 0.5}{0.1\ t_{stage}} \quad (7.20)$$

$$W_{air} = \frac{24.3\ NumItem}{t_{stage}} \quad (7.21)$$

where t_{stage} = length of the present process stage (s)

(ii) next 20% of process time

$$W_{air} = \frac{12.1\ NumItem}{t_{stage}} \quad (7.22)$$

(iii) last 20% of process time

$$W_{air} = \frac{12.1\ NumItem}{t_{stage}} \quad (7.23)$$

lamb and sheep carcasses:

(i) first 10% of process time

$$W_{air} = \frac{(0.135 * 1.2\ NumItem)\ 3\ *\ 0.5}{0.1\ t_{stage}} \tag{7.24}$$

$$W_{air} = \frac{2.43\ NumItem}{t_{stage}} \tag{7.25}$$

(ii) next 20% of process time

$$W_{air} = \frac{1.22\ NumItem}{t_{stage}} \tag{7.26}$$

(iii) last 20% of process time

$$W_{air} = \frac{1.22\ NumItem}{t_{stage}} \tag{7.27}$$

cartons:

(i) first 10% of process time

$$W_{air} = \frac{(0.026\ NumItem)\ 4\ *\ 0.5}{0.1\ t_{stage}} \tag{7.28}$$

$$W_{air} = \frac{0.52\ NumItem}{t_{stage}} \tag{7.29}$$

(ii) next 20% of process time

$$W_{air} = \frac{0.26\ NumItem}{t_{stage}} \tag{7.30}$$

(iii) last 20% of process time

$$W_{air} = \frac{0.26\ NumItem}{t_{stage}} \tag{7.31}$$

The value of t_{stage} is determined by subtracting two successive values of t_{start} in the user data file (e.g. Table 7.1).

7.4.4 Hot Water Hosing

Chillers are sanitised with hot water prior to reuse for a new batch. The analysis of Section 6.1.5.4 suggests a good practice water requirement of 6 kg/m^2 of floor area. The hot water enters at up to 82°C and typically enters the drain at 10-15°C. This corresponds to about 1800 kJ/m^2 of floor area.

Assuming that this heat enters the concrete and is removed later over the first 25% of the chiller cycle then:

beef carcasses:

$$Q_{hw} = (1800*10^3)\left(\frac{(0.81\ *\ 1.2\ NumItem)}{0.25\ t_{stage}}\right) \tag{7.32}$$

$$Q_{hw} = \frac{(7.0\ *\ 10^6)\ NumItem}{t_{stage}} \tag{7.33}$$

lamb and sheep carcasses:

$$Q_{hw} = (1800\ *\ 10^3)\left(\frac{0.1\ *\ 1.2\ NumItem)}{0.25\ t_{stage}}\right) \tag{7.34}$$

$$Q_{hw} = \frac{(0.864 \ *10^6)\ NumItem}{t_{stage}} \tag{7.35}$$

where Q_{hw} = chiller hot water hose down heat load (W)

7.4.5 Other Loads

These should be small, but may include heat gain to refrigerant piping, electrical control and conveying systems, etc. An allowance of 5% of the total load calculated in Sections 7.4.1 to 7.4.4 was included.

7.4.6 Electrical Load

The model described in Figure 7.1 requires electrical components of the load to be identified. These are:

(i) fan power (Section 7.4.1),

(ii) 67% of door-associated loads for lights (Section 7.4.3),

(iii) an arbitrary 50% of the other loads (Section 7.4.5) door and personnel heat gains.

7.5 BASE LOADS

Sections 7.3 and 7.4 considered heat loads that are product-related; that is, in a good practice refrigeration operation the loads only arise if product is being processed. There are also a number of heat loads that arise relatively independently of refrigeration demands by product. In particular these are:

(i) cold and cool stores and

(ii) air-conditioning.

It could be argued that part of the door heat load for refrigerated stores is product heat load related, and this is certainly true. However, the bulk of the heat load in stores can be modelled without reference to product flows, so the complete store heat loads were treated as baseloads.

Product heat load in air-conditioning is included in the batch system. Some parts of the other heat loads in air conditioned areas could be product-related, e.g. door openings for product to enter and leave. However, other than determining refrigeration start and stop times product has little effect on many air-conditioning heat loads. For convenience, the whole non-product load was treated as baseload.

7.5.1 Cold and Cool Stores

Typical cold store operational air temperatures are -12 to -20°C. A standard of -20°C was adopted. Cool stores tend to operate just below 0°C; -1°C was adopted as the standard value. Both temperatures were stored in the standard data file.

Heat load sources that were considered sufficiently important to require evaluation in some detail were:

- (i) insulation heat load,
- (ii) air interchange heat load,
- (iii) fan power, and
- (iv) lights.

Heat loads considered sufficiently minor to enable a simple allowance to be used to represent them include:

- (i) product,
- (ii) people,
- (iii) forklifts and machinery, and
- (iv) defrosting.

The nature of the refrigeration model did not allow room by room considerations, but rather required consideration of good practice for the activity as a whole. In the following sections, the methods proposed are described. The total heat load for cool and cold stores is the sum of all the individual loads.

7.5.1.1 Insulation heat load

The model used was similar to that of Section 7.4.3. Equation (7.14) was applied with data determined as follows:

(i) For each type of store the user specified:
- total refrigerated air volume, V_{st} (m^3)
- mean room height, Z_h (m)
- mean external (ambient) temperature, T_{ext} (°C)

(ii) The insulation thicknesses for good practice are assumed to be:
- cold stores 0.20 m
- cool stores 0.15 m

The insulation thermal conductivity is assumed to be 0.033 W/mK (polystyrene foam).

(iii) The internal air temperature has been specified

(iv) The external temperature is the mean value to which the cold store block as a whole is subject. It is assumed that there is a well designed weather shield so roof and walls are exposed to temperatures only slightly above ambient during the day. Conversely, the under floor temperature is normally below ambient. It is assumed that these effects cancel. Diurnal variations in external air temperature were ignored because the thermal capacity of the building structures tends to dampen any effect varying ambient temperature might have.

(v) The insulation effectiveness factor was set at 1.25 to represent good practice.

(vi) The approach of Section 7.4.3 suggested that for a rectangular block of dimensions $R * \beta R * Z_h$ (m) the ratio of surface area to floor area was:

$$\frac{2(\beta R + \beta Z_h + Z_h)}{\beta R} \tag{7.15}$$

The floor area can be determined from available data as V_{st} / Z_h, so the total surface area is:

$$A_{ext} = \frac{V_{st}}{Z_h} \frac{2(\beta R + \beta Z_h + Z_h)}{\beta R} \tag{7.36}$$

This then requires a value of β. Typically this parameter might be in the range 1-3. A midpoint value of $\beta = 2$ was adopted yielding:

$$A_{ext} = 2 \frac{V_{st}}{Z_h} + 3\sqrt{2 Z_h V_{st}} \tag{7.37}$$

Thus, the insulation heat load could be estimated.

7.5.1.2 Air interchange

The good practice model for air interchange was based on the following assumptions:

(i) load-in occurred via an enclosed (but unrefrigerated) chamber (commonly called an environmental load-in),

(ii) load-out occurred independently at the other end of the store block via an enclosed (but unrefrigerated) load-out area into which trucks and/or railway wagons could be driven, and

(iii) doors are of minimum necessary size and have either plastic strip curtains in good condition, or infra-red sensors which activate the recently released fast-acting doors.

The most recent substantive study of New Zealand meat industry cold store doors was that of Pham and Oliver (1983), who studied cold stores with volumes greater than $5000m^3$ and air temperatures below -12°C. They developed two equations to best fit their results:

Non-operational hours:

$$W_{air} = K\, A_{door} \frac{(V_{st})^{0.2}}{3600} \tag{7.38}$$

where K	=	air interchange factor
	=	3.8 (totally unprotected doors)
	=	2.6 (enclosed doors, no plastic strip curtain)
	=	1.1 (enclosed door plastic strip curtain)
W_{air}	=	volumetric air flow through doors (m^3/s)

Operational hours:

$$W_{air} = 0.167\, \sqrt{A_{door}} \tag{7.39}$$

The air flow in non-operational hours represented that through door seals, pressure equalisation devices, etc. Pham and Oliver noted that during operational hours, doors with good protection tended to be left open, whereas unprotected doors were closed when not in use. These effects roughly cancelled so equation (7.39) has no dependence on type of protection. In the present good practice model the user will be required to input:

(i) door surface area, and

(ii) start and stop times for "operational" activities.

During non-operational hours, equation (7.38) will be used with $K = 1.1$; that is:

$$W_{air} = (3.06 * 10^{-4})\, A_{door}\, (V_{st})^{0.2} \tag{7.40}$$

During operational hours, equation (7.39) is inappropriate. The analysis associated with equation (7.38) suggests that good practice has $K = 1.1$, and the worst practice $K = 3.8$. As equation (7.39) represents no protection, but good opening practice, the effect of protection could well be to lower the load to a fraction 1.1/3.8 of what equation (7.39) suggests. In the lack of better information this was adopted. That is, during operational hours:

$$W_{air} = 0.048 \sqrt{A_{door}} \tag{7.41}$$

Equation (7.38) and (7.39) are based on a purely cold store analysis. There is no equivalent analysis for cool stores. The major difference expected is that the density difference between outside and inside air is lower. For example, for outside air at 20°C, inside air at either -1°C or -20°C. Tamm's equation (Tamm 1965) predicts a theoretical velocity through a 3m high door of 1.02 m/s for the cool store, but 1.38 m/s for the cold store. In the lack of better information, the coefficients in equation (7.40) and (7.41) were reduced in proportion to these values for cool stores:

Non-operational hours:

$$W_{door} = 2.26 * 10^{-4} A_{door} (V_{st})^{0.2} \tag{7.42}$$

Operational hours:

$$W_{door} = 0.0355 \sqrt{A_{door}} \tag{7.43}$$

Thus, estimates of good practice air interchange rate were established. Calculations of heat load then proceed via equation (7.19) which was presented earlier:

$$Q_{door} = W_{air} \rho_{ins} (h_{out} - h_{ins}) \tag{7.19}$$

Values of ρ_{ins} and h_{ins} can be found from the store temperatures, and assuming a typical relative humidity of 85%. Only h_{out} need then be known. This is the enthalpy of air in the environmental load-in and load-out areas. Typically these areas are cooler than ambient, but quantitative data could not be found. It was arbitrarily decided that these areas would be approximately 5°C colder than the ambient air temperature input by the user (Section 7.5.1.1), and the relative humidity would be 85%.

7.5.1.3 Fan power

The fan power requirement arises from the quantity of air to be circulated. In a good practice storage complex at least 50% of the heat load should be via the insulation (because other loads, particularly doors, are controlled). It was assumed that the quantity of air circulation needed was that to remove twice the insulation load (as sensible heat load) with no more than a 1.5°C rise in air temperature. By energy balance:

$$W_{air} = \frac{2\ Q_{ext}}{\rho_{ins}\ (1010.0\ *\ 1.5)} \tag{7.44}$$

$$W_{air} = (1.32\ *\ 10^{-3})\ \frac{Q_{ins}}{\rho_{ins}} \tag{7.45}$$

The factor of 1010 J/kgK is the specific heat of thestore air.

A typical coil might have a pressure drop (ΔP_{coil}) of 100-150 Pa, and the room pressure drop (ΔP_{stow}) should be low, no more than 50 Pa. A total pressure drop of 175 Pa was assumed. An adaptation of equation (7.7):

$$Q_{fan} = \frac{W_{air}\ \Delta P_{room}}{\eta_f\ \eta_m} \tag{7.46}$$

can then be applied, using ΔP_{room} = 175 Pa, η_f = 0.65 and η_m = 0.9 (as in Section 7.4.1.2).

During non-operational hours when heat loads are lower air movement can be reduced. However, too much reduction can lead to hot spots in the store. It was decided that a good practice system would have fan speed control, but that the lower limit would be a fan speed of 50% of full. The fan speed would change with load, but an average might be 75% of full load. Applying the standard cube power law this suggests a reduction in fan power to 42% of that calculated by equation (7.7). This level of reduction was assumed to commence 2 hours after operations ceased each day to allow time to "catch up" on heat load from the operational period in order to maximise good practice product quality. Present industry cost-saving practice utilises fan speed control regimes which are diametrically opposed to this proposal, in order to minimise energy use in high cost tariff periods. However such practices lead to poor temperature control of stores and were not considered appropriate for an industry which wishes to maintain the highest possible product quality.

7.5.1.4 Lights

Lighting at a level of 10 W/m^2 during operational hours was assumed.

7.5.1.5 Other loads

In a good practice system product will enter a store at store temperature. Hence product heat load was considered negligibly small.

Discussions with a forklift supplier suggested that a 2.5 tonne capacity machine might discharge heat at a mean rate of about 4.5 kW whilst in a store. It is impossible to know how many forklifts (and associated people) will be present in a block of stores at any time. Therefore, an even load allowance between the operational start and stop times was considered appropriate. Typical rates of forklift use for a 5,000 to 10,000 m^3 store might be 2 forklifts present about 60% of the time. Using 4.5 kW per machine this translates to a store volume-related allowance of:

$$Q_{flift} = \frac{(4.5 * 2 * 0.6)}{7500} V_{st} * 1000 \tag{7.47}$$

$$Q_{flift} = 0.720 \ V_{st} \tag{7.48}$$

where Q_{flift} = mean heat load generated by all forklifts within the store (W)

The allowance for defrost, people and any other small loads was assumed to be 20% of the total insulation load, or about 10% of the total load.

7.5.1.6 Electrical loads

The fan power, lights and forklift loads were summed, the latter justified on the basis of recharging energy use.

7.5.2 Air-conditioning Baseload

Air-conditioning is used for two reasons:

(1) regulatory requirements, and
(2) comfort.

The latter typically arises when excess heat load occurs in a space to which it is difficult to circulate normal ventilated air. On a good practice plant, proper control of heat loads and use of ventilation should virtually always achieve the necessary user comfort levels. Therefore, only regulatory air-conditioning to 8 - 10°C in boning rooms and cutting rooms was considered. As was the case with cold and cool stores specific rooms were not considered, but rather the activity of air conditioning as a whole. Heat loads considered to be of importance in a good practice model were:

(i) insulation,
(ii) air interchange,
(iii) fan power,
(iv) hot water use (both during production and clean-up),
(v) machinery,
(vi) people, and
(vii) lights.

Product heat load is not included. This is because it has already been included in the product heat load model, but without product-related heat loads whilst in air conditioned areas (Section 7.3).

Following the philosophy used in other models the data requested from the user were kept as few as possible. Data requested are:

(i) refrigerated air volume, V_{ac} (m^3)
(ii) mean room height (m),
(iii) external air temperature (°C)
(iv) time refrigeration is turned on,
(v) time meat processing commences,
(vi) time meat processing ceases (and major daily clean-up starts), and
(vii) time clean-up finishes, and
(viii) number of personnel.

Minor clean-ups are assumed to occur every two hours from when meat processing starts, and if meat processing continues for more than 12 hours, a more significant clean-up midway through the period is assumed.

Start and stop times need not occur within a 0 to 24 hour period. For example, if a start time of 6 a.m. and finish time of 2 a.m. was entered, the active times would be midnight to 2 a.m. and 6 a.m. to midnight.

The models used for each of the various loads are described in the following sections:

7.5.2.1 Insulation

The model of Section 7.5.1.1 was applied but replacing the store volume V_{st} with the air-conditioned air volume V_{ac}, and the store height Z_h with the air-conditioned area height Z_l. A custom-built facility would be expected to have 0.15m sandwich panel wall construction. Internal room temperature was assumed to be 8°C. All other data were determined as in Section 7.5.1.1.

7.5.2.2 Air interchange

Whilst an objective will be to minimise air interchange through doors, etc., ventilation is necessary to maintain air quality for workers present. ASHRAE Standard 62-1989 recommends 11 litres/second per person for modern buildings. A typical boning room might have about 50 people present, so ventilation alone requires air interchange of 0.55 m^3/s on a continuous basis. This is roughly equivalent to a 3m * 3m door with plastic strips left open continuously, which would not be good practice.

The good practice air interchange heat load, whilst meat processing is occurring, was therefore estimated on the basis of minimum ventilation requirements:

$$W_{air} = 0.011\ No_p \tag{7.49}$$

where No_p = number of personnel present

Equation (7.19) can then be applied using data for ρ_{ins} and h_{ins} applying to air at 8°C and 85% relative humidity.

The air interchange load during initial room precooling (from refrigeration turning on to meat processing start) should be small. It was arbitrarily set to 20% of that during meat processing.

During end of day clean-up, the best refrigeration practice is to turn refrigeration completely off but to replace the air-conditioning by a ventilation system, drawing large quantities of ambient air through the room. The refrigeration repercussions of this are that there is a significant precooling load at next start-up but no refrigeration load during the ventilation period.

7.5.2.3 Personnel

Typical load allowances per person are 300-500W, the allowance increasing as air temperature drops, and the degree of activity increases. A standard allowance of 350W was adopted. During meat processing:

$$Q_{pers} = 350\ No_p \tag{7.50}$$

where Q_{pers} = heat load generated by personnel (W)

After refrigeration start-up and before meat processing commences, 10% of this load was assumed to occur.

7.5.2.4 Lights

Good lighting (15 W/m^2) was assumed from refrigeration start-up to cleaning finish, although it only represents a refrigeration load until cleaning starts. The model is:

$$Q_l = 15\ \frac{V_{ac}}{Z_l} \tag{7.51}$$

where Q_l = light heat load (W)

V_{ac} = air conditioned room volume (m^3)

Z_l = air conditioned room mean height (m)

7.5.2.5 Machinery

Shrink-wrap tunnels in particular are heavy energy users. In a good practice system these are externally vented so perhaps only 20-25% of the energy input enters the room. Other machines e.g. conveyors put all their energy directly into the room. The user will be required to input:

(i) total shrink-wrap power, Q_{sw}, and

(ii) total other machine power, Q_{conv}.

The machinery heat load in a good-practice system is assumed to be:

$$Q_{mach} = 0.2\ Q_{sw} + Q_{conv} \tag{7.52}$$

where Q_{mach} = total machine heat load (W)

Q_{sw} = shrink tunnel heat load (W)

Q_{conv} = conveyor and ancillary heat load (W)

This level of load applies only whilst meat processing occurs. To allow for shrink-wrap machine start-up during the time from when refrigeration is turned on until meat processing starts:

$$Q_{mach} = 0.2\ Q_{sw} \tag{7.53}$$

7.5.2.6 Hot water use during production

A small number of sterilisers, apron and hand washes, etc. will be present. Their heat loss is a refrigeration load. It seemed appropriate to index these loads to the people present. With good practice device designs (Chapter 6) the loads should be small. No quantitative data could be found so it was arbitrarily assumed that:

$$Q_{hwp} = 0.5\ Q_{pers}. \tag{7.54}$$

where Q_{hwp} = production hot water heat load (W)

Hot water hosing should not occur during production.

7.5.2.7 Hot water use during clean-up

Minor clean-ups were assumed to be performed "dry" (i.e. picking up of meat scraps). Major clean-ups were assumed to conform to good practice. That is, 6kg hot water/m^2 floor area (Chapter 6).

(i) End of day clean-up. The heat added is assumed to be removed in the next day start-up.

(ii) During production clean-up (production run > 12 hours). The heat added is assumed to be removed in one hour. Calculation in the manner of equation (7.32) yields:

$$Q_{hw} = (1900 * 10^3) \frac{V_{ac}}{Z_l} \frac{1}{3600} \tag{7.55}$$

$$Q_{hw} = 528 \frac{V_{ac}}{Z_l} \tag{7.56}$$

where Q_{hw} = clean-up hot water heat load (W)

which applies to the mid-point hour in the production run.

7.5.2.8 Fan power

A similar philosophy to that applied in Section 7.5.1.3 was adopted. The air circulation rate was calculated as that required to remove all heat (treated as sensible heat) from insulation, air interchange, people, lights and machines with only a 1.5°C air temperature rise.

$$W_{air} = \frac{(Q_{ins} + Q_{air} + Q_{pers} + Q_l + Q_{mach} + Q_{hwp} + Q_{startup})}{\rho_{ins}\ (1010 * 1.5)} \tag{7.57}$$

Equation (7.46) was then applied with $\eta_f = 0.65$, $\eta_m = 0.90$ and $\Delta P_{room} = 175$ Pa.

This calculation was performed for meat processing conditions and the same fan power assumed to occur in room precooling.

During clean-up, the refrigeration system is off and a ventilation system on. In the interests of simplicity the ventilation system was assumed to have the same fan power as the refrigeration system.

7.5.2.9 Room precooling

Heat in structures, etc. from the previous washdown, plus any heat introduced by ventilation, plus natural rewarming during the "off" period could all be important. The dominant material to be recooled is the floor. The use of 6kg hot water/m^2 leads to heat gain of 1900 kJ/m^2 of floor.

Allowing a further 35% for other reheating effects then:

$$Q_{pre} = \frac{1900 * 10^3 * 1.35 \frac{V_{ac}}{Z_l}}{t_{pre}} \tag{7.58}$$

$$Q_{pre} = 2.57 * 10^6 \frac{V_{ac}}{Z_l \, t_{pre}} \tag{7.59}$$

where Q_{pre} = room precooling heat load (W)

t_{pre} = time from refrigeration start to meat processing start (s)

7.5.2.10 Other loads

Any other load sources were considered sufficiently small to be neglected.

7.5.2.11 Electrical loads

The electrical loads were summed as follows:

(i) fan power,

(ii) lights,

(iii) shrink-wrap power, (not during clean-up)

(iv) other machinery power, (not during clean-up or precooling).

This assumes that all shrink-wrap machines are electrically heated. Some steam heating is used, but this generally requires a steam pipe run to boning areas for this sole purpose. The industry trend is towards the convenience of electrical heating.

7.6 ENGINEROOM ENERGY USE

In Sections 7.3 to 7.5 the various models used to determine the heat loads on the refrigeration system have been described. The net result of application of these models is a heat load vs time profile, (and also an electrical load vs time profile for all the refrigeration applications). The heat load at the engineroom was assumed to be 5% larger than that calculated above to allow for heat gains to refrigerant pipelines, etc. The next stage is to calculate how a good practice refrigeration system will respond to the loads, and the resultant electricity consumption vs time profile.

In Section 7.1 a typical refrigeration system for a meat plant was described. Pump-circulated ammonia is by far the most common system used so the good practice engineroom model was formulated for such a system. The energy usage rates for other types of system will not be very different provided such systems are designed to good practice.

7.6.1 Pots and Temperatures

When using a pump circulation system it is common to use vessels, often known as surge pots, separators, or sometimes just "pots" as the sources of refrigerant for each of the applications. Two such pots are shown in Figure 7.2. For each application a maximum possible evaporation temperature can be defined. The system designer then groups applications to pots. For example, in the two pot system of Figure 7.2 applications would be grouped as follows:

Pot 1 - -5 to -10°C
air conditioning,
chilling and cool stores.

Pot 2 - -30 to -35°C
cold stores and freezers.

The temperature of each pot is defined according to the "worst case" application supplied refrigerant from the vessel. There are severe energy penalties in having pots operate at lower temperatures than absolutely necessary. For example, if one major freezer requires -37°C refrigerant, but the other freezers only -30°C, operation of a single pot at -37°C is much less energy efficient than having 2 separate pots at -30°C and -37°C respectively.

The good practice model was therefore constructed having up to 5 pots. Any pot operating below -25°C was assumed to use two-stage compression in the manner of Figure 7.2.

When the user data file and Table 7.1 were discussed in Section 7.3, a variable, *Pot* was introduced. This associates any particular product and product-related heat load with a numbered pot at any time of the day. Product, in moving from room to room, is thus exposed to refrigerant from different sources. The three baseloads, cool stores, cold stores and air conditioning must also be associated with pots. This is accomplished by requiring the following user inputs as the first stage of the refrigeration model:

(i) number of pots in use,
(ii) operating temperatures of these pots, (°C),
(iii) pot numbers with which to associate the three baseloads, and
(iv) ambient wet bulb temperature (°C).

In practice, energy-efficient control strategies require that pot temperatures change with time during the day. This action was simulated as follows:

(i) at any time the model searches all applications supplied refrigerant from each pot and finds the lowest air temperature for each pot,

(ii) the pot temperature is set to either the user-input value (above) or 7°C lower than the lowest air temperature being supplied at the time, whichever is higher. The 7°C allows for 2°C equivalent of pipeline pressure drop, and 5°C temperature difference for the room evaporator.

The ambient wet bulb temperature is used to determine the good practice refrigerant condensation temperature. Either an evaporative condenser or water-cooled condenser plus cooling tower system could be expected to have a condensation temperature about 8°C above the wet bulb temperature (cooling water approaches within 2°C of the wet bulb temperature, about 5-6°C temperature difference in the condenser).

7.6.2 Compressor Electrical Energy Use

Cleland (1988) proposed the following formula for calculating compressor energy use:

$$E_c = \frac{Q_{pot}\,(T_c - T_{pot})}{[(273 + T_{pot})\,(1 - \alpha\, x)^n\, \eta_i]} \tag{7.60}$$

where E_c = compressor electrical load (W)

T_c = refrigerant condensation temperature (°C)

T_{pot} = refrigerant evaporation temperature (°C)

α = empirical refrigerant constant

x = fractional vapourisation on pressure reduction from the discharge pressure to the suction pressure (bars)

η_i = compressor isentropic efficiency including motor.

For ammonia α = 1.11; for one stage compression n = 1, and for both two stage compression and expansion (as in Figure 7.2) n = 0.5. For ammonia values of x can be calculated using:

$$x = 0.00376\ (1 + 0.00012\ T_c + 0.00273\ T_{pot})\ (T_c - T_{pot}) \qquad (7.61)$$

(Cleland 1993). These calculation formulae predict E_c within about ±3% provided accurate data are available for η_i. Determination of η_i proceeds as follows:

(i) The suction and discharge pressures (P_s and P_d respectively) corresponding to T_{pot} and T_c are found, conveniently using the curve-fit thermodynamic property routines of Cleland (1986).

(ii) The pressure ratio is calculated:

$$PR = \frac{P_d}{P_s} \qquad (7.62)$$

where PR	=	pressure ratio
P_d	=	discharge pressure (Pa absolute)
P_s	=	suction pressure (Pa absolute)

(iii) For pots operating above -25°C, $n = 1$ and PR is used to determine η_i as shown in Step (iv). For pots operating below -25°C two stage compression is assumed; $n = 0.5$ and $\sqrt{PR}$ is used to determine η_i as shown in Step (iv).

(iv) Cleland (1988) presents good practice η_i data for fully loaded compressors. These have been curve-fitted yielding:

$$\eta_{ifull} = 0.753 - 0.000948\ (PR)^2 \qquad (7.63)$$

η_i is then calculated using:

$$\eta_i = \eta_{ifull}\ \eta_m\ \eta_{part} \qquad (7.64)$$

where η_{ifull}	=	full load compressor efficiency
η_m	=	motor efficiency
η_{part}	=	part load efficiency

The motor efficiency, η_m was assumed to be 0.90. Operational control requires some compressor part-loading. However, in a good practice system such operation will be minimised, and η_{part} should approach unity. A value of 0.90 was used.

7.6.3 Engineroom Ancillary Energy Use

Engineroom operation requires liquid refrigerant pumps, condenser coolant pumps and fans and control systems to be run. Cleland and Cleland (1992) suggest a 10-15% allowance, but the exact requirement will vary according to local circumstances. In the lack of better information a 10% allowance (10% of compressor energy use) was adopted.

7.6.4 Link to Hot Water Recovery

In the long term links between the refrigeration model and heat recovery model are required. None have been made at present, but there is no technological impediment. The engineroom temperatures and pressures, the total refrigeration system heat load and the energy use can be used to calculate all necessary inputs to the refrigeration system heat recovery model of Section 6.3.2.6.

7.7 TOTAL ELECTRICAL REFRIGERATION LOAD

The calculation methods to determine all electrical loads have been discussed in Sections 7.3 to 7.6. At any time during a simulation the total electrical load can be summed according to the protocol shown in Figure 7.3.

7.8 MODEL IMPLEMENTATION

Initially an attempt was made to implement the models of Sections 7.2 to 7.6 in the ESL programming language. Whilst a successful implementation for a single batch of product was achieved (Appendix D1) the language proved unsuitable for implementing the whole model. Implementation in the PASCAL programming language was therefore used. The ESL program was retained to check correct implementation of the product heat load model.

The main PASCAL program (Appendix D2) used 4th order Runge-Kutta numerical integration to solve the differential equations within the product heat load model. It calculated all other heat loads as well. There was no time step control to check integration error, but checks against the outputs from the ESL model showed the integration error was negligibly small at time steps of 60s. All other calculations carried out by the model are algebraic, so hand calculations could be used for checking. The second PASCAL program performs only algebraic engineroom calculations.

7.8.1 Data Inputs

The model uses these input files:

(i) two user data files, and
(ii) standard data file.

The first user data file contains information on all the product batches as described in Section 7.3, plus user input data for all other heat load models. Appendix D3 contains an example data file, and comments on it.

The second user data file contains user input data required by the secondary PASCAL programme and described in Section 7.6.1. Appendix D7 contains an example data file and comments on it.

The standard data file contains default values the program user would not normally need to change. This file is described in Appendix D4.

7.8.2 Main Program Outputs

The main program creates two output files. The first is intended to be read by the user. It gives batch by batch information in a user-friendly form, plus aggregated pot by pot heat and electrical loads. These are given for the full 4 day simulation. However, baseloads are only given for the first 24 hours. Table 7.4 shows an example section from this output file.

Table 7.4

Main program user-friendly output file 20 hours into a simulation.

```
T -     20.00 BatchNo   Tma     Qprod  Qprodrel  Elecprod  PotNo     Ta      Airvel
                 1     19.16    11.25     5.44     4.71      1       4.00     0.60
                 2     20.12     6.17     2.80     2.42      1       4.00     0.60
                 3     21.55    10.07     4.27     3.71      1       4.00     0.60
                 4     22.63     3.69     1.47     1.28      1       4.00     0.60
                 5     22.92     6.79     2.61     2.25      1       4.00     0.60
                 6     23.52     3.15     1.17     1.01      1       4.00     0.60
                 7     23.38     5.99     2.19     1.86      1       4.00     0.60
                 8     23.71     3.14     1.13     0.96      1       4.00     0.60
                 9     23.77     6.64     2.29     1.92      1       4.00     0.60
                10     24.50     3.55     1.18     0.99      1       4.00     0.60
                11     26.54     6.42     2.40     1.68      1       4.00     0.60
                12     26.94     3.37     1.24     0.86      1       4.00     0.60
                13     27.23     6.25     3.86     1.53      1       4.00     0.60
                14     27.66     3.28     1.99     0.79      1       4.00     0.60
                15     30.66     1.40     0.71     0.34      1       4.00     0.60
                16     31.07     0.73     0.36     0.17      1       4.00     0.60
                17     30.33     7.08     3.99     1.47      1       4.00     0.60
                18     17.77    11.47     2.91     2.47      2     -30.00     3.00

                   Pot1       Pot2      Pot3       Pot4      Pot5

                 Refrigeration product and product-related load
                128.07     14.38      0.00       0.00      0.00

                        Electrical product-related load
                 27.97      2.47      0.00       0.00      0.00

                          Refrigeration base-load
                  7.41     59.89      0.00       0.00      0.00

                            Electrical base-load
                  0.66      5.12      0.00       0.00      0.00

                  Refrigeration load-Coldstore             59.89
                  Refrigeration load-Coolstore              7.41
                  Qaircon                                   0.00
                  Electrical load-Cold and Cool stores      5.78
                  Electrical load-Aircon                    0.00
```

The second output file is an intermediary output file designed to be read by the secondary program. It contains columns of data as follows:

(i) time (hours),
(ii) pot heat loads (kW) - excluding baseloads,
(iii) electrical loads associated with each pot (kW) - excluding baseloads,
(iv) lowest temperature of a room supplied refrigerant from each pot (°C)
(v) pot baseload heat loads (kW) - 24 hours only
(vi) baseload electrical loads (kW) - 24 hours only.

7.8.3 Secondary PASCAL Program

The secondary PASCAL program reads the second output file described in Section 7.8.2 and the second data file. It consolidates the heat and electrical loads to a 24 hour basis using the process described in Section 7.2. It then implements the engineroom model of Section 7.6 and creates two further output files:

(i) a user-friendly description of total heat load and electrical energy use vs time (e.g. Table 7.5) and
(ii) a file containing the following results in tabular form suitable to be read into a spreadsheet for graphical presentation.
    - Time (hours)
    - Total electrical load (kW)
    - Engineroom electrical load (kW)
    - Non engineroom electrical load (kW)
    - Total heat load (kW)
    - Compressor electrical load, by pot (kW)
    - Heat load presented to the engineroom, by pot (kW)

Table 7.5

Engineroom user-friendly output file 20 hours into a simulation.

```
Time -    20.00   Engine room electrical load          190.87
                  Non-engineroom electrical load        84.71
                  Total electrical load                275.58
                  Total heat load                      428.60

                   Pot1      Pot2      Pot3      Pot4     Pot5
                       Engineroom electrical load by Pot
                   44.60    146.27

                               Total heat load by Pot
                  152.82    275.78
```

7.9 MODEL TESTING

7.9.1 Mathematical Verification

Hand calculations were carried out at various model run time intervals to ensure that model predictions were accurate. All room types, product types and packaging types were tested. Model predictions were in good agreement with hand calculations in all cases.

7.9.2 Measurements Collected at the Host Plant

Data were measured on the same plant as had been used for hot water usage data measurements (Section 6.1.5).

7.9.2.1 Product data

The beef only plant killed about 250 animals per shift, producing cold boned beef meat in cartons, approximately 50% frozen and 50% chilled. There were 10 side chillers, and each day most of these were in use either for chilling or holding chilled sides. The boning room operation and air conditioning systems were conventional. There were two air blast carton freezers, and two major cold stores. The single carton coolstore also operated as the carton chiller.

The boning room was newly constructed, but the chillers, carton freezers and all cool and cold stores were old, although of relatively good technological standard. As a result of age there may be insulation deterioration in some of these facilities. Therefore the real heat loads could well exceed good practice.

The plant had an excellent weight/grade system so that an accurate time-variable record was available throughout the day for both beef carcasses entering the chiller and cartons exiting the boning room to either freezers or chillers.

7.9.2.2 Engine room and other electrical loads

A two stage pump-circulation ammonia system of the type shown in Figure 7.2 was used. The intermediate pressure surge pot operated at a nominal -10°C, and the lower pressure pot at -33°C. Water-cooled condensers were used with water supplied from a nearby river at an inlet temperature of about 12-14°C at the time of the test. This resulted in typical condensation temperatures of about 28°C. Only screw compressors were used, and these could be capacity-controlled by either speed control (one large machine on the IP suction), or by slide-valve unloading. At the time of the test compressors were being controlled to maintain constant suction pressures. The plant has electrical load shedding fitted but this was not in operation.

A recording ammeter was provided by the local electrical power supplier and engineroom electrical loads recorded over four days, (Monday to Thursday). This included all compressors, all engineroom ancillaries plus the fans on some application areas. It was not possible to measure total refrigeration-related electricity use.

7.9.2.3 Batch data preparation

Three types of product batch were required - meat ultimately ending up frozen, meat ultimately ending up chilled, and frozen offals. A total of 9 frozen meat batches, 8 chilled meat batches and 1 offal batch were used.

The nine frozen meat batches were not of even size; rather their start and stop times were defined whenever a significant change in animal size occurred. In the worst case production leaving the slaughter board over a two hour period was grouped into one batch. On average a new batch was started about every hour through the production day of 10 hours. It was considered that this adequately represented the real flow to the chillers. Each batch was subjected to a standard 24 hour chilling cycle before one hour in the boning room and 48 hours in the carton tunnel. In practice, the time in the chillers would vary to some extent but no attempt was made to model this.

The eight chilled meat batches were also not of even size for the same reasons as the frozen meat. Again, in the worst case a single batch had to represent 2 hours of continuous production, but on average each batch represented about one hours kill. These batches also had a 24 hour chilling process and then one hour in the boning room before 48 hours in carton chilling mode.

The offals are a small product flow relative to the meat. For convenience they were represented as a single batch going to 48 hour carton freezing at the end of the production day.

7.9.2.4 Engineroom data processing

The measured engine room current use was converted to kW using a power factor of 0.95 which was considered realistic by the plant chief engineer on the basis of the performance of the installed power factor correction equipment. The fan motor electrical loads for fans fed from the same distribution board were measured, and these loads subtracted from the engineroom electricity use. The resultant data were electrical use by the compressors and engineroom ancillaries only.

7.9.2.5 Other data

Other data required to use the models were estimated as follows:

(i) To force the model to predict condensation temperatures of 28°C (to match plant practice) a wet bulb temperature of 20°C was input.

(ii) A cold store volume of 12230 m^3 exists on plant. The door cross-sectional area for the stores is approximately 19 m^2. Operational hours were assumed to be from 6 a.m. to 5 p.m. which approximately matches plant practice.

(iii) Because there was no separate coolstore and carton chiller it is difficult to estimate the coolstore volume accurately. The total volume was 2100 m^3, of which perhaps only 1500 m^3 could be ascribed as coolstore. The same operational hours were from 6 a.m. to 10 a.m. The door cross-sectional area was approximately 9 m^2.

(iv) The boning room air volume was approximately 4000 m^3 with a height of 5.5m. The boning room operational times were set to match plant practice (4 a.m. cooling starts, 6 a.m. production starts, 5 p.m. production ceases). There were 53 workers present.

(v) The external ambient temperature at the time of the test was about 14°C.

7.9.3 Comparison of Measured and Prepared Data

The plant was simulated with measured product data for the Thursday's kill. Other days had slightly different kill patterns, but the differences should not be that large.

Figure 7.9 shows engineroom electrical usage for the plant plotted against time over 24 hours on Wednesday of the week measurements took place, and Figure 7.10 a similar plot for Thursday.

Considering first the shape of the predicted line the following events can be discerned. At 0400 hours the air-conditioning is switched on to precool the boning room and a subsequent load rise may be observed. Further load is incurred from 0600 hours when production starts in both the beef kill and boning areas. The apparent dip in engineroom power use at 6 a.m. corresponds to the finish of precooling of the air conditioning, and this is before the product load starts to become very significant. There are small step increase as new batches enter the system from 8 a.m. onwards. Electricity use continues to increase until 1600 hours when production and air-conditioning ceases. Cold stores are also closed up for the night at 1700 hours and the load continues to drop as the night progresses.

The operation of the plant on Wednesday (Figure 7.9) was not typical of normal practice. A large compressor was broken down that day and was not restarted until about 3 p.m. As a result there was insufficient capacity operating during the working day to hold the suction pressures as low as they should be and room air temperatures had risen. Total electricity drawn was also low because the largest power user was off. All other machinery was fully loaded. At 3 p.m. the large machine was restarted and the plant operated in a manner to recover the lost room temperatures. This resulted in very high evening power consumption.

Relating this behaviour to the predictions the lack of fit can now be largely explained. The low real use during the working day was because real compressor availability was too low to cope with the heat loads, and in the evening there is a catch-up. The model assumed that sufficient capacity was always available.

The operation of the engineroom on Thursday (Figure 7.10) was more typical of normal practice. Apart from the cycling of measured electricity use (which is probably due to loading and unloading of screw compressors) the fit between predicted and measured is excellent except in the early morning, and to a lesser extent in the evening. In practice, cold store and carton freezer temperatures may rise during the day and be recovered at night. This means that some of the heat load from the day is actually removed at night. In contrast the good practice model assumes that the air temperatures remain constant and heat is removed as it enters.

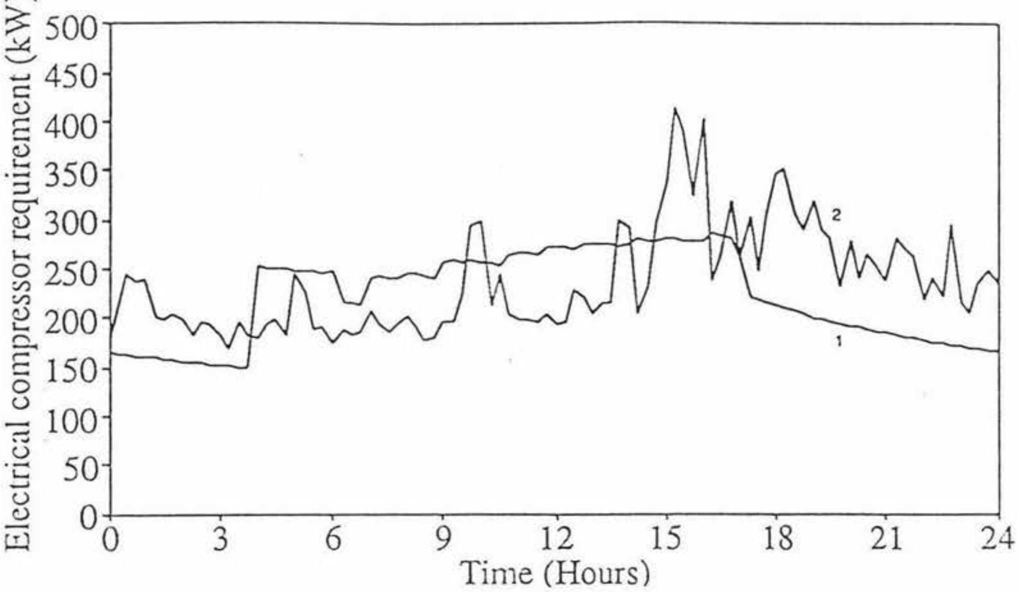


Figure 7.9 Engineroom electrical load (kW) vs time (hours); 1 - predicted data, 2 -measured data (Wednesday).

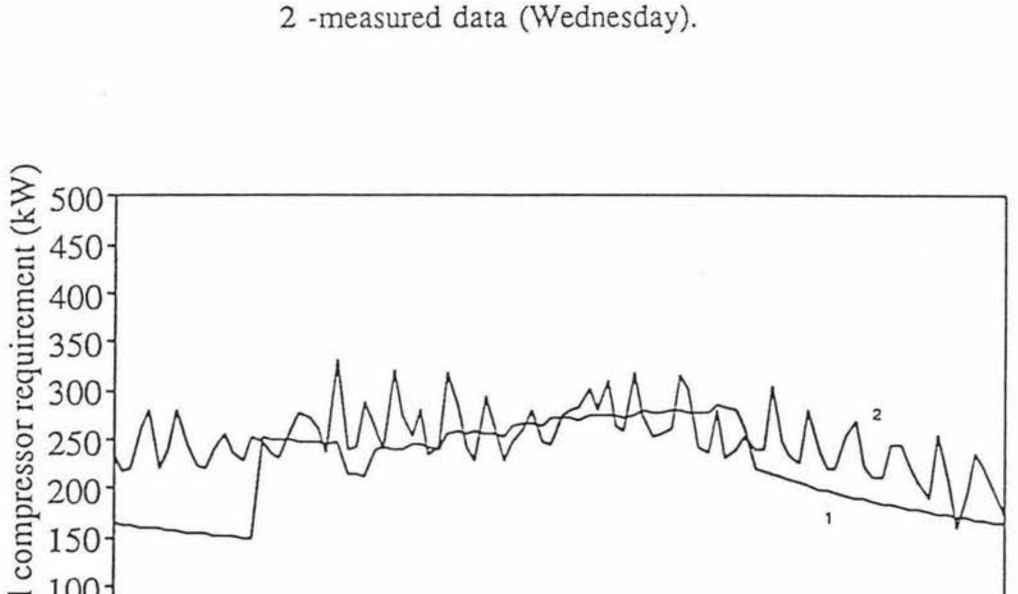


Figure 7.10 Engineroom electrical load (kW) vs time (hours); 1 - predicted data, 2 -measured data (Thursday).

The net effect is that measured data are likely to show a less peaky heat load and hence energy use profile than the good practice model. However, on average the measured data should be higher if there are inefficiencies in practice, or if the ageing of the refrigerated rooms has led to insulation deterioration. Figure 7.10 is consistent with these expectations. The very high measured power consumption early in the morning is probably no more than an extension of the "catch-up" from Wednesday's compressor failure.

7.10 DISCUSSION AND CONCLUSIONS

When comparing the predicted and measured results it must be remembered that the predictions were generated with very few plant-specific data, and virtually no room-specific data. Precise agreement between measured and predicted data cannot therefore be expected. Taking these factors into account the agreement is excellent, thus validating the modelling approach taken. Key aspects of the modelling system include:

(i) Product related load (which is the major heat load) is predicted by use of proven methodology (Lovatt 1992).

(ii) The methodologies used to estimate product-related loads are based on realistic and practical analyses.

(iii) Engineroom calculations were carried out using methodologies which have been shown to return predictions with an accuracy of ± 3% (Cleland 1988).

(iv) The provision of standard data files means that designers may structure certain standard values to suit local conditions.

The overall refrigeration model uses a minimum of user data inputs. A criticism of other models is that specialist knowledge is required to supply input data. This is both expensive, and difficult to achieve at all, at a time that the meat industry is downsizing its on-plant technical staff. The data requirements of this model are production driven and as such are readily available through modern weight/grading systems. Although the measured data used for this study had to be hand collated, there is potential for automatic data transfer from the weight/grading and inventory control systems to the refrigeration system model. Thus the model could provide on-line predictions to engineroom control systems.

8 DISCUSSION

8.1 INTRODUCTION

The purpose of this work was to model the time-variable energy usage use of the major energy users commonly found within the New Zealand meat industry. The models should be capable of integration so that a unified plant-wide energy model can eventually be developed.

8.2 RENDERING

The rendering models were to some extent limited by the assumption that all transport processes were instantaneous. Measured data and personal observations on plant suggested that there were appreciable time delays e.g. from the time of steam consumption to condensate appearing. Further, the model assumed that some types of cookers and dryers were perfectly mixed vessels whereas in practice material moves systematically from one end to the other. Use of overall heat transfer coefficients rather than moisture content-dependent values is also a limitation.

It would be possible to make the model more complex to remove these weaknesses. However, the model as it stands predicts energy usage rates that were in good general agreement with the measured data.

The model designs are such that the linkage of the waste heat available to the hot water system model can be easily accomplished.

A spin-off benefit of some rendering models is the prediction of moisture content at the discharge end of the cookers and dryer. Production managers may find this information useful as a tool to study the effects different rendering operating regimes have upon end-point meat meal moisture content.

8.3 HOT WATER

The concept of defining "good practice" flow rates developed as part of the hot water model is powerful, and could be further explored, in particular for sheep plant operations. Further investigation of hand tool sterilisers and hosing practices by the meat industry is urgently required and could result in substantial savings in heated water and thermal energy use, thereby allowing the use of smaller heat generation and exchanger units.

A spin-off benefit of the hot water storage and generation model, is that by taking account of time-based variations in demand and available water from recovery systems, tank sizes and heat requirements for both hot and warm water can be predicted more accurately than was previously possible.

As yet the generic model for product flow has no direct link to hot water demand and supply models. However departmental start, stop, restbreak and other event times which are important to the hot water models are available within the generic model. It is envisaged that the totally integrated meat plant model, to be developed at a later stage, will contain an implemented link between the two models to achieve this.

8.4 REFRIGERATION

The model has been developed using a novel "non-room specific" concept. This overcomes the criticisms of other models that specialist knowledge is required to supply input data, and that this is both expensive and difficult to achieve at a time when many companies are down-sizing their on-site technical staff.

Time constraints prevented implementation of links between the generic and the refrigeration models. However the models were designed so that the links can be created simply.

9 CONCLUSIONS

The major energy users on a meat plant are rendering, hot water generation and refrigeration. Time-variabilities in energy demand must be considered if an optimised energy supply is to be developed.

In spite of ignoring time taken for transport processes and assuming perfect mixing in cookers and dryers, the ordinary differential equation-based models developed for rendering systems predict measured data with adequate accuracy. The model designs will facilitate later development of linkages between product flows, rendering system performance and hot water recovery.

The "good practice" models for hot water use have highlighted major needs for equipment development for both tool sterilisation and cleanup hosing. The models for heat recovery and for hot water storage and supply contain few major assumptions, and so although untested in practice, are expected to be accurate.

The refrigeration model accurately predicted the overall refrigeration system energy use versus time profile without recourse to a room by room analysis. The low data requirements are likely to lead to a more rapid uptake of the models by the New Zealand meat industry than has been the case with other more complex refrigeration models.

There are no major technological impediments to construction of an integrated energy model based on the individual models developed within this work. Such a model will have major benefits for the New Zealand meat industry by enabling better design of energy supply and usage systems.

NOMENCLATURE

$(B_f\, x_b)$	moisture mass flow rate in the boning stream (kg water/s)
$(K_f\, x_k)$	Moisture mass flow rate in the kill stream (kg water/s)
$(M_{tot}T_z)c_w$	total embodied energy in system (J)
(Px_p)	combined moisture flow rate to the raw material bin (kg water/s)
(Py_p)	total fat flow rate to the raw material bin (kg fat/s)
$(Rmgx_g)$	mass of moisture in the raw material bin (kg water)
$(Rmgy_g)$	mass of fat in the raw material bin (kg fat)
α	empirical constant (kg dry solids/kg water)
α	empirical refrigerant constant (Section 7.6.2)
Δh	enthalpy change in isentropic compression (J/kg)
Δh_s	enthalpy change of steam in cooker (J/kg)
ΔP_1	pressure drop at original air velocity (Pa)
ΔP_2	pressure drop at new air velocity (Pa)
ΔP_{coil}	air pressure differential through coil (Pa)
$\Delta P_{refstow}$	air pressure differential through product stow (Pa)
ΔP_{room}	pressure difference across fan (Pa)
$\Delta P_{room(full)}$	air pressure differential with fan at full speed
ΔT	temperature difference between saturation and superheat positions (°C)
ΔT_a	approach to maximum possible condensation temperature in the heat recovery unit (°C)
ΔT_b	approach to the water inlet temperature (°C)
ΔT_c	approach to the inlet cooling water temperature (°C)
ΔT_d	approach to 100°C of water flowing to the heat supply model (°C)
ΔT_e	approach to steriliser water temperature (°C)
ΔT_f	approach to hand apron wash water temperature (°C)
ΔT_g	approach to cold water inlet temperature (°C)
ΔT_h	approach to mean recovered water temperature (°C)
η_{fan}	fan efficiency

η_i	compression isentropic efficiency including motor.
η_{ifull}	full load compressor efficiency
η_m	motor efficiency
η_{motor}	motor efficiency
η_{part}	part load efficiency
θ	approach to the temperature of the discharge gas at the oil cooler exit (°C)
λ	approach to the temperature of the discharge gas at the exit of the desuperheater (°C)
ν_v	saturated suction vapour specific volume (m^3/kg)
ρ	density (kg/m^3)
ρ_{ins}	density of the inside air (kg/m^3)
A	exposed surface area of the meal (m^2)
A	area surface (m^2)
A_β	surface area of the tank (m^2)
A_1	cooker shell heating surface area (m^2)
A_2	area of the cooker outer shell surface (m^2)
A_{ext}	exterior surface area (m^2)
airvel	air velocity over product (m/s)
A_j	heating surface of jacket (m^2)
area	free area per product item (m^2)
a_w	water activity of meal
a_w	water activity of meal
B	total energy content of the cooker (J)
B	total energy content of the dryer first compartment (J) *(Section 5.3.4.1)*
bb_{amen}	total grouped beef boning shower flow rate (kg/s)
bb_{apron}	mean beef boning apron wash flow rate (kg/s)
bb_{hand}	mean beef boning hand wash flow rate (kg/s)
bb_{hose}	total grouped beef boning cleanup hose flow rate (kg/s)
bb_{ks}	mean beef boning group knife steriliser flow rate (kg/s)
bbm	beef boning dry solids flow rate (kg dry solids/s)
bbx	moisture content of the beef boning material (kg water/kg dry solids)

B_f	boning stream dry solids flow rate (kg dry solids/s)
bk_{amen}	total grouped beef kill shower flow rate (kg/s)
bk_{anc}	total beef kill ancillaries flow rate (kg/s)
bk_{apron}	mean beef kill apron wash flow rate (kg/s)
bk_{bs}	brisket saw steriliser flow rate (kg/s)
bk_{dhi}	total dehider steriliser flow rate (kg/s)
bk_{dho}	dehorner steriliser flow rate (kg/s)
bk_e	elastorator steriliser flow rate (kg/s)
bk_{et}	eviscerate table flow rate (kg/s)
bk_{gb}	gut buggy steriliser flow rate (kg/s)
bk_{hand}	mean beef kill hand wash flow rate (kg/s)
bk_{hh}	head hook steriliser flow rate (kg/s)
bk_{hk}	total hockcutter steriliser flow rate (kg/s)
bk_{hose}	total grouped beef kill cleanup hose flow rate (kg/s)
bk_{ks}	mean group knife steriliser flow rate (kg/s)
bkp_{hose}	total grouped beef kill production hose flow rate (kg/s)
bk_{ss}	side saw steriliser flow rate (kg/s)
bk_t	trolley steriliser flow rate (kg/s)
bk_{wash}	rotary washers etc, (if any) flow rate (kg/s)
bk_{wr}	weasand steriliser flow rate (kg/s)
$Blood_{Beef}$	beef house blood dry solids flow rate (kg dry solids/s)
$Blood_{Lamb}$	lamb kill blood dry solids flow rate (kg dry solids/s)
bm	beef house dry solids(kg dry solids/s)
$bodyspace$	area allowance per carcass (m^2)
B_t	total plant blood stream dry solids flow rate (kg dry solids/s)
bx	moisture content of the beef house material (kg water/kg dry solids)
c	empirical coefficient (Cleland 1986) condensing vapour side (kJ/kg)
c_{dry}	specific heat capacity of dry solids (J/kg K)
c_{fat}	specific heat capacity of fat (J/kgK)
cl	unfrozen material specific heat capacity (J/m^3K)
c_{pd}	specific heat of inlet dry gas (J/kgK)
c_{po}	specific heat of outlet dry gas (J/kgK)

c_s	specific heat capacity of fat-free dry solids (J/kgK)
cs	frozen material specific heat capacity (J/m^{3}K)
c_{st}	specific heat capacity of steel in cooker shell (J/kg K)
c_v	mean specific heat of vapour (J/kg°C)
c_{vd}	specific heat of inlet water vapour (J/kgK)
c_{vo}	specific heat of outlet water vapour (J/kgK)
c_w	specific heat capacity of water (J/kg K)
c_w	specific heat capacity of water (J/kgK)
D_{flow}	mean device flow rate (kg/hr)
D_{inst}	instantaneous device flow rate (kg/s)
E	equivalent heat transfer dimensionality
E_c	compressor electrical load (kW)
E_i	insulation effectiveness factor
em	effluent dry solids flow rate (kg dry solids/s)
ex	moisture content of the effluent solids (kg water/kg dry solids)
F	total dry solids flow rate (kg total dry solids/s)
F_b	blood feed rate to blood plant (kg dry solids/s)
F_d	feed from raw material bin (kg dry solids/s)
F_d	feed rate to dryer (kg fat-free dry solids/s) (Section 5.3)
F_{fl}	flow rate of fat (kg/s)
F_{ft}	total liquid phase flow (kg/s)
F_{fw}	flow rate of fat-free stickwater (kg/s)
F_j	steam flow (kg/s) (Section 5.2.5)
F_j	makeup water flow (kg/s)
$floorarea$	area allowance per batch (m^2)
F_p	product flow from cooker (kg dry solids/s)
F_p	product flow rate from dryer first compartment (kg fat-free dry solids/s) (Section 5.3.4.1)
F_r	feed rate to decanting centrifuge (kg fat-free dry solids/s)
G	fat-free dry solids flow rate to the rendering (kg fat-free dry solids/s)
G_b	boning room fat-free dry solids flow rate (kg fat-free dry solids/s)
G_k	kill stream fat-free dry solids flow rate (kg fat-free dry solids/s)

h	surface heat transfer coefficient (W/m^2K)
H_β	energy required by any heat exchanger (W)
h_1	enthalpy of dry steam at 9.0 bars absolute.
h_2	enthalpy of condensate at 130°C
h_a	air-side or plate to product heat transfer coefficient (W/m^2K)
$h_{acarcass}$	product heat transfer coefficient for carcasses (W/m^2K)
$h_{acarton}$	product heat transfer coefficient for cartons (W/m^2K)
h_{fg}	latent heat of condensation at T_{st} (J/kg)
h_{fg}	latent heat of condensation at 100°C (J/kg)
H_{fg}	latent heat of vapourisation of water at 0°C (J/kg) (Section 6.3.2.2.)
h_{i2}	intermediate enthalpy value (J/kg)
h_{i1}	enthalpy intermediate value (J/kg)
h_{out}	enthalpy of the outside air (J/kg)
h_{ins}	enthalpy of the inside air (J/kg)
H_r	relative humidity of ambient air
h_{r1}	isentropic discharge enthalpy (J/kg)
h_{r2}	uncooled compressor discharge enthalpy (kJ/kg)
h_{r3}	enthalpy of the discharge gas at the desired oil cooler exit temperature (J/kg)
h_{r4}	enthalpy of the discharge gas at the desuperheater exit (J/kg)
$h_{r\beta}$	superheat enthalpy (J/kg)
H_{tot}	total daily heat requirement (J)
h_{vs}	saturated suction vapour enthalpy (J/kg
h_w	enthalpy of exiting water vapour (J/kg)
h_w	enthalpy of exiting water vapour dryer first compartment (J/kg) (Section 5.3.4.1)
I	moisture content of outlet gas (kg water /kg dry gas)
I_d	moisture content of inlet gas (kg water/kg dry gas)
I_o	outlet air humidity (kg water/kg dry air)
K	energy embodied in the product leaving the cooker (W)
K	energy embodied in the product leaving the dryer first compartment (W) (Section 5.3.4.1)

K	air interchange factor (Section 7.5.1.2)
k_a	thermal conductivity of air (W/mK)
K_f	kill stream dry solids flow rate (kg dry solids/s)
k_g	mass transfer coefficient (s/m) or (kg/m^{2}sPa)
k_i	thermal conductivity of insulation (W/mK)
kl	unfrozen material thermal conductivity (W/mK)
k_p	thermal conductivity of the packaging material (W/mK)
ks	frozen material thermal conductivity (W/mK)
L	enthalpy change in freezing (J/m^3)
lb_{amen}	total grouped lamb boning shower flow rate (kg/s)
lb_{apron}	mean apron wash flow rate (kg/s)
lb_{hand}	mean lamb boning hand wash flow rate (kg/s)
lb_{hose}	total grouped lamb boning cleanup hosing consumption (kg/s)
lb_{ks}	mean lamb boning knife steriliser flow rate (kg/s)
lbm	lamb boning dry solids flow rate (kg dry solids/s)
lbx	moisture content of the lamb boning material (kg water/kg dry solids)
L_j	latent heat of steam at jacket flow meter pressure (kJ/kg)
lk_{amen}	total grouped lamb kill shower flow rate (kg/s)
lk_{anc}	total lamb kill ancillaries flow rate (kg/s)
lk_{apron}	mean lamb kill apron wash flow rate (kg/s)
lk_{bc}	brisket cutter steriliser flow rate (kg/s)
lk_{bd}	brisket drill steriliser flow rate (kg/s)
lk_{dp}	total depelter steriliser flow rate (kg/s)
lk_e	eviscerator steriliser flow rate (kg/s)
lk_{et}	eviscerate table steriliser flow rate (kg/s)
lk_{fhc}	fore leg hock cutter steriliser flow rate (kg/s)
lk_{hand}	mean lamb kill hand wash flow rate (kg/s)
lk_{hose}	total grouped lamb kill cleanup hose flow rate (kg/s)
lk_{ks}	mean lamb kill knife steriliser flow rate (kg/s)
lkm	lamb chain dry solids(kg dry solids/s)
lk_{nb}	neck breaker steriliser flow rate(kg/s)
lk_{nr}	nose roller steriliser flow rate (kg/s)

lkp_{hose}	total grouped lamb kill production hose flow rate (kg/s)
lk_{rhc}	rear hock cutter steriliser flow rate (kg/s)
lk_{wash}	rotary washers etc (if any) flow rate (kg/s)
lk_{wr}	lamb weasand rod steriliser flow rate (kg/s)
lkx	moisture content of the lamb chain material (kg water/kg dry solids)
M	mass dry solids in cooker (kg dry solids)
M	mass of fat-free dry solids in the dryer first compartment (kg fat-free dry solids) (Section 5.3.4.1)
M_{st}	mass of cooker steel components (kg)
Mt_1	mass of water in Tank 1 (kg)
Mt_2	mass of water in Tank 2 (kg)
M_{tot}	total mass within the system (kg)
M_{trial}	total mass held within system (kg)
Mx	mass of moisture in cooker (kg water)
Mx	mass of moisture in the dryer first compartment (kg water) (Section 5.3.4.1)
N	shape factor (Lovatt *et al.* 1993)
N_{bb}	number of knife sterilisers within the boning room
N_{bba}	number of apron washes within the beef boning
N_{bbh}	number of hand washes within the beef boning
N_{bk}	number of knife sterilisers within the beef house
N_{bka}	number of apron washes within the beef house
N_{bkh}	number of hand washes within the beef house
N_{lb}	number of knife sterilisers within lamb boning
N_{lba}	number of apron washes within the lamb boning
N_{lbh}	number of hand washes within the lamb boning
N_{lk}	number of knife sterilisers within the lamb kill
N_{lka}	number of apron washes within the lamb kill
N_{lkh}	number of hand washes within the lamb kill
No_p	number of personnel present
NumItem	number of product items
ohm	outside material dry solids flow rate (whole plant) (kg dry solids)

ohx	moisture content of the outside material (kg water/kg dry solids)
opm	outside material dry solids flow rate (hide fleshings/butchers shop)(kg dry solids/s)
Op_{rate}	frequency of use (operations per hour)
opx	outside material moisture content (kg water/kg dry solids)
P	total fat-free dry solid flow rate to the raw material bin (kg fat-free dry solids/s)
P_1	absolute suction pressure (kPa)
P_2	absolute discharge pressure (kPa)
P_d	flow rate of dry gas (kg dry gas/s)
P_d	discharge pressure (absolute) (Section 6.3.2.6)
PR	compressor pressure ratio
P_s	suction pressure (absolute)
p_{wa}	vapour pressure of water at air temperature (Pa)
p_{wp}	vapour pressure of water at meal temperature (Pa)
p_{wp}	vapour pressure of water at meal temperature within the dryer first compartment (Pa). (Section 5.3.4.1)
Q_{air}	instantaneous heat load due to air interchange (W)
Q_{assoc}	heat load generated by lights and personnel (W
Q_{conv}	conveyor and ancillary heat load (kW)
Q_d	steam consumption rate (kg/s)
Q_d	energy input required to heat incoming air (W) (Section 5.3.3.3)
Q_d	steam condensate flow rate through the heat exchanger (kg/s) (Section 6.3.2.3)
Q_{ext}	heat gain through wall (W)
Q_{fan}	required fan power/batch (W)
Q_{flift}	mean heat load generated by all forklifts within the store (kW)
Q_{hw}	clean-up hot water heat load (W)
Q_{hwp}	production hot water heat load (W)
Q_l	light heat load (W)
Q_{mach}	total machine heat load (kW)
Q_{pers}	heat load generated by personnel (W)

Q_{pre}	room precooling heat load (W)
Q_r	reactor steam consumption flow rate (kg/s)
Q_{sw}	shrink tunnel heat load (kW)
R	the discharge gas flow rate (kg/s)
$Rate$	rate of valve opening (s^{-1})
R_B	mass of dry solids in the raw blood tank (kg dry solids)
$rend_{hose}$	total rendering hose flow rate (kg/s)
$rend_{proc}$	total rendering process flow rate (kg/s)
Rmg	mass of fat-free dry solids in the raw material bin (kg fat-free dry solids)
T_2	temperature of contents (°C)
t_a	mean activation time (s)
T_{amb}	ambient temperature (°C)
T_{amb}	temperature of the ambient air (°C)
T_c	refrigerant condensation temperature (°C)
Tc_2	temperature of cold water supply (°C)
T_{cond}	temperature of the cooled steam condensate leaving the heat exchanger (°C)
T_{crec}	temperature of cold water to heat exchanger (°C)
T_d	temperature of solids exiting the decanting centrifuge (°C)
T_{desup}	temperature of the water flow leaving the desuperheater (°C)
T_{drain}	temperature of the flow from the drain heat recovery system (°C)
T_e	refrigerant evaporation temperature (°C)
T_{ex}	condensate exit temperature (°C)
T_{ext}	external temperature (C°)
T_f	temperature of the feed (°C)
T_f	product initial freezing temperature (°C) (Section 7.3.2.2)
Tin_β	temperature of flow to heat exchanger (°C)
Tin_2	required final temperature to plant (°C)
T_{int}	meal temperature in the cooker (°C)
T_j	temperature of steam, saturated at jacket pressure (°C) (Section 5.2.5)
T_j	temperature of makeup water (°C)

Tk_β	temperature of the tank contents (°C)
Tk_2	temperature of water in Tank 2 (°C)
T_{oil}	temperature of the water flow leaving the oil cooler (°C)
T_{pd}	temperature of inlet gas to dryer (°C)
T_{pot}	refrigerant evaporation temperature (°C)
t_{pre}	time from refrigeration start to meat processing start (s)
Tpu_β	required temperature of outlet water (°C)
Tpu_2	temperature of steriliser water (°C)
Tpu_3	temperature of the hand apron wash water (°C)
Tr_β	temperature of ring main return (°C)
T_{r2}	temperature of hosing and steriliser ring main return flow from plant (°C)
T_{r3}	temperature of discharge gas at the oil cooler exit (°C)
T_{r4}	temperature of the discharge gas at the exit of the desuperheater (°C)
T_{reac}	temperature of the raw material exiting the reactor vessel (°C)
T_{refr}	temperature of the flow from the refrigeration heat recovery system (°C)
T_{rendr}	temperature of flow from the rendering recovery system (°C)
T_{renin}	inlet temperature of the cooling water (°C)
T_{rout}	temperature of the outlet waste stream (°C)
T_s	superheat temperature (°C)
T_{sat}	maximum possible condensation temperature of the moisture in the gas outlet stream (°C)
T_{satr}	temperature of saturated refrigerant vapour (°C)
T_{sc}	temperature of flow from the steam condensate heat recovery system (°C)
T_{scin}	temperature of cooling water to the heat exchanger (°C)
T_{st}	temperature at which steam condenses in the jacket (°C)
T_{trial}	total heat held within system (J)
T_{wi}	mean temperature of recovered waste flow (°C)
T_{wo}	temperature of the waste water out °C
U_β	heat transfer coefficient for losses from the tank surfaces (W/m^{2}K)

U_1	cooker shell heat transfer coefficient (W/m^2K)
U_2	cooker outer shell heat transfer coefficient (W/m^2K)
U_{jacket}	heat transfer coefficient of jacket (W/m^2K)
U_{shaft}	heat transfer coefficient of shaft (W/m^2K)
v_1	original air velocity (m/s)
v_2	new air velocity (m/s)
V_{ac}	air conditioned room volume (m^3)
v_{full}	velocity of air at full speed (m/s)
v_{ref}	reference velocity of air over product (m/s)
W	moisture evaporation rate (kg/s)
W	moisture evaporation flow rate in the dryer first compartment (kg water/s) (Section 5.3.4.1)
$W_{2\beta 1}$	recovered steriliser waste water flow rate from user selected departments (kg/s)
W_{2bb}	total grouped beef boning steriliser and hosing flow rate (kg/s)
W_{2bb1}	total grouped beef boning steriliser flow rate (kg/s)
W_{2bk}	total grouped beef kill steriliser and hosing flow rate (kg/s)
W_{2bk1}	total grouped beef kill steriliser flow rate (kg/s)
W_{2lb}	total grouped lamb boning steriliser and hosing flow rate (kg/s)
W_{2lb1}	total grouped lamb boning steriliser flow rate (kg/s)
W_{2lk}	total grouped lamb kill steriliser and hosing flow rate (kg/s)
W_{2lk1}	total grouped lamb kill steriliser flow rate (kg/s)
W_{2rend}	total grouped rendering hosing and processing flow rate (kg/s)
$W_{3\beta 1}$	recovered hand and apron wash water flow rate from user selected department (kg/s)
W_{3bb}	total grouped beef boning hand, apron wash and shower flow rate (k (kg/s)
W_{3bb1}	total grouped beef boning hand and apron wash flow rate (kg/s)
W_{3bk}	total grouped beef kill hand, apron wash and shower flow rate (kg/s)
W_{3bk1}	total beef kill grouped hand and apron wash flow rate (kg/s)
W_{3lb}	total grouped lamb boning hand, apron wash and shower flow rate (kg/s)
W_{3lb1}	total grouped lamb boning hand and apron wash flow rate (kg/s)

W_{3lk}	total grouped lamb kill hand, apron wash and shower flow rate (kg/s)
W_{3lkl}	total grouped lamb kill hand and apron wash flow rate (kg/s)
W_{4bk}	beef kill carcass wash consumption rate (kg/s)
W_{4lk}	lamb kill carcass wash consumption rate (kg/s)
W_{air}	instantaneous volumetric flow rate through door (m^3/s)
Wb_2	warm water flow rate to Tank 2 (kg/s)
Wb_3	warm water flow rate to Tank 3 (kg/s)
Wb_4	warm water flow rate to Tank 4 (kg/s)
Wb_{rendr}	cooling water flow rate to rendering heat exchanger (kg/s)
Wb_{sc}	cooling water flow rate to steam condensate desuperheater (kg/s)
Wb_t	total supply flow rate from Tank 1 (kg/s)
Wc_2	cold water flow rate (kg/s)
Wc_{tot}	total cold water requirement (kg)(includes heat recovery inlets)
W_{desup}	flow rate of water through the desuperheater (kg/s)
W_{drain}	water flow rate through drain recovery heat exchanger (kg/s)
Win_β	flow rate of water to heat exchanger (kg/s)
Win_2	total required flow rate (kg/s)
Wo_{flow}	overspill flow rate from Tank 2 to Tank 1
W_{oil}	flow rate of water through the oil cooler (kg/s)
Wpu_β	plant consumption flow rate (kg/s)
Wpu_2	hot water flow rate to the plant (kg/s)
Wpu_3	total plant hand, apron wash and shower water flow rate (kg/s)
Wr_β	flow rate into the ring main (kg/s)
Wr_2	combined flow rate of hot water to plant and return to Tank 2 (kg/s)
W_{refr}	water flow rate through refrigeration heat exchanger (kg/s)
W_{rendr}	water flow rate through rendering heat exchanger (kg/s)
W_{sc}	water flow rate through steam condensate heat exchanger (kg/s)
W_{spill}	overflow rate from Tank 1 to waste (kg/s)
Wt_1	flow rate from Tank 2 (kg/s)
W_{waste}	total drain flow rate recovered (kg/s)
x	moisture content in the cooker (kg water/kg dry solids)

x	moisture content in the dryer first compartment (kg water/kg fat-free dry solids) (Section 5.3.4.1)
$x1$	fractional vapourisation on pressure reduction from the discharge pressure to the suction pressure (bars)
X	critical dimension (m)
x_a	thickness of air film trapped by packaging (m)
x_{Beef}	moisture content in the beef house stream (kg water/kg dry solids)
x_d	moisture content of the raw material (kg water/kg fat-free dry solids)
x_d	moisture content of feed to dryer (kg water/kg fat-free dry solids) (Section 5.3.4.1)
x_f	moisture content of the raw material (kg water/kg dry solids)
x_{fb}	moisture content of blood feed rate to blood plant (kg water/kg dry solids)
x_g	moisture content of material in the raw material bin (kg water/kg fat-free dry solids)
x_{gb}	moisture content of the boning stream (kg water/kg fat-free dry solids)
x_{gk}	moisture content of the kill stream (kg water/kg fat-free dry solids)
x_i	insulation thickness (m)
x_{Lamb}	moisture content in the lamb kill blood stream (kg water/kg dry solids)
x_p	moisture content of combined stream to raw material bin (kg water/kg fat-free dry solids)
x_p	thickness of the packaging material (m) (Section 7.3.2.3)
x_r	moisture content of material fed to the decanting centrifuge (kg water/kg fat-free dry solids)
x_t	moisture mass flow rate in the total plant stream (kg water/s)
Y_d	steam energy input (W)
Y_d	steam energy input to dryer first compartment (W) (Section 5.3.4.1)
Y_d	total inlet energy (W) (Section 5.3.4.3)
y_g	fat content of material in the raw material bin (kg fat/kg fat-free dry solids)
y_{gb}	fat content of the boning stream (kg fat/kg fat-free dry solids)
y_{gk}	fat content of the kill stream (kg fat/kg fat-free dry solids)
Y_i	enthalpy of the gas stream into the heat exchanger (kJ/kg)

Y_l	enthalpy of the outgoing condensed liquid stream (kJ/kg)
Y_o	enthalpy of the outgoing air (kJ/kg)
y_p	fat content of the combined flow to the raw material bin (kg fat/kg fat-free dry solids)
y_r	fat content of material to the decanting centrifuge (kg fat/kg fat-free dry solids)
Y_{rend}	enthalpy change across the rendering heat exchanger on the condensing vapour side (kJ/kg)
Z	energy loss from cooker shell to ambient air (W)
Z	energy loss from dryer first compartment shell to ambient air (W) (Section 5.3.4.1)
Z_l	estimated steam usage rate to overcome losses (kg/s)
Z_l	air conditioned room mean height (m) (Section 7.5.2.4)
Zp_β	heat losses from ring main associated with Tank β (W)
Zt_β	heat loss from Tank β (W)

REFERENCES

Anon (1972)

Internal memorandum. Confidential interplant survey, Meat Industry Research Institute of New Zealand (MIRINZ), Hamilton, New Zealand.

Brown, G.I., Willix, J. and Bayliss, M. (1988).

The use of meat and bone meal temperature for end-point control in drying. MIRINZ 856. MIRINZ, Hamilton, New Zealand.

Caddigan, M.S.C. and Swan, J.E. (1985).

Energy use in MIRINZ low temperature rendering plants. MIRINZ 839. MIRINZ, Hamilton, New Zealand.

Chan, C.Y., Haselden, G.G. (1981a).

Computer-based refrigerant thermodynamic properties - Part 1. *International Journal of Refrigeration*, **4**, 7-12

Chan, C.Y., Haselden, G.G. (1981b).

Computer-based refrigerant thermodynamic properties - Part 2. *International Journal of Refrigeration,* **4**, 52-60

Chan, C.Y., Haselden, G.G. (1981c).

Computer-based refrigerant thermodynamic properties - Part 3. *International Journal of Refrigeration,* **4**, 131-134

Cleland, D.J., Boyd, N.S. and Cleland, A.C. (1982).

A model for fish freezing on board small New Zealand fishing vessels, *Refrig Sci Technol* (1982-1) 147-156

Cleland, A.C. (1983).

Simulation of industrial refrigeration plants under variable load conditions, *International Journal of Refrigeration,* **6**, 11-19

Cleland, A.C. (1985a).

Experimental verification of a mathematical model for simulation of industrial refrigeration plants, *International Journal of Refrigeration,* **8**, 275-282

Cleland, A.C. (1986a).

Computer subroutines for rapid evaluation of refrigerant thermodynamic properties, *International Journal of Refrigeration,* **9**, 346-351

Cleland, A.C. (1986b).

Use of dynamic simulation in the design of food freezing equipment, *Food Engineering and Process Applications,* **Vol.24**, Le Maguer and Jelen (eds), Elsevier Applied Science Publishers, London, 55-65

Cleland, A.C. (1988).

A rapid empirical method for estimation of energy savings resulting from refrigeration plant alterations. Proc. Meeting of Commissions, C2 Di D2/3 Ei of Int. Inst of Refrigeration, Brisbane 5-9 September.

Cleland, A.C. (1990).

Food Refrigeration Processes - Analysis, Design and Simulation, Elsevier Science Publishers, London.

Cornelius, M.J. and Cleland, A.C. (1990).

Energy and Power Cost Savings. *Course Notes.* Massey University, Palmerston North, New Zealand.

Cleland, A.C. and Cleland, D.J. (1992).

Cost effective refrigeration. *Course Notes.* Massey University, Palmerston North, New Zealand.

Cleland, A.C. (1993).

Polynomial curve-fits for refrigerant thermodynamic properties - extension to include R134a. *International Journal of Refrigeration.* (in press).

Cornelius, M.J. (1991).

Refrigeration Analysis, Design and Simulation Package: "RADS" - *Notes for users (revised), Release 3.1*, Food Technology Research Centre, Massey University, Palmerston North, New Zealand.

D'Souza, G.B. and Scriven, A.P. (1983).

Evaluation of the effectiveness of low temperature cleaners in reducing sanitation energy costs in the food industry. Ottawa, Ontario, Canada; November 1983. Contract file #34SZ-01843-1-EP09.

Darkey, P. and Crosbie, C. (1987).

Sheepmeat processing plant simulation. *Proceedings of the 23rd Annual Conference - Operational Research Society of NZ.* August 24-25, 1987, Victoria University, Wellington.

Davies, A.J. (1989).

The structure and function of carcass tissue in relation to meat production. *Meat Production and Processing*. NZ Society of Animal Production. No 11. 43-60

Downey, J. and Fox, J. (1987).

Steamless meat works. MIRINZ P117, MIRINZ, Hamilton, New Zealand.

Fernando, T. and Dunn, S.E. (1979).

Effects of agitator speed, blade clearance and heat transfer area on cooking times of dry batch rendering cookers. *MIRINZ 718*. MIRINZ, Hamilton, New Zealand.

Fleming, A.K. (1969).

Calorimetric properties of lamb and other meats, *Journal of Food Technology, 4, 199-215*

Fleming, A.K. (1976).

Refrigeration demands for meat processing, *Refrigeration Science and Technology*, **1,** 285-292

Graham, A. (1972)

Steam usage for hot water production in Australian abbatoirs. Meat Research Report 5/72. Cannon Hill, Brisbane, Australia: CSIRO; 1972.

Hansen, C.L., White, R.K. and Okos, M.R. (1984).

Optimization of water management and associated energy in a meat packing plant. American Society of Agricultural Engineers 0001-2351/84/2701-0305 305-310

Haughey, D.P. and McConnell, I.W. (1973).

Pilot-scale investigation of heat and mass transfer during dry rendering. MIRINZ 287. MIRINZ, Hamilton, New Zealand.

Hay , J.L., Pearce, J.G., Turnbull, L. and Crosbie, R.E. (1988).

ESL Software User Manual. European Space Agency Contract Report, Ref. Cs - 1019/04 - SUM. Prepared by ISIM Simulation, a Division of Salford University Business Services Limited Business House, University Road, Salford M5 4pp.

Herbert, L.S. and Norgate, T.E. (1971).

Heat and mass transfer in a batch dry rendering cooker. *Journal of Food Science,* Vol **35**, 294-298

Hossain, Md. M., Cleland, D.J., Cleland, A.C. (1992a).

Prediction of freezing and thawing times for foods of two-dimensional irregular shape using a semi-analytical geometric factor, *International Journal of Refrigeration*, **15**, 235-240.

Hossain, Md. M., Cleland, D.J., Cleland, A.C. (1992b).

Prediction of freezing and thawing times for foods of three-dimensional irregular shape using a semi-analytical geometric factor, *International Journal of Refrigeration*, **15**, 241-246.

Husband, P.M. and McPhail, N.G. (1978).

The use of 82°C water in meat plant cleaning operations. Meat Research Report 2/78, Cannon Hill, Brisbane, Australia: CSIRO; 1978.

Johnson, B.Y. (1980).

Meat byproducts quality control workshop notes. July 1980, Hawkesbury Agricultural College, School of Food Sciences, Richmond, NSW, Australia. 42-75.

Langrish , T.A.G., Keey, R.B. and Fernando, T. (1990).

Sterilisation of Meal from Meat Works Waste in a Cascading Rotary Dryer. *Proc. 26th Meat Industry Research Conference*. 269-280

Lively, L.D. (1975).

Water Conservation and Waste Control in a Meat Packing Plant. *Industrial Process Design for Pollution Control. AI CHE Workshop. Vol 7.* Publication. American Institute of Chemical Engineers. New York.

Loeffen, M.P.F., Earle, R.L., Cleland, A.C. (1981).

Two simple methods for predicting food freezing times with time-variable boundary conditions, *Journal of Food Science*, **46**, 1032-1034

Loeffen, M.P.F., Pooley, E.J. and Swan, J.E. (1987).

Production monitoring and control in a rendering department. MIRINZ 850. MIRINZ, Hamilton, New Zealand.

Lovatt, S.J. (1992).

A dynamic modelling methodology for the simulation of industrial refrigeration systems. *Ph. D. Thesis, Massey University, Palmerston North, New Zealand.*

Lovatt, S.J., Pham, Q.T., Cleland, A.C. and Loeffen, M.P.F. (1993).

A new method of predicting the time-variability of product heat load during food cooling - Pt 1: Theoretical considerations. *Journal of Food Engineering,* **18,** 13-36

Lovatt, S.J., Pham, Q.T., Loeffen, M.P.F. and Cleland, A.C. 1993).

A new method of predicting the time-variability of product heat load during food cooling - Pt 2: Experimental Testing. *Journal of Food Engineering*, **18,** 37-62

Marshall, S.A. and James, R.W. (1975).

Dynamic analysis of an industrial refrigeration system to investigate capacity control. *Proc. Inst. Mech. Engrs.* **189** 44-75.

Oldfield, S. (1987).

Meat processing - Meat Industry By-Products - Rendering. *Meat Diploma Notes*, 4th Edition, Massey University, Palmerston North, New Zealand.

Peacham, T. (1993).

Personal communication. Environmental Research Officer, MIRINZ Hamilton, New Zealand.

Pearson, R.G. (1981).

Knife Steriliser Design. *Energy Conservation Case Studies, P51.* New Zealand Research and Development Committee. 18-27.

Pham, Q.T. (1991).

Temperature vs. enthalpy data for Tylose MH1000, Personal communication February 1991 (with S Lovatt)

Pham, Q.T. (1991).

Computer calculation of meat plant refrigeration requirements. MIRINZ 881. MIRINZ, Hamilton, New Zealand.

Pham, Q.T., Wee, H.K., Kemp, R.M. and Lindsay, D.T. (1993).
Determination of the enthalpy of foods by an adiabatic calorimeter. *Journal of Food Engineering* (in press)

Pham, Q.T. and Willix, J. (1989).
Thermal Conductivity of fresh lamb meat, offals and fat in the range -40 to +30°C: measurements and correlations. *Journal of Food Science,* **54**, No.3, 508-515

Pham, Q.T. and Oliver, D.W. (1983).
Infiltration of air into cold stores, *Proc. 16th International Congress of Refrigeration*, **4**, 67-72

Shaw, W. (1991).
Optimisation of overheat and water flow in knife steriliser design. Unpublished report. Massey University, Palmerston North, New Zealand.

Spooner, W.F. (1992).
By-Product yields from sheep and cattle. Meat Research Report 2/92. Division of Food Processing, Meat Research Laboratory, CSIRO, Cannon Hill, Queensland, Australia.

Tamm, W. (1965).
Air flow within air curtains to protect cold rooms, *Proc.11th International Congress of Refrigeration*, **2**, 1025-1033

Wee, H.K. and Kemp, R.M. (1992).
Survey of energy use in the New Zealand Meat Industry for the 1989/90 season. MIRINZ 877. MIRINZ, Hamilton, New Zealand.

White, F. (1992).
Personal communication. Manager, Keith Engineering Pty, Auckland, New Zealand.

APPENDIX A1 - GENERIC MODEL LISTING

```
study
model Generic(real:xf,rm);
--
--Beef house rendering mass feed rates.
--
       constant real:bko/0.0/,bk1/0.6/,bk2/0.66/,bk3/0.716/;
--
--Beef house rendering feed moisture rates.
--
       constant real:bxo/0.0/,bx1/0.85/,bx2/0.95/,bx3/1.3/;
--
--
--Beef house daily time steps.
--
--
       constant real:bsto/0.0/,bst1/7200.00/,bst2/15600.0/,
       bst3/25000.0/,bst4/33600.0/,bsto1/14400.0/,bsto2/21600.0/,
       bsto3/32400.0/,bsto4/37200.0/,bch1/18000.0/,bch2/27600.0/;
--
--
--Beef boning room rendering mass rates.
--
       constant real:bbo/0.0/,bb1/0.6/,bb2/0.912/,bb3/1.0/;
--
--Beef boning room rendering moisture feed rates.
--
      constant real:bbxo/0.0/,bbx1/0.9/,bbx2/0.95/,bbx3/1.0/;
--
--
--Beef boning room daily time steps.
--
--
       constant real:bbsto/0.0/,bbst1/7200.0/,bbst2/15600.0/,
       bbst3/25000.0/,bbst4/33600.0/,bbsto1/14400.0/,bbsto2/21600.0/,
       bbsto3/32400.0/,bbsto4/37200.0/,bbch1/18000.0/,bbch2/27600.0/;
--
--
--Lamb chain rendering mass rates.
--
        constant real:lko/0.0/,lk1/0.81/,lk2/0.45/,lk3/0.45/;
--
--      Lamb chain rendering moisture feed rates.
--
        constant real:lxo/0.0/,lx1/1.5/,lx2/1.0/,lx3/1.0/;
--
--
--Lamb chain daily time steps.
--
--
       constant real:lkst0/0.0/,lkst1/7200.0/,lkst2/15600.0/,
       lkst3/25000.0/,lkst4/33600.0/,lksto1/14400.0/,lksto2/21600.0/,
       lksto3/32400.0/,lksto4/37200.0/,lkch1/18000.0/,lkch2/27600.0/;
--
--
--Lamb boning room rendering mass rates.
--
       constant real:lbo/0.0/,lb1/0.65/,lb2/0.45/,lb3/0.45/;
--
--Lamb boning room rendering moisture feed rates.
--
       constant real:lbxo/0.0/,lbx1/0.5/,lbx2/0.5/,lbx3/0.5/;
--
--
--Lamb boning room time steps.
--
```

```
--
       constant real:lbsto/0.0/,lbst1/7200.0/,lbst2/15600.0/,
       lbst3/25000.0/,lbst4/33600.0/,lbsto1/14400.0/,lbsto2/21600.0/,
       lbsto3/32400.0/,lbsto4/37200.0/,lbch1/18000.0/,lbch2/27600.0/;
--
--
--Outside rendering mass rates.
--
       constant real:omo/0.0/,om1/16.6/;
--
--
--Outside rendering moisture feed rates.
--
       constant real:oxo/0.0/,ox1/1.3/;
--
--
--Outside rendering time steps.
--
    constant real :osto/0.0/,ost1/36000.0/,osto1/36900.0/;
--
--DAF rendering mass rates.
--
       constant real:dmo/0.0/,dm1/0.2/;
--
--
--DAF rendering moisture feed rates.
--
       constant real:dxo/0.0/,dx1/0.5/;
--
--
--DAF rendering time steps.
--
       constant real :dsto/0.0/,dst1/3600.0/,dsto1/42000.0/;
--
--
       Real:rmxf,bm,bx,bbm,bbx,lkm,lkx,lbm,lbx,om,ox,dm,dx,f,KF,BF,GK,GB;
       Real:xk,xb,xgk,xgb,ygk,ygb,ohm/0.1/,ohx/0.1 /,opm/0.1/,opx/0.1/,KFxk,BFxb
;

Initial
--
-- Rm:=1.0;rmxf:=0.0;f:=0.0;
--
--
Dynamic
--
--
     KF:=bm+lkm+dm+ohm;
     KFxk:=bm*bx+lkm*lkx+dm*dx+ohm*ohx;
     xk:=KFxk/KF;
     BF:=bbm+lbm+opm;
     BFxb:=bbm*bbx+lbm*lbx+opm*opx;
     xb:=BFxb/BF;
--   GK*(1+xgk+ygk):=KF*(1+xk);
     GK:=0.45*KF;
     xgk:=2.222*xk;
     ygk:=(KF/GK)-1;
  -- GB*(1+xgb+ygb):=KF*(1+xb);
     GB:=0.562*BF;
     xgb:=1.779*xb;
     ygb:=(BF/GB)-1;
--   xf:=Rmxf/rm;
--   Rm':=bm+lkm+bbm+lbm+om+dm-f;

--   Rmxf':=(bm*bx+bbm*bbx+lkm*lkx+lbm*lbx+om*ox+dm*dx-f*xf);
     when t < 7200.0 and rm < 2.0 then f:=0.0;
```

```
     when t >= 7200.0 and rm >=2.0 then f :=0.9;end_when;
--
--
--BEEF KILL-----------------------------------
--
--Solids mass
--
        bm:= if t > bsto4 then bko else_if t > bst4 then bk3
        else_if t > bsto3 then bko else_if t > bch2 then bk3
        else_if t > bst3 then bk2 else_if t > bsto2 then bko
        else_if t> bch1 then bk2 else_if t > bst2 then bk1
        else_if t > bsto1 then bko else_if t> bst1 then bk1
        else bko;
--
--Moisture mass
--
       bx:= if t < bst1 then bxo else_if t < bsto1 then bx1
       else_if t < bst2 then bxo else_if t < bch1 then bx1
       else_if t < bsto2 then bx2 else_if t < bst3 then bxo
       else_if t < bch2 then bx2 else_if t < bsto3 then bx3
       else_if t < bst4 then bxo else_if t < bsto4 then bx3
       else bko;

--
--BEEF BONING------------------------------
--
--Solids mass
--
        bbm:= if t < bbst1 then bbo else_if t < bbsto1 then bb1
        else_if t < bbst2 then bbo else_if t < bbch1 then bb1
        else_if t < bsto2 then bb2 else_if t < bbst3 then bbo
        else_if t < bbch2 then bb2 else_if t < bsto3 then bb3
        else_if t < bbst4 then bbo else_if t < bsto4 then bb3
        else bbo;
--
--Moisture mass
--
       bbx:= if t < bbst1 then bbxo else_if t < bbsto1 then bbx1
       else_if t < bbst2 then bbxo else_if t < bbch1 then bbx1
       else_if t < bbsto2 then bbx2 else_if t < bbst3 then bbxo
       else_if t < bbch2 then bbx2 else_if t < bbsto3 then bbx3
       else_if t < bbst4 then bbxo else_if t < bbsto4 then bbx3
       else bbxo;
--
--
--LAMB KILL------------------------------
--
--Solids mass
--
        lkm:= if t < lkst1 then lko else_if t < lksto1 then lk1
        else_if t < lkst2 then lko else_if t < lkch1 then lk1
        else_if t < lksto2 then lk2 else_if t < lkst3 then lko
        else_if t < lkch2 then lk2 else_if t < lksto3 then lk3
        else_if t < lkst4 then lko else_if t < lksto4 then lk3
        else lko;
--
--Moisture mass
--
       lkx:= if t < lkst1 then lxo else_if t < lksto1 then lx1
       else_if t < lkst2 then lxo else_if t < lkch1 then lx1
       else_if t < lksto2 then lx2 else_if t < lkst3 then lxo
       else_if t < lkch2 then lx2 else_if t < lksto3 then lx3
       else_if t < lkst4 then lxo else_if t < lksto4 then lx3
       else lxo;
--
--
```

```
--LAMB BONING------------------------------
--
--Solids mass
--
        lbm:= if t < lbst1 then lbo else_if t < lbsto1 then lb1
        else_if t < lbst2 then lbo else_if t < lbch1 then lb1
        else_if t < lbsto2 then lb2 else_if t < lbst3 then lbo
        else_if t < lbch2 then lb2 else_if t < lbsto3 then lb3
        else_if t < lbst4 then lbo else_if t < lbsto4 then lb3
        else lbo;
--
--Moisture mass
--
       lbx:= if t < lbst1 then lbxo else_if t < lbsto1 then lbx1
       else_if t < lbst2 then lbxo else_if t < lbch1 then lbx1
       else_if t < lbsto2 then lbx2 else_if t < lbst3 then lbxo
       else_if t < lbch2 then lbx2 else_if t < lbsto3 then lbx3
       else_if t < lbst4 then lbxo else_if t < lbsto4 then lbx3
       else lbxo;
--
--
--OUTSIDE RENDERING-------------------------------------------------
--
--Solids mass
--
      om:= if t < ost1 then omo else_if t <osto1 then om1 else omo;
--
--Moisture mass.
--
      ox:= if t < ost1 then oxo else_if t < osto1 then ox1 else oxo;
--
--DISSOLVED AIR FLOTATION-------------------------------------------
--
--Solids mass.
--
      dm:= if t < dst1 then dmo else_if t < dsto1 then dm1 else dmo;
--
--Moisture mass.
--
      dx:= if t < dst1 then dxo else_if t < dsto1 then dx1 else dxo;
--
step
--
communication
      Tabulate t,xk,KF,KFxk,BF,BFxk;
--
      prepare"generic",t,lbx,dx;
--
end generic;
--
--experiment
--
        real:xf,rm;
        algo:=rk4;cint:=600.0;tfin:=12000.0;
        generic(xf,rm);
--
end_study
```

APPENDIX B1 - CONTINUOUS DRY RENDERING MODEL LISTING

```
study
model Kieth(real:x:=real:U1);
     constant real:Cdry/1850.0/,Cw/4180.0/;
     constant real:Cst/450.0/,Tf/25.0/;
     constant real:Tamb/25.0/,Full/9500.0/,Tmax/140.0/,Tmin/130.0/;
     constant real:Hr/0.75/,Mst/29000.0/,tim/30.0/;
     constant real:A1/88.0/;
     constant real:U2/0.0/,A2/0.0/,pwa/2.34/,xf/1.242/;
     constant real:LHST/2350E3/,D/0.0211/,qdmax/1.4/;
--=====================================================
--Constants for Rendering heat recovery
--=====================================================
      constant real:Cv/1890.0/,Hfg/2258E3/,Trenin/15.0/;
      constant real:nu/10.0/,zeta/10.0/;
--================================================
--Constants for Steam condensate heat recovery
--================================================
      constant real:Cwh/4268.0/,omega/10.0/,sigma/5.0/;
      constant real:Tscin/15.0/,Tsat/100.0/;
--================================================
     Real:M,Mx,B,aw,K,Z,Yd,R,W,hw;
     Real:tint,fp,fd,Tst,sd,qd,td,pwp;
--===================================================
      Real:Trend,Wrend,Trout,Yrend;
--===================================================
      Real:Tex,Tcond,Tsc,Wsc,Wsc1;
--
INITIAL
    M:=7778.0;Fp:=0.0;Mx:=M*0.05;
    B:=(M*Cdry+M*0.1*Cw+Mst*Cst)*60;
--
--
DYNAMIC
    pwp:=exp(23.4795-(3990.56/(Tint+233.833)))*0.001;
    aw:=1-exp(-2.4*x);
    hw:=2.476E6 + 2000 *Tint;
    R:=M*(1+x);
    td:=(Tst-Tint);
    Qd:=(U1*A1*td)/LHST;
    Yd:=sd*LHST;
    W:=D*(aw*pwp-Hr*pwa);
    Z:=U2*A2*(Tint-Tamb);
    K:=(Fp*Cdry+Cw*x)*Tint;
    x:=Mx/M;
    M':=Fd-Fp;
    Mx':=Fd*(xf)-W-Fp*x;
    Tint:=B/(M*Cdry+M*x*Cw+Mst*Cst);
    B':=((Fd*Cdry+Fd*x*Cw)*Tf+yd-Z-K-(W*hw));
    when t < 3000 then fp:=0.0;
    When t >= 3000 then fp:=0.79;end_when;
    Fd:= if t < 1800 then 0.0 else 0.79;
    Tst:= if t < 1800 then 159.0 else_if t < 4800
    then 152.0 else_if t < 5700 then 159.0 else 175.0;
    sd:= if qd < 0.0 then 0.0 else_if qd > qdmax then qdmax else qd;
--===================================================
-- Rendering heat recovery
--===================================================
      Trend:=Tsat-nu;
      Trout:=Trenin+zeta;
      Yrend:=W*((Cv*(Tint-100))+Hfg+(Cw*(100-Trout)));
      Wrend:=(Yrend*W)/((Trend-Trenin)*Cw);
--===================================================
--Steam condensate heat recovery
--===================================================
      Tex:=Tint;
```

```
      Tsc:=100.0-sigma;
      Tcond:=Tscin+omega;
      Wscl:=(Qd*Cwh*(Tex-100.0))/(Cw*(Tsc-Tscin));
      Wsc:= if Wscl < 0.0 then 0.0 else Wscl;
STEP
--
--
COMMUNICATION
   tabulate t,tint,W,Wrend,Trend,Tsc,Sd,Wsc,Trend;
   Prepare "Kieth",t,W,Wrend,Sd,Wsc;
--
--
END Kieth;
--
--
--EXPERIMENT
    real:Fp,x,Ul;
-- Set integration parameters.
    algo:=rk5;  cint:=300.0;tfin:=14400.0;
    read Ul;
    kieth(x:=Ul);
END_STUDY
```

APPENDIX B1.1 - RANGIURU DATA

Rangiuru consumption calculations.

COMMENTS				Time (minutes)	Steam flow (reading)	Steam used. (Kg.)	Steam used (Kg/s)	Steam Press BarG	Tint oC	Moisture kg/s.
	0	0	8.41				0.47	6.00	56	0.00
	300									
	432.54									
	432.54									
	600									
Started feed out also.	750									
	900									
	1050									
	1200	1200	8.74	20.00			1.25	6.00	90	0.00
	1500	1500	8.83	5.00			1.25	5.50	110	0.54
Large amount of moisture	1760.1									
	1800	1800	8.91	5.00			1.25	5.70	120	0.36
	1800									
	1950									
	2100									
	2400	2400	9.08	10.00	25537.00		0.76	4.20	135	0.29
	2623.1									
	2700	2700	9.16	5.00	25752.00	215.00	0.57	3.50	136	0.33
	2801.8									
	3000									
	3000									
	3300	3300	9.33	10.00	26071.00	319.00	0.53	3.90	133	0.49
	3600									
	3900	3900	9.49	10.00	26520.00	449.00	0.75	4.30	134	0.58
	4140.9									
	4200									
	4326									
	4500	4500	9.66	10.00	27009.00	489.00	0.82	4.50	134.7	0.59
	4650									
	4800									
	4800									
	5044.7									
	5100	5100	9.83	10.00	27565.00	556.00	0.93	5.50	134.7	0.71
	5250									
	5400									
	5550									
	5700	5700	9.99	10.00	28237.00	672.00	1.12	6.50	132.6	0.72
	5700									
	5850									
	5937.3									
	5937.3									
	6000									
	6150									
	6300									
	6450									
	6600									
	6750									
	6900									
	7050									
	7200									
	7500	7500	10.49	30.00	30527.00	2290.00	1.27	8.10	131	0.93
	7800	7800	10.58	5.00	30795.00	268.00	0.89	7.50	133	0.88
	8100									
	8400									
	8700	8700	10.83	15.00	31830.00	1035.00	1.15	8.10	135	0.85
	9000									
	9300									
	9600									
	9900									
	10200	10200	11.24	25.00	33624.00	1794.00	1.20	7.40	131.8	0.94
	10500									
	10800	10800	11.41	10.00	34269.00	645.00	1.08	6.50	128.4	0.96
	11100									
	11400	11400	11.58	10.00	35062.00	793.00	1.32	8.10	135.9	0.71
	11700									
	12000	12900.00	11.99	25.00	36112.00	1050.00	0.70		136	0.69
										0.72

APPENDIX B2 - BATCH DRY RENDERING MODEL LISTING

```
study
model batch (real:Fp,x:=real:xf);
     constant real:Cdry/1642.0/,Cw/4180.0/;
     constant real:Cst/450.0/,Tf/25.0/;
     constant real:Tamb/25.0/,Full/3700.0/;
     constant real:Hr/0.75/,Mst/10250.0/;
     constant real:As/10.2/,Fd/0.0/;
     constant real:U2/0.0/,A2/0.0/,pwa/2.34/;
     constant real:kgA/0.0034/,qdmax/1.56/;
     constant real:BB/0.0083/,tshut/4440.0/;
     constant real:topen/5040.0/,Umax/5000.0/,tmax/130.0/;
--
--
     Real:M,Mx,B,aw,K,Z,Yd,R,W,hw,Uj,Ujack,Us,Ushaft,AA,rate;
     Real:tint,sd,qd,td,pwp,hs,Aj,P,O,Wb,Wshut,Wcrack,Wopen;
     Real:tcrack/90000.0/,tst;
--
--
INITIAL
    M:=1950.0;Fp:=0.0;Mx:=M*1.12;Wcrack:=0.0;
    B:=(M*Cdry+M*1.12*Cw+Mst*Cst)*35.0;
--
--
DYNAMIC
  --
    x:=Mx/M;
    pwp:=exp(23.4795-(3990.56/(Tint+233.833)))*0.001;
    aw:=1-exp(-2.4*x);
    hw:=2.476E6 + 2000 *Tint;
    hs:=(2027E3)+(Cw*(Tst-Tint));
    R:=M*(1+x);
    td:=(Tst-Tint);
--  Uj:=256.0*exp(1.25*x);
--  Us:=332.3*exp(1.012*x);
    Uj:=350*exp(1.4*x);
    Us:=350*exp(1.4*x);
    Qd:=(((Ujack*Aj)+(Ushaft*As))*td)/hs;
    Yd:=sd*hs;
    AA:=(M*Cdry+M*x*Cw+Mst*Cst);
    Wb:=kgA*(aw*pwp-Hr*pwa);
    Wshut:=0.0*Wb;
    Wopen:=(BB*AA+Yd)/hw;
    Z:=U2*A2*(Tint-Tamb);
    K:=(Fp*Cdry+Cw*x)*Tint;
    rate:=if t < tcrack then 0.0 else 0.001;
    Wcrack':=Rate*Wb;
 -- M':=Fd-Fp;
    Mx':=Fd*(xf)-W-Fp*x;
    Tint:=B/AA;
    B':=((Fd*Cdry+Fd*x*Cw)*Tf+yd-Z-K-(W*hw));
    P:=(Fd*Cdry+Fd*x*Cw)*Tf;
    O:=(W*hw);
 --
 -- when t < 3000 then fp:=0.0;
 -- When t >= 3000 then fp:=0.79;end_when;
 -- Fd:= if t < 0.00 then 2.166 else 0.0;
 --
    Tst:= if t < 360 then 135.0 else_if t < 1080
    then 148.0 else_if t < 2520 then 154.0 else_if t < 4320 then 158 else 162.0;
 --
    W:= if t < tshut then Wb else_if t > tshut and
    t <= tcrack then Wshut else_if Wcrack < Wb and
    t > tcrack then Wcrack else Wb;
--
    Ujack:=if Uj >Umax then Umax else Uj;
```

```
    Ushaft:= if Us > Umax then Umax else Us;
--
    Aj:=if t < 120 then 0.0 else_if t < 7290 then 16.07 else 0.0;
    sd:= if qd < 0.0 then 0.0 else_if qd > qdmax then qdmax else qd;
--

--
--
STEP
   If t > tshut and tint > 135.0 and tcrack=
   90000.0 then tcrack:=t;end_if;

--

--
COMMUNICATION
   Prepare "batch",t,x,fd,w,sd,tint;
   tabulate t,x,fd,w,sd,tint;
--
--
END Batch;
--
--
--EXPERIMENT
    real:Fp,x,xf;
   read xf;
-- Set integration parameters.
    algo:=rk5;  cint:=60.0  ;tfin:=7920.0;
    batch(Fp,x:=xf);
END_STUDY→
```

APPENDIX B3 - LOW TEMPERATURE RENDERING MODEL LISTING

```
--ONLY FOR TRIALS ON MIRINZ DATA;
--CHANGE BACK TF,TAMB TJ REAC EQ. CFAT TO CW;

study
model mltr(real:x,xq:=real:G,xg,yg);
constant real:Cs/1300.0/,Cw/4200.0/;
constant real:Cfat/2200.0/,Cst/450.0/,Tf/10.0/;
Constant real:Tamb/25.0/,Td/93.0/;
constant real:Hr/0.75/,Mst/10875.00/,U1/121.0/;
constant real:A1/60.5/,Tst/162.0/;
constant real:Treac/95.0/,U2/121.0/,A2/0.0/,pwa/2.4/,xd/1.0/;
constant real:hs/2077E3/,kgA/0.0016/,Fj/0.5/,Tj/93.0/;
--
--
Real:M,M2,Mx,M2xq,Fr,Qr,B,B2,Aw,Aw2,xr,yr,P,O,P2,O2;
Real:K,K2,Z,Z2,Yd,Yd2,R,R2,pwp,pwp2,Hw,Hw2,W,W2,tint,tint2;
Real:fd,fp,fq,qd,qd2,qdt,qt,Fft,Ffl,Ffw,rat,E,I;
--
--
INITIAL
--DRIER 1------------
M:=1400.0;Fd:=0.0;
Mx:=M*0.05;Fp:=0.0;
B:=(M*Cs+M*0.1*Cw+Mst*Cst)*60;
--DRIER 2------------------
M2:=300.0;Fp:=0.0;
M2xq:=M2*0.05;Fq:=0.0;
B2:=(M2*Cs+M2*0.1*Cw+Mst*Cst)*60;
--
DYNAMIC
--
--DRIER 1------------------
    pwp:=exp(23.4795-(3990.56/(Tint+233.833)))*0.001;
    AW:=1-exp(-3.6*x);
    Hw:=(2.476E6+(2000 * tint));
    R:=M*(1+x);
--
--DRIER 2--------------------
    pwp2:=exp(23.4795-(3990.56/(Tint2+233.833)))*0.001;
    AW2:=1-exp(-3.6*xq);
    Hw2:=(2.476E6+(2000 * tint2));
    R2:=M2*(1+xq);
--
--GENERAL-----------------------
--  G*(1+xg+yg)=Fj*(1+xr+yr);
    Fr:=G;
    xr:=((G*xg)+Fj)/Fr;
--  G*xg+Fj:=Fr*xr;
    yr:=yg;
    Fft:=Fr*(1+xr+yr)-Fd*(1+xd);
    Ffw:=(Fr*xr)-(Fd*xd);
    Ffl:=Fr*yr;
    rat:=qdt/I;
    Qr:=(((G*Cs+G*yg*Cfat+G*xg*Cw))*(Treac-Tf)+Fj*Cfat*(Treac-Tj))/hs;
    Qdt:=Qd+Qd2;
    Qt:=Qdt+Qr;
--
--FIRST DRIER------------------------
    Qd:=(U1*A1*(Tst-Tint))/hs;
    Yd:=Qd*hs;
    W:=kgA*(AW*pwp-Hr*pwa);
    Z:=U2*A2*(Tint-Tamb);
  --  Z:=10000.0;
    K:=((Fp*Cs)+(Fp*Cw*x))*Tint;
    x:=Mx/M;
```

```
    M':=Fd-Fp;
    Mx':=Fd*xd-W-Fp*x;
    Tint:=B/(M*Cs+M*x*Cw+Mst*Cst);
    B':=(((Fd*Cs)+(Fd*xd*Cw))*Td+yd-Z-K-(W*Hw));
    P:=((Fd*Cs)+(Fd*xd*Cw))*Td;
    O:=(W*Hw);
    E:=(Fp*x);
    I:=(W+W2);
--
--SECOND DRIER------------------------
    Qd2:=(U2*A1*(Tst-Tint2))/hs;
    Yd2:=Qd2*hs;
    W2:=kgA*(AW2*pwp2-Hr*pwa);
    Z2:=U2*A2*(Tint2-Tamb);
    --Z2:=10000.0;
    K2:=((Fq*Cs)+(Fq*Cw*xq))*Tint2;
    xq:=M2xq/M2;
    M2':=Fp-Fq;
    M2xq':=Fp*x-W2-Fq*xq;
    Tint2:=B2/(M2*Cs+M2*xq*Cw+Mst*Cst);
    B2':=(((Fd*Cs)+(Fd*x*Cw))*Tint+yd2-Z2-K2-(W2*Hw2));
    P2:=((Fd*Cs)+(Fd*x*Cw))*Tint;
    O2:=(W2*Hw2);

--
--
STEP

--
--FIRST DRIER LOGIC------------------------------
    if Tint>=115 then Fd:=Fr; end_if;
    if Tint <105 and t < 1000 then Fd:=0;end_if;
    if M < 1300/(1+x) then Fp:=0;end_if;
    if M >= 1300/(1+x)then Fp:= Fd;end_if;
--
 --SECOND DRIER LOGIC----------------------------
    if M2 < 1700/(1+xq) then Fq:=0;end_if;
    if M2 >= 1700/(1+xq)then Fq:= Fd;end_if;

--
--
COMMUNICATION
   tabulate t,x,xq,w,w2,qd,qd2,qdt,qr,tint,tint2,rat;
   Prepare "MLTR",t,x,xq,w,w2,qd,qd2,qdt,qr,tint,tint2,rat;
--
--
END MLTR;
--
--
--EXPERIMENT
real:x,xq,Fp,G,xg,yg;
-- Set integration parameters.
   algo:=rk5;  cint:=360.0  ;tfin:=36000.0;
--
   read G,xg,yg;
   mltr (x,xq:=G,xg,yg);
END_STUDY→
```

APPENDIX B4 - LOW TEMPERATURE RENDERING ROTARY LISTING

```
study
model rotary (real:yd,I,Tpo:=real:G,xg,yg);
constant real:Cs/1600.0/,Cw/4180.0/,cvd/2100.0/,cvo/2100.0/;
constant real:Cfat/2150.0/,Tf/25.0/;
Constant real:Tamb/25.0/,Td/30.0/,tint/115.0/,tpd/800.0/;
constant real:cpd/1070.0/,cpo/1070.0/,Pd/1.6/,Id/0.112/,Hfg/2500E3/;
constant real:Treac/95.0/,xd/1.5/,x/0.08/,U2/0.0/,A2/0.0/;
constant real:Fj/0.5/,Tj/82.0/,hs/2296E3/;
--
--
Real:Fr,Qr,xr,yr;
Real:K,Z,W;
Real:fd,fp,fq,qd,qt,Fft,Ffl,Ffw,Qp;
--
--
INITIAL

DYNAMIC
--
--
--
--GENERAL-----------------------
--  G*(1+xg+yg)=Fj*(1+xr+yr);
    Fr:=G;
    Fd:=Fr;
    xr:=((G*xg)+Fj)/Fr;
--  G*xg+Fj:=Fr*xr;
    yr:=yg;
    Fft:=Fr*(1+xr+yr)-Fd*(1+xd);
    Ffw:=(Fr*xr)-(Fd*xd);
    Ffl:=Fr*yr;
    Qr:=(((G*Cs+G*yg*Cfat+G*xg*Cw))*(Treac-Tf)+Fj*Cw*(Treac-Tj))/hs;

--
--DRYER------------------------
    I:=Id+(Fd/Pd)*(xd-x);
    Yd:=(Fd*(cs+cw*xd))*Td+(Pd*((cpd+cvd*Id)*Tpd+(Hfg*Id)));
    Z:=U2*A2*((tpd-110.0)/2)-Tamb;

    Tpo:=(Yd-Z-((Fd*(cs+cw*x))*Tint)-(Pd*Hfg*I))/(Pd*(cpo+cvo*I));
    W:=I*Pd;
    Qp:=Pd*(((cpd+cvd*Id)*Tpd+(Hfg*Id)))*0.001;
--
--
--
STEP
--
--
--
--
COMMUNICATION
    Prepare "Rotary",t,tint,Qp;
    tabulate t,Yd,I,W,Tpo,Qp;
--
--
END Rotary;
--
--
--EXPERIMENT
real:yd,I,Tpo,Fp,G,xg,yg;
-- Set integration parameters.
   algo:=rk5;  cint:=300.0  ;tfin:=3000.0;
--
   read G,xg,yg;
   rotary (Yd,I,Tpo:=G,xg,yg);

END_STUDY
```

APPENDIX C1 - HOT WATER USAGE MODEL LISTING

```
study
model Hotuse(real:Wpu2,Wpu3,Wpu4:=real:U1);
--
--Beef house hosing and steriliser flow rates.
--
constant real:bkwr/0.0153/,bkdho/0.0024/,bkdhi/0.0/,bkhk/0.0458/;
constant real:bke/0.0153/,bkbs/0.0194/,bkss/0.1564/,bket/0.4694/;
constant real:bkgb/0.0/,bkhh/0.05/,bkt/0.0/,bkks/0.0067/;
constant real:IOH/0.2222/,Nbk/22.0/,bkhose/2.0/;
--=========================================
--Beef house wash an apron wash flow rates
--
constant real:bkhand/0.02/,Nbkh/4.0/;
constant real:bkapron/0.011/,Nbka/18.0/;
constant real:bkamen/0.15/,Nbks/15.0/;
constant real:Wtongue/0.3/,Chutepaunch/0.36/;
--
--Beefhouse carcase wash
--
constant real:W4bk/0.0/;
--
--Beef house daily time steps.
--==========================================
--
constant real:bst1/0.0/,bst2/9000.00/,bst3/15300.0/,

bst4/25200.0/,bsto1/8100.0/,bsto2/14400.0/,

bsto3/23400.0/,bsto4/32400.0/,bsto5/33900.0/,bsto6/37800.0/;
--
--
--Beef boning room hosing and steriliser flow rates.
--
constant real:bbks/0.011/,Nbb/5.0/,bbhose/2.0/;
--
--Beef boning room hand and apron wash rates.
--================================================
constant real:bbhand/0.0/,Nbbh/0.0/,bbapron/0.022/,Nbba/4.0/;
constant real:bbamen/0.15/,Nbbs/15.0/;
--
--Beef boning room daily time steps.

constant real:bbst1/0.0/,bbst2/9000.00/,bbst3/15300.0/,

bbst4/25200.0/,bbsto1/8100.0/,bbsto2/14400.0/,

bbsto3/23400.0/,bbsto4/32400.0/,bbsto5/33900.0/,bbsto6/37800.0/;
--
--
--
--
--Lamb chain hosing and steriliser rates.
--
constant real:lkwr/0.1/,lkrhc/0.1/,lknb/0.1/,lknr/0.1/;
constant real:lkdh/0.1/,lkbd/0.1/,lkfhc/0.1/,lkbc/0.1/;
constant real:lke/0.1/,lket/0.1/,lkks/0.5/,Nks/35.0/,lkhose/0.0/;

--Lamb chain hand and apron wash rates.
--
constant real:lkhand/0.7/,Nlkh/30.0/,lkapron/0.5/,Nlka/8.0/;
constant real:lkamen/0.1/,Nlks/20.0/;
--
--Lamb chain carcass wash flow rates.
--
constant real:W4lk/1.0/;
--
```

```
--Lamb chain daily time steps.
--
--
constant real:lkst0/0.0/,lkst1/7200.0/,lkst2/15600.0/,

lkst3/25000.0/,lkst4/33600.0/,lksto1/14400.0/,lksto2/21600.0/,
lksto3/32400.0/,lksto4/37200.0/;
--
--
--Lamb boning room hosing and steriliser flow rates.
--
constant real:lbks/0.2/,Nlb/20.0/,lbhose/0.0/;
--
--Lamb boning room hand and apron wash flow rates.
--
constant real:lbhand/0.7/,Nlbh/20.0/,lbapron/0.5/,Nlba/8.8/;
constant real:lbamen/0.2/,Nlbs/20.0/;
--
--
--Lamb boning room time steps.
--
--
constant real:lbsto/0.0/,lbst1/7200.0/,lbst2/15600.0/,
lbst3/25000.0/,lbst4/33600.0/,lbsto1/14400.0/,lbsto2/21600.0/,
lbsto3/32400.0/,lbsto4/37200.0/;
--
--Rendering hose and process flow rates
--
constant real:rendhose/0.0/,rendproc/0.0/;
--
--Rendering Time steps
constant real:rendst0/0.0/,rendst1/900.0/,rendst2/2160.0/,
rendst3/43200.0/,rendst/46800.0/,rendsto1/2700.0/,
rendsto2/23000.0/,rendsto4/66600.0/;
--
Real:W2bk,W2bb,W2lk,W2lb,Wpu2tot,Wpu3tot;
Real:W3bk,W3bb,W3lk,W3lb,W2bktot,W2bbtot;
Real:W2rend,Wamen,W3bktot,W3bbtot;
real:W2bk1,W2bb1,W2lk1,W2lb1;
Real:W3bk1,W3bb1,W3lk1,W3lb1;
--
Initial
W2bk:=bkhose;W2bb:=bbhose;W2lk:=lkhose;W2lb:=lbhose;
W2rend:=rendhose;
W3bk:=0.0;W3bb:=0.0;W3lk:=0.0;W3lb:=0.0;
Wpu2tot:=0.0;Wpu3tot:=0.0;W2bktot:=0.0;W2bbtot:=0.0;
W3bktot:=0.0;W3bbtot:=0.0;
Dynamic
--
--Hosing and Sterilisers-------------
--===================================
W2bk1:=bkwr+bkdho+bkdhi+bkhk+bke+bkbs+bkss+bket+bkgb+
bkhh+bkt+(bkks*Nbk)+IOH;
W2bb1:=(bbks*Nbb);
--W2lk1:=lkwr+lkrhc+lknb+lknr+lkdh+lkbd+lkfhc+lkbc+lke+lket
--+(lkks*Nks);
--W2lb1:=(lbks*Nlb);
Wpu2:=W2bk+W2bb;
--===================================
--Hand and Apron washes
--===================================
W3bk1:=(bkhand*Nbkh)+(bkapron*Nbka)+Wtongue+chutepaunch;
W3bb1:=(bbhand*Nbbh)+(bbapron*Nbba);
--W3lk1:=(lkhand*Nlkh)+(lkapron*Nlka);
--W3lb1:=(lbhand*Nlbh)+(lbapron*Nlba);
Wpu3:=W3bk+W3bb;
```

```
--====================================
--Carcass Washes
--====================================
--Wpu4:=W4bk+W4lk;
Wpu2tot':=W2bk+W2bb;
Wpu3tot':=W3bk+W3bb;
W2bktot':=W2bk;
W2bbtot':=W2bb;
W3bktot':=W3bk;
W3bbtot':=W3bb;
--
step
prepare"generic";
--

--
--BEEF Kill--------------------------
--Start run 1.
if t >= bst1 then
      W2bk:=W2bk1;
      W3bk:=W3bk1;
end_if;
--
-- 1st smoko
--
if t >= bsto1 then
      W2bk:=0.0;
      W3bk:=0.0;
end_if;
--
-- Start run 2
--
if t >= bst2 then
      W2bk:=W2bk1;
      W3bk:=W3bk1;
end_if;
--
--2nd smoko
--
if t >= bsto2 then
      W2bk:=0.0;
      W3bk:=0.0;
end_if;
--
--Start run 3
--
if t >= bst3 then
      W2bk:=W2bk1;
      W3bk:=W3bk1;
end_if;
--
--lunch
--
if t >= bsto3 then
      W2bk:=0.0;
      W3bk:=0.0;
end_if;
--
--Start run 4
--
if t >= bst4 then
      W2bk:=W2bk1;
      W3bk:=W3bk1;
end_if;
--
--Finish Production
```

```
--
if t >= bsto4 then
      W2bk:=bkhose;
      W3bk:=(bkamen*Nbks);
end_if;
--Finish showers
--
if t >= bsto5 then
      W2bk:=bkhose;
      W3bk:=0.0;
end_if;
--Finish hosing
--
if t >= bsto6 then
      W2bk:=0.0;
      W3bk:=0.0;
End_if;
--
--BEEF BONING---------------------------
--Start run 1
--
if t >= bbst1 then
      W2bb:=W2bb1;
      W3bb:=W3bb1;
end_if;
--


--
--1st smoko
--
if t >= bbsto1 then
      W2bb:=0.0;
      W3bb:=0.0;
end_if;
--
-- Start run 2
--
if t >= bbst2 then
      W2bb:=W2bb1;
      W3bb:=W3bb1;
end_if;
--
--2nd smoko
--
if t >= bbsto2 then
      W2bb:=0.0;
      W3bb:=0.0;.
end_if;
--
--Start run 3
--
if t >= bbst3 then
      W2bb:=W2bb1;
      W3bb:=W3bb1;
end_if;
--
--lunch time
--
if t >= bbsto3 then
      W2bb:=0.0;
      W3bb:=0.0;
end_if;
--
--Start run 4
--
if t >= bbst4 then
```

```
      W2bb:=W2bb1;
      W3bb:=W3bb1;
end_if;
--
--Finish Production
--
if t >= bbsto4 then
      W2bb:=bbhose;
      W3bb:=(bbamen*Nbbs);
end_if;
--
--Finish showers
--
if t >=bbsto5 then
      W2bb:=bbhose;
      W3bb:=0.0;
end_if;
--Finish hosing
if t >= bbsto6 then
      W2bb:=0.0;
      W3bb:=0.0;
End_if;

--LAMB KILL--------------------
--
--Start run 1.
if t > lkst0 then
      W2lk:=lkhose;
      W3lk:=W2lk1;
end_if;
if t >= lkst1 then
      W2lk:=W2lk1;
      W3lk:=W3lk1;
end_if;
--
--Morning smoko
--
if t >= lksto1 then
      W2lk:=0.0;
      W3lk:=0.0;
end_if;
--
-- Start run 2
--
if t >= lkst2 then
      W2lk:=W2lk1;
      W3lk:=W3lk1;
end_if;
--
--Lunchtime
--
if t >= lksto2 then
      W2lk:=0.0;
      W3lk:=0.0;
end_if;
--
--Start run 3
--
if t >= lkst3 then
      W2lk:=W2lk1;
      W3lk:=W3lk1;
end_if;
--
--Afternoon smoko
--
if t >= lksto3 then
```

```
if t >= lbst4 then
      W2lb:=W2lbl;
      W3lb:=W3lbl;
end_if;
--
--Finish Production
if t >= lbsto4 then
      W2lb:=lbhose;
      W3lb:=lbamen;
end_if;
--===========================
--Rendering

--Start run 1.
--
if t >= rendstl then
      W2rend:=rendhose;
end_if;
--
--1st process batch
--
if t >= lbstol then
      W2rend:=rendproc;
end_if;
--
-- cleanup
--
if t >= lbst2 then
      W2rend:=rendhose;
end_if;
--
--2nd process batch
--
if t >= lbsto2 then
      W2rend:=rendproc;
end_if;
--
--cleanup
--
if t >= lbst3 then
      W2rend:=rendhose;
end_if;
--
--3rd process batch
--
if t >= lbsto3 then
      W2rend:=rendproc;
end_if;
--
--cleanup
--
if t >= lbst4 then
      W2rend:=rendhose;
end_if;
--
--4th process batch
--
if t >= rendsto4 then
      W2rend:=rendproc;
end_if;
--===========================
```

```
--
communication
Tabulate t,Wpu3tot,W3bk,W3bb;
prepare"hotuse",t,Wpu3tot,W3bktot,W3bbtot;
--
end hotuse;
--
--experiment
--
        real:Wpu2,Wpu3,Wpu4,u1;
        algo:=rk5;cint:=300.0;tfin:=40000.0;
--      xf:=1.3;
        Hotuse(Wpu2,Wpu3,Wpu4:=u1);
--
end_study
```

APPENDIX C2 - HOT WATER GENERATION AND STORAGE SYSTEMS MODEL LISTING

```
study
model hotstor(real:Wc3:=real:Mt3radius,Mt3height);
--------------------------------------------
--Recovered Water Temperatures
--------------------------------------------
constant real:cw/4200.0/,trendr/100.0/,tsc/100.0/;
--============================================
--Cool Water Temperatures
--============================================
Constant real:tamb/12.0/,tc1/15.0/,tc2/15.0/,
tc3/15.0/,tc4/15.0/,tcrec/15.0/;
--============================================
--Tank Temperatures
--============================================
Constant real:tk3set/45.0/,tk4set/35.0/;
--============================================
--Required plant Temperatures
--============================================
constant real:tpu2/85.0/,tpu3/45.0/,tpu4/35.0/;
--============================================
--Plant return temperatures
--============================================
constant real:tr3/43.0/,tr4/31.0/,tr2/82.0/;
--============================================
--Required Plant Water Flows
--============================================
--constant real:Wpu1/1.5/,Wpu2/3.0/,Wpu3/1.0/,Wpu4/1.0/;
--============================================
-- Static Tank Levels
--============================================
constant real:Mt3/1400.0/,Mt4/1400.0/;
--============================================
--Tank minimum and maximum Levels
--============================================
constant real:min1level/600.0/,max1level/136000.0/,
min2level/600.0/,max2level/136000.0/;
--============================================
--Tank Reset levels
--============================================
constant real:rst1level/4000.0/,rst2level/4000.0/;
--============================================
--Tank Dimensions
--============================================
constant real :Mt1radius/2.0/,Mt1height/7.3/,
Mt2radius/2.0/,Mt2height/7.3/,
Mt4radius/1.2/,Mt4height/1.0/;
--============================================
--Variables
--============================================
Real:A1,A2,A3,A4;
Real:H2,H3,H4;
Real:Mt1,Mt2,Mt1tk1,Mt2tk2,Mt3tk3,Mt4tk4;
Real:Mtot,Mtottz,Mtrial;
Real:swlevel1,swlevel2,Rcode,Scode,refcode,rendcode;
Real:drainmodel,refrigmodel,rendmodel;
Real:th2,th3,th4,tin2,tin3,tin4,tk4,tk1,tk2,tk3;
Real:tdrainin,trenin,tscin,trefin,trefr,tdrain;
Real:tz,ttrial;
Real:Wb2/0.0/,Wb3/0.0/,Wb4/0.0/;
Real:Wbrcode,Wcrendrcode,Wrefrcode,Ocode,Spcode,Qd;
Real:Wc1,Wc2/0.0/,Wc4,Wcm3,Wcm4,Win2/0.0/,Wput2/1.0/,Wh3,Wh4;
Real:Wt1/1.0/,Wt2/2.5/,Wt3,Wt4,Wr3,Wr4,Wr2/4.0/;
Real:Wcruntot,Hruntot,Wctot,Htot;
Real:Wbrendr,Wcrendr,Wrendr,Wbscode,Wcscode,
Wdraincode,draincode;
Real:Wdrain,Wcdrain,Wrefr,Wcrefr,Wsc,Wbsc,Wcsc,Wcrec;
```

```
Real:Woflow,Wspill,Wpu2,Wpu3,Wpu4;
Real:Zt1,Zp1,Zt2,Zp2,Zt3,Zp3,Zt4,Zp4;
Real:Wb1code,Wb2code,Wt1code,Wt2code,Wb3code,Wb4code,
Wt3code,Wt4code;
--
INITIAL
--=============================================
th3:=tpu2;th4:=tpu2;tin2:=tc2;tk3:=45.0;tk4:=31.0;
tin2:=tc2;tin3:=th3;tin4:=th4;Wt1:=0.0;
swlevel1:=rst1level;swlevel2:=min2level;
Mt1:=12000.0;Mt1tk1:=Mt1*40.0;Mt2:=12000.0;Mt2tk2:=Mt2*80.0;
Mtot:=(Mt1+Mt2);Mtottz:=(Mt1*40.0)+(Mt2*80.0)+
(1400.0*tk3)+(1400.0*tk4);
tdrain:=0.0;trefr:=0.0;
Wctot:=0.0;Htot:=0.0;
Wdrain:=0.0;Wrefr:=0.0;Wrendr:=0.0;Wsc:=0.0;
Ocode:=-1.0;Spcode:=-1.0;Scode:=0.0;Rcode:=0.0;
Wb1code:=-1.0;Wb2code:=-1.0;Wb3code:=-1.0;Wb4code:=-1.0;
Wt1code:=-1.0;Wt2code:=-1.0;Wt3code:=-1.0;Wt4code:=-1.0;
Wbrcode:=-1.0;Wbscode:=-1.0;Wcrendrcode:=-1.0;Wcscode:=-1.0;
Wdraincode:=-1.0;draincode:=-1.0;Wrefrcode:=-1.0;
refcode:=-1.0;
Woflow:=0.0;Wspill:=0.0;Wbrendr:=0.0;Wcrendr:=0.0;
Wcdrain:=0.0;Wcrefr:=0.0;Wcsc:=0.0;Wbsc:=0.0;
Wc2:=0.0;Wc3:=0.0;Wc4:=0.0;Wh3:=0.0;
Wpu2:=0.0;Wpu3:=0.0;Wpu4:=0.0;
tdrainin:=15.0;trefin:=15.0;trenin:=15.0;tscin:=15.0;
--Calculate Tank dimensions------------------------------
--=========================================
A1:= 3.1416*2*((Mt1radius**2)+(Mt1radius*Mt1height));
A2:= 3.1416*2*((Mt2radius**2)+(Mt2radius*Mt2height));
A3:= 3.1416*2*((Mt3radius**2)+(Mt3radius*Mt3height));
A4:= 3.1416*2*((Mt4radius**2)+(Mt4radius*Mt4height));
--=============================================
DYNAMIC
--
--Mt3---------------------------------
--=========================================
Procedural;

if Wt3code < 0.0 then
      Wt3:=0.0;
      th3:=tk1;
else
      Wb3:=0.0;
      th3:=tpu2;
End_if;

if Wt4code < 0.0 then
      Wt4:=0.0;
      th4:=tk1;
else
      Wb4:=0.0;
      th4:=tpu2;
End_if;


if Wt1code > 0.0 then
      Wb2:=0.0;
else_if Wb1code > 0.0 then
      Wt1:=0.0;
else
      Wt1:=0.0;
      Wb2:=0.0;
End_if;
```

```
--=====================================
--Tank 3
--======================================
if Wt3code < 0.0 and Wb3code < 0.0 then
      Wh3:=0.0;
      Wt3:=0.0;
      Wb3:=0.0;
      Wc3:=Wpu3;
      tin3:=tc3;
else_if th3 > tk3set then
      tin3:=tk3set;
      Wh3:=(Wpu3*(tin3-tc3))/(th3-tc3);
      Wc3:=Wpu3-(Wh3);
      if Wb3code > 0.0 then
           Wb3:=Wh3;
           th3:=tk1;
      Else_if Wt3code > 0.0 then
           Wt3:=Wh3;
           th3:=tpu2;
end_if;
else_if th3   <= tk3set then
         Wc3:=0.0;
         tin3:=th3;
      if Wb3code > 0.0 then
          Wb3:=Wh3;
           Wh3:=Wpu3;
      else_if Wt3code > 0.0 then
          Wt3:=Wh3;
      End_if;
End_if;
--===================================
--Tank 4
--===================================
if Wt4code < 0.0 and Wb4code < 0.0 then
      Wh4:=0.0;
      Wc4:=Wpu4;
      Wb4:=0.0;
      Wt4:=0.0;
      tin4:=tc4;
else_if th4 > tk4set then
      tin4:=tk4set;
      Wh4:=(Wpu4*(tin4-tc4))/(th4-tc4);
      Wc4:=Wpu4-Wh4;
      if Wb4code > 0.0 then
      Wb4:=Wh4;
      th4:=tk1;
      else_if Wt4code > 0.0 then
           Wt4:=Wh4;
           th4:=tpu2;
      End_if;
Else_if th4 <= tk4 then
           Wc4:=0.0;
           tin4:=th4;
      if Wb4code > 0.0 then
           Wb4:=Wh4;
           Wh4:=Wpu4;
      else_if Wt4code>0.0 then
           Wt4:=Wh4;
      End_if;
End_if;

--===================================
--Tank 2
--===================================
Wt2:=Wt3+Wt4;
Wr2:=(1.5*Wpu2);
```

```
Wput2:=Wt2+Wr2;
Win2:=Wput2;
if (Wt1code < 0.0 and Wb2code < 0.0) then
      Wc2:=(Win2);
      tin2:=tc2;
else_if (Wt1code < 0.0 and Wb2code > 0.0) then
      Wc2:=0.0;
      Wb2:=Win2;
      tin2:=tk1;
      H2:=Win2*cw*(tpu2-tin2);
else_if (Wt1code > 0.0 and Wb2code < 0.0) then
      if (tk2 < tpu2) then
            Wc2:=0.0;
            Wt1:=Win2;
            tin2:=tk2;
      else_if tk2>= tpu2 then
            tin2:=tpu2;
            Wc2:=(Win2)*(tin2-tk2)/(tc2-tk2);
            Wt1:=(Win2)-Wc2;
      End_if;
End_if;
--
--========================================
--Recovered flows to Tanks Mt1 and Mt2
--========================================
if Rcode > 0.0 then
      if Wbrcode > 0.0 then
            trenin:=tk1;
            Wrendr:=2.5;
            Wbrendr:=Wrendr;
            Wcrendr:=0.0;
      else
            trenin:=tcrec;
            Wrendr:=1.5;
            Wcrendr:=Wrendr;
            Wbrendr:=0.0;
      end_if;
else
      Wbrendr:=0.0;
      Wcrendr:=0.0;
      Wrendr:=0.0;
End_if;
if Scode > 0.0 then
      if Wbscode > 0.0 then
            tscin:=tk1;
            Wsc:=1.0;
            Wbsc:=Wsc;
            Wcsc:=0.0;
      else
            tscin:=tcrec;
            Wsc:=0.75;
            Wcsc:=Wsc;
            Wbsc:=0.0;
      end_if;
else
      Wbsc:=0.0;
      Wcsc:=0.0;
      Wsc:=0.0;
End_if;
if Refcode > 0.0 then
     Wcrefr:=2.0;
     Wrefr:=Wcrefr;
     trefin:=tcrec;
     trefr:=50.0;
else
     Wcrefr:=0.0;
```

```
       Wrefr:=0.0;
 End_if;
 if draincode > 0.0 then
      Wcdrain:=2.0;
      Wdrain:=Wcdrain;
      tdrainin:=tcrec;
      tdrain:=50.0;
 else
      Wcdrain:=0.0;
       Wdrain:=0.0;
 End_if;

 --================================
 --Spillover from Tank 2
 --================================
 if Ocode > 0.0 then
      Woflow:=Wrendr+Wsc+(Wr2-Wput2)-Wt1;
 else
      Woflow:=0.0;
 End_if;
 --==================================
 --Spill over from Tank 1
 --==================================
 if Spcode > 0.0 then
     Wspill:=Woflow -Wbsc-Wrefr-Wbrendr-Wb2-Wb3-Wb4;
 else
     Wspill:=0.0;
 End_if;

 --===================================
 End_Procedural;
 --====================================
 --Cold recovery water flow
 --====================================
 Wcrec:=Wcdrain+Wcrefr+Wcrendr+Wcsc;
 --====================================
 --Tank 3
 --====================================
 Wr3:=2*Wpu3;
 Zt3:=10*A3*(tk3-tamb);
 Zp3:=(Wr3-Wpu3)*cw*(tpu3-tr3);
 H3:=Wr3*cw*(tpu3-tk3);
 --Mt4----------------------------------
 --=======================================
 Wr4:=2*Wpu4;
 Zt4:=10*A4*(tk4-tamb);
 Zp4:=(Wr4-Wpu4)*cw*(tpu4-tr4);
 H4:=Wr4*cw*(tpu4-tk4);
 --
 --Mt2 tank--------------------------------
 --

 tk2:=Mt2tk2/Mt2;
 Zt2:=10*A2*(tk2-tamb);
 Zp2:=(Wr2-Wpu2)*cw*(tpu2-tr2);
 H2:=Wput2*cw*(tpu2-tin2);
 --=========================================
 --
 --Mt1 Tank------------------------------
 tk1:=Mt1tk1/Mt1;
 Zt1:=10*A1*(tk1-tamb);
 --========================================
 --Trial mass and energy balances
 --========================================
 ttrial:=((Mt1*tk1)+(Mt2*tk2)+(Mt3*tk3)+(Mt4*tk4));
 tz:=Mtottz/Mtot;
```

```
Mtrial:=Mt1+Mt2;
Wcruntot:=Wcrec+Wc2+Wc3+Wc4;
Hruntot:=H2+H3+H4;
--
--ODE'S====================================
--========================================
Mt1':=Wdrain+Wrefr+Woflow-Wb3-Wb4-Wb2-Wspill-Wbrendr-Wbsc;
Mt1tk1':=(Wdrain*tdrain)+(Wrefr*trefr)+(Woflow*tk2)-(Wb3*tk1)-
(Wb4*tk1)
-(Wb2*tk1)-(Zt1/cw)-((Wspill+Wbrendr+wbsc)*tk1);
tk3':=(Wpu3*tin3+(Wr3-Wpu3)*tr3-(Wr3*tk3)-(zt3/cw))/Mt3;
tk4':=(Wpu4*tin4+(Wr4-Wpu4)*tr4-(Wr4*tk4)-(zt4/cw))/Mt4;
Mt2':=Wrendr+Wsc-Wt1+(Wr2-Wpu2)-Woflow;
Mt2tk2':=(Wrendr*trendr)+(Wsc*tsc)+((Wr2-Wpu2)*tr2)
-(Woflow*tk2)-(Wt1*tk2)-(Zt2/cw);
Mtot':=Wc2+Wc3+Wc4+Wcdrain+Wcrefr+Wcrendr+Wcsc
-Wpu2-Wpu3-Wpu4-Wspill;
Mtottz':=(Wc2*tc2)+(Wc3*tc3)+(Wc4*tc4)
+((Wcdrain+Wcrefr+Wcrendr+Wcsc)*tcrec)+((H2+H3+H4)/cw)
+(Wcrefr*(Trefr-trefin))+(Wcdrain*(tdrain-tdrainin))
+(Wrendr*(trendr-trenin))+(Wsc*(tsc-tscin))
-(Zt1/cw)-(Zt2/cw)-(Zt3/cw)-(Zt4/cw)
-(Zp3/cw)-(Zp4/cw)-(Zp2/cw)
-(Wpu2*tpu2)-(Wpu3*tpu3)-(Wpu4*tpu4)
-(Wspill*tk1);
Wctot':=Wcrec+Wc2+Wc3+Wc4;
Htot':=H2+H3+H4;

--==================================
 STEP
--Timesteps
--==================================
If t < 90000.0 then
     rendmodel:=-1.0;
else_if t < 72000.0 then
     rendmodel:=1.0;
else
     rendmodel:=-1.0;
end_if;

if t < 90000.0 then
     qd:=-1.0;
else_if t < 72000.0 then
     qd:=1.0;
else
     qd:=-1.0;
end_if;

if t < 600.0 then
      refrigmodel:=-1.0;
else_if t < 86400.0 then
     refrigmodel:=1.0;
else
     refrigmodel:=-1.0;
end_if;

if t < 600.0 then
     drainmodel:=-1.0;
else_if t < 45000.0 then
     drainmodel:=1.0;
else
     drainmodel:=-1.0;
end_if;

--=======================================
--================================
```

```
if (swlevel1-Mt1) <= 0.0 then
      Wb3code:=1.0;
      Wt3code:=-1.0;
      Wb4code:=1.0;
      Wt4code:=-1.0;
else_if (swlevel2-Mt2) <= 0.0 then
      Wt3code:=1.0;
      Wb3code:=-1.0;
      Wb4code:=-1.0;
      Wt4code:=1.0;
else
      Wb3code:=-1.0;
      Wt3code:=-1.0;
      Wb4code:=-1.0;
      Wt4code:=-1.0;
End_if;
if (swlevel2-Mt2) <= 0.0 then
      Wt1code:=1.0;
      Wb2code:=-1.0;
else_if (swlevel1-Mt1) <= 0.0 then
      Wt1code:=-1.0;
      Wb2code:=1.0;
else
      Wt1code:=-1.0;
      Wb2code:=-1.0;
End_if;

if Wb3code < 0.0 then
     swlevel1:=rst1level;
else
     swlevel1:=min1level;
end_if;

if Wt1code < 0.0 then
    swlevel2:=rst2level;
else
    swlevel2:=min2level;
end_if;

--==================================
--Cooling flows to Mt1 and Mt2
--==================================
--Rendering recovery
--==================================
if rendmodel > 0.0 then
      Rcode:= 1.0;
      if (swlevel1 - Mt1)<= 0.0 and Tk1 < 50.0 then
           Wbrcode:= 1.0;
           Wcrendrcode:=-1.0;
      else
           Wbrcode:= -1.0;
           Wcrendrcode:= 1.0;
     end_if;
else
     Rcode:= -1.0;
     Wbrcode:=-1.0;
     Wcrendrcode:=-1.0;

end_if;
--====================================
--Steam condensate recovery
--====================================
if Qd > 0.0 then
      Scode:=1.0;
      if (swlevel1 - Mt1)<= 0.0 and Tk1 < 50.0 then
           Wbscode:= 1.0;
```

```
                Wcscode:=-1.0;
          else
                Wbscode:=-1.0;
                Wcscode:= 1.0;
          end_if;
else
          Scode:= -1.0;
          Wbscode:= -1.0;
          Wcscode:= -1.0;
end_if;
--======================================
--Refrigeration recovery
--======================================
if  refrigmodel > 0.0 then
            refcode:=1.0;
            Wrefrcode:=1.0;
else
            refcode:=-1.0;
            Wrefrcode:=-1.0;
end_if;
--======================================
--Production drain recovery
--===================================
if  Drainmodel > 0.0 then
            draincode:=1.0;
            Wdraincode:=1.0;
else
            draincode:=-1.0;
            Wdraincode:=-1.0;
end_if;
--Spill over Tank 2
--===================================
if Mt2 > max2level then
            Ocode:=1.0;
else
            Ocode:=-1.0;
End_if;
--=====================================
--Spill over Tank 1
--=====================================
if Mt1 > max1level then
            Spcode:= 1.0;
else
            Spcode:=-1.0;
End_if;
--====================================
--Hot water flows to departments
--====================================
if t < 8100 then
      Wpu2:=1.1986;
      Wpu3:=1.026;
      Wpu4:=0.0;

else_if t < 9000.0 then
      Wpu2:=0.0;
      Wpu3:=0.0;
      Wpu4:=0.0;

else_if t < 14400 then
      Wpu2:=1.1986;
      Wpu3:=1.026;
      Wpu4:=0.0;

else_if t < 15000.0 then
      Wpu2:=0.0;
      Wpu3:=0.0;
```

```
       Wpu4:=0.0;

else_if t < 23400 then
       Wpu2:=1.1986;
       Wpu3:=1.026;
       Wpu4:=0.0;

else_if t < 25200.0 then
       Wpu2:=0.0;
       Wpu3:=0.0;
       Wpu4:=0.0;

else_if t < 32400 then
       Wpu2:=1.1986;
       Wpu3:=1.026;
       Wpu4:=0.0;

else_if t < 33900.0 then
       Wpu2:=4.0;
       Wpu3:=4.5;
       Wpu4:=0.0;

else_if t < 37800.0 then
       Wpu2:=4.0;
       Wpu3:=0.0;
       Wpu4:=0.0;

else
       Wpu2:=0.0;
       Wpu3:=0.0;
       Wpu4:=0.0;

End_if;

COMMUNICATION
   tabulate t,Wpu2,Wpu3;
   Prepare "HOTSTOR",
--t,Wdrain,Wrefr,Wrendr,Wsc,Wcrec;
--Wc2,Wc3,Wc4,Wpu2,Wpu3,Wpu4;
--Woflow,Wspill,Wcruntot,Hruntot;
t,Wpu2,Wctot,Htot,Mt1,Mt2;
--
END HOTSTOR;
--
--
--EXPERIMENT
real:wc3,mt3radius,mt3height;
-- Set integration parameters.
algo:=rk5; cint :=60.0; tfin:=86700.0;

--
   read Mt3radius,Mt3height;
   HOTSTOR (Wc3:=Mt3radius,Mt3height);
END_STUDY
```

APPENDIX D1 - PRODUCT LOAD MODEL LISTING (ESL)

```
study
model refcalc(real:Tma);
--Refcalc is used to carry out freezing calculations
--
constant real:Cs/2.2E6/,Cl/3.6E6/,ks/1.5/,kl/0.5/;
constant real:E/1.3/,h/7.3/,L/2.1E8/,N/1.8/,X/0.077/;
constant real:Ta/-30.0/,Tf/-1.0/,Ti/40.0/,V/0.0257/;

--Variables
--===================================
real:a,b,c,Bi,G1,G2;
real:Hbase/0.0/,Hf,HFrez/0.0/,Hsub;
real:K,n1,Tmad,Tuse,Tstor,Tbase/-100.0/;
real:Pchill/1.0/,Pfrez/1.0/,Bet1,Betel,Pprod,Psub;
real:S,Val,vf,vg,Unfroz/1.0/,xf,xfd,Y,Z,D,F;
integer:I,mode,newmode;
--====================================
INITIAL
--====================================
Newmode:=-99;
Mode:=1;
Tbase:=-100.0;
Tma:=Ti;
Tmad:=Ti;
Tstor:=Tma;
Tuse:=Tf;
a:=Hbase-(Cs*Tbase);
b:=Cs;
c:=L*Tf;
--D:=0.0;
Bi:=h*X/kl;
G1:=0.001;G2:=3.14159;
--=================
For I:=1..50 step 1
   LOOP
      vg:=(G1+G2)/2;
   Val:=(vg*cos(vg)/sin(vg))+Bi-1.0;
   if Val >= 0.0  then
      G1:=(G1+G2)/2;
   else
      G2:=(G1+G2)/2;
   end_if;
End_loop;
Bet1:=(G1+G2)/2.0;
Betel:=Bet1;
--================
Hf:=L+Cs*(Tf-Tbase);
n1:=E-1;
vf:=V/X**N;
xf:=X;
xfd:=X;
Hsub:=Hf+Cl*(Ti-Tf);
--===================================
DYNAMIC
--===================================
Procedural;
--===================================
--chill phase
--===================================
if Mode > 0 then
     Tuse:=Tf;
     Unfroz:=1.0;
     Pchill:=(E/3)*((V*Bet1**2*kl)/(X**2))*(Tmad-Ta);
     Z:=(xf**(1-n1)-X**(1-n1))/(ks*(1-n1));
     K:=(Vf*N*xf**(N-1));
     Pfrez:=-((Ta-Tuse)/((xf**n1)*(1/(h*X**n1)-Z)))*K;
```

```
      Xf:=Xfd;
      Tma:=Tmad;
      Pprod:=Pchill;
--================================
--During freezing
--================================
else_if Mode = 0 then
      Pchill:=0.0;
      xf:=xfd;
      unfroz:=(xf/X)**N;
      Z:=(xfd**(1-n1)-X**(1-n1))/(ks*(1-n1));
      K:=(Vf*N*xfd**(N-1));
      Pfrez:=-((Ta-Tuse)/((xfd**n1)*(1/(h*X**n1)-Z)))*K;
      Hfrez:=unfroz*(L+Cl*(Tstor-Tf))+Cs*(Tf-Tbase);
      Pprod:=Pfrez;

      if Hfrez > Hf  then
           Tma:=((Hfrez-Hf)/Cl)+Tf;
           Tuse:=Tf;
      else
           Tma:=((Hfrez-a)-SQRT((Hfrez-a)**2-4*b*c))/(2*b);
           Tuse:=Tma;
      end_if;
--================================
--During subcooling
--================================
else_if Mode < 0 then
      Tma:=((Hsub-a)-SQRT((Hsub-a)**2-4*b*c))/(2*b);

      Psub:=E/3*((Betel**2*ks)/X**2)*(Tma-Ta)*V;
      Pprod:=Psub;
      Unfroz:=Tf/Tma;
      Xf:=(V*Unfroz/Vf)**(1/N);
end_if;

end_procedural;
--ODE's
Tmad':= If Mode > 0 Then
             (E/3)*((V*Bet1**2*kl)/(X**2))*(Ta-Tmad)/(V*cl)
         Else 0.0;


S:=(1/(h*(X**n1)))-((xfd**(1-n1)-X**(1-n1))/(ks*(1-n1)));
Y:=((L+cl*(Tstor-Tf))*(xfd**n1))*s;
xfd':= If Mode = 0 Then
           (Ta-Tuse)/Y
        Else 0.0;

Hsub':= If Mode < 0 Then
            E/3*((Betel**2*ks)/X**2)*(Ta-Tma)
        Else_if Mode > 0 Then
            (-Pchill/V)
        Else  (-Pfrez/V);


--=================

STEP
--==================================
--at chill transition
--==================================
If (Mode > 0 and Pchill > Pfrez) then
      Newmode:=1;
Else_if (Mode > 0 and Pchill <= Pfrez) then
      Newmode:=0;
      unfroz:=1.0;
```

```
      Tstor:=Tma;
      Xf:=X;
Else_if (Mode = 0 and Unfroz > 0.2) then
      Newmode:=0;
Else_if Mode = 0 and Unfroz <= 0.2 then
   Newmode:=-1;
   Tma:=((Hsub-a)-SQRT((Hsub-a)**2-(4*B*C)))/(2*b);
   Betel:=SQRT((Pfrez*3*X**2)/(E*V*ks*(Tma-Ta)));
Else_if Mode < 0 Then
   Newmode:=-1;
End_if;
Mode:=Newmode;

COMMUNICATION
tabulate t,xf,Tma,Unfroz,Mode,Pprod;
Prepare "refcalc",t,tma,Pprod;
END refcalc;
--
--EXPERIMENT
real:Tma;
--Set iteration parameters.
nstep:=20; algo:=rk4; cint:=3600.0; tfin:=36000.0;
refcalc(Tma);
end_study
```

APPENDIX D2 - PRODUCT HEAT LOAD MODEL LISTING

```
program ref(input,output);
{$N+}
{$M 65520,0,655360}

uses

procunit;

type
sections = array[0..30] of real;
Items = array[0..30,0..8] of real;
Chitems = array[0..30,0..8] of char;


var

infile,outfile,stdfile,outfile1:text;
filename1,filename2,filename3,filename4:string[20];

time,airtemp,airvel,Relspd,Yield,Averagemass,totalmass:items;


E,Cs,Cl,ks,kl,N,L,Tf,X,V,h,Ti,Tma,Tmad,
Tstor,Tuse,a,b,c,Hf,Hsub,Hbase,Hfrez,xf,xfd,
nl,vf,unfroz,Qprod,Qfreez,Qchill,Qsub,Hsubd,
Bet1,Bete1,Bi,ZZ,Ha,Htp,PrNo,Rho,Tmassn,
Qbatch,NumItem,freesp:sections;

energy:sections;

airv,ta,tim,rlspd,yld,avm,tms,Tbase,Ploading:real;
RKtma:array[0..30,0..4] of real;
RKxf:array[0..30,0..4] of real;
RKhsub:array[0..30,0..4] of real;
Potload:array[1..5] of real;
Baseload:array[1..5] of real;
Elecload:array[1..5] of real;
Ebaseload:array[1..5] of real;
Taworst:array[1..5] of real;

Telaps,T,Delt,Total,Tprint:real;

itemNo,lastSection:integer;
pot,number_sect,oldsection:integer;
I,J,K,M,Q:integer;

listlength:array[0..30] of integer;
potno:array[0..30,0..8] of integer;
stage:array[0..30] of integer;

code:StdNo;
Refvel,Qfan:stds;
Rev:real;
Mode:array[0..30] of char;
roomType,Packagingtype,Producttype:chitems;

Ch,rty,pat,prt:char;

{ Cold and Cool store data follows: }



VAR
cVst,cZh,Ctext,cAdoor,ctstart,cTstop:real;
cPot:integer;
sVst,sZh,sText,sAdoor,sTstart,sTstop:real;
```

```
sPot:integer;
cTa,sTa,cXi,sXi,ki,Eins,cAirnon,cAirop,sAirnon,sAirop,
AirinRH,Texdiff,EnvinRh,Airflowfactor,dproom,Etaf,Etam,Partloadfans,
Timedelay,cslites,Flift,defrost,celec,selec: real;

cTmp,cTmp1,ctmp2,ctmp3,ctmp4
,sTmp,stmp1,stmp2,stmp3,stmp4: real;

{Air-conditioning data follows}
VAR

Vac,Z1,Atext,aTstart,aprodTstart,aprodTstop,
acleanTstop,aQsw,aQconv,aNop: real;
aPot:integer;

aTa,aXi,aki,aEins,acintop,
acintnop,ainRh,aextRh,aQp,alites,aQstart,aclhw,adproom: real;
aTmp,Aelec,Qaircon,Qlite,Qstor: real;

{Product-related data follows}

ccfdp,csfdp,cccdp,cscdp,scfdp,ssfdp,sccdp,sscdp,
mcfdp,msfdp,mccdp,mscdp,pcfdp,psfdp,pccdp,pscdp,
petaf,petam,pcXi,PsXi,pinRh,pextRh,pQhw,pQother,
pAextb,pAextl,pAextc,pBassoc,pLassoc,pCassoc,
Zb,Zs,Zc:real;
Qprodrel,pelec:sections;
epot:integer;


procedure Data_read;
Begin
for K := 1 to 8 do
    Readln(Stdfile,Refvel[K]);


{cold, cool store and air-conditioning data input from std file}
Readln(Stdfile);Readln(Stdfile);
Readln(Stdfile,cTa,sTa);
Readln(Stdfile,cXi,sXi);
Readln(Stdfile,ki);
Readln(Stdfile,Eins);
Readln(Stdfile,cAirnon,cAirop);
Readln(Stdfile,sAirnon,sAirop);
Readln(Stdfile,AirinRH);
Readln(stdfile,Texdiff);
Readln(stdfile,EnvinRh);
Readln(Stdfile,Airflowfactor);
Readln(Stdfile,dproom);
Readln(Stdfile,Etaf,Etam);
Readln(Stdfile,Partloadfans);
Readln(Stdfile,Timedelay);
Readln(Stdfile,cslites);
Readln(Stdfile,Flift);
Readln(Stdfile,Defrost);

Readln(Stdfile);Readln(Stdfile);
Readln(Stdfile,aTa);
Readln(Stdfile,aXi);
Readln(Stdfile,aki);
Readln(Stdfile,aEins);
Readln(Stdfile,acintop);
Readln(Stdfile,acintnop);
Readln(Stdfile,ainRh);
Readln(Stdfile,aextRh);
Readln(Stdfile,aQp);
```

```
Readln(Stdfile,alites);
Readln(stdfile,aQstart);
Readln(stdfile,aclhw);
Readln(Stdfile,adProom);

Readln(Stdfile);Readln(Stdfile);
Readln(Stdfile,ccfdp,csfdp);
Readln(Stdfile,cccdp,cscdp);
Readln(Stdfile,scfdp,ssfdp);
Readln(Stdfile,sccdp,sscdp);
Readln(Stdfile,mcfdp,msfdp);
Readln(Stdfile,mccdp,mscdp);
Readln(Stdfile,pcfdp,psfdp);
Readln(Stdfile,pccdp,pscdp);
Readln(Stdfile,petaf,petam);
Readln(Stdfile,pcXi,PsXi);
Readln(stdfile,pinRh,pextRh);
Readln(stdfile,pQhw,pQother);
Readln(Stdfile,pAextb,pAextl,pAextc);
Readln(Stdfile,pBassoc,pLassoc,pCassoc);
Readln(Stdfile,Zb,Zs,Zc);
end;

BEGIN

writeln;
write('Data Filename?               ');
readln(filename1);
write('Results Filename?            ');
readln(filename2);
write('Std values data Filename?  ');
readln(Filename3);
Write('Heatload filename?           ');
readln(filename4);
writeln;

assign(infile,filename1);

reset(infile);
assign(outfile,filename2);
rewrite(outfile);
assign(Stdfile,filename3);
reset(Stdfile);
assign(outfile1,filename4);
rewrite(outfile1);


{read in cool store, cold store  and airconditioning data}

Readln(infile);
Readln(infile,cVst);
Readln(infile,cZh);
Readln(infile,cText);
Readln(infile,cAdoor);
Readln(infile,ctstart);
Readln(infile,cTstop);
Readln(infile,cPot);

Readln(infile);
Readln(infile,sVst);
Readln(infile,sZh);
Readln(infile,sText);
Readln(infile,sAdoor);
Readln(infile,ststart);
Readln(infile,sTstop);
Readln(infile,sPot);
```

```
Readln(infile);
Readln(infile,Vac);
Readln(infile,Zl);
Readln(infile,aText);
Readln(infile,aTstart);
Readln(infile,aprodTstart);
Readln(infile,aprodTstop);
Readln(infile,acleanTstop);
Readln(infile,aQsw);
Readln(infile,aQconv);
Readln(infile,aPot);
Readln(infile,aNop);

Readln(infile);

readln(infile,delt,total,tprint);

writeln(outfile,'Time step (s) =   ',Delt:8:2);
writeln(outfile,'Total Time (s) =  ',Total:8:2);
writeln(outfile,'Print freq (s) =  ',Tprint:8:2);
writeln(outfile);

For J:=1 to 3 do
        READln(infile);

Writeln(Outfile,'section time  airtemp  airvel  Relspd  PotNo  Yield Avemass   T
otMass Room Pack  Prod');
Writeln(Outfile);

lastSection := 0;
while not eof (infile) do
begin
       READln(infile,I,tim,ta,airv,Rlspd,pot,yld,avm,tms,Ch,RTy,Ch,Pat,Ch,Prt);
       if i > lastSection then
              begin
              listlength[lastsection]:=itemNo;
              itemNo := 1;
              lastSection := I;
              end
       else
              begin
              itemNo := itemNo + 1;
              if (itemNo > 8) then
                     Writeln('Too many Items');
       end;

       number_sect:=I;
       time[I,itemNo] := tim;
       airtemp[i,itemNo] := ta;
       airvel[i,itemNo]:= airv;
       Relspd[i,itemNo]:=Rlspd;
       PotNo[i,itemNo]:= pot;
       Roomtype[i,itemNo]:=Upcase(RTy);
       PackagingType[i,itemNo]:=Upcase(Pat);
       ProductType[i,itemNo]:=Upcase(PrT);
       Yield[i,itemNo]:=Yld;
       Averagemass[i,itemNo]:=Avm;
       TotalMass[i,itemNo]:=Tms;
       Writeln(Outfile,number_sect:5,time[I,itemNo]:8:2,airtemp[i,itemNo]:8:1,
       airvel[i,itemNo]:8:1,Relspd[i,itemNo]:8:2,PotNo[i,itemNo]:6,Yield[i,itemN
o]:8:1,
       Averagemass[i,itemNo]:8:1,TotalMass[i,itemNo]:12:1,
       Roomtype[i,itemNo]:4,PackagingType[i,itemNo]:4,ProductType[i,itemNo]:4);
End;
listlength[lastsection]:=itemno;
```

```
For M:=1 to 2 do
        READln(Stdfile);

Data_read;

Close(infile);
Close(Stdfile);
Tbase:=-100.0;

{define thermal properties
B= beef
S= sheep
O= offal}

for I :=  1 to number_sect do
begin
        energy[I]:=0;
        if   time[I,1] > 0 then
             begin
             ZZ[I]:=0.0;
             stage[I]:=0;
             end
        else
             begin
             ZZ[I]:=1.0;
             stage[I]:=1;
        end;

        critdem(ProductType[I,1],PackagingType[I,1],
        Averagemass[I,1],X[I],Freesp[I]);

        if   productType[I,1] = 'B' then
             begin
             beefprops(PackagingType[I,1],Cs[I],
             Cl[I],L[I],ks[I],kl[I],Tf[I],E[I],N[I],Rho[I]);
             musclegeom(packagingType[I,1],airvel[I,1],
             h[I]);
             end
        else if  productType[I,1] = 'S' then
             begin
             sheeprops(PackagingType[I,1],Cs[I],Cl[I],
             L[I],ks[I],kl[I],Tf[I],E[I],N[I],Rho[I]);
             musclegeom(packagingType[I,1],airvel[I,1],h[I]);
             end
        else if productType[I,1]= 'O' then
             offalprops(airvel[I,1],Cs[I],Cl[I],
             L[I],ks[I],kl[I],Tf[I],E[I],N[I],h[I],Rho[I]);


        genvar(h[I],Totalmass[I,1],Yield[I,1],Averagemass[I,1],
        Rho[I],X[I],N[I],E[I],Cs[I],Tbase,L[I],Tf[I],kl[I],Bi[I],
        Bet1[I],V[I],vf[I],n1[I],Hbase[I],a[I],b[I],c[I],hf[I],
        NumItem[I],Tmassn[I]);

        Tma[I]:=40.0;
        Unfroz[I]:=1.0;
        Mode[I]:='C';
        Hsub[I]:=Hf[I]+Cl[I]*(Tma[I]-Tf[I]);
        Betel[I]:=Bet1[I];
        Xf[I]:=X[I];
        Tuse[I]:=Tf[I];
        OD1(x[I],E[I],Bet1[I],Betel[I],kl[I],ks[I],cl[I],cs[I],L[I],
        N[I],n1[I],Tuse[I],Tstor[I],Airtemp[I,1],Delt,h[I],Vf[I],
        V[I],Tf[I],ZZ[I],Qchill[I],Qfreez[I],Qsub[I],RKTma[I,1],
        RKxf[I,1],RKhsub[I,1],Tma[I],xf[I],Hsub[I],Qprod[I],Mode[I]);
```

```
end;

t:=0;
Telaps:=9999999;

While t+Delt <= Total Do
       begin


       For I:= 1 to number_sect do
       begin
               oldsection:=stage[I];
               if  t/3600 < time[I,1] then
                     begin
                     stage[I]:=0;
                     ZZ[I]:=0;
                     oldsection:=0;
                     end
               else if  t/3600 >= time[I,listlength[I]] then
                     begin
                     stage[I]:=0;
                     ZZ[I]:=0;
                     oldsection:=0;
                     end
               else if t/3600 >= time[I,stage[I]+1] then
                     begin
                     stage[I]:=stage[I]+1;
                     ZZ[I]:=1;
               end;
               Q:=Stage[I];

               if   (oldsection <> stage[I]) and (productType[I,Q] = 'B') then
               begin
                      beefprops(PackagingType[I,Q],Cs[I],Cl[I],L[I],ks[I],
                      kl[I],Tf[I],E[I],N[I],Rho[I]);
                      musclegeom(PackagingType[I,Q],airvel[I,Q],h[I]);
                      end

               else if (oldsection <> stage[I]) and (productType[I,Q] = 'S') the
n
                      begin
                      sheeprops(PackagingType[I,Q],Cs[I],Cl[I],L[I],ks[I],kl[I],
                      Tf[I],E[I],N[I],Rho[I]);
                      musclegeom(PackagingType[I,Q],airvel[I,Q],h[I]);
                      end

               else if (oldsection <> stage[I]) and (productType[I,Q] = 'O')
                      then
                      offalprops(airvel[I,Q],Cs[I],Cl[I],
                      L[I],ks[I],kl[I],Tf[I],E[I],N[I],h[I],Rho[I]);


              If oldsection <> stage[I] then
              begin
                 critdem(ProductType[I,Q],PackagingType[I,Q],
                 Averagemass[I,Q],X[I],freesp[I]);

                 genvar(h[I],Totalmass[I,Q],Yield[I,Q],Averagemass[I,Q],
                 Rho[I],X[I],N[I],E[I],Cs[I],Tbase,L[I],Tf[I],kl[I],
                 Bi[I],Bet1[I],V[I],vf[I],n1[I],Hbase[I],a[I],b[I],
                 c[I],hf[I],NumItem[I],Tmassn[I]);
                 Hsub[I]:=Hf[I]+Cl[I]*(Tma[I]-Tf[I]);
                 Betel[I]:=Bet1[I];
                 if mode[I] = 'C' then
```

```
                Xf[I]:=X[I];
             Tuse[I]:=Tf[I];
          end;

    end;

    If Telaps >= Tprint then
    Begin
        Telaps:=0.0;
        writeln(outfile);
        Writeln(Outfile,'T = ',t/3600:8:2,' BatchNo  Tma   Qprod  Qprodrel  E
lecprod  PotNo   Ta      Airvel');

        For I:= 1 to 5 do
           begin
            potLoad[I] := 0.0;
            elecload[I] :=0.0
           end;
        For I:= 1 to number_sect do
        begin
              If Stage[I] > 0 Then
                 Q:= Stage[I]
              Else
                 Q:=1;

              If  (ZZ[I] <> 0) Then
                Begin
                   Qprodrel[I]:=0.0;
                   pelec[I]:=0.0;

                  {Product- related loads do the calculations}

                  pQfans (refvel,roomType[I,Q],ProductType[I,Q],
                  PackagingType[I,Q],numItem[I],airvel[I,Q],
                  relspd[I,Q],airtemp[I,Q],Time[I,Q+1],
                  Time[I,Q],Averagemass[I,Q],Eins,Ki,cText,t,
                  ccfdp,csfdp,cccdp,cscdp,scfdp,
                  ssfdp,sccdp,sscdp,mcfdp,msfdp,mccdp,mscdp,
                  pcfdp,psfdp,pccdp,pscdp,petaf,petam,pcXi,
                  PsXi,pinRh,pextRh,pQhw,pQother,
                  pAextb,pAextl,pAextc,pBassoc,pLassoc,
                  pCassoc,Zb,Zs,Zc,Qprodrel[I],pelec[I]);

                   load(Numitem[I],Qprod[I],Qprodrel[I],pelec[I],
                   Qbatch[I],potload[potNo[I,Q]],elecload[potNo[I,Q]]);
                   Writeln(Outfile,'          ',I:6,Tma[I]:10:2,
                   Qbatch[I]:10:2,Qprodrel[I]:8:2,Pelec[I]:8:2,PotNo[I,Q]:6,
                   Airtemp[I,Q]:10:2,Airvel[I,Q]:10:2);

                end

        Else
                   Writeln(Outfile,'          ',I:6,'      Not active');
        end;


        Writeln(outfile);

        Writeln('Time elapsed = ',t/3600:8:2,' hours');
        Writeln(Outfile,'                    Pot1      Pot2      Pot3      Pot4
 Pot5');
        Write(Outfile,'          ');

        write(outfile1,T/3600:7:2);
        For I := 1 to 5 do
         begin
```

```
  Baseload[I]:=0;
  ebaseload[I]:=0;
  end;

If (t/3600 <= 24.0) Then
begin

   { coldstores, do the model calculations }

   QInsulation (cVst,cZh,Eins,Ki,cXi,cText,cTa,Ctmp);
   Baseload[cpot] := Baseload[cpot] + Defrost * Ctmp/1000;

   QFanload (cTmp,cTa,dProom,Etaf,Etam,Airinrh,Airflowfactor,
   cTstart,cTstop,Timedelay,Partloadfans,t,Ctmp1);
   Baseload[cPot] := Baseload[cPot] + Ctmp1/1000;

   Qdoors (cAdoor,cVst,cta,Texdiff,ctext,t,ctstart,ctstop,
   Airinrh,envinrh,cairnon,cairop,Ctmp2);
   Baseload[cPot] := Baseload[cPot] + Ctmp2;

   Qlight(cVst,cZh,cslites,t,ctstart,ctstop,Flift,Ctmp3);
   Baseload[cPot] := Baseload[cPot] + Ctmp3/1000;
   Ebaseload[cPot] :=Ebaseload[cPot] + cTmp1/1000+cTmp3/1000;
   celec := Ctmp1/1000 + Ctmp3/1000;


   { coolstores}

   QInsulation (sVst,sZh,Eins,Ki,cXi,sText,sTa,stmp);
   Baseload[spot] := Baseload[spot] + Defrost * stmp/1000;

   QFanload (sTmp,sTa,dProom,Etaf,Etam,Airinrh,Airflowfactor,
   sTstart,sTstop,Timedelay,Partloadfans,t,stmp1);
   Baseload[sPot] := Baseload[sPot] + stmp1/1000;


   Qdoors (sAdoor,sVst,sta,Texdiff,stext,t,ststart,ststop,
   Airinrh,envinrh,sairnon,sairop,stmp2);
   Baseload[sPot] := Baseload[sPot] + stmp2;

   Qlight(sVst,sZh,cslites,t,ststart,ststop,Flift,stmp3);
   Baseload[sPot] := Baseload[sPot] + stmp3/1000;
   Ebaseload[sPot] :=Ebaseload[sPot] + (sTmp1+sTmp3)/1000;
   selec := stmp1/1000 + stmp3/1000;

   Aelec:=0;
   Qaircon:=0;


    begin
     ACgeneral (t,aTstart,acleanTstop,aprodTstart,alites,Vac,Zl
     ,aQsw,aQstart,aprodTstop,aQconv,aNop,aQp,aclhw,aTa,ainRh,
     aText,aextRh,acintop,acintnop,aEins,aKi,aXi,airflowfactor,
     adProom,etaf,etam,Qaircon,Aelec,Qstor);
     Baseload[aPot] := Baseload[aPot] + Qaircon;
     Ebaseload[aPot] := (Ebaseload[aPot] + Aelec/1000);
    end;
end;

  For J:= 1 to 5 do
    begin
      Taworst[J]:= 999;
      for I:= 1 to number_sect do
        begin
          if (t/3600 >= time[I,1]) and (t/3600 <
          time[I,listlength[I]]) then
```

```
                    begin
                      If (airtemp[I,stage[I]] <= Taworst[J]) and
                      (J= Potno[I,stage[I]]) then
                        Taworst[J]:=airtemp[I,stage[I]];
                    end;
                 end;
              end;

              If (cTa <= Taworst[cPot]) then
                Taworst[cPot]:=cTa;

              If (sTa <= Taworst[sPot]) then
                Taworst[sPot]:=sTa;

              If (aTa <= Taworst[aPot]) then
                Taworst[aPot]:=aTa;


{Print to -outfiles Section}

                   write(potload[I]:8:2);
                 writeln(outfile);
                 writeln(outfile,'              Refrigeration product and produ
ct-related load');
                 write(outfile,'          ');

             For I := 1 to 5 do
              begin
                 Write (outfile,Potload[I]:10:2);
                 Write (outfile1,Potload[I]:8:2);
             end; write(outfile);
                  writeln(outfile);
                  writeln(outfile);
                  writeln(outfile,'                              Electrical product-re
lated load');
                  write(outfile,'          ');

              For I := 1 to 5 do
               begin
                 write(outfile,Elecload[I]:10:2);
                 Write (outfile1,Elecload[I]:8:2);
               end;

                For I:= 1 to 5 do
                  write(outfile1,Taworst[I]:8:2);
                  writeln(outfile);


              If (t/3600 <= 24) then
                begin
                  writeln(outfile);
                  write(outfile,'                              Refrigeration base-lo
ad');
                  Writeln (outfile);
                  Write(outfile,'          ');


                 For I:= 1 to 5 do
                 Begin
                    Write(outfile,baseload[I]:10:2);
                    Write (outfile1,baseload[I]:8:2);
                 end;
                    writeln(outfile);
                    writeln(outfile);
                    write(outfile,'                              Electrical base-lo
ad');
```

```
                writeln(outfile);
                write(outfile,'          ');

          For I := 1 to 5 do
            begin
              Write (outfile,ebaseload[I]:10:2);
              Write (outfile1,ebaseload[I]:10:2);
            end;

              writeln (outfile);
              Writeln(outfile);
              writeln(outfile,'                    Refrigeration load-Coldstore
',
              Baseload[cpot]:8:2);
              writeln(outfile,'                    Refrigeration load-Coolstore
',
              ((stmp*defrost)+stmp1+stmp2*1000+stmp3)/1000:8:2);
              writeln(outfile,'                    Qaircon
',
              Qaircon:8:2);
              Writeln(outfile,'                    Electrical load-Cold and Cool
stores',
              (Celec + Selec):8:2);

              Writeln(outfile,'                    Electrical load-Aircon
',
              (Aelec/1000):8:2);
             end;

              Writeln(Outfile);Writeln(Outfile);

              Writeln(outfile1);

              Writeln(Outfile);
      end;


      For I:= 1 to number_sect do
         Begin
            If Stage[I] > 0 Then
                Q:= Stage[I]
            Else
                Q:=1;
            If ZZ[I] <> 0 then
                Begin
                  If        (Mode[I] = 'C') and (Qchill[I] >= Qfreez[I]) then
                             Mode[I] := 'C'
                  Else if   (Mode[I]= 'C') and (Qchill[I] < Qfreez[I]) then
                             Begin
                                Mode[I]:= 'F';
                                Tstor[I]:=Tma[I];
                             end
                  Else if (Mode[I] = 'F') and (Unfroz[I] > 0.2) then
                           Mode[I] := 'F'
                  Else if (Mode[I] = 'F') and (Unfroz[I] <= 0.2) then
                             Begin
                                Mode[I]:= 'S';
                                Hsub[I]:=Hfrez[I];
                                Tma[I]:=((Hsub[I]-A[I])-sqrt(sqr(Hsub[I]-
                                A[I])-4*B[I]*C[I]))/(2*B[I]);
                                BeTE1[I]:=sqrt(Qfreez[I]*3*sqr(x[I])/
                                (E[I]*V[I]*ks[I]*(Tma[I]-Airtemp[I,Q])));
                  end;
            end;
```

```
   end;

T:=T+Delt;
Telaps:=Telaps+Delt;

For I:= 1 to number_sect do
begin
     If Stage[I] > 0 Then
          J:= Stage[I]
     Else
          J:=1;
     OD1(x[I],E[I],Bet1[I],Betel[I],kl[I],ks[I],cl[I],cs[I],L[I],
     N[I],nl[I],Tuse[I],Tstor[I],Airtemp[I,J],Delt,h[I],Vf[I],
     V[I],Tf[I],ZZ[I],Qchill[I],Qfreez[I],Qsub[I],RKTma[I,1],
     RKxf[I,1],RKhsub[I,1],Tma[I],xf[I],Hsub[I],Qprod[I],Mode[I]);

     Energy[I]:=Energy[I]+Qprod[I]/6*delt*numItem[I];

     Update(X[I],Tma[I],xf[I],Hsub[I],Tuse[I],Tf[I],N[I],
     RKTMA[I,1]/2,RKXF[I,1]/2,RKHSUB[I,1]/2,A[I],B[I],C[I],
     Unfroz[I],Hfrez[I],L[I],Cl[I],Cs[I],Ks[I],Tstor[I],Tbase,
     Mode[I],Tmad[I],xfd[I],Hsubd[I]);

     OD1(x[I],E[I],Bet1[I],Betel[I],kl[I],ks[I],cl[I],cs[I],L[I],
     N[I],nl[I],Tuse[I],Tstor[I],Airtemp[I,J],Delt,h[I],Vf[I],
     V[I],Tf[I],ZZ[I],Qchill[I],Qfreez[I],Qsub[I],RKTma[I,2],
     RKxf[I,2],RKhsub[I,2],Tmad[I],xfd[I],Hsubd[I],Qprod[I],Mode[I]);

     Energy[I]:=Energy[I]+Qprod[I]/3*delt*numItem[I];

     Update(X[I],Tma[I],xf[I],Hsub[I],Tuse[I],Tf[I],N[I],
     RKTMA[I,2]/2,RKXF[I,2]/2,RKHSUB[I,2]/2,A[I],B[I],C[I],
     Unfroz[I],Hfrez[I],L[I],Cl[I],Cs[I],Ks[I],Tstor[I],Tbase,
     Mode[I],Tmad[I],xfd[I],Hsubd[I]);

     OD1(x[I],E[I],Bet1[I],Betel[I],kl[I],ks[I],cl[I],cs[I],L[I],
     N[I],nl[I],Tuse[I],Tstor[I],Airtemp[I,J],Delt,h[I],Vf[I],
     V[I],Tf[I],ZZ[I],Qchill[I],Qfreez[I],Qsub[I],RKTma[I,3],
     RKxf[I,3],RKhsub[I,3],Tmad[I],xfd[I],Hsubd[I],Qprod[I],Mode[I]);

     Energy[I]:=Energy[I]+Qprod[I]/3*delt*numItem[I];

     Update(X[I],Tma[I],xf[I],Hsub[I],Tuse[I],Tf[I],N[I],
     RKTMA[I,3],RKXF[I,3],RKHSUB[I,3],A[I],B[I],C[I],
     Unfroz[I],Hfrez[I],L[I],Cl[I],Cs[I],Ks[I],Tstor[I],Tbase,
     Mode[I],Tmad[I],xfd[I],Hsubd[I]);

     OD1(x[I],E[I],Bet1[I],Betel[I],kl[I],ks[I],cl[I],cs[I],L[I],
     N[I],nl[I],Tuse[I],Tstor[I],Airtemp[I,J],Delt,h[I],Vf[I],
     V[I],Tf[I],ZZ[I],Qchill[I],Qfreez[I],Qsub[I],RKTma[I,4],
     RKxf[I,4],RKhsub[I,4],Tmad[I],xfd[I],Hsubd[I],Qprod[I],Mode[I]);

     Energy[I]:=Energy[I]+Qprod[I]/6*delt*numItem[I];

     If (Mode[I] = 'C') Then
         Tma[I]:=Tma[I]+ZZ[I]*(RKTMA[I,1]+2*RKTMA[I,2]+
         2*RKTMA[I,3]+RKTMA[I,4])/6
     Else if (Mode[I] = 'F') then
         BEGIN
         xf[I]:=xf[I]+ZZ[I]*(RKXF[I,1]+2*RKXF[I,2]+
         2*RKXF[I,3]+RKXF[I,4])/6;
         Unfroz[I]:=POWER(xf[I]/x[I],N[I]);
         Hfrez[I]:=Unfroz[I]*(L[I]+cl[I]*(Tstor[I]-Tf[I]))+
         cs[I]*(Tf[I]-Tbase);
         If Hfrez[I] > Hf[I] then
              Begin
```

```
                    Tuse[I]:=Tf[I];
                    Tma[I]:=((Hfrez[I]-Hf[I])/cl[I])+Tf[I];
                    end
               Else
                    begin
                    Tma[I]:=((Hfrez[I]-A[I])-sqrt(sqr(Hfrez[I]-A[I])
                    -4*B[I]*C[I]))/(2*B[I]);
                    Tuse[I]:=Tma[I];
                    end
               END
          Else if (Mode[I] = 'S') then
               BEGIN
               Hsub[I]:=Hsub[I]+ZZ[I]*(RKHSUB[I,1]+2*RKHSUB[I,2]+
               2*RKHSUB[I,3]+RKHSUB[I,4])/6;
               Tma[I]:=((Hsub[I]-A[I])-sqrt(sqr(Hsub[I]-A[I])
               -4*B[I]*C[I]))/(2*B[I]);
          END;


     END;
end;


Flush(Outfile);
Close(Outfile);
Close(outfile1);


end.
```

```
Unit Procunit;
{$N+}

INTERFACE

type

Stds=array[1..8] of real;
StdNo=array[1..8] of integer;


Function Power(X,Y:real):real;

Function Upcase(Z:Char):Char;

Procedure Roots(Bi:real; var Beta:real);

PROCEDURE OD1(x,E,B1,Bel,kl,ks,cl,cs,L,N,nu,Tuse,Tstor,Ta,Dt,h,Vf,
          V,Tf,ZZ:Real;
          var Qchill,Qfreez,Qsub,dTma,dxf,dHsub,Tma,xf,Hsub,Qprod:Real;
              Mode:Char);

Procedure Update(X,Tma,xf,Hsub,Tuse,Tf,N,P1,P2,P3,A,B,C,Unfrozen,Hfreez,
    L,Cl,Cs,Ks,Tstor,Tbase:real;
    Mode:Char; var Tmad,xfd,Hsubd:real);

procedure critdem(ProductType,PackagingType:char;

Averagemass:real;var X,Freesp:real);

procedure beefprops(PackagingType:char;var Cs,Cl,L,ks,kl,
Tf,E,N,Rho:real);

procedure musclegeom(packagingType:char;Airvel:real;
var h:real);

procedure sheeprops(packagingType:char;var Cs,Cl,L,ks,kl,
Tf,E,N,Rho:real);

procedure offalprops(airvel:real; var Cs,Cl,L,ks,kl,
Tf,E,N,h,Rho:real);

procedure genvar(h,Totalmass,Yield,Averagemass,Rho,X,N,E,Cs,
Tbase,L,Tf,kl:real;var Bi,Betl,
V,vf,nl,Hbase,a,b,c,hf,NumItem,Tmassn:real);

procedure load(Numitem,Qprod,Qprodrel,pelec:real;var Qbatch,
potload,elecload:real);

Procedure Airprops(Temp,Rh:real;var density,enthalpy:real);

Procedure QInsulation (Vst,Zl,Eins,ki,xi,Text,Ta:real; var Qins:real);

Procedure QFanload (Qinsulation,Ta,dProom,Feff,Meff,Rh,Trise,Tstart,Tstop,
Timedelay,Partloadfans,t:real; var Qfan:real);

Procedure Qdoors (Adoor,Vst,Ta,Trise,Text,t,tstart,tstop,Rhin,Rhout,
Factor1,Factor2:real; var Qdoor:real);

Procedure Qlight(Vst,Zh,Light,t,tstart,tstop,Flift:real; var Qlites:real);

{air-conditioning}

Procedure ACgeneral (t,aTstart,acleanTstop,aprodTstart,alites,Vac,Zl,
aQsw,aQstart,aprodTstop,aQconv,Nop,aQp,aclhw,aTa,ainRh,aText,aextRh,
acintop,acintnop,aEins,aKi,aXi,Trise,adProom,etaf,etam:real;
```

```
var Qaircon,Aelec,Qstor:real);

{Product-related loads}

Procedure pQfans (refvel:stds;roomType,ProductType,PackagingType:char;
var numItem,airvel,relspd,Ta,Time,Time_last,Averagemass,
Eins,Ki,Text,t,
ccfdp,csfdp,cccdp,cscdp,scfdp,ssfdp,sccdp,sscdp,
mcfdp,msfdp,mccdp,mscdp,pcfdp,psfdp,pccdp,pscdp,
petaf,petam,pcXi,PsXi,pinRh,pextRh,pQhw,pQother,
pAextb,pAextl,pAextc,pBassoc,pLassoc,pCassoc,Zb,Zs,Zc:real;
var Qprodrel,pelec:real);


IMPLEMENTATION

Procedure Airprops(Temp,Rh:real;var density,enthalpy:real);

var Vh,Ho,vp,pvo:real;

Begin
   If(Temp <= 0) Then
      vp:=28.7775 - 6071.67/(Temp+271.511)
   Else
      vp:=23.4795 - 3990.56/(Temp+233.833);
   vp := 7.499e-3 * exp( vp );
   pvo:=Rh*vp;
   Ho:=18/29*pvo/(760-pvo);
   Enthalpy:=100+1.01*Temp+Ho*(2500+1.88*Temp);
   Vh:=22.4*(273.15+Temp)/273.15*(1/29+Ho/18);
   Density:=(1+Ho)/Vh;
End;

Procedure QInsulation (Vst,Zl,Eins,ki,xi,Text,Ta:real; var Qins:real);
   VAR
     Temp,Aext : real;
   begin
   Aext := 2*(Vst/Zl)+3*sqrt(2*Zl*Vst);
   Qins := Eins*(ki/xi)*Aext*(Text-Ta);
   {writeln ('Qins ',Qins:8:2,Eins:8:2,ki:8:2,xi:8:2,
   Aext:8:2,Text:8:2,Ta:8:2);}
   end;

Procedure QFanload (Qinsulation,Ta,dProom,Feff,Meff,Rh,Trise,Tstart,Tstop,
Timedelay,Partloadfans,t:real; var Qfan:real);

   VAR
      Wair,Rhoins,Enthalpy : real;
   begin
   Airprops(Ta,Rh,Rhoins,enthalpy);
   Wair := 2*Qinsulation/(Rhoins*1010*Trise);
   QFan := Wair*dProom/(Feff*Meff);

   if tstart < tstop then
      begin
      if    (Tstop+Timedelay <= 24) then
          begin
          if ((t/3600 <= Tstart) or (t/3600 >= (Tstop +Timedelay))) then
             Qfan:= Wair*dProom/(Feff*Meff) * partloadfans;
          end
      else
          begin
          if (t/3600 <= Tstart) and (t/3600 >= Tstop + Timedelay - 24) then
             Qfan:=Wair*dProom/(Feff*Meff)*partloadfans;
          end
      End
```

```
    else
       begin
       if (t/3600 <= tstart) and (t/3600 >= tstart + Timedelay) then
             Qfan:=Wair*dProom/(Feff*Meff)*Partloadfans
       end;
          {writeln('Qfan',Qfan:8:2,Wair:8:2,Qinsulation:8:2,Rhoins:8:2,
          Trise:8:2);}
    end;

Procedure Qdoors (Adoor,Vst,Ta,Trise,Text,t,tstart,tstop,Rhin,Rhout,
Factor1,Factor2:real; var Qdoor:real);
    VAR
       Wair,Rhoins,Rhoout,Enthin,Enthout:real;
    begin
    Airprops(Ta,Rhin,Rhoins,enthin);
    Airprops(Text-Trise,Rhout,Rhoout,enthout);
    Wair:=0.0;
    If tstart < tstop Then
       Begin
       if (t/3600 > tstart) and (t/3600 < tstop) then
          Wair:=Factor2*sqrt(Adoor)
       else
          Wair:=Factor1*Adoor*power(Vst,0.2)
       end
    Else
       Begin
       if (t/3600 > tstart) or (t/3600 < tstop) then
          Wair:=Factor2*sqrt(Adoor)

       else
          Wair:=Factor1*Adoor*power(Vst,0.2)
     end;
    Qdoor:= Wair*Rhoins*(Enthout-Enthin);


    {writeln( 'Qdoor',Qdoor:8:3,Wair:8:4,Adoor:8:2,Ta:8:2,
    Text:8:2,Rhin:8:2,Rhout:8:2,Rhoins:8:2,Rhoout:8:2,enthin:8:2,enthout:8:2);}
    end;

Procedure Qlight(Vst,Zh,Light,t,tstart,tstop,Flift:real; var Qlites:real);
       begin
       If Tstart < tstop then
          Begin
          If (t/3600 > tstart) and (t/3600 < tstop) then
             Qlites:=Light*(Vst/Zh)+Flift*Vst
          else
             Qlites:=0.001;
          end
       Else
          Begin
          If (t/3600 > tstart) or (t/3600 < tstop) then
             Qlites:=Light*(Vst/Zh)+Flift*Vst
          else
             Qlites:=0.001;
          end;
          {writeln ('Qlite',Qlites:8:3)};
       end;


{air-conditioning}


Procedure ACgeneral (t,aTstart,acleanTstop,aprodTstart,alites,Vac,Zl,
aQsw,aQstart,aprodTstop,aQconv,Nop,aQp,aclhw,aTa,ainRh,aText
,aextRh,acintop,acintnop,aEins,aKi,aXi,Trise,adProom,etaf,etam:real;
var Qaircon,Aelec,Qstor:real);
```

```
Var temp,temp2,aRhoins,aenthin,aRhoout,aenthout,Winter,Aext,
Qlite,Qhw,Qpeople,Qstartup,Qinter,Afans,Qinsul,Wair,elec,Efans:real;


        Begin
                Aelec:=0;
                elec:=0;
                efans:=0;
                Afans:=0;
                Qlite:=0;
                Aext:=0;
                Qhw:=0;
                Qpeople:=0;
                Qstartup:=0;
                Qinter:=0;
                winter:=0;
                Qinsul:=0.0;
                temp:=0.0;
                Qaircon:=0;

      airprops (aTa,ainRh,aRhoins,aenthin);
      airprops (aText,aextRh,aRhoout,aenthout);



        If (aTstart < acleanTstop) then
            begin
            if (t/3600 >= aTstart) and (t/3600 <= aprodTstart) then
               begin
                 Qlite:= (alites* Vac/Zl)+0.2*aQsw;
                 elec:=alites*Vac/Zl+aQsw;
                 Qstartup:=aQstart*Vac/Zl/3600/(aProdtstart-aTstart);
                 Aext :=   2*(Vac/Zl)+3*sqrt(2*Zl*Vac);
                 Winter:= acintnop * Nop;
               end
            else if (t/3600 >= aprodTstart) and (t/3600 <= aprodTstop) then
               begin
                 Qlite:= (alites* Vac/Zl)+0.2*aQsw+aQconv;
                 elec:=alites*Vac/Zl+aQsw+AQconv;
                 Aext :=   2*(Vac/Zl)+3*sqrt(2*Zl*Vac);
                 Qpeople:= Nop*aQp;
                 Qhw:=0.5* Qpeople;
                 Winter:= acintop * Nop;
                  If(Aprodtstop - Aprodtstart >= 12) Then
                  begin
                   temp:=Aprodtstart+((Aprodtstop-Aprodtstart)/2)-0.5;
                   If(t/3600 >= Temp) and (t/3600 <= Temp+1) Then
                     Qhw:=Qhw + aclhw * Vac/Zl;
                  end
                end;
             if     (t/3600 >= aprodTstop) and (t/3600 <= acleanTstop) then
                      elec:= (alites* Vac/Zl);
            end

        Else if (aTstart < aprodTstop) and (atstart > acleantstop) then
            begin
              if (t/3600 >= aTstart) and (t/3600 <= aprodTstart) then
                begin
                 Qlite:= (alites* Vac/Zl)+0.2*aQsw;
                 elec:= alites*Vac/Zl+aQsw;
                 Qstartup:=aQstart*Vac/Zl/(3600*(aProdtstart-aTstart));
                 Winter:= acintnop * Nop;
                 Aext :=   2*(Vac/Zl)+3*sqrt(2*Zl*Vac);
```

```
              end
          else if (t/3600 >= aprodTstart) and (t/3600 <= aprodTstop) then
              begin
               Qlite:= (alites* Vac/Z1)+0.2*aQsw+aQconv;
               elec:=alites*Vac/Z1 +aQsw + aQconv;
               Aext :=   2*(Vac/Z1)+3*sqrt(2*Z1*Vac);
               Qpeople:=Nop*aQp;
               Qhw:=0.5*Qpeople;
               Winter:= acintop * Nop;
                 If(Aprodtstop - Aprodtstart >= 12) Then
                  begin
                   temp:=Aprodtstart+(Aprodtstop-Aprodtstart)/2-0.5;
                     If(t/3600 >= Temp) and (t/3600 <= Temp+1) Then
                       Qhw:=Qhw + aclhw * Vac/Z1;
                  end
              end;

               if (t/3600 >aprodTstop) or (t/3600 <= acleanTstop) then
                 elec:= alites* Vac/Z1;
               end

      Else if (aTstart > aprodTstop) then
          begin
            if (t/3600 >= aTstart) and (t/3600 <= aprodTstart) then
              begin
                Qlite:= (alites* Vac/Z1)+0.2*aQsw;
                elec:= alites*Vac/Z1 + aQsw;
                Qstartup:=aQstart*Vac/Z1/3600/(aProdtstart-aTstart);
                Winter:= acintnop * Nop;
                Aext :=   2*(Vac/Z1)+3*sqrt(2*Z1*Vac);
              end
          else if (t/3600 > aprodTstart) or (t/3600 < aprodTstop) then
              begin
                 Qlite:= (alites* Vac/Z1)+0.2*aQsw+aQconv;
                 elec:= alites*Vac/Z1 + aQsw + aQconv;
                 Aext :=   2*(Vac/Z1)+3*sqrt(2*Z1*Vac);
                 Qpeople:=Nop*aQp;
                 Qhw:=0.5*Qpeople;
                 Winter:= acintop * Nop;
              If ((Aprodtstop +24) - Aprodtstart >= 12) Then
                  begin
                       temp:=Aprodtstart+(((Aprodtstop+24)-Aprodtstart)
                       /2)-0.5;
                       if      (Temp>= 24) then
                               Temp:=Temp - 24;
                               Temp2:=Temp + 1;
                       if      (temp2 >= 24) then
                                Temp2:= Temp2 - 24;
                       if       (Temp2 > Temp) and (t/3600 >= Temp) and
                                (t/3600 <= Temp2) then
                                Qhw:=Qhw + aclhw * Vac/Z1
                  else if       (Temp2 < Temp) and ((t >= Temp) or
                                (t/3600 <= Temp2)) then
                                Qhw:=Qhw+ aclhw*Vac/Z1;
                 end
              end;

                if (t/3600 >= aprodTstop) and (t/3600 <= acleanTstop)
                then
                elec:= alites* Vac/Z1;
          end;

{calculate air interchange, insulation and fan heat loads}

          Qinter:=  (Winter*aRhoins*(aenthout-aenthin))*1000;
```

```
Qinsul:=  aEins*(aki/axi)*Aext*(aText-aTa);
temp2:=   (Qinsul +Qinter +Qpeople + Qlite
+ Qhw +Qstartup);
Wair:=    temp2/(aRhoins*1010*Trise);

Afans:=   Wair* adProom/(etaf*etam);



if   (aprodTstart < aprodTstop) then
  begin
    If       ((t/3600 >= aprodTstart) and (t/3600 <= aprodTstop))
    then
             Qstor:= Afans;
  end

else if (aprodTstart > aprodTstop) then
      begin
        if ((t/3600 <= aprodTstop) or (t/3600 >= aprodTstart))
        then
          Qstor:= Afans;
end;

if(acleanTstop > aprodTstop) then
    begin
      if ((t/3600 >= aprodTstop) and (t/3600 <= acleanTstop))
      then
              Efans:=Qstor;
    end
Else if (acleanTstop < aprodTstop) then
   begin
      if ((t/3600 >= aprodTstop) or (t/3600 <= acleanTstop))
      then
              Efans:= Qstor

end;

Aelec:=elec+Efans;
Qaircon:= (temp2 + Afans)/1000;



    End;

{AIRCON ENDS}

{CALCULATE PRODUCT-RELATED LOADS}

Procedure pQfans (refvel:stds;roomType,ProductType,PackagingType:char;
var numItem,airvel,relspd,Ta,Time,Time_last,Averagemass,
Eins,Ki,Text,t,
ccfdp,csfdp,cccdp,cscdp,scfdp,ssfdp,sccdp,sscdp,
mcfdp,msfdp,mccdp,mscdp,pcfdp,psfdp,pccdp,pscdp,
petaf,petam,pcXi,PsXi,pinRh,pextRh,pQhw,pQother,
pAextb,pAextl,pAextc,pBassoc,pLassoc,pCassoc,Zb,Zs,Zc:real;
var Qprodrel,pelec:real);

var area,Qext,dPcoil,dPstow,dProom_full,pdProom,Xi,tstage,
Qassoc,Vfull,Rhoins,penthin,Rhoout,penthout
,Aext,Wair,Qhw,fans,Qdoor,vel_ref:real;

Begin

 airprops (Ta,pinRh,Rhoins,penthin);
```

```
 airprops (Text,pextRh,Rhoout,penthout);

{set dP's}                Qhw:=0.0;
                          Qassoc:=0.0;
                          pdProom:=0.0;
                          Qprodrel:=0.0;
                          pelec:=0.0;

          if (roomType = 'C') and (Ta <= -2.0) then
            begin
              dpcoil:= ccfdp;
              dpstow:=csfdp ;
              vel_ref:=Refvel[1];
            end
          else if (roomType = 'C') and (Ta >= -2.0) then
            begin
              dpcoil:=cccdp ;
              dpstow:=cscdp;
              vel_ref:=refvel[2];
            end
          else if (roomType = 'S') and (Ta <= -2.0) then
            begin
              dpcoil:=scfdp ;
              dpstow:=ssfdp ;
              vel_ref:=refvel[3];
            end

          else if (roomType = 'S') and (Ta >= -2.0) then
            begin
              dpcoil:=sccdp ;
              dpstow:=sscdp ;
              vel_ref:=refvel[4];
            end

          else if (roomType = 'M') and (Ta <= -2.0) then
             begin
              dpcoil:=mcfdp;
              dpstow:=msfdp;
              vel_ref:=refvel[5];
             end

          else if (roomType = 'M') and (Ta >= -2.0) then
             begin
              dpcoil:=mccdp ;
              dpstow:=mscdp ;
              vel_ref:=refvel[6];
             end

          else if (roomType = 'P') and (Ta <= -2.0) then
             begin
              dpcoil:=pcfdp ;
              dpstow:=psfdp ;
              vel_ref:=0.01
             end

          else if (roomType = 'P') and (Ta >= -2.0) then
             begin
               dpcoil:=pccdp;
               dpstow:=pscdp;
               vel_ref:=0.01;
             end

             else if (roomType = 'A') and (Ta <= -2.0) then
              begin
                dpcoil:=0.01 ;
```

```
          dpstow:=0.01;
          vel_ref:=refvel[7];
        end

  else if (roomType = 'A') and (Ta >= -2.0) then
      begin
        dpcoil:=0.0;
        dpstow:=0.0;
        vel_ref:=refvel[8];
  end;


 Vfull:= airvel/relspd;



 dProom_full:=dpcoil+ (dpstow * SQR(Vfull/vel_ref));
 pdProom:=dProom_full*SQR(Relspd);
 tstage:= time-time_last ;


        if (RoomType ='A') then
         begin
            area:=0.0;
            Aext:=0.0;
            Wair:=0.0;
            Qassoc:=0.0;
            Qhw:=0.0;
            Rhoins:=0.0;
            penthin:=0.0;
            penthout:=0.0;
         end

else      if (productType = 'B') and ((PackagingType='N') or
          (PackagingType='P')) and (roomType='S') then
     begin
         area:=0.0062*power(Averagemass,0.83);
         Aext:=pAextb*numItem;


       if(t/3600 >= time_last) and (t/3600 <= time_last +
       (0.1 * tstage)) then
         Begin
           Wair:= 4.86 *numItem * Zb/tstage;
           Qassoc:=pBassoc*numItem;
         end

       else if (t/3600 >= (time_last + 0.1 * tstage)) and
       (t/3600 <= (time_last+ 0.3 * tstage)) then
           Wair:= 2.43 * numItem * Zb/tstage

       else if ((t/3600 > (time_last + 0.3 * tstage)) and
       (t/3600 <=(time_last+ 0.8 * tstage))) then
           Wair:= 0.0

       else if (t/3600 > time_last + 0.8 * tstage) and
       (t/3600 <= time_last+ tstage) then
         Begin
           Wair:= 2.43 * numItem * Zb/tstage;
           Qassoc:=pBassoc*numItem;
         end

       else Wair:=0.0;

         if (Ta >= -2) and
         (t/3600 >= time_last) and (t/3600 <=time_last +
```

```
        0.25 * tstage) then
          Qhw:=7.0E6 * numItem/(tstage*3600)

        else Qhw:=0.0;
end

else if (productType = 'S') and ((PackagingType='N') or
  (PackagingType='P')) and (roomType= 'S') then
  Begin
    area:=0.0042*power(Averagemass,1.16);
    Aext:= pAextl* numItem;


    if(t/3600 >= time_last) and (t/3600 <= time_last+
    (0.1 * tstage)) then
       begin
          Wair:= 0.81 * numItem * Zs/tstage;
          Qassoc:=pLassoc*numItem;
       end

     else if (t/3600 > time_last + 0.1 * tstage) and
     (t/3600 <= time_last+ (0.3 * tstage)) then
         Wair:= 0.41 * numItem * Zs/tstage

     else if (t/3600 > time_last + 0.3 * tstage) and
     (t/3600 <= time_last + (0.8 * tstage)) then
         Wair:= 0.0

     else if (t/3600 > time_last + 0.8 * tstage) and
     (t/3600 <= time_last+ tstage) then
       begin
         Wair:= 0.41 * numItem * Zs/tstage;
         Qassoc:=pLassoc*numItem;
       end

     else Wair:=0.0;

      if (Ta >=-2.0) and (t/3600 <= (Time_last + 0.25 *
     tstage)) then
         Qhw:=0.864E6 * numItem/(tstage*3600);
end


  else if (productType = 'S') and ((PackagingType= 'N') or
    (PackagingType='P')) and (roomType = 'M') then
   Begin
      area:=0.00105*power(Averagemass,1.16);
      Aext:=pAextl * numItem;

   if(t/3600 >= time_last) and (t/3600 <= time_last +
   (0.1 * tstage)) then
         begin
             Wair:= 0.81 * numItem * Zs/tstage;
             Qassoc:=pLassoc * numItem;
         end

   else if (t/3600 > time_last + 0.1 * tstage) and
   (t/3600 <= time_last+ (0.3 * tstage)) then
         Wair:= 0.41 * numItem * Zs/tstage

     else if (t/3600 > time_last + 0.3 * tstage) and
     (t/3600 <= time_last+ (0.8 * tstage)) then
         Wair:= 0.0

     else if (t/3600 > time_last + 0.8 * tstage) and
     (t/3600 <= time_last+ tstage) then
```

```
            begin
             Wair:= 0.41 * numItem * Zs/tstage;
             Qassoc:=pLassoc * numItem;
            end


      else  if (Ta >= -2) and (t/3600 >= Time_last) and
         (t/3600 <=Time_last + 0.25 * tstage) then

          Qhw:=0.864E6 * numItem/(tstage*3600);

       end


   else if (packagingType = 'C') and (roomType= 'C') then
     Begin
       area:=0.011;
       Aext:= pAextc * numItem;


       if(t/3600 >= time_last) and (t/3600 <= time_last +
       (0.1 * tstage)) then
           begin
              Wair:= 0.13 * numItem * Zc/tstage;
              Qassoc:=pCassoc*numItem;
           end

        else if (t/3600 > time_last + 0.1 * tstage) and
        (t/3600 <= time_last+(0.3 * tstage)) then
             Wair:= 0.065 * numItem * Zc/tstage

        else if (t/3600 > time_last + 0.3 * tstage) and
        (t/3600 <= time_last+(0.8 * tstage)) then
             Wair:= 0.0

        else if (t/3600 > time_last + 0.8 * tstage) and
        (t/3600 <= time_last+tstage) then
           begin
              Wair:= 0.065 * numItem * Zc/tstage;
              Qassoc:=pCassoc*numItem;
           end
        else Wair:= 0.0;


      end;

        fans:= (airvel*area*pdProom*numItem)/(petaf*petam);
        {writeln('Qfans',fans:8:2,pdProom:8:2,airvel:8:2,area:8:2,numitem
        vel_ref:8:2);}


{set insulation thickness}

   if (ta <= -2.0) then

           Xi:=pcXi
      else Xi:=psXi;


   Qext:=Eins*(ki/Xi)*Aext*(Text-Ta);


{door infiltration load}

   Qdoor:=Wair * Rhoins * (penthout - penthin);
```

```
        Qprodrel:=((fans+Qext+Qdoor+Qassoc+Qhw)*1.05)/1000;
        pelec:=(fans+(Qassoc*0.66))/1000;

end;



Function Power(X,Y:real):real;
    Begin
    Power:=exp(ln(X)*Y);
    End;

Function Upcase(Z:Char):Char;
Begin
    If Z = 'b' Then
       Upcase:='B'
    Else if Z = 'c' Then
       Upcase:='C'
    Else if Z = 'n' Then
       Upcase:='N'
    Else if Z = 'o' Then
       Upcase:='O'
    Else if Z = 'p' Then
       Upcase:='P'
    Else if Z = 's' Then
       Upcase:='S'
    Else
       Upcase:=Z;
End;

Procedure Roots(Bi:real; var Beta:real);
    Var
    G1,G2,Vg,Val:real;
    J:integer;
    Begin
    G1:=0.001;
    G2:=3.14159;
    For j:= 1 to 50 do
        begin
        vg:=(G1+G2)/2;
        Val:=(vg*cos(vg)/sin(vg))+Bi-1.0;
        if Val >= 0.0  then
              G1:=(G1+G2)/2
        else
              G2:=(G1+G2)/2;
        end;
    Beta:=(G1+G2)/2.0;
    end;

PROCEDURE OD1(x,E,B1,Be1,k1,ks,c1,cs,L,N,nu,Tuse,Tstor,Ta,Dt,h,Vf,
          V,Tf,ZZ:Real;
          var Qchill,Qfreez,Qsub,dTma,dxf,dHsub,Tma,xf,Hsub,Qprod:Real;
              Mode:Char);
  var
  D,R,Z,Y:real;

  BEGIN
  If (Mode = 'C') or (Mode = 'F') then
     Begin
     D:=power(xf,(1-nu));
     R:=power(x,(1-nu));
     Z:=1/(h*power(x,nu));
     Y:=ks*(1-nu);
     Qfreez:=ZZ*Vf*N*power(xf,(N-1))*(Tuse-Ta)/(power(xf,nu)*(Z-((D-R)/Y)));
```

```
        If (Mode='C') then
           Begin
           Qchill:=ZZ*(Tma-Ta)*(E/3)*V*B1*B1*kl/(x*x);
           Qprod:=Qchill;
           dTma:=ZZ*Dt*(Ta-Tma)*(E/3)*B1*B1*kl/(cl*x*x);
           dxf:=0;
           dHsub:=0;
           end
        Else If (Mode='F') then
           Begin
           dxf:=ZZ*Dt*(Ta-Tuse)/((L+cl*(Tstor-Tf))*power(xf,nu)* (Z-((D-R)/Y)));
           Qprod:=ZZ*Qfreez;
           dHsub:=0;
           dTma:=0;
           end;
        end
   Else If (Mode='S') then
        Begin
        Qsub:=ZZ*(E/3)*(Tma-Ta)*V*Bel*Bel*ks/(x*x);
        Qprod:=Qsub;
        dHsub:=ZZ*Dt*(Ta-Tma)*(E/3)*Bel*Bel*ks/(x*x);
        dxf:=0;
        dTma:=0
        end;

   End;

Procedure Update(X,Tma,xf,Hsub,Tuse,Tf,N,P1,P2,P3,A,B,C,Unfrozen,Hfreez,
    L,Cl,Cs,Ks,Tstor,Tbase:real;
    Mode:Char; var Tmad,xfd,Hsubd:real);
      Begin
      Tmad:=Tma+P1;
      xfd:=xf+P2;
      Hsubd:=Hsub+P3;
      If Mode = 'C' then
         Tuse:=Tf
      Else if Mode = 'F' then
           Begin
           Unfrozen:=power(xfd/x,N);
           Hfreez:=Unfrozen*(L+cl*(Tstor-Tf))+cs*(Tf-Tbase);
           Tmad:=((Hfreez-A)-sqrt(sqr(Hfreez-A)-4*B*C))/(2*B);
           If Tmad<Tf then
              Tuse:=Tmad
           Else
               Tuse:=Tf;
           End
      Else
          Tmad:=((Hsubd-A)-sqrt(sqr(Hsubd-A)-4*B*C))/(2*B);
      End;


{general procedure region}

procedure critdem(ProductType,PackagingType:char;
Averagemass:real;var X,Freesp:real);
begin
     if   (productType='B') and (PackagingType='N') then
          begin
          X:=0.0194*power(Averagemass,0.33);
          Freesp:=0.006218*power(2*Averagemass,0.830043);
          end
  else if (ProductType='S') and ((PackagingType='N')
          or (PackagingType='P')) then
          begin
          X:=0.023*power(Averagemass,0.33);
```

```
          Freesp:=0.015205*power(Averagemass,0.6080807)
          end
  else if Averagemass >= 14.0 then
          begin
          X:=0.077;
          Freesp:=0.009
          end
  else
          Begin
          X:=0.0385;
          Freesp:=0.009
          end
end;

procedure beefprops(PackagingType:char;var Cs,Cl,L,ks,kl,
Tf,E,N,Rho:real);
begin
  if (PackagingType ='N')or
     (PackagingType='P') then
      begin
          Cs:=1.9E6;
          Cl:=3.4E6;
          L :=2E8;
          ks:=1.43;
          kl:=0.46;
          Tf:=-1.0;
          E:=1.3;
          N:=E+0.5;
          Rho:=1025.0
      end
  else if (PackagingType='C') then
          begin
            Cs:=1.9E6;
            Cl:=3.6E6;
            L :=2.15E8;
            ks:=1.5;
            kl:=0.48;
            Tf:=-1.0;
            E:=1.3;
            N:=E+0.5;
            Rho:=1060.0
         end

end;


procedure musclegeom(packagingType:char;Airvel:real;
var h:real);
begin
     if   packagingType = 'N'  then
          h:=12.5*power(airvel,0.6)
     else if   packagingType = 'P' then
          h:=1/(1/(12.5*power(airvel,0.6))+0.06)
     else if   packagingType = 'C' then
          h:=1/(1/(7.3*power(airvel,0.8))+0.08);
     end;

procedure sheeprops(packagingType:char;var Cs,Cl,L,ks,kl,
Tf,E,N,Rho:real);
begin

  if (PackagingType ='N')or
     (PackagingType='P') then
      begin
         Cs:=1.85E6;
         Cl:=3.2E6;
```

```
            L :=1.7E8;
            ks:=1.35;
            kl:=0.45;
            Tf:=-1.0;
            E:=2.01;
            N:=E+0.5;
            Rho:=1025.0
        end
   else if (PackagingType='C') then
            begin
              Cs:=2.1E6;
              Cl:=3.5E6;
              L :=2.2E8;
              ks:=1.45;
              kl:=0.46;
              Tf:=-1.0;
              E:=1.3;
              N:=E+0.5;
              Rho:=1060.0
           end
end;

procedure offalprops(airvel:real; var Cs,Cl,L,ks,kl,
Tf,E,N,h,Rho:real);
begin
     Cs:=2.25E6;
     Cl:=3.6E6;
     L :=2.1E8;
     ks:=1.5;
     kl:=0.5;
     Tf:=-1.0;
     h:=1/(1/(7.3*power(airvel,0.8))+0.08);
     E:=1.3;
     N:=E+0.5;
     Rho:=1060.0
end;

procedure genvar(h,Totalmass,Yield,Averagemass,Rho,X,N,E,Cs,
Tbase,L,Tf,kl:real;var Bi,Bet1,
V,vf,n1,Hbase,a,b,c,hf,NumItem,Tmassn:real);
begin
     Bi:=h*X/kl;
     Roots(Bi,Bet1);
     V:=Averagemass/Rho;
     vf:=V/Power(X,N);
     n1:=E-1;
     Hbase:=0.0;
     a:=Hbase-Cs*Tbase;
     b:=Cs;
     c:=L*Tf;
     hf:=L+Cs*(Tf-Tbase);
     Tmassn:=Totalmass * Yield;
     NumItem:=Tmassn/Averagemass;
end;

procedure load(Numitem,Qprod,Qprodrel,pelec:real;
var Qbatch,potload,elecload:real);
Begin
     Qbatch:=Numitem*Qprod/1000;
     potload:=potload+Qbatch+Qprodrel;
     elecload:=elecload+pelec;
End;
end.
```

APPENDIX D2.1 - PRODUCT USER DATA FILE

```
{cold stores}
     12230          {store volume}
     6.0            {store height}
     20             {external air temp}
     19             {door cross-sectional area}
     6.0            {door operational start time}
     17.0           {door operational stop time}
     2              {pot No}
{coolstores}
     1500           {store volume}
     5.0            {store height}
     25             {external air temp}
     9.0            {door cross-sectional area}
     6.0            {door operational start time}
     10.0           {door operational stop time}
     1              {pot No}
{air-conditioning}
     4000           {aircon room volume}
     5.5            {aircon room height}
     25             {external air temperature}
     4              {aircon start time}
     6              {production start time}
     17             {production stop time}
     18             {cleanup stop time}
     30000          {shrink tunnel heat load}
     25000          {conveyor heat load}
     1              {pot No}
     53             {number of personnel in aircon room}

180  349200  900    {time step, total simulation time, printout frequency}
```

Batch	Time	Ta	airvel	Relsp	Pot	Yield	AveMass	St Mss		Rm	PkPr
1	6.00	4.00	0.60	1.00	1	1.00	304.00	13041	S	N	B
1	30.00	8.00	0.60	1.00	1	0.67	27.20	0.0	A	C	B
1	31.00	-30.00	3.00	1.00	2	0.67	27.2	13041	C	C	B
1	78.00	-30.00	3.00	1.00	2	0.67	27.20	13041	C	C	B
2	7.00	4.00	0.60	1.00	1	1.00	304.00	6718	S	N	B
2	31.00	8.00	0.60	1.00	1	0.67	18.00	0.0	A	C	B
2	32.00	-1.00	0.60	1.00	1	0.67	18.00	6718	C	C	B
2	56.00	-1.00	0.60	1.00	1	0.67	18.00	6718	C	C	B
3	8.00	4.00	0.60	1.00	1	1.00	325.00	10403	S	N	B
3	32.00	8.00	0.60	1.00	1	0.67	27.20	0.0	A	C	B
3	33.00	-30.00	3.00	1.00	2	0.67	27.20	10403	C	C	B
3	81.00	-30.00	3.00	1.00	2	0.67	27.20	10403	C	C	B
4	9.00	4.00	0.60	1.00	1	0.67	325.00	5360	S	N	B
4	33.00	8.00	0.60	1.00	1	0.67	18.00	0.0	A	C	B
4	34.00	-1.00	0.60	1.00	1	0.67	18.00	5360	C	C	B
4	82.00	-1.00	0.60	1.00	1	0.67	18.00	5360	C	C	B
5	9.75	4.00	0.60	1.00	1	1.00	294.00	6209	S	N	B
5	33.75	8.00	0.60	1.00	1	0.67	27.20	0.0	A	C	B
5	34.75	-30.00	3.00	1.00	2	0.67	27.20	6209	C	C	B
5	82.75	-30.00	3.00	1.00	2	0.67	27.20	4160	C	C	B
6	10.25	4.00	0.60	1.00	1	0.67	294.00	4160	S	N	B
6	34.25	8.00	0.60	1.00	1	0.67	18.00	0.0	A	C	B
6	35.25	-1.00	0.60	1.00	1	0.67	18.00	4160	C	C	B
6	59.25	-1.00	0.60	1.00	1	0.67	18.00	4160	C	C	B
7	10.75	4.00	0.60	1.00	1	1.00	256.00	5014	S	N	B
7	34.75	8.00	0.60	1.00	1	0.67	27.20	0.0	A	C	B
7	35.75	-30.00	3.00	1.00	2	0.67	27.20	5014	C	C	B
7	83.75	-30.00	3.00	1.00	2	0.67	27.20	5014	C	C	B
8	11.00	4.00	0.60	1.00	1	1.00	256.00	2583	S	N	B
8	35.00	8.00	0.60	1.00	1	0.67	18.00	0.0	A	C	B
8	36.00	-1.00	0.60	1.00	1	0.67	18.00	2583	C	C	B
8	60.00	-1.00	0.60	1.00	1	0.67	18.00	2583	C	C	B
9	11.75	4.00	0.60	1.00	1	1.00	214.00	5014	S	N	B

9	35.75	8.00	0.60	1.00	1	0.67	27.20	0.0	A	C	B
9	36.75	-30.00	3.00	1.00	2	0.67	27.20	5014	C	C	B
9	84.75	-30.00	3.00	1.00	2	0.67	27.20	5014	C	C	B
10	12.25	4.00	0.60	1.00	1	1.00	214.00	2583	S	N	B
10	36.25	8.00	0.60	1.00	1	0.67	18.00	0.0	A	C	B
10	37.25	-1.00	0.60	1.00	1	0.67	18.00	2583	C	C	B
10	61.25	-1.00	0.60	1.00	1	0.67	18.00	2583	C	C	B
11	13.25	4.00	0.60	1.00	1	1.00	237.00	4458	S	N	B
11	37.25	8.00	0.60	1.00	1	0.67	27.20	0.0	A	C	B
11	38.25	-30.00	3.00	1.00	2	0.67	27.20	4458	C	C	B
11	86.25	-30.00	3.00	1.00	2	0.67	27.20	4458	C	C	B
12	13.5	4.00	0.60	1.00	1	1.00	237.00	2296	S	N	B
12	37.5	8.00	0.60	1.00	1	0.67	18.00	0.0	A	C	B
12	38.5	-1.00	0.60	1.00	1	0.67	18.00	2296	C	C	B
12	62.5	-1.00	0.60	1.00	1	0.67	18.00	2296	C	C	B
13	14.00	4.00	0.60	1.00	1	1.00	212.00	4000	S	N	B
13	38.00	8.00	0.60	1.00	1	0.67	27.20	0.0	A	C	B
13	39.00	-30.00	3.00	1.00	2	0.67	27.20	4000	C	C	B
13	87.00	-30.00	3.00	1.00	2	0.67	27.20	4000	C	C	B
14	14.25	4.00	0.60	1.00	1	1.00	212.00	2060	S	N	B
14	38.25	8.00	0.60	1.00	1	0.67	18.00	0.0	A	C	B
14	39.25	-1.00	0.60	1.00	1	0.67	18.00	2060	C	C	B
14	63.25	-1.00	0.60	1.00	1	0.67	18.00	2060	C	C	B
15	15.00	4.00	0.60	1.00	1	1.00	323.00	948	S	N	B
15	39.00	8.00	0.60	1.00	1	0.67	27.20	0.0	A	C	B
15	40.00	-30.00	3.00	1.00	2	0.67	27.20	948	C	C	B
15	88.00	-30.00	3.00	1.00	2	0.67	27.20	948	C	C	B
16	15.25	4.00	0.60	1.00	1	1.00	323.00	488	S	N	B
16	39.25	8.00	0.60	1.00	1	0.67	18.00	0.0	A	C	B
16	40.25	-1.00	0.60	1.00	1	0.67	18.00	488	C	C	B
16	64.25	-1.00	0.60	1.00	1	0.67	18.00	488	C	C	B
17	16.00	4.00	0.60	1.00	1	1.00	182.00	3731	S	N	B
17	40.00	8.00	0.60	1.00	1	0.67	27.20	0.0	A	C	B
17	41.00	-30.00	3.00	1.00	2	0.67	27.20	3731	C	C	B
17	89.00	-30.00	3.00	1.00	2	0.67	27.20	3731	C	C	B
18	16.10	-30.00	3.00	1.00	2	1.00	17.28	2488	C	C	O
18	64.10	-30.00	3.00	1.00	2	1.00	17.28	2488	C	C	O

APPENDIX D2.2 - PRODUCT STANDARD DATA FILE

```
3.0                       {Product-related reference velocities}
0.6
1.0
0.6
1.0
0.6
0.1
0.1

{COLD AND COOLSTORE STANDARD DATA VALUES}
 -20       -1             {cold store and cool store air temps}
 0.20      0.15           {insulation thicknesses, cold and cool stores}
 0.033                    {insulation thermal conductivity}
 1.25                     {insultation effectiveness}
 3.06e-4   0.048          {air interchange - non-op & op, cold stores}
 2.26e-4   0.0355         {air interchange - non-op & op, cool stores}
 0.85                     {inside air rel humidity}
 5                        {temp diff from external air to env load-in}
 0.85                     {environmental loadin rel humidity}
 1.5                      {air flow factor - temp rise around store}
 175                      {room air pressure differential}
 0.65      0.90           {fan and motor efficiencies}
 0.42                     {fan partload factor}
 2                        {time delay until part load starts}
 10                       {light load }
 7.2e-1                   {combined store forklift load}
 1.2                      {defrost factor}

{AIR-CONDITIONING STANDARD DATA VALUES}
 8                        {aircon room air temp}
 0.15                     {insulation thickness}
 0.033                    {insulation thermal conductivity}
 1.25                     {insulation effectiveness}
 1.1e-2                   {air interchange factor-op
 2.2e-3                   {air interchange factor- non-op}
 0.85                     {internal rel humidity}
 0.85                     {external relative humidity}
 350                      {personnel heat load}
 15                       {aircon light load}
 2.57e6                   {startup heat load factor}
 528                      {cleanup hot water heat load}
 175                      {room differential air pressure}

{PRODUCT-RELATED STANDARD DATA VALUES}
 150       150            {coil and stow dP carton freezer}
 100       50             {coil and stow dP carton chiller}
 75        100            {coil and stow dP carcass freezer}
 75        75             {coil and stow dP carcass chiller}
 150       125            {coil and stow dP multiple carcass freezer}
 100       75             {coil and stow dP multiple carcass chiller}
 0.01      0.01           {coil and stow dP plate freezer}
 0.01      0.01           {coil and stow dP plate chiller}
 0.65      0.9            {efficiency factors for fans and motors}
 0.2       0.15           {insulation thickness freezers and chillers}
 0.85      0.75             {internal and external rel humidity}
 1800      5              {cleanup hosing factor and "other loads" % allowance}
 2.527   0.421   0.068    {external surface factor: beef,lamb and cartons}
 14.58   2.43    0.40     {associated loads factor}
 5       3       4        {environment height}
 1.2     1.2     1.3      {equipment allowance factor}
```

APPENDIX D2.3 - PRODUCT OUTPUT DATA FILE #2

0	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
0.25	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
0.75	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
1	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
1.25	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
1.5	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
1.75	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
2	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
2.25	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
2.5	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
2.75	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
3	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
3.25	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
3.5	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
3.75	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
4	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	346.56	59.89	0	0	0	41.57	5.12	0	0	0
4.25	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	346.56	59.89	0	0	0	41.57	5.12	0	0	0
4.5	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	346.56	59.89	0	0	0	41.57	5.12	0	0	0
4.75	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	346.56	59.89	0	0	0	41.57	5.12	0	0	0
5	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	346.56	59.89	0	0	0	41.57	5.12	0	0	0
5.25	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	346.56	59.89	0	0	0	41.57	5.12	0	0	0
5.5	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	346.56	59.89	0	0	0	41.57	5.12	0	0	0
5.75	0	0	0	0	0	0	0	0	0	0	-1	-20	999	999	999	346.56	59.89	0	0	0	41.57	5.12	0	0	0
6	38.4	0	0	0	0	5.12	0	0	0	0	-1	-20	999	999	999	346.56	59.89	0	0	0	41.57	5.12	0	0	0
6.25	38	0	0	0	0	5.12	0	0	0	0	-1	-20	999	999	999	149.23	109.72	0	0	0	71.57	41.38	0	0	0
6.5	37.59	0	0	0	0	5.12	0	0	0	0	-1	-20	999	999	999	149.23	109.72	0	0	0	71.57	41.38	0	0	0
6.75	37.19	0	0	0	0	5.12	0	0	0	0	-1	-20	999	999	999	149.23	109.72	0	0	0	71.57	41.38	0	0	0
7	56.59	0	0	0	0	7.76	0	0	0	0	-1	-20	999	999	999	149.23	109.72	0	0	0	71.57	41.38	0	0	0
7.25	55.99	0	0	0	0	7.76	0	0	0	0	-1	-20	999	999	999	149.23	109.72	0	0	0	71.57	41.38	0	0	0
7.5	55.4	0	0	0	0	7.76	0	0	0	0	-1	-20	999	999	999	149.23	109.72	0	0	0	71.57	41.38	0	0	0
7.75	54.83	0	0	0	0	7.76	0	0	0	0	-1	-20	999	999	999	149.23	109.72	0	0	0	71.57	41.38	0	0	0
8	83.84	0	0	0	0	11.78	0	0	0	0	-1	-20	999	999	999	149.23	109.72	0	0	0	71.57	41.38	0	0	0
8.25	82.98	0	0	0	0	11.78	0	0	0	0	-1	-20	999	999	999	149.23	109.72	0	0	0	71.57	41.38	0	0	0
8.5	80.5	0	0	0	0	11.36	0	0	0	0	-1	-20	999	999	999	149.23	109.72	0	0	0	71.57	41.38	0	0	0
8.75	79.66	0	0	0	0	11.36	0	0	0	0	-1	-20	999	999	999	149.23	109.72	0	0	0	71.57	41.38	0	0	0
9	89.05	0	0	0	0	12.75	0	0	0	0	-1	-20	999	999	999	149.23	109.72	0	0	0	71.57	41.38	0	0	0
9.25	88.12	0	0	0	0	12.75	0	0	0	0	-1	-20	999	999	999	149.23	109.72	0	0	0	71.57	41.38	0	0	0
9.5	86.38	0	0	0	0	12.54	0	0	0	0	-1	-20	999	999	999	149.23	109.72	0	0	0	71.57	41.38	0	0	0
9.75	104.09	0	0	0	0	15	0	0	0	0	-1	-20	999	999	999	149.23	109.72	0	0	0	71.57	41.38	0	0	0
10	103.01	0	0	0	0	15	0	0	0	0	-1	-20	999	999	999	139.39	109.72	0	0	0	67.49	41.38	0	0	0
10.25	110.3	0	0	0	0	16.1	0	0	0	0	-1	-20	999	999	999	139.39	109.72	0	0	0	67.49	41.38	0	0	0
10.5	107.95	0	0	0	0	15.79	0	0	0	0	-1	-20	999	999	999	139.39	109.72	0	0	0	67.49	41.38	0	0	0
10.75	122.99	0	0	0	0	17.84	0	0	0	0	-1	-20	999	999	999	139.39	109.72	0	0	0	67.49	41.38	0	0	0
11	130.03	0	0	0	0	18.9	0	0	0	0	-1	-20	999	999	999	139.39	109.72	0	0	0	67.49	41.38	0	0	0
11.25	128.66	0	0	0	0	18.9	0	0	0	0	-1	-20	999	999	999	139.39	109.72	0	0	0	67.49	41.38	0	0	0
11.5	126.9	0	0	0	0	18.79	0	0	0	0	-1	-20	999	999	999	139.39	109.72	0	0	0	67.49	41.38	0	0	0
11.75	143.36	0	0	0	0	20.94	0	0	0	0	-1	-20	999	999	999	139.39	109.72	0	0	0	67.49	41.38	0	0	0
12	141.84	0	0	0	0	20.94	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
12.25	145.05	0	0	0	0	21.84	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
12.5	143.47	0	0	0	0	21.84	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
12.75	141.55	0	0	0	0	21.75	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
13	140.02	0	0	0	0	21.75	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
13.25	149.9	0	0	0	0	23.42	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
13.5	155.56	0	0	0	0	24.28	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
13.75	153.84	0	0	0	0	24.28	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
14	166.4	0	0	0	0	26	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
14.25	167.79	0	0	0	0	26.66	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
14.5	165.88	0	0	0	0	26.66	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
14.75	163.55	0	0	0	0	26.54	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
15	164.42	0	0	0	0	26.91	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
15.25	162.31	0	0	0	0	27.1	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
15.5	160.48	0	0	0	0	27.1	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
15.75	157.98	0	0	0	0	26.92	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
16	168.49	0	0	0	0	28.49	0	0	0	0	-1	-20	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
16.25	166.32	19.03	0	0	0	28.49	2.47	0	0	0	-1	-30	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
16.5	162.9	18.63	0	0	0	28.31	2.47	0	0	0	-1	-30	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
16.75	160.68	18.25	0	0	0	28.21	2.47	0	0	0	-1	-30	999	999	999	138.48	109.72	0	0	0	66.57	41.38	0	0	0
17	156.71	17.87	0	0	0	28.21	2.47	0	0	0	-1	-30	999	999	999	138.48	66.96	0	0	0	29.41	12.19	0	0	0
17.25	154.05	17.51	0	0	0	28.21	2.47	0	0	0	-1	-30	999	999	999	7.41	66.96	0	0	0	29.41	12.19	0	0	0
17.5	151.96	17.15	0	0	0	28.19	2.47	0	0	0	-1	-30	999	999	999	7.41	66.96	0	0	0	29.41	12.19	0	0	0
17.75	150.16	16.8	0	0	0	28.17	2.47	0	0	0	-1	-30	999	999	999	7.41	66.96	0	0	0	29.41	12.19	0	0	0
18	146.02	16.46	0	0	0	28.17	2.47	0	0	0	-1	-30	999	999	999	7.41	66.96	0	0	0	29.41	12.19	0	0	0
18.25	144.11	16.13	0	0	0	28.17	2.47	0	0	0	-1	-30	999	999	999	7.41	66.96	0	0	0	0.66	12.19	0	0	0
18.5	140.65	15.81	0	0	0	27.97	2.47	0	0	0	-1	-30	999	999	999	7.41	66.96	0	0	0	0.66	12.19	0	0	0
18.75	139.02	15.49	0	0	0	27.97	2.47	0	0	0	-1	-30	999	999	999	7.41	66.96	0	0	0	0.66	12.19	0	0	0
19	136.9	15.18	0	0	0	27.97	2.47	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
19.25	135.33	14.88	0	0	0	27.97	2.47	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
19.5	131.91	14.59	0	0	0	27.97	2.47	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
19.75	129.56	14.46	0	0	0	27.97	2.47	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
20	128.07	14.38	0	0	0	27.97	2.47	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
20.25	124.99	14.29	0	0	0	27.97	2.47	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
20.5	122.3	14.2	0	0	0	27.97	2.47	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
20.75	120.66	14.11	0	0	0	27.97	2.47	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
21	119.26	13.88	0	0	0	27.97	2.44	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
21.25	117.21	13.79	0	0	0	27.97	2.44	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
21.5	115.51	13.7	0	0	0	27.97	2.44	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
21.75	114.18	13.62	0	0	0	27.97	2.44	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
22	112.88	13.53	0	0	0	27.97	2.44	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
22.25	109.78	13.45	0	0	0	27.97	2.44	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
22.5	108.48	13.36	0	0	0	27.97	2.44	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
22.75	107.24	13.28	0	0	0	27.97	2.44	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
23	106.02	13.19	0	0	0	27.97	2.44	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
23.25	104.35	13.11	0	0	0	27.97	2.44	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
23.5	103.17	13.02	0	0	0	27.97	2.44	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
23.75	102.01	12.94	0	0	0	27.97	2.44	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0
24	100.87	12.85	0	0	0	27.97	2.44	0	0	0	-1	-30	999	999	999	7.41	59.89	0	0	0	0.66	5.12	0	0	0

APPENDIX D3 - ENGINEROOM MODEL LISTING

```
Program Eng (input,output);

VAR

infile,outfile,heatfile,outfile1:text;
filename1,filename2,filename3,filename4:string[20];

refType:real;
Npot:integer;
ancill,Twamb,linegain:real;

Tim:array[0..200] of real;
Qprod:array[1..200,1..5]of real;
Qbase:array[1..200,1..5]of real;
Eprod:array[1..200,1..5]of real;
Ebase:array[1..200,1..5]of real;
Taworst:array[1..200,1..5] of real;
Qtotal:array[1..200,1..5] of real;
Etotal:array[1..200,1..5] of real;
Qgrand:array[1..200] of real;
Egrand:array[1..200] of real;
Ecomp:array[1..200,1..5] of real;
Elect:array[1..200] of real;
Tpot:array[1..5] of real;
Te:array[1..200,1..5] of real;

Time,temp1,temp2,temp3,temp4,temp5
,temp6,temp7,temp8,temp9,temp10,
Temp11,Temp12,Temp13,Temp14,Temp15:real;

I,J,K,M:integer;

a1,a2,a3,b1,b2,b3,alpha:real;
Tc,x1,Pc,Pe,Pr,n:real;
etacompf,etacompm,etacompp,etacomp:real;

function Power(X,Y:real):real;
  begin
    Power:=exp(ln(X)*Y);
  end;

BEGIN

writeln;
write('Data Filename?                ');
readln(filename1);
write('Results Filename?             ');
readln(filename2);
write('Heat load Filename?           ');
readln(Filename3);
Write('graph filename?               ');
readln(filename4);
writeln;

assign(infile,filename1);
reset(infile);

assign(outfile,filename2);
rewrite(outfile);

assign(Heatfile,filename3);
reset(Heatfile);

assign(outfile1,filename4);
rewrite(outfile1);
```

```
Readln(infile);Readln(infile);
Readln(infile,Reftype);
Readln(infile,Npot);
For J:= 1 to Npot do
   Readln(infile,Tpot[J]);
Readln(infile,Twamb);
Readln(infile,linegain);
Readln(infile,ancill);
readln(infile);Readln(infile);


close(infile);

Tim[0]:=0.0;
I:=1;

While Tim[I-1] < 24.0 do
        Begin
          Readln(heatfile,Tim[I],Qprod[I,1],Qprod[I,2],Qprod[I,3],
          Qprod[I,4],Qprod[I,5],Eprod[I,1],Eprod[I,2],Eprod[I,3],
          Eprod[I,4],Eprod[I,5],Taworst[I,1],Taworst[I,2],Taworst[I,3],
          Taworst[I,4],Taworst[I,5],Qbase[I,1],Qbase[I,2],Qbase[I,3],
          Qbase[I,4],Qbase[I,5],Ebase[I,1],Ebase[I,2],Ebase[I,3],
          Ebase[I,4],Ebase[I,5]);
          I:=I + 1;
        End;

While not EOF (heatfile) do
          Begin
          Readln(heatfile,Time,Temp1,Temp2,Temp3,Temp4,Temp5,Temp6,Temp7,
          Temp8,Temp9,Temp10,Temp11,Temp12,Temp13,Temp14,Temp15);
          While time > 24.0 do
              begin
              time :=Time - 24.0;
              end;
          I := 1;
          While time > tim[I] do
              begin
              I := I + 1;
              end;
          Qprod[I,1]:=Temp1 + Qprod[I,1];
          Qprod[I,2]:=Temp2 + Qprod[I,2];
          Qprod[I,3]:=Temp3 + Qprod[I,3];
          Qprod[I,4]:=Temp4 + Qprod[I,4];
          Qprod[I,5]:=Temp5 + Qprod[I,5];

          Eprod[I,1]:=Temp6  + Eprod[I,1];
          Eprod[I,2]:=Temp7  + Eprod[I,2];
          Eprod[I,3]:=Temp8  + Eprod[I,3];
          Eprod[I,4]:=Temp9  + Eprod[I,4];
          Eprod[I,5]:=Temp10 + Eprod[I,5];

          If (Taworst[I,1] > Temp11) then
          Taworst[I,1]:=Temp11;
          If (Taworst[I,2] > Temp12) then
          Taworst[I,2]:=Temp12;
          If (Taworst[I,3] > Temp13) then
          Taworst[I,3]:=Temp13;
          If (Taworst[I,4] > Temp14) then
          Taworst[I,4]:=Temp14;
          If (Taworst[I,5] > Temp15) then
          Taworst[I,5]:=Temp15;
          end;

I:=0;
While Tim[I] < 24.0 Do
```

```
      I:=I+1;

For J:=1 to 5 do
      begin
      Qprod[1,J]:=Qprod[I,J];
      Eprod[1,J]:=Eprod[I,J];
      Taworst[1,J]:=Taworst[I,J];
      end;

I:=0;
While tim[I] < 24.0 do
       Begin
       I:=I+1;
       Qgrand[I]:=0.0;
       Egrand[I]:=0.0;
       For J :=1 to Npot do
            Begin
            Qtotal[I,J]:=Qprod[I,J] + Qbase[I,J];
            Etotal[I,J]:=Eprod[I,J] + Ebase[I,J];
            Qgrand[I]:=Qgrand[I] + Qtotal[I,J];
            Egrand[I]:=Egrand[I] + Etotal[I,J];
            end;
       End;

if refType = 717 then
       begin
       a1:=22.11874;
       a2:=2233.8226;
       a3:=244.20;
       b1:=0.00376;
       b2:=0.00012;
       b3:=0.00273;
       alpha:=1.11;
       end
else if refType = 22 then
       begin
       a1:=21.25384;
       a2:=2025.4518;
       a3:=248.94;
       b1:=0.00563;
       b2:=0.00149;
       b3:=0.00398;
       alpha:=0.77
       end;
Tc:= Twamb + 8;

I:=0;
while tim[I] < 24.0 do
      begin
      I:=I+1;
      Qgrand[I]:=Qgrand[I] * linegain;
      Elect[I]:=Egrand[I];
      For J := 1 to Npot do
           begin
           Qtotal[I,J]:=Qtotal[I,J] * linegain;
           Te[I,J]:=Taworst[I,J]-7.0;
           If(Tpot[J] > Te[I,J]) Then
                Te[I,J]:=Tpot[J];
           Pc:=exp(a1-a2/(Tc+a3));
           Pe:=exp(a1-a2/(Te[I,J]+a3));
           x1:=b1*(1+b2*Tc+b3*Te[I,J])*(Tc-Te[I,J]);
           PR:=Pc/Pe;

           if (Te[I,J] >= -25.0) then
              begin
              etacompf:=0.753-0.000948*SQR(PR);
```

```
            n:=1.0;
            end
         else if  (Te[I,J] < -25.0) then
            begin
            etacompf:=0.753-0.000948*PR;
            n:=0.5
            end;

         etacompm:=0.9;
         etacompp:=0.9;
         etacomp:=etacompf*etacompm*etacompp;

         Ecomp[I,J]:=(Qtotal[I,J]*(Tc-Te[I,J]))/((273+Te[I,J])*
               (power((1-alpha * x1),n))*etacomp)*ancill;
        Elect[I]:=Elect[I]+Ecomp[I,J];

        end;
    end;

I:=0;
While(Tim[I] < 24.0) Do
     Begin
     i:=i+1;
     WRITE(OUTFILE,'Time = ',Tim[I]:8:2);

      writeln(outfile,'   Engine room electrical load
      (Elect[I]-Egrand[I]):8:2);

      writeln(outfile);
      writeln(outfile,'                          Non-engineroom electrical load
      Egrand[I]:8:2);

      writeln(outfile);
      writeln(outfile,'                          Total electrical load
      elect[I]:8:2);


      writeln(outfile);
      writeln(outfile,'                          Total heat load
      Qgrand[I]:8:2);



      write(outfile1,tim[I]:8:2,elect[I]:8:2,(Elect[I]-Egrand[I]):8:2,
      Egrand[I]:8:2,Qgrand[I]:8:2);

      writeln(outfile);
      writeln(outfile);
      writeln(outfile,'                          Pot1      Pot2      Pot3      Pot4
ot5');
              writeln(outfile,'                          Engineroom electrical l
d by Pot           ');

     write(outfile,'                  ');
     For J:= 1 to Npot do
         begin
         write(outfile,Ecomp[I,J]:8:2);
         write(outfile1,Ecomp[I,J]:8:2);
         end;
         writeln(outfile);
         writeln(outfile);
      writeln(outfile,'                              Total heat load by Pot');

     write(outfile,'                  ');
     For J:= 1 to Npot do
         begin
```

```
            write(outfile,Qtotal[I,J]:8:2,Taworst[I,J]:8:2,Te[I,J]:8:2);
            write(outfile1,Qtotal[I,J]:8:2);
            end;
            writeln(outfile);
            writeln(outfile);
            writeln(outfile);
            writeln(outfile1);
        End;

    flush(outfile);
    flush(outfile1);
    close(outfile);
    close(outfile1);

    end.
```

APPENDIX D3.1 - ENGINEROOM USER DATA FILE

```
{engine-room}

   717            {type of refrigerant, R717 or R22}
     2            {number of operational pots}
   -10            {Pot operating Temperature}
   -30
    20            {ambient wet bulb temperature}
    1.05          {suction line heat gain factor}
    1.1           {engineroom ancillary load}
```

APPENDIX D3.2 - ENGINEROOM OUTPUT DATA FILE #2

0	249.31	164.51	84.8	365.33	35.79	128.72	122.64	242.69
0.25	247.99	163.19	84.8	362.27	35.42	127.77	121.36	240.91
0.5	246.73	161.93	84.85	359.36	35.09	126.84	120.21	239.15
0.75	245.49	160.64	84.85	356.39	34.73	125.91	119	237.39
1	244.2	159.35	84.85	353.43	34.38	124.97	117.8	235.63
1.25	244	158.69	85.31	352.4	34.53	124.15	118.31	234.09
1.5	242.85	157.54	85.31	349.71	34.19	123.34	117.16	232.55
1.75	241.7	156.39	85.31	347.02	33.86	122.53	116	231.02
2	240.56	155.25	85.31	344.38	33.53	121.72	114.89	229.49
2.25	239.94	154.39	85.55	342.66	33.47	120.92	114.66	228
2.5	238.8	153.25	85.55	340.02	33.15	120.11	113.57	226.45
2.75	237.67	152.12	85.55	337.4	32.83	119.28	112.5	224.9
3	236.61	151.06	85.55	334.94	32.53	118.53	111.46	223.48
3.25	236.44	150.47	85.97	334.06	32.68	117.79	111.96	222.1
3.5	235.36	149.41	85.97	331.6	32.38	117.03	110.94	220.66
3.75	234.36	148.39	85.97	329.22	32.09	116.3	109.95	219.27
4	378.2	251.32	126.88	682.98	135.74	115.58	465.07	217.92
4.25	377.41	250.43	126.98	681.08	135.58	114.85	464.54	216.54
4.5	376.43	249.45	126.98	678.79	135.3	114.15	463.57	215.22
4.75	375.52	248.52	127	676.62	135.03	113.49	462.64	213.98
5	375.01	247.8	127.21	675.22	135	112.79	462.56	212.67
5.25	374.04	246.83	127.21	673	134.74	112.09	461.65	211.34
5.5	373.33	246	127.33	671.18	134.59	111.41	461.13	210.05
5.75	372.35	245.02	127.33	668.96	134.34	110.68	460.27	208.69
6	370.21	248.21	122	656.56	142.05	106.16	456.71	200.15
6.25	402.93	214.58	188.35	529.93	81.35	133.23	278.73	251.2
6.5	402.01	213.61	188.4	527.66	81.06	132.55	277.74	249.92
6.75	401.09	212.65	188.44	525.33	80.73	131.92	276.6	248.72
7	432.65	238.46	194.19	580.04	84.66	153.79	290.07	289.97
7.25	435.3	241.08	194.22	584.46	84.32	156.76	298.9	295.56
7.5	434.37	240.01	194.36	582.1	84.09	155.92	288.12	293.98
7.75	433.15	238.79	194.36	579.23	83.73	155.06	286.68	292.35
8	438.49	244.13	194.36	598.67	89.94	154.18	308.16	290.7
8.25	437.18	242.82	194.36	595.75	89.52	153.3	306.71	289.04
8.5	435.41	241.27	194.14	591.79	88.64	152.43	304.39	287.4
8.75	434.35	240.12	194.23	589.16	88.54	151.59	303.34	285.81
9	450.23	256	194.23	621.59	90.16	165.84	306.91	312.68
9.25	452.13	257.71	194.42	624.48	89.95	167.76	306.18	316.3
9.5	450.45	256.15	194.3	620.69	89.39	166.77	306.25	314.43
9.75	452.96	258.54	194.32	630.41	92.77	165.77	317.86	312.55
10	444.96	254.74	190.24	618.96	89.99	164.75	306.33	310.63
10.25	445.27	255	190.27	621.41	91.27	163.73	312.7	308.71
10.5	443.03	253.1	189.93	616.48	90.38	162.72	309.68	306.8
10.75	453.8	263.68	189.92	641.28	93.29	170.59	319.64	321.64
11	455.8	265.87	189.93	646.93	94.53	171.34	323.87	323.05
11.25	455.03	264.9	190.13	645.31	94.67	170.23	324.34	320.96
11.5	453.18	263.15	190.03	641.04	94.02	169.13	322.15	318.68
11.75	462.18	272.24	189.94	663.29	97.35	174.89	333.53	329.75
12	461.12	272.1	189.02	662.12	96.76	175.34	331.53	330.59
12.25	459.79	270.98	188.81	660.1	96.82	174.16	331.73	328.38
12.5	458.05	269.24	188.81	655.94	96.25	172.99	329.77	326.16
12.75	463.04	274.32	188.72	664.48	95.58	178.74	327.48	337
13	463.05	274.33	188.72	663.65	95.03	179.3	325.59	338.06
13.25	463.43	274.9	188.53	667.44	96.79	178.11	331.62	335.82
13.5	463.09	274.65	188.44	666.41	97.72	176.93	334.82	333.58
13.75	461.22	272.83	188.39	663.99	97.08	175.75	332.63	331.36
14	462.33	274	188.33	670.04	99.57	174.43	341.17	328.87
14.25	466.86	278.76	188.1	678.56	99.28	179.48	340.16	338.4
14.5	466.67	278.59	188.08	677.54	98.83	179.76	338.61	338.93
14.75	464.57	276.61	187.96	672.63	98.07	178.54	336	336.63
15	468.71	280.8	187.91	680.35	97.95	182.85	335.6	344.75
15.25	468.17	280.26	187.91	678.25	97.25	183.01	333.19	345.06
15.5	466.3	278.39	187.91	673.8	96.64	181.75	331.11	342.69
15.75	463.89	276.23	187.66	668.41	95.8	180.43	328.22	340.19
16	465.89	278.31	187.58	675.33	97.74	180.57	334.87	340.46
16.25	473.05	285.47	187.58	687.83	97.09	188.39	332.64	355.19
16.5	470.36	282.96	187.4	681.42	96	186.96	328.92	352.5
16.75	468.01	280.75	187.26	676.15	95.29	185.46	326.48	349.67
17	380.18	259.29	120.89	633.73	94.01	165.29	322.09	311.64
17.25	339.14	218.25	120.89	493.14	52.99	165.26	181.56	311.59
17.5	337.01	216.14	120.87	488.12	52.32	163.82	179.25	308.88
17.75	334.83	214.03	120.8	483.21	51.71	162.32	177.16	306.05
18	332.12	211.32	120.8	476.1	50.41	160.92	172.7	303.4
18.25	301.36	209.31	92.05	471.36	49.79	159.52	170.58	300.77
18.5	298.67	206.82	91.85	464.93	48.67	158.15	166.75	298.18
18.75	296.75	204.91	91.84	460.5	48.13	156.78	164.9	295.6
19	283.7	196.93	84.77	448.18	47.45	151.49	162.56	285.62
19.25	281.74	197	84.74	443.73	46.92	150.08	160.75	282.98
19.5	279.33	194.59	84.74	437.52	45.84	148.75	157.06	280.47
19.75	277.35	192.61	84.74	432.63	45.09	147.52	154.49	278.14
20	275.58	190.87	84.71	428.6	44.6	146.27	152.82	275.78
20.25	273.42	188.71	84.71	423.03	43.63	145.08	149.49	273.55
20.5	271.37	186.66	84.71	417.82	42.76	143.9	146.51	271.31
20.75	269.94	185.15	84.79	414.15	42.23	142.92	144.69	269.46
21	268.19	183.43	84.76	410.2	41.77	141.66	143.11	267.09
21.25	266.26	181.5	84.76	405.56	41.12	140.38	140.88	264.68
21.5	264.56	179.8	84.76	401.5	40.57	139.23	138.99	262.51
21.75	262.97	178.21	84.76	397.81	40.12	138.09	137.46	260.36
22	261.32	176.59	84.73	394.11	39.69	136.9	135.99	258.12
22.25	259.22	174.49	84.73	388.65	38.72	135.78	132.65	256
22.5	257.66	172.93	84.73	385.02	38.28	134.65	131.15	253.88
22.75	256.15	171.42	84.73	381.55	37.87	133.54	129.76	251.79
23	254.63	169.9	84.73	378.07	37.47	132.43	128.38	249.69
23.25	253.15	168.42	84.73	374.45	36.93	131.48	126.55	247.91
23.5	251.94	167.14	84.8	371.45	36.55	130.59	125.22	246.23
23.75	250.62	165.82	84.8	368.36	36.17	129.65	123.91	244.45
24	249.31	164.51	84.8	365.33	35.79	128.72	122.64	242.69