

Ref. no.	: 88-054	Title	MODELLING TEMPERATURE DISTRIBUTION IN
File no.	: 8725-19335		PRODUCTS MOVING IN COLD CHAINS
Publ. no.	: CB/054		
Date	: February 1988		

Publication

Author(s):
R.J.M. van Gerwen

Presented at the I.I.F.-I.I.R. meeting of
commissions B1, B2, C2, D1, D2, D3 -
Wageningen (The Netherlands) - 1988.

MODELLING TEMPERATURE DISTRIBUTION IN PRODUCTS MOVING IN COLD CHAINS

R.J.M. van Gerwen

Department of Heat and Refrigeration Technology
The Netherlands organization for applied scientific research TNO
Apeldoorn (The Netherlands)

1. INTRODUCTION

Computer simulation is a well-known technique for the assessment of the thermal behaviour of products moving in cold chains.

The computer package BERTEM has been developed for computations of the time dependent temperature distribution in inhomogeneous solids and fluid flows of arbitrary geometry.

In this paper a description of this package is presented and some successful applications are mentioned. The use of the BERTEM package for computations of the temperature distributions in pig carcasses is described in detail.

The scope of this paper has been restricted to the technical aspects. The economic aspects have already been discussed by Moerman [7]. In general terms the tools for accurate computations of the temperature distribution in products moving in cold chains can contribute to the optimization of the cold chain in economic respect.

2. COMPUTER PACKAGE "BERTEM"

2.1 Background

The computer package BERTEM has been based on the finite element method (FEM); solid and fluid flow are divided into elements of arbitrary shape. This technique has been discussed in detail by Comini [1] and Cleland [2], [3].

FEM is a very flexible and universal method: inhomogeneous multi-dimensional shapes of irregular geometry can be handled. An other well-known method based on finite differences (FDM) is limited by practical considerations to use for one-dimensional and regular multi-dimensional shapes where evenly spaced grids can be used. However, the flexibility of FEM can lead to excessive computation costs. In the case of BERTEM this disadvantage is countered thanks to the adaptation to the purpose of the computations, which leads to a reduction of computation time and costs. Thus BERTEM is more suited for those calculations than general purpose computer packages like PHOENICS (Spalding [4]).

2.2 Thermal model

The solid and/or fluid flow is divided into elements of an arbitrary geometry (one, two or three dimensions).

An element can represent a thermal mass, a flow part, a junction of flows, a boundary or an interpolation of temperatures of neighbour-elements.

The elements can be characterised by a heat capacity, an internal heat generation or a latent heat, temperature dependent if required.

All elements are linked by connectors between the central points of the elements, representing the heat or fluid flow between them.

The computation of all the data are completed by the use of an automatic stable integration method, i.e. a combination of Euler-Runge, Adams-Moulton and an extrapolation method. The choice of the integration time interval will only affect the accuracy of the results.

The boundary conditions and computation time interval can be adjusted and instantaneous results can be obtained during computation in an interactive session.

The program package has been written in FORTRAN 77 language for use on mini computers and mainframes. Recently, a version for use on an IBM 3030/31 computer has been developed.

3 APPLICATIONS

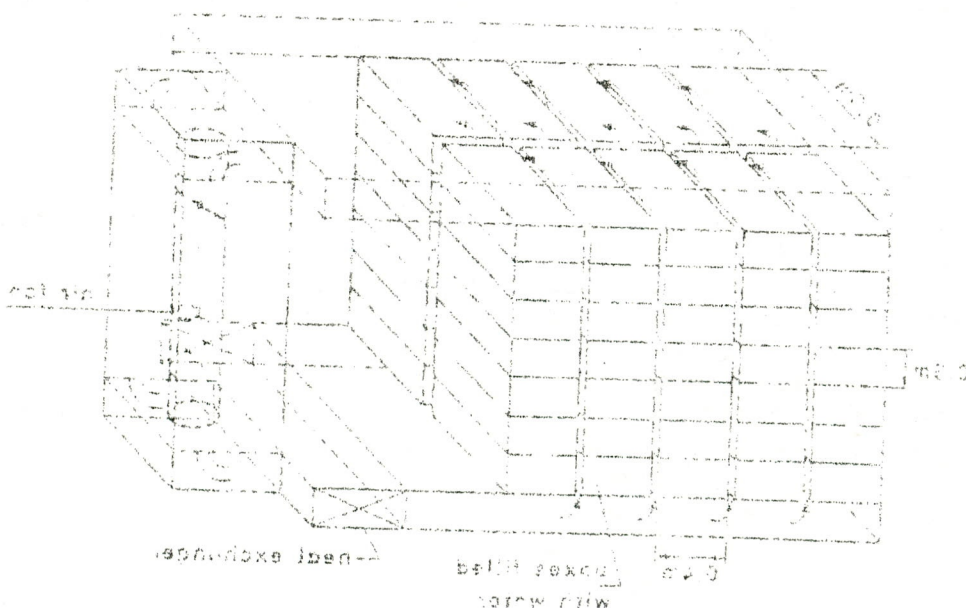
3.1 General applications

The computer package RESTEM has been successfully used for a wide range of thermal problems:

- capacity and temperature distribution of soil heat exchangers for seasonal storage
- heat storage
- assessment and optimization of floor heating systems
- assessment of the heating system of an office
- capacity of the heating system in the walls of brick kilns and stoves
- temperature distribution in the walls of brick kilns and stoves

3.2 Applications in refrigeration engineering

RESTEM has also been used for several calculations in the field of refrigeration engineering. In this context investigations have been carried out into ventilation systems. The usefulness of the package for this application has been investigated by comparing computations and measurements for a well-defined test-case. Figure 1 shows a composite sketch of boxes filled with water and with forced ventilation through the drawers. In figure 2, experimental as well as computed results are shown. There proved to be a satisfactory agreement between them.



2.3 Computation method

The temperatures of all the elements are computed by the use of fundamentally stable integration methods, i.e. a combination of Dufort-Frankel, Crank-Nicholson and an extrapolation method, so the choice of the computation time interval will only affect the accuracy of the results.

If desired, the boundary conditions and computation time interval can be adjusted and intermediate results can be obtained during computations in an interactive session.

The program package has been written in the FORTRAN 77 language for use on mini computers and mainframes. Recently, a version for use on an IBM PC/XT/AT compatible personal computer has been developed.

3. APPLICATIONS

3.1 General applications

The computer package BERTEM has been successfully used for quite a range of thermal problems:

- capacity and temperature distribution of soil heat exchangers for seasonal thermal storage;
- assessment and optimization of floor heating systems;
- capacity of the heating system of an oil tank;
- temperature distribution in the walls of brick kilns and stoves.

3.2 Applications in refrigeration engineering

BERTEM has also been used for several calculations in the field of refrigeration engineering.

In this context investigations have been carried out into ventilated cargoes. The usefulness of the package for this application has been investigated by comparing computations and measurements for a well-defined test-case.

Figure 1 shows a composite stack of boxes filled with water and with forced ventilation through the crevices.

In figure 2, experimental as well as computed results are shown. There proved to be a satisfactory agreement between them.

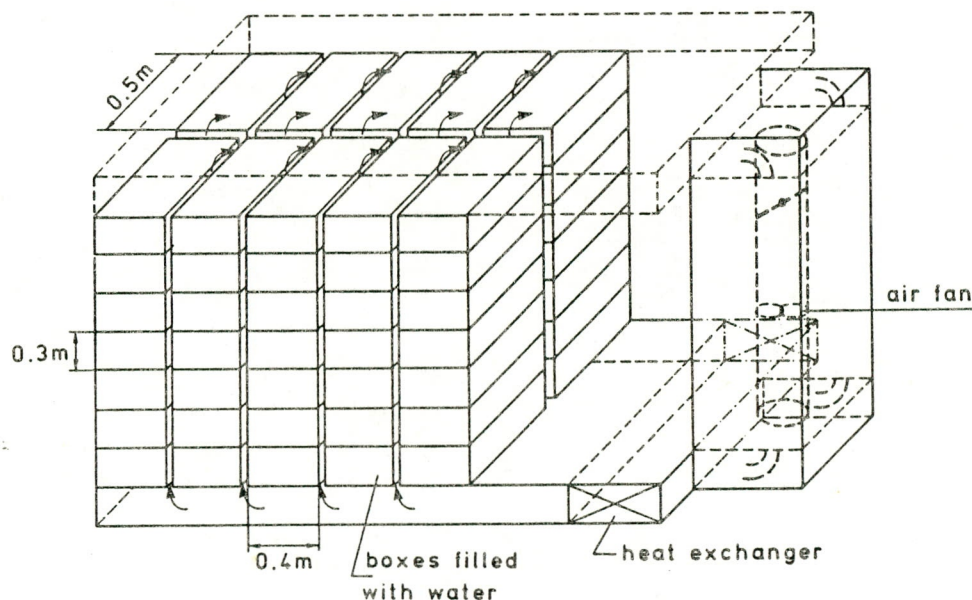


Fig. 1 - Composite stack of boxes.

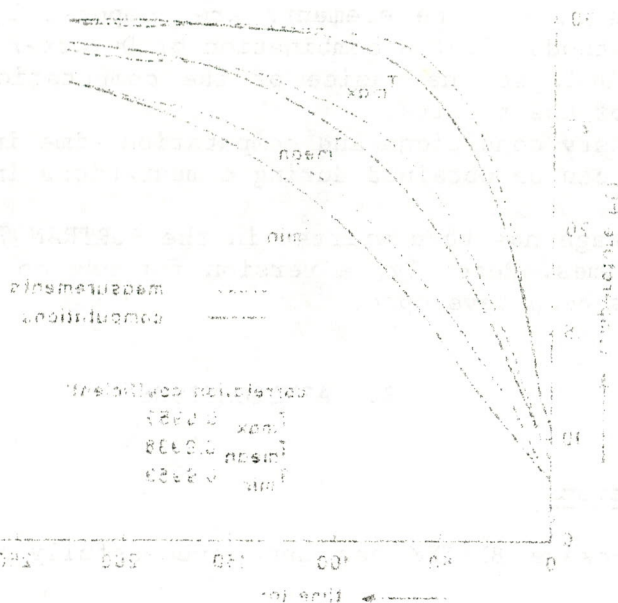


Fig. 2 - Measured and computed temperatures in the boxes of a composite beam. Air temperature jump from 15°C to 30°C.

Van de Kree (5) has described computation of the temperature distribution in ventilated carcases in relation to the air circulation number. BERTHM proved to be a useful tool.

A comparison has been made between BERTHM and an other computer program, based on the Finite Difference Method (FDM), called (6). The cooling- and freezing times of a homogeneous rectangular brick filled with water have been computed. The computed results are summarized in Table I. The differences between the results of both of the computer programs are within 1%. However, the computation by BERTHM has taken 1% of the time needed by the FDM program.

TABLE I
Comparison of computer programs

	BERTHM	FDM
computation time	200	1400
temperature of coldest element (°C)	-17.3	-17.3
change in energy content	558,000	550,000
freezing time (h) coldest element	3130	3150
reaches 25°C	1400	1400
cooling time (h) coldest element	40	25
calculation time interval	40	25

- number of elements: 123 (1/3 of a brick)
 - thermal conductivity and specific heat capacity of water
 - brick dimensions: 1.1 x 0.1 m²
 - surface heat transfer coefficient: 30 W/m²K
 - initial temperature: 20°C
 - ambient air temperature: -20°C
 - a shorter time interval or extension of the number of elements did not affect the results significantly.

In the above paper the application of BERTHM for computation of the temperature distribution in a single brick is discussed in detail.

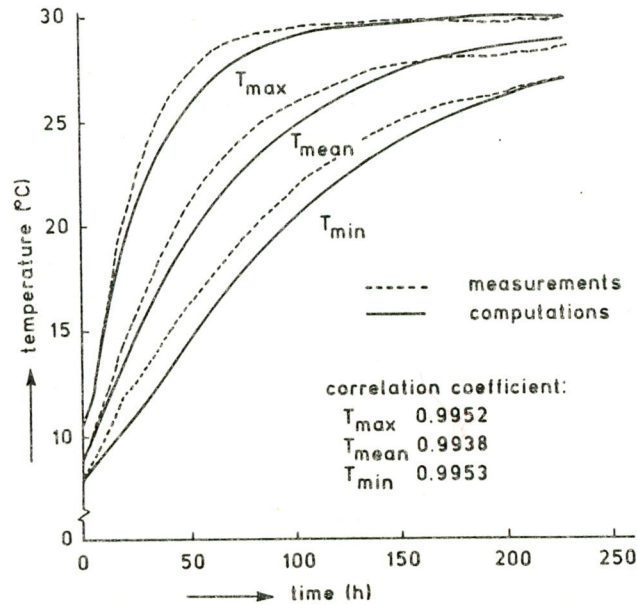


Fig. 2 - Measured and computed temperatures in the boxes of a composite stack. Air temperature jump from 7.5°C to 30.5°C.

Van de Ree [5] has described computations of the temperature distribution in ventilated cargoes in relation to the air circulation number. BERTEM proved to be a useful tool.

A comparison has been made between BERTEM and an other computer program, based on the Finite Difference Method (FDM), Cleland [6]. The cooling- and freezing times of a homogeneous rectangular brick filled with water have been computed. The computed results are summarized in Table I. The differences between the results of both of the computer programs are within 1%. However, the computation by BERTEM has taken 14% of the time needed by the FDM program.

TABLE I
Comparison of computer programs

	BERTEM	FDM
calculation time interval (s)	40	25
cooling time (hottest element reaches 25°C) (s)	2400	2400
freezing time (hottest element reaches -5°C) (s)	21280	21500
change in energy content (J)	568,000	570,000
temperature of coldest element (°C)	-17.2	-17.9
computation time (s)	200	1400

- number of elements: 125 (1/8 of a brick)
- thermal conductivity and specific heat capacity of water
- brick dimensions: 0.1 x 0.1 x 0.1 m³
- surface heat transfer coefficient: 30 Wm⁻²K⁻¹
- initial temperature : 50°C
- ambient air temperature: -20°C
- a shorter time interval or extension of the number of elements did not affect the results significantly

In the next chapter the application of BERTEM for computations of the temperature distribution in slaughtered pigs is discussed in detail.

4.1 Background

According to the EC-regulations for fresh meat, carcasses shall be chilled after slaughter to an internal temperature of 7°C or lower before being transported to other countries in the Common Market. The aim of the investigation was to study the influence of transport on the temperature distribution and bacteriological condition of half pig carcasses before the internal temperature reaches 7°C . Moreover, the conditions can be formulated under which such a transport could be allowed to be carried out taking the required hygienic quality of the meat into account. These investigations have been carried out in co-operation with IMV-GIVO Food Technology Institute, Wageningen Centre for Meat Technology and are described in detail by Noorman [7].

The thermal investigations consisted of the construction of a finite element model of half a pig carcass as a part of the BETHEM computer package, temperature measurements during several test transports in order to validate the model and comparisons with BETHEM for a lot of storage and transport cases. In the next paragraphs will be discussed in more detail.

4.2 Model set up

A finite element model of half a pig carcass has been designed by dividing the carcass in 318 cubic elements of $5 \times 5 \times 5 \text{ cm}^3$. Three types of elements have been used: bone, fat and meat with corresponding thermal properties. The special geometry of the computation model has been determined by cutting a real carcass into a 5 cm thickness (see figure 3).

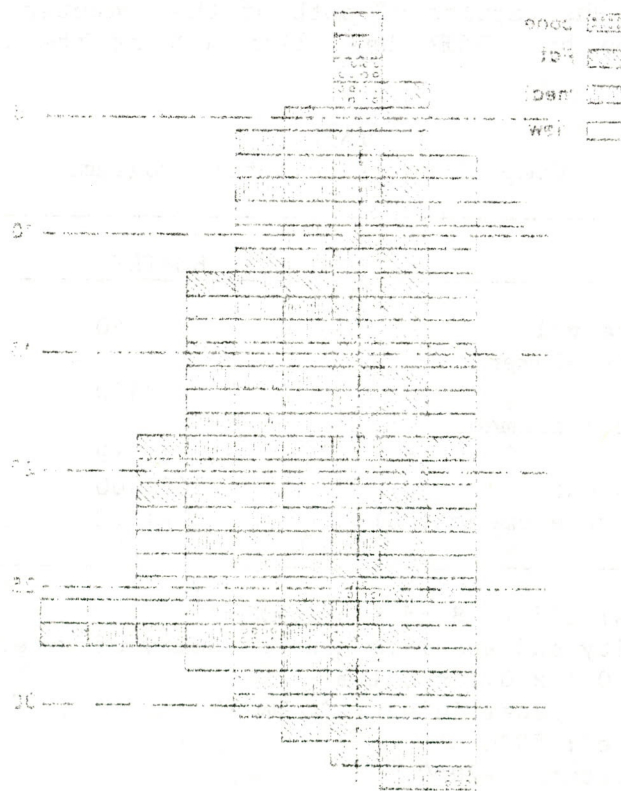


Fig. 3. Cross section of carcass model.

4. TEMPERATURE DISTRIBUTION IN SLAUGHTERED PIGS

4.1 Background

According to the EC-regulations for fresh meat, carcasses shall be chilled after slaughter to an internal temperature of 7°C or lower before being transported to other countries in the Common Market. The aim of the investigations was to study the influence of transport on the temperature distribution and bacteriological condition of half pig carcasses before the internal temperature reaches 7°C. Moreover the conditions had to be formulated under which such a transport could be allowed to be carried out taking the required hygienic quality of the meat into account. These investigations have been carried out in co-operation with TNO-CIVO Food Technology Institute, Netherlands Centre for Meat Technology and are described in detail by Moerman [7].

The thermal investigations consisted of the construction of a finite element model of half a pig carcass as a part of the BERTEM computer package, temperature measurements during several test transports in order to validate the model and computations with BERTEM for a lot of storage and transport cases. In the next paragraphs this will be discussed in more detail.

4.2 Model set up

A finite element model of half a pig carcass has been designed by dividing the carcass in 338 cubic elements of 5 x 5 x 5 cm³. Three types of elements have been used: bone, fat and meat with corresponding thermal properties. The spacial geometry of the computation model has been determined by cutting a real carcass into slabs of 5 cm thickness (see figure 3).

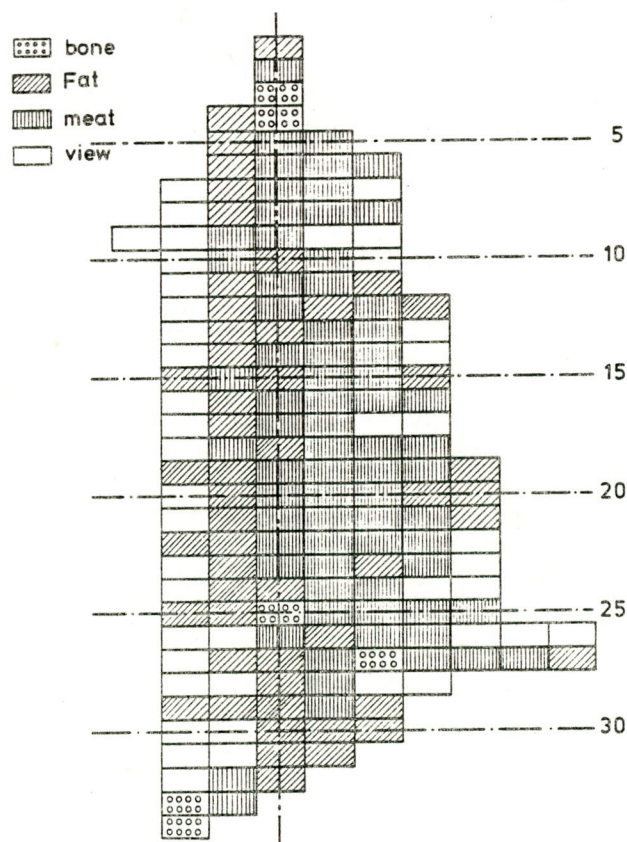


Fig. 3 - Cross section of carcass model.

Flow and boundary elements represent the airflow around the carcass.

The design of such a model as a rather than computing ability; on the other hand the computation with time and position dependent initial and boundary values are very easy to carry out.

The carcass model has been incorporated in the BERTIM package. Combined with input concerning initial and boundary values, the time dependent temperature distribution, heat content and the heat emission of the pig carcass are computed.

4.3 Experimental validation

The temperature distribution in a pig carcass has been measured during a large part of the cold chain. An example of the experimental results as well as the computed results for an identical case are presented in Figure 4. In Figure 5 the measured and calculated temperatures are compared. The results show a good agreement and justify the usefulness for other computations.

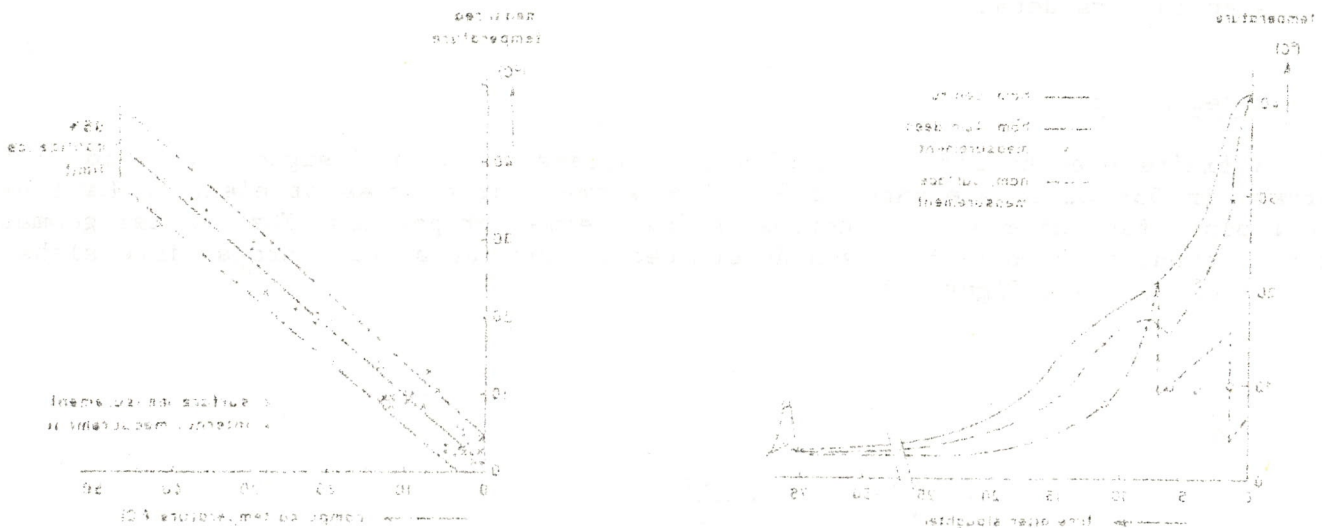


Fig. 4 - Comparison of computed and measured temperatures for a real case.
Fig. 5 - Relation between computed and measured values.

4.4 Computations and results

The temperature distribution in pig carcasses and the related heat emission have been computed for a range of practical cases with transport before and after the internal temperature has reached 7°C. The computations show what time, air temperature, air velocity and refrigerating capacity are required during the successive phases of the cold chain, to obtain the desired time-temperature course in a pig carcass. As an overall result of the study, the conditions have been determined to allow transport of pig carcasses before the internal temperature reaches 7°C. These conditions have been accepted by the Dutch authorities for inland transport. Computations with the BERTIM package form part of the procedure for granting a license. In this case, the use of computer simulation leads to a drastic reduction of time and costs because of a strong reduction of repeated measurements and the possibility of optimizing the cold chain.

4.5 Suggestions for other applications

The scheme described in the previous paragraphs is also applicable for other products. The method is especially suited for computations of temperature distribution in homogeneous and irregular shaped bodies such as sheep and bovine carcasses, poultry or fish and with fruit or vegetables.

The design of such a model is a rather time-consuming affair; on the other hand the computations with time and position dependent initial and boundary values are very easy to carry out.

The carcass model has been incorporated in the BERTEM package. Combined with input concerning initial and boundary values, the time dependent temperature distribution, heat content and the heat emission of the pig carcass are computed.

4.3 Experimental validation

The temperature distribution in a pig carcass has been measured during a large part of the cold chain. An example of the experimental results as well as the computed results for an identical case are presented in figure 4.

In figure 5 the measured and calculated temperatures are compared. The results show a good agreement and justify the usefulness for other computations.

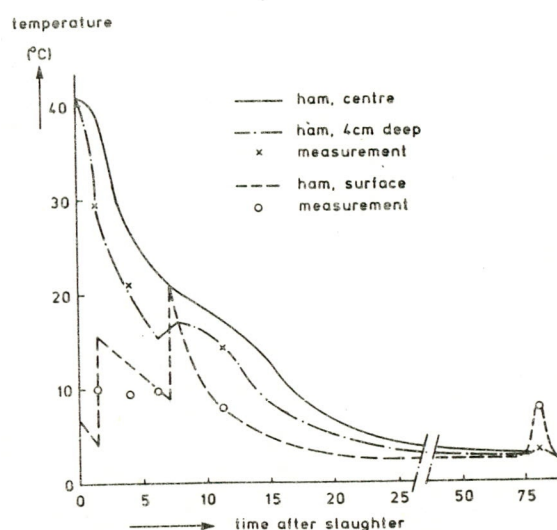


Fig. 4 - Computations and measurements for a test-case.

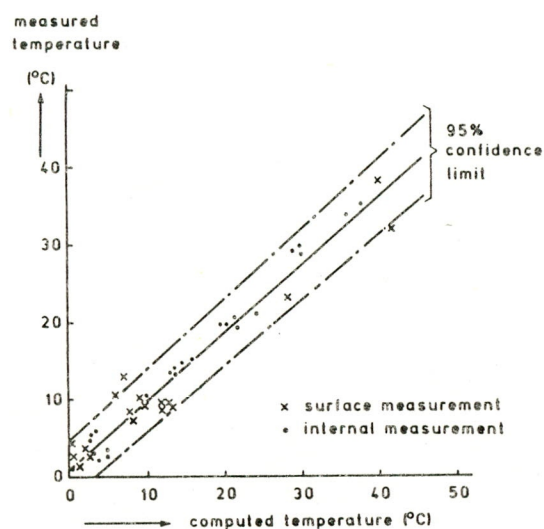


Fig. 5 - Relation between computed and measured values.

4.4 Computations and results

The temperature distribution in pig carcasses and the related heat emission have been computed for a range of practical cases with transport before and after the internal temperature has reached 7°C.

The computations show what time, air temperature, air velocity and refrigerating capacity are required during the successive phases of the cold chain, to obtain the desired time-temperature course in a pig carcass.

As an over-all result of the study, the conditions have been determined to allow transport of pig carcasses before the internal temperature reaches 7°C.

These conditions have been accepted by the Dutch authorities for inland transport. Computations with the BERTEM package form part of the procedure for granting a licence. In this case, the use of computer simulation leads to a drastic reduction of time and costs because of a strong reduction of required measurements and the possibility of optimizing the cold chain.

4.5 Suggestions for other applications

The scheme described in the previous paragraphs is also applicable for other products. The method is eminently suited for computations of temperature distributions in inhomogeneous and irregular shaped bodies such as sheep and bovine carcasses, poultry or pallets with fruit or vegetables.

5. CONCLUSIONS

- The computer package BERTEM has been developed for computations of the time dependent temperature distribution in inhomogeneous solids and fluid flows of arbitrary shape.
- The package has been successfully applied for a range of thermal problems.
- In the field of refrigeration engineering BERTEM has been used for computations related to ventilated cargoes and cooling or freezing of solids, surrounded by fluid flow (e.g. air).
- The computer package has showed to be a very appropriate tool for the computation of temperature distributions in pig carcasses. The method is eminently suited for computations and irregular shaped bodies such as sheep and bovine carcasses, poultry or pallets with fruit or vegetables.

REFERENCES

- [1] G. Comini et al;
The finite element method in refrigeration engineering;
Int. Journal of Refrigeration (1978), 2.
- [2] D.J. Cleland et al;
Prediction of rates of freezing, thawing or cooling in solids of arbitrary shape using the finite element method;
Int. Journal of Refrigeration (1984), 1.
- [3] D.J. Cleland et al;
Prediction of freezing and thawing times for multi-dimensional shapes by numerical methods;
Int. Journal of Refrigeration (1987), 1.
- [4] D.B. Spalding;
General purpose computer program for multi-dimensional 1- and 2-phase flow;
Journal of Mathematics and computers in Simulation (1981), pp. 267-276.
- [5] H. van de Ree et al;
Prediction of temperature distributions in cargoes with the aid of a computer program using the method of finite elements;
IIF-IIR-commission D2, Wageningen, 1974-2.
- [6] A.C. Celand;
RADS - a computer package for refrigeration analysis, design and simulation;
Int. Journal of Refrigeration (1985), 11.
- [7] P.C. Moerman;
Experience with quick chilling and transport of pig carcasses;
I.I.F.-I.I.R.-commission C2, Bristol, 1986-3.

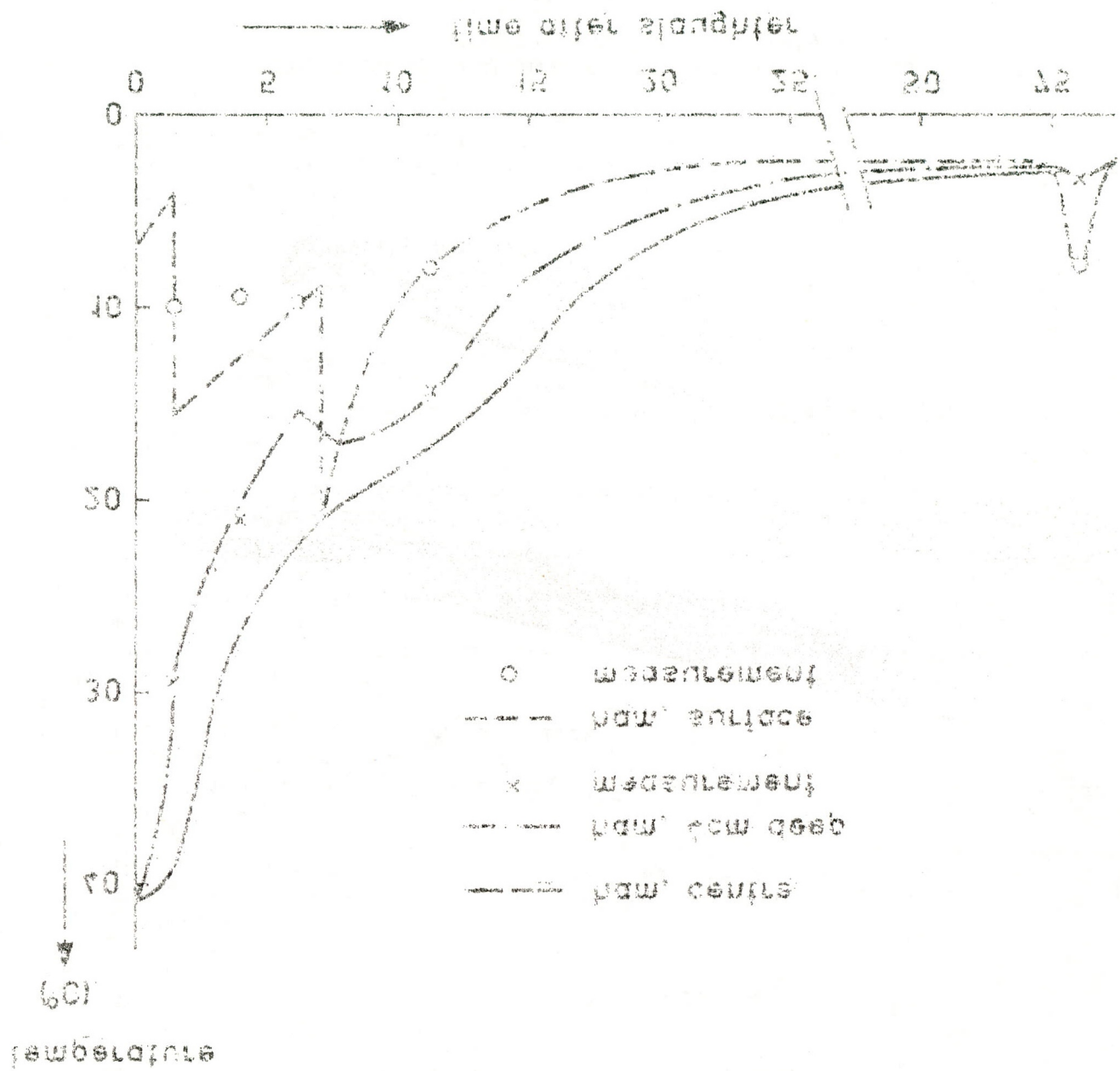
MODELER LA RÉPARTITION DES TEMPÉRATURES DANS LES PRODUITS MOUVANT EN CHAÎNE FRIGORIFIQUE

RÉSUMÉ: Le programme d'ordinateur BERTEM a été développé pour calculer la répartition des températures dans des solides de géométrie quelconque avec des propriétés variables.

Le programme s'appuie sur la méthode des éléments finis.

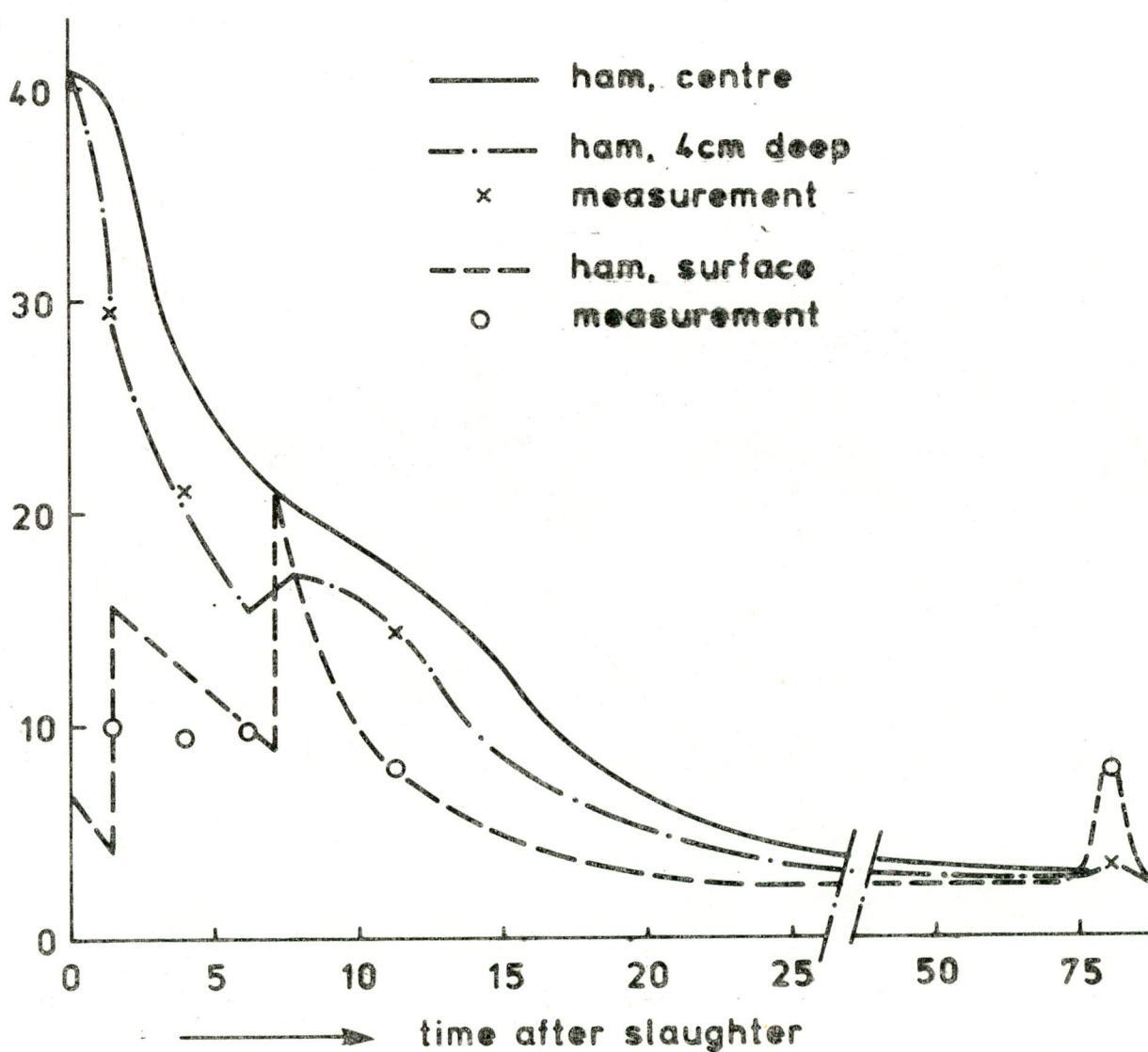
On examine les caractéristiques du programme et on les illustre avec plusieurs exemples d'application.

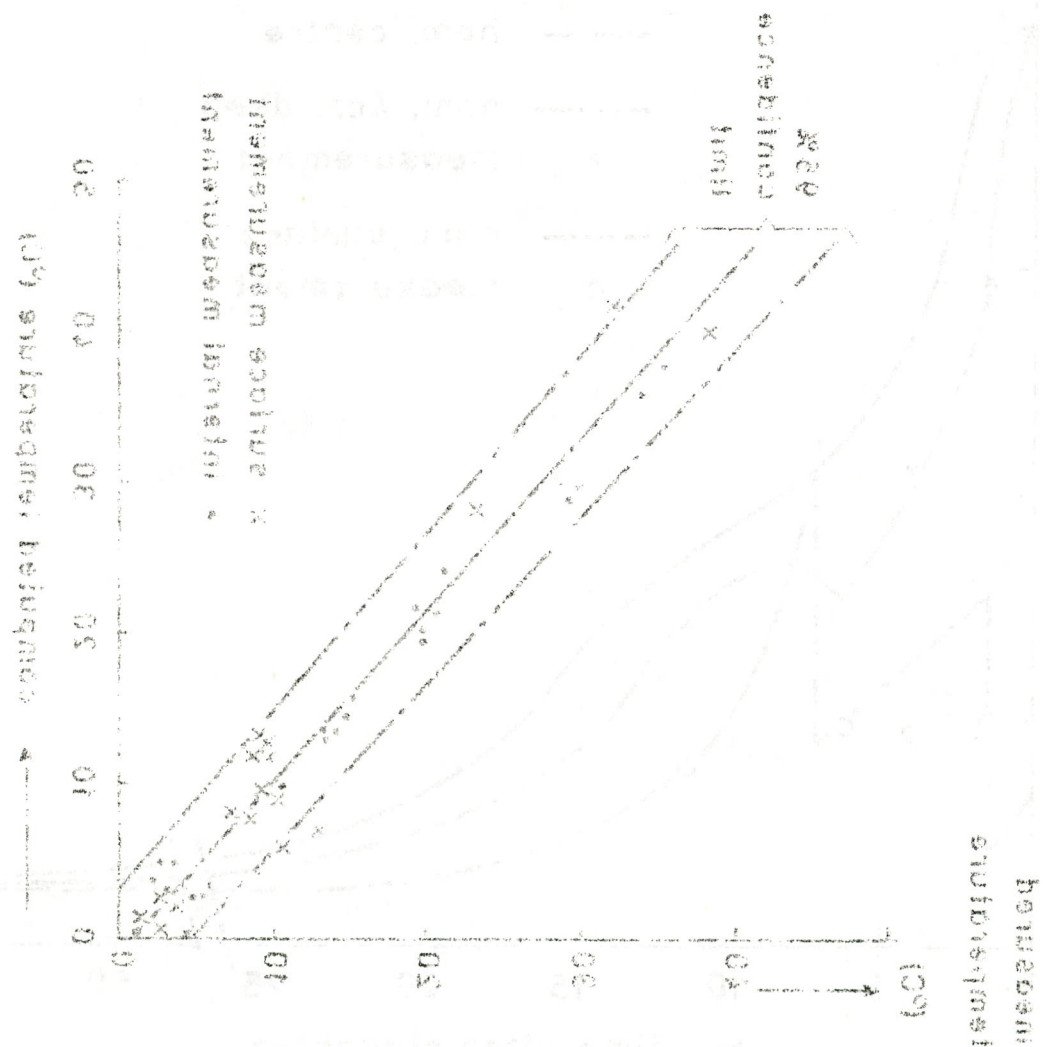
On décrit au détail l'usage du programme BERTEM pour calculer la répartition des températures dans les carcasses des cochons.



temperature

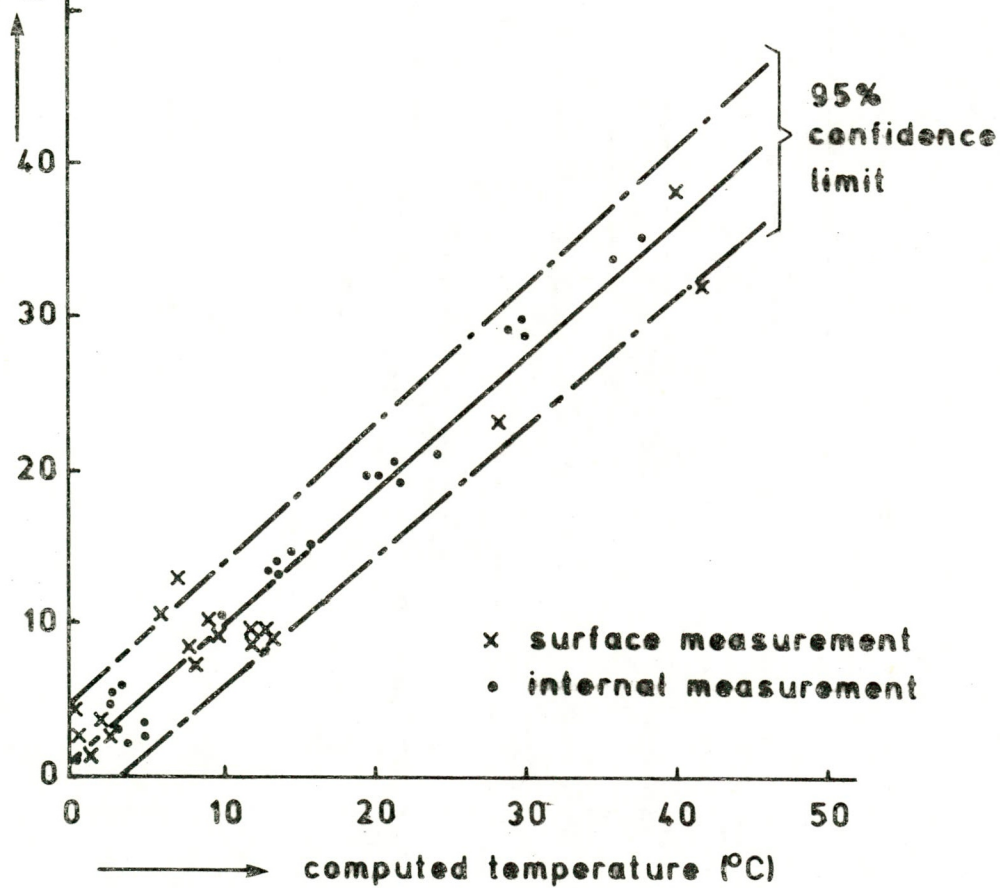
(°C)

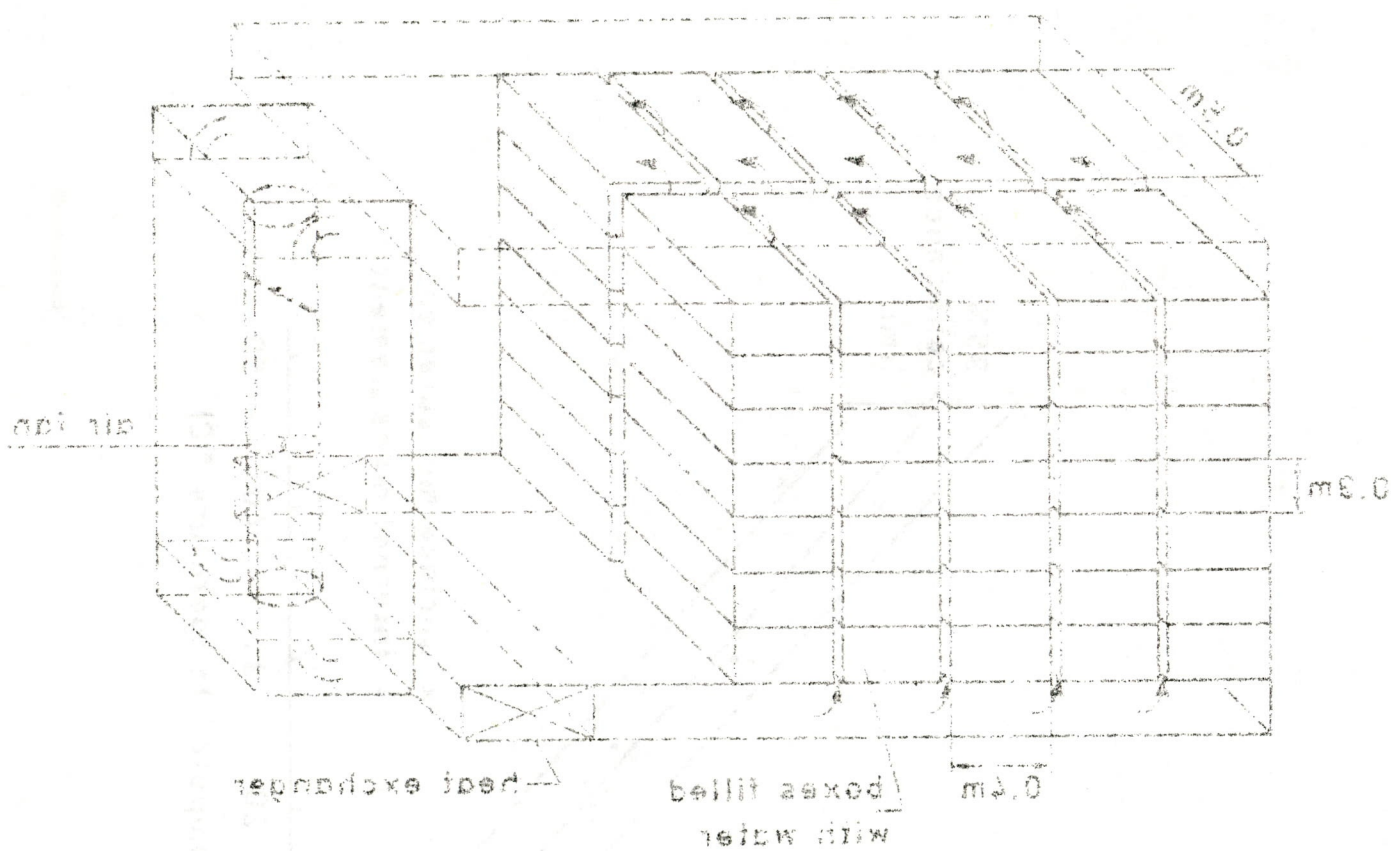


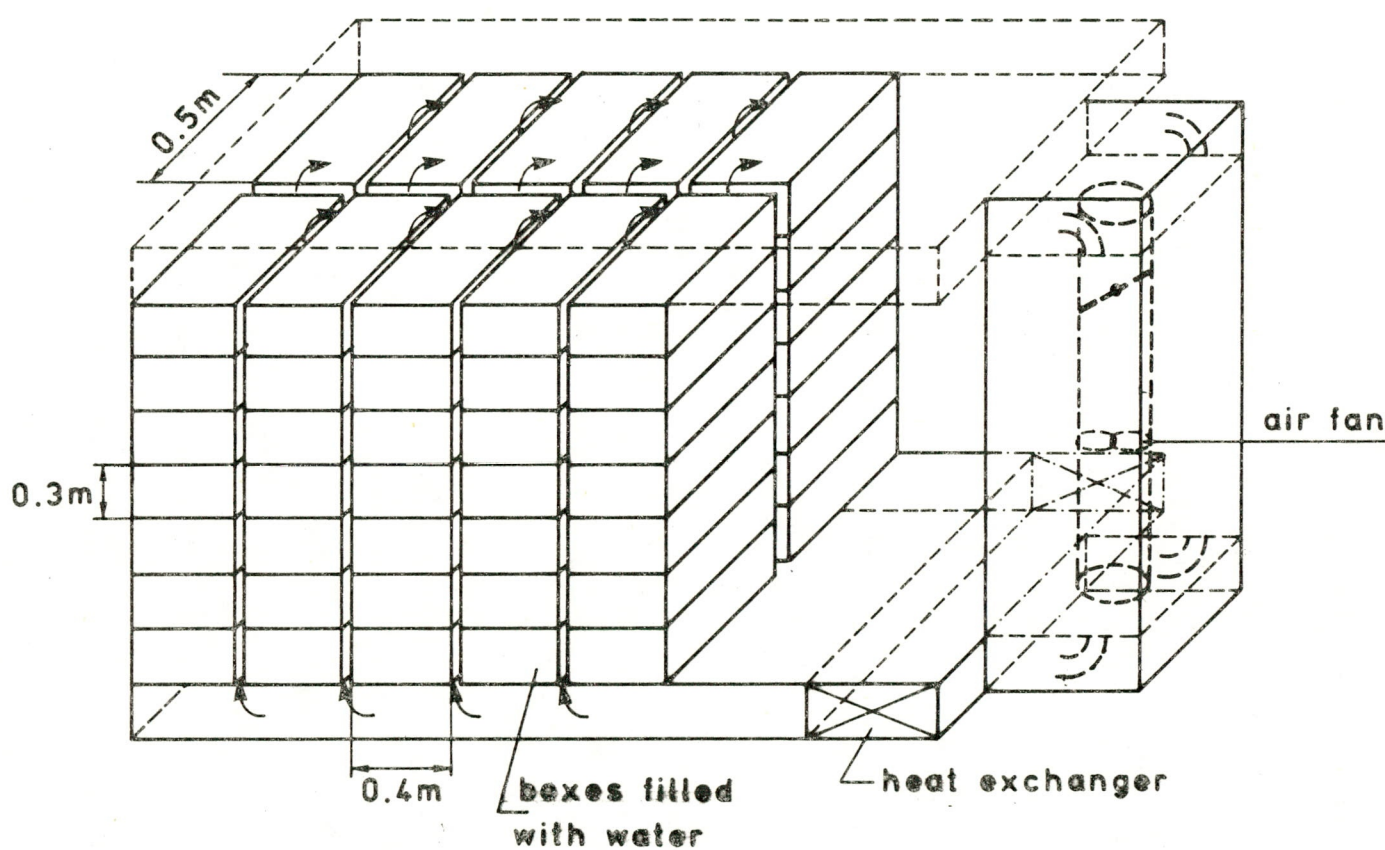


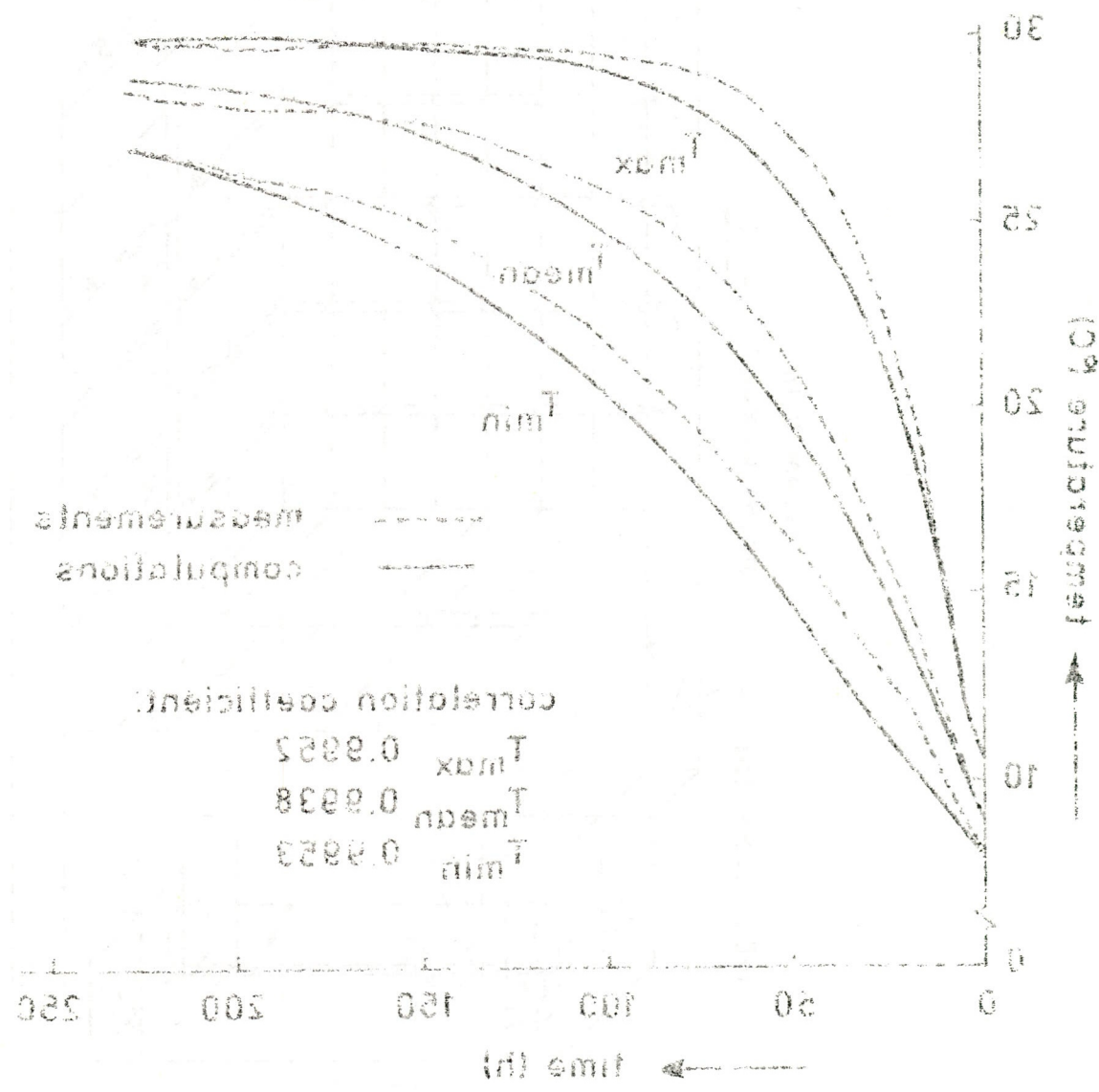
measured
temperature

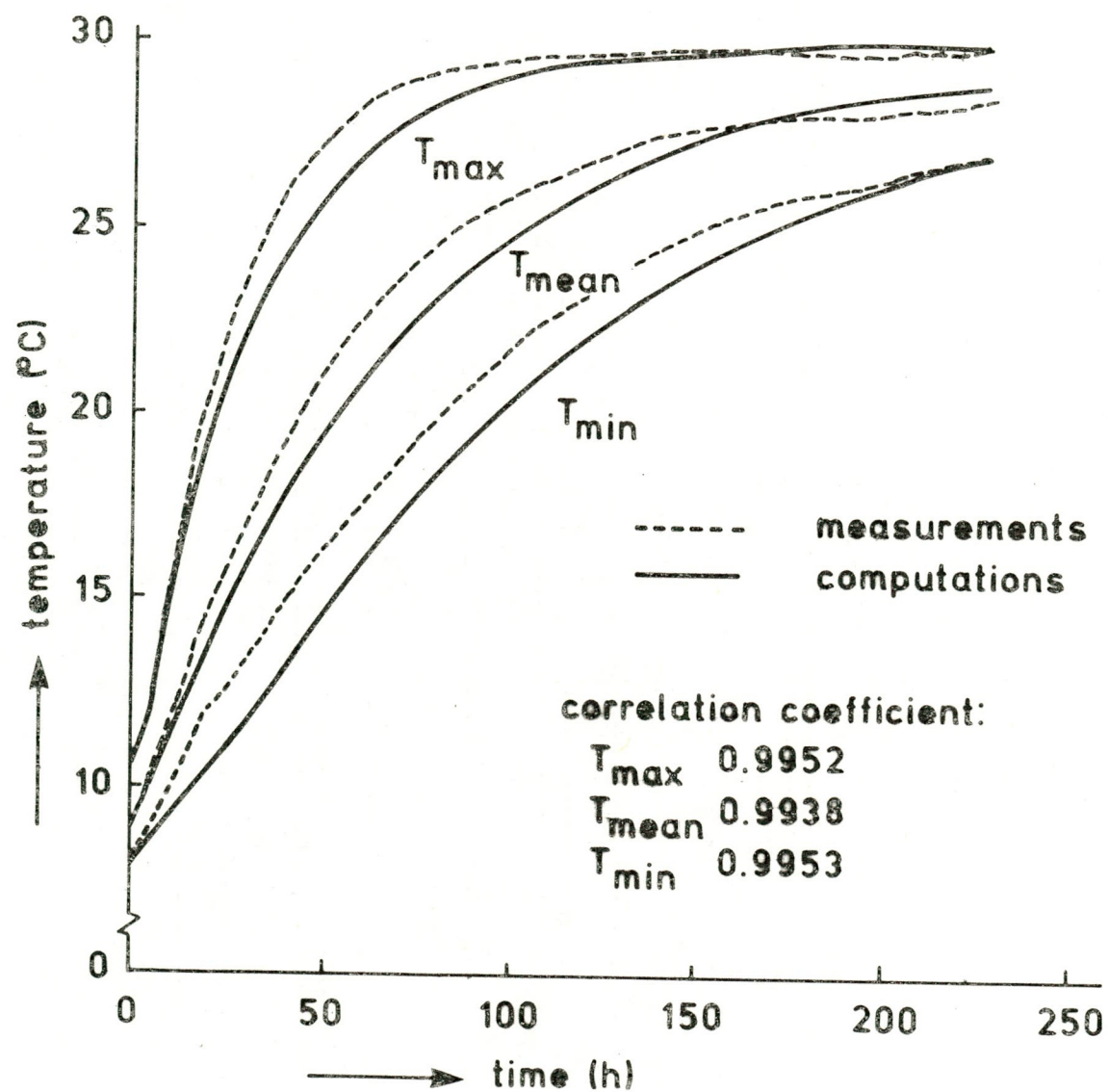
(°C)



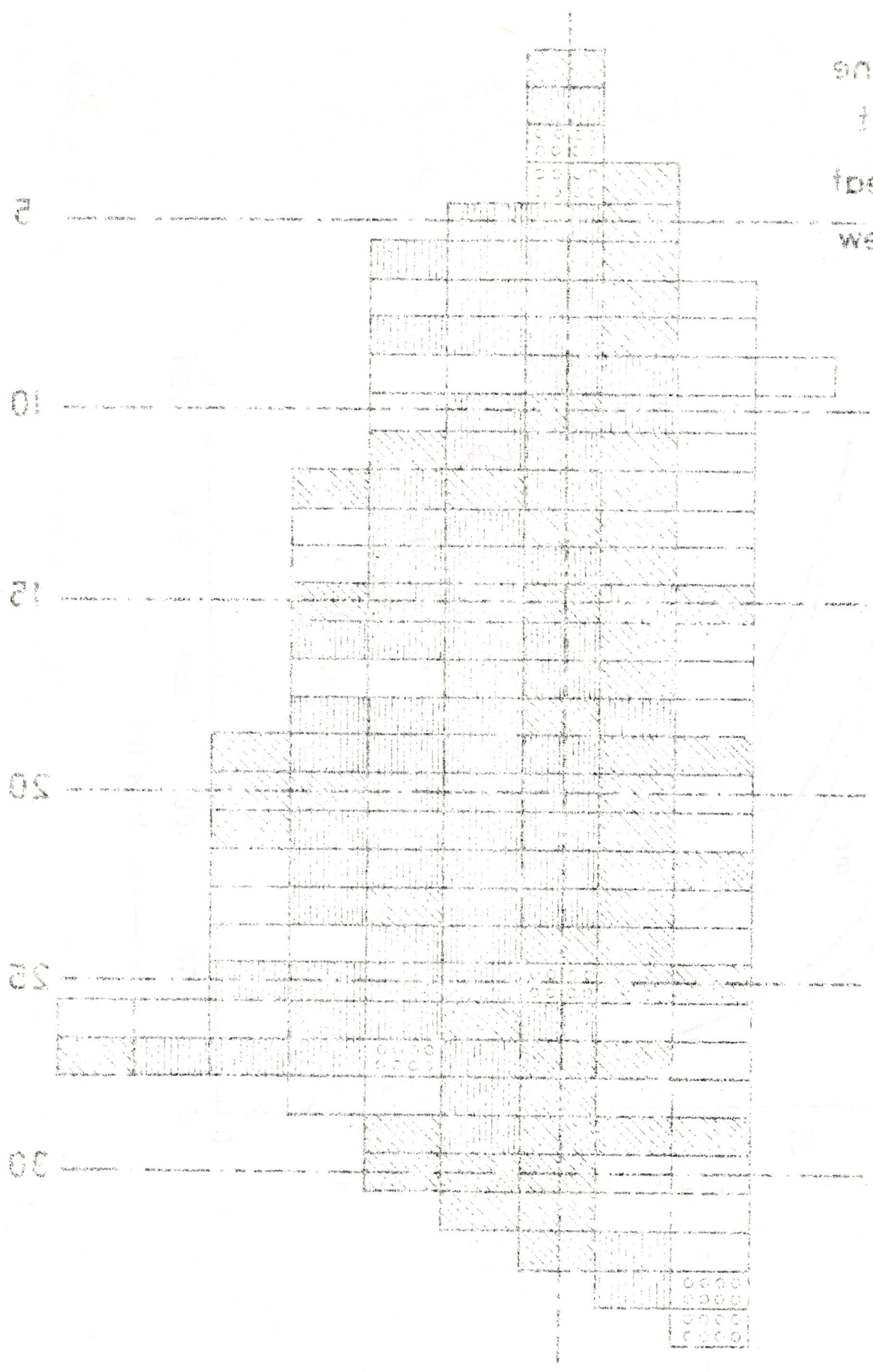








bone 
 fat 
 meat 
 vein 

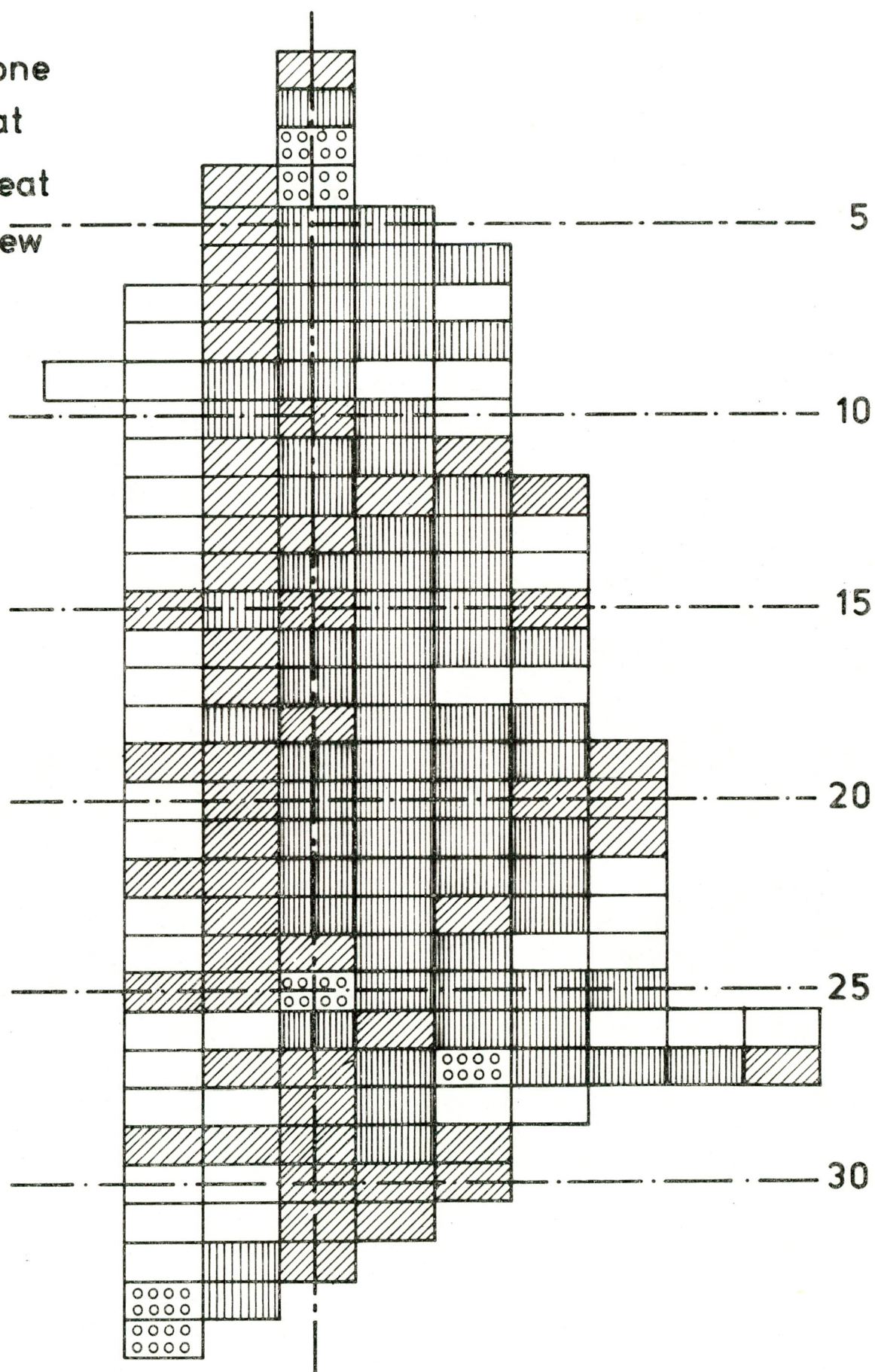


bone

Fat

meat

view



2.3 Computation method

The temperatures of all the elements are computed by the use of fundamentally stable integration methods, i.e. a combination of Dufort-Frankel, Crank-Nicholson and an extrapolation method, so the choice of the computation time interval will only affect the accuracy of the results. If desired, the boundary conditions and computation time interval can be adjusted and intermediate results can be obtained during computations in an interactive session.

The program package has been written in the FORTRAN 77 language for use on mini computers and mainframes. Recently, a version for use on an IBM PC/XT/AT compatible personal computer has been developed.

3. APPLICATIONS

3.1 General applications

The computer package BERTEM has been successfully used for quite a range of thermal problems:

- capacity and temperature distribution of soil heat exchangers for seasonal thermal storage;
- assessment and optimization of floor heating systems;
- capacity of the heating system of an oil tank;
- temperature distribution in the walls of brick kilns and stoves.

3.2 Applications in refrigeration engineering

BERTEM has also been used for several calculations in the field of refrigeration engineering.

In this context investigations have been carried out into ventilated cargoes. The usefulness of the package for this application has been investigated by comparing computations and measurements for a well-defined test-case.

Figure 1 shows a composite stack of boxes filled with water and with forced ventilation through the crevices.

In figure 2, experimental as well as computed results are shown. There proved to be a satisfactory agreement between them.

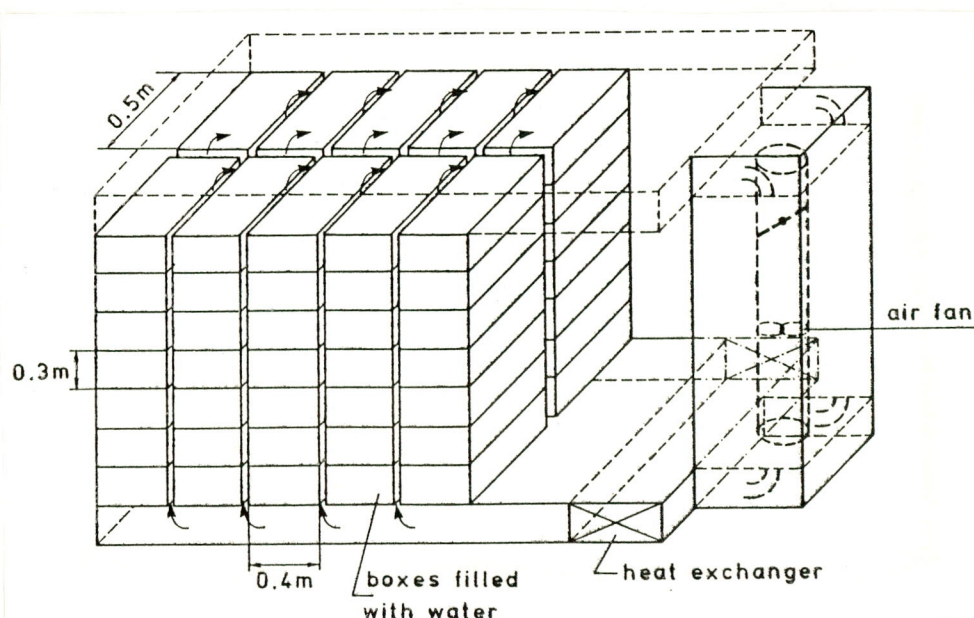


Fig. 1 - Composite stack of boxes.

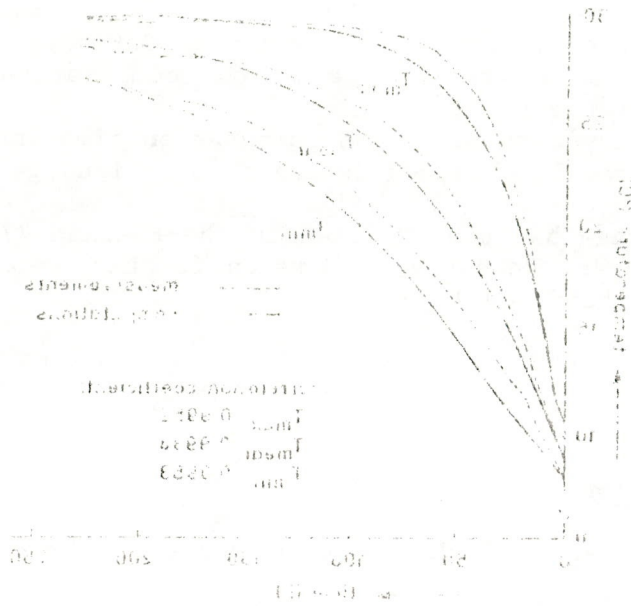


Fig. 1. Dependence of the logarithm of the rate constant on the inverse of temperature for the three systems.

From the data in Fig. 1, the activation energy of the reaction of the system I was calculated to be 10.5 kcal/mole, for system II 12.5 kcal/mole, and for system III 14.5 kcal/mole.

In comparison with the results of [1] and [2], it can be seen that the activation energy of the reaction of the system I is lower than that of the system II, and that of the system II is lower than that of the system III. This is due to the fact that the concentration of the active species in the system I is higher than that in the system II, and that of the system II is higher than that in the system III.

The results of the experiments show that the rate of the reaction of the system I is higher than that of the system II, and that of the system II is higher than that of the system III.

System	log k	1/T x 10^3
I	2.5	2.8
I	2.0	3.0
I	1.5	3.2
I	1.0	3.4
I	0.5	3.6
II	2.0	2.8
II	1.5	3.0
II	1.0	3.2
II	0.5	3.4
II	0.0	3.6
III	1.5	2.8
III	1.0	3.0
III	0.5	3.2
III	0.0	3.4
III	-0.5	3.6

The results of the experiments show that the rate of the reaction of the system I is higher than that of the system II, and that of the system II is higher than that of the system III. This is due to the fact that the concentration of the active species in the system I is higher than that in the system II, and that of the system II is higher than that in the system III.

In the case of the reaction of the system I, the rate of the reaction is higher than that of the system II, and that of the system II is higher than that of the system III.

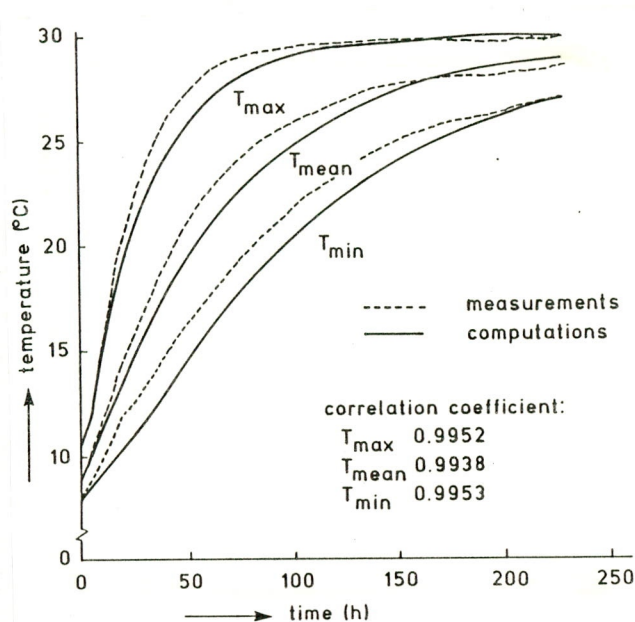


Fig. 2 - Measured and computed temperatures in the boxes of a composite stack. Air temperature jump from 7.5°C to 30.5°C.

Van de Ree [5] has described computations of the temperature distribution in ventilated cargoes in relation to the air circulation number. BERTEM proved to be a useful tool.

A comparison has been made between BERTEM and an other computer program, based on the Finite Difference Method (FDM), Cleland [6]. The cooling- and freezing times of a homogeneous rectangular brick filled with water have been computed. The computed results are summarized in Table I. The differences between the results of both of the computer programs are within 1%. However, the computation by BERTEM has taken 14% of the time needed by the FDM program.

TABLE I
Comparison of computer programs

	BERTEM	FDM
calculation time interval (s)	40	25
cooling time (hottest element reaches 25°C) (s)	2400	2400
freezing time (hottest element reaches -5°C) (s)	21280	21500
change in energy content (J)	568,000	570,000
temperature of coldest element (°C)	-17.2	-17.9
computation time (s)	200	1400

- number of elements: 125 (1/8 of a brick)
- thermal conductivity and specific heat capacity of water
- brick dimensions: 0.1 x 0.1 x 0.1 m³
- surface heat transfer coefficient: 30 Wm⁻²K⁻¹
- initial temperature : 50°C
- ambient air temperature: -20°C
- a shorter time interval or extension of the number of elements did not affect the results significantly

In the next chapter the application of BERTEM for computations of the temperature distribution in slaughtered pigs is discussed in detail.

4. TEMPERATURE DISTRIBUTION IN SLAUGHTERED PIGS

4.1 Background

According to the EC-regulations for fresh meat, carcasses shall be chilled after slaughter to an internal temperature of 7°C or lower before being transported to other countries in the Common Market. The aim of the investigations was to study the influence of transport on the temperature distribution and bacteriological condition of half pig carcasses before the internal temperature reaches 7°C. Moreover the conditions had to be formulated under which such a transport could be allowed to be carried out taking the required hygienic quality of the meat into account. These investigations have been carried out in co-operation with TNO-CIVO Food Technology Institute, Netherlands Centre for Meat Technology and are described in detail by Moerman [7].

The thermal investigations consisted of the construction of a finite element model of half a pig carcass as a part of the BERTEM computer package, temperature measurements during several test transports in order to validate the model and computations with BERTEM for a lot of storage and transport cases. In the next paragraphs this will be discussed in more detail.

4.2 Model set up

A finite element model of half a pig carcass has been designed by dividing the carcass in 338 cubic elements of 5 x 5 x 5 cm³. Three types of elements have been used: bone, fat and meat with corresponding thermal properties. The spacial geometry of the computation model has been determined by cutting a real carcass into slabs of 5 cm thickness (see figure 3).

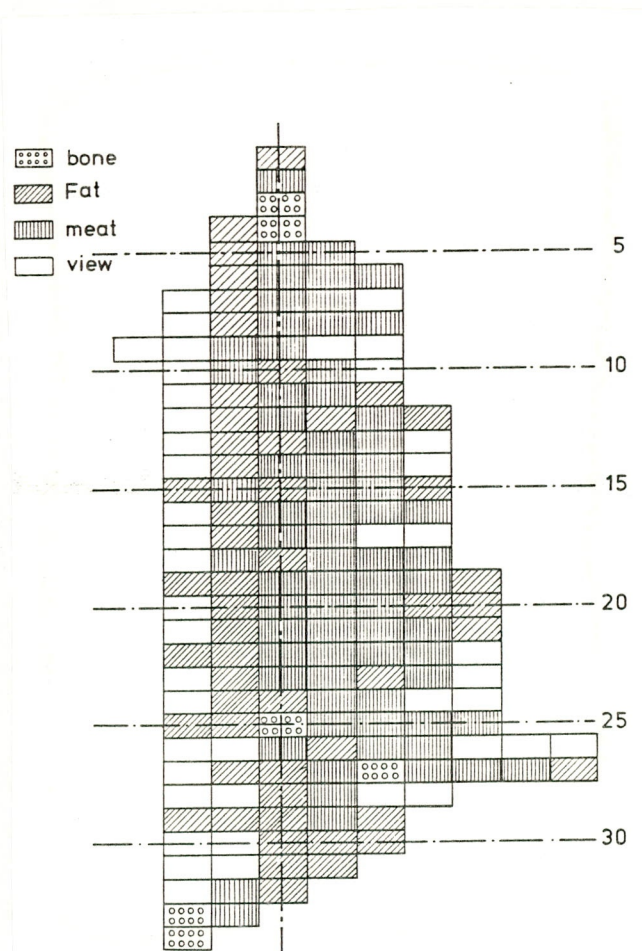


Fig. 3 - Cross section of carcass model.

Flow and boundary elements represent the airflow around the carcass.

The design of such a model is a rather time-consuming affair; on the other hand the computations with time and position dependent initial and boundary values are very easy to carry out.

The carcass model has been incorporated in the BERTEM package. Combined with input concerning initial and boundary values, the time dependent temperature distribution, heat content and the heat emission of the pig carcass are computed.

4.3 Experimental validation

The temperature distribution in a pig carcass has been measured during a large part of the cold chain. An example of the experimental results as well as the computed results for an identical case are presented in figure 4.

In figure 5 the measured and calculated temperatures are compared. The results show a good agreement and justify the usefulness for other computations.

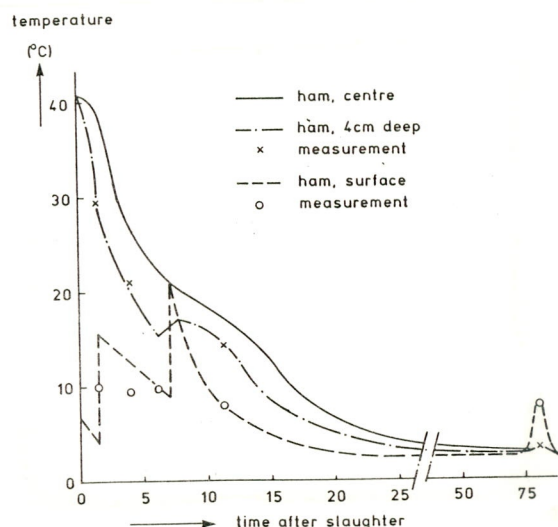


Fig. 4 - Computations and measurements for a test-case.

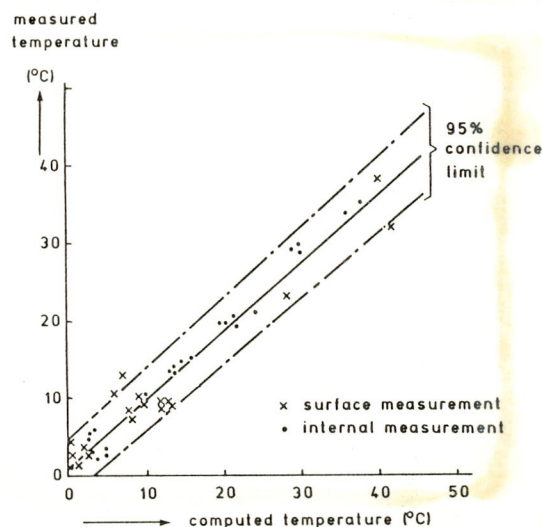


Fig. 5 - Relation between computed and measured values.

4.4 Computations and results

The temperature distribution in pig carcasses and the related heat emission have been computed for a range of practical cases with transport before and after the internal temperature has reached 7°C.

The computations show what time, air temperature, air velocity and refrigerating capacity are required during the successive phases of the cold chain, to obtain the desired time-temperature course in a pig carcass.

As an over-all result of the study, the conditions have been determined to allow transport of pig carcasses before the internal temperature reaches 7°C.

These conditions have been accepted by the Dutch authorities for inland transport. Computations with the BERTEM package form part of the procedure for granting a licence. In this case, the use of computer simulation leads to a drastic reduction of time and costs because of a strong reduction of required measurements and the possibility of optimizing the cold chain.

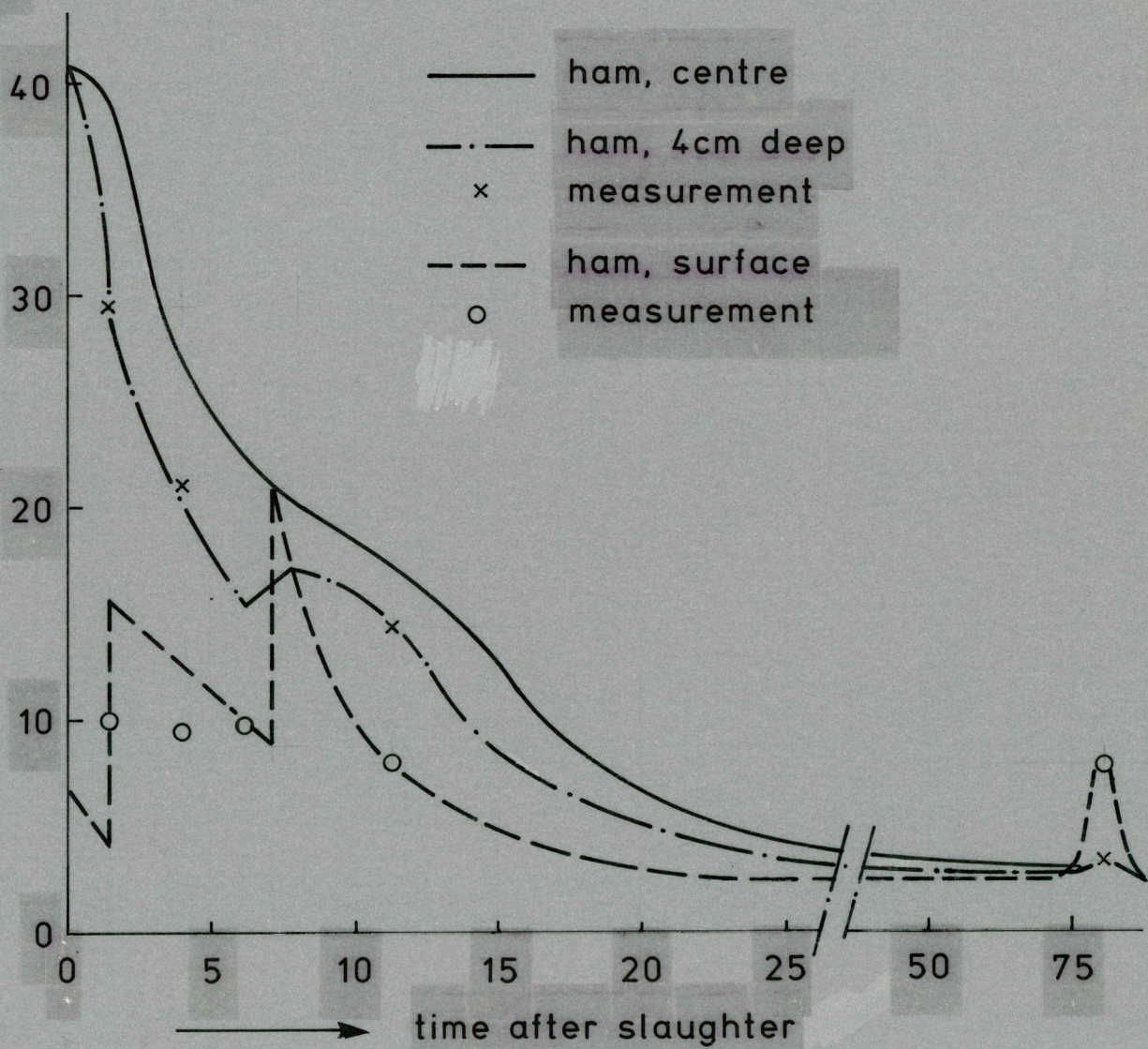
4.5 Suggestions for other applications

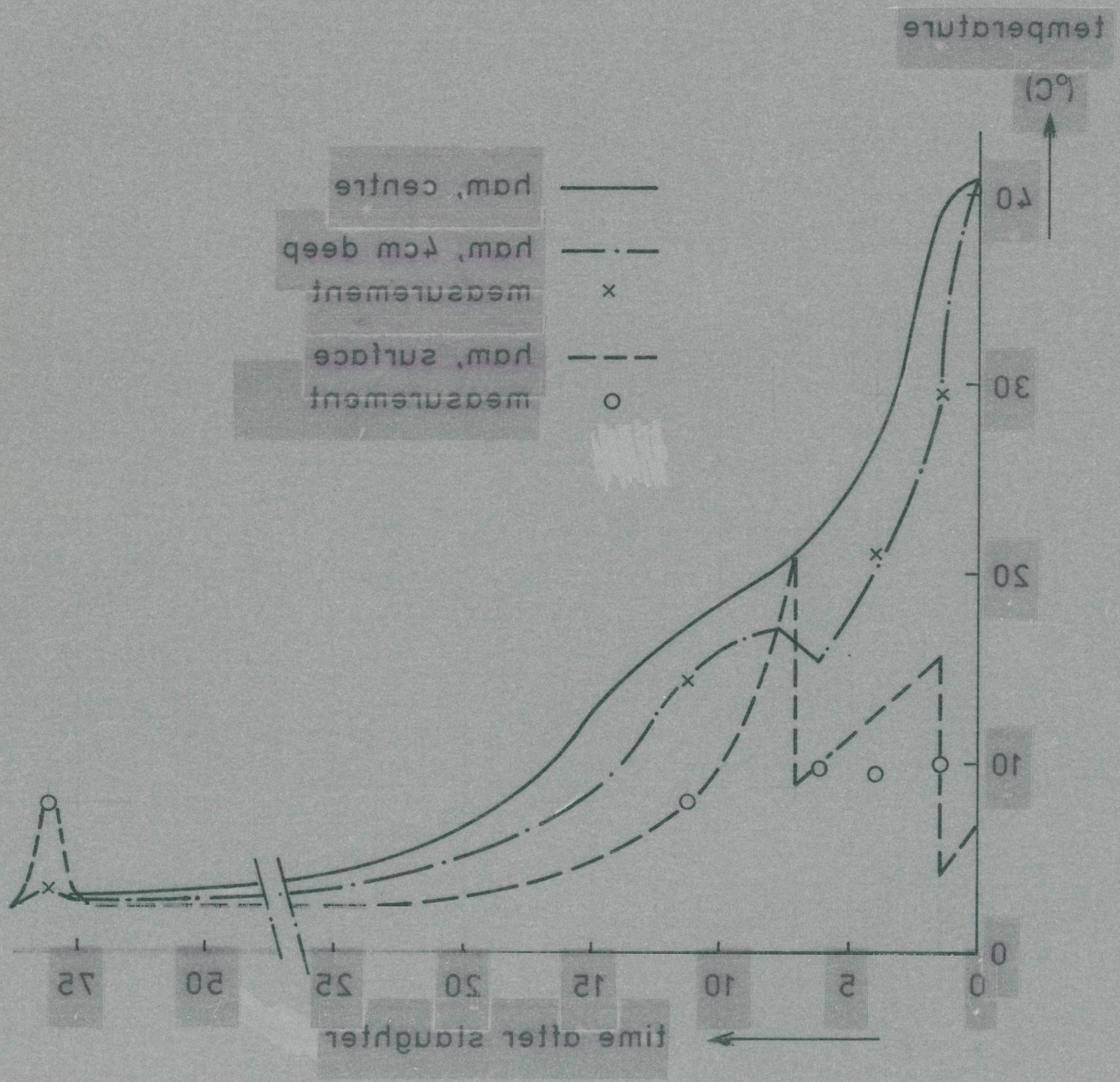
The scheme described in the previous paragraphs is also applicable for other products. The method is eminently suited for computations of temperature distributions in inhomogeneous and irregular shaped bodies such as sheep and bovine carcasses, poultry or pallets with fruit or vegetables.



temperature

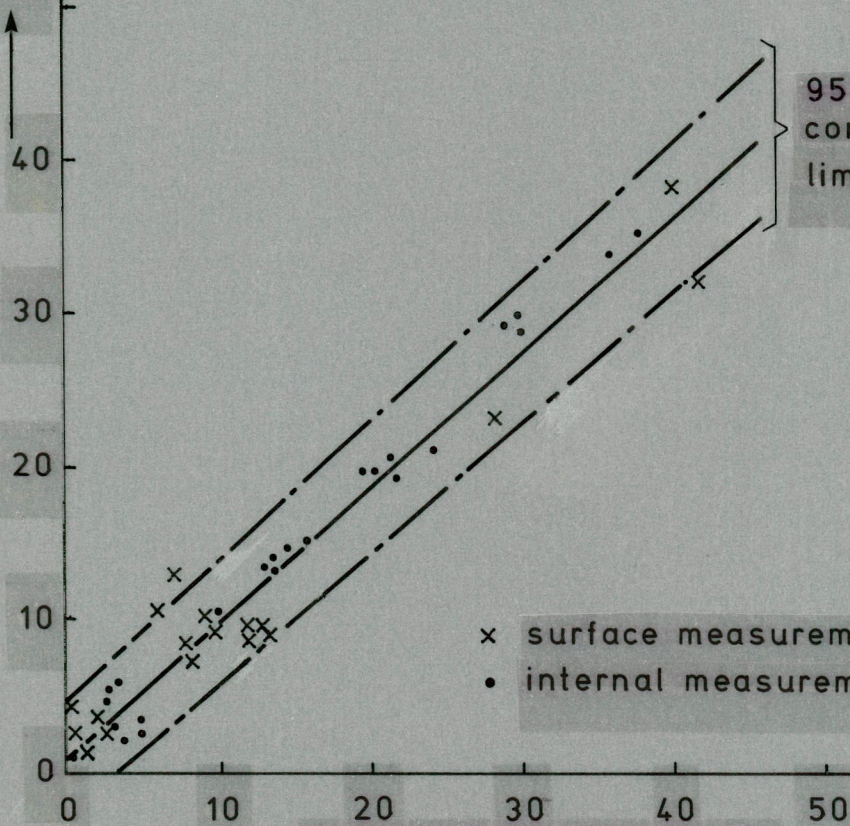
(°C)





measured
temperature

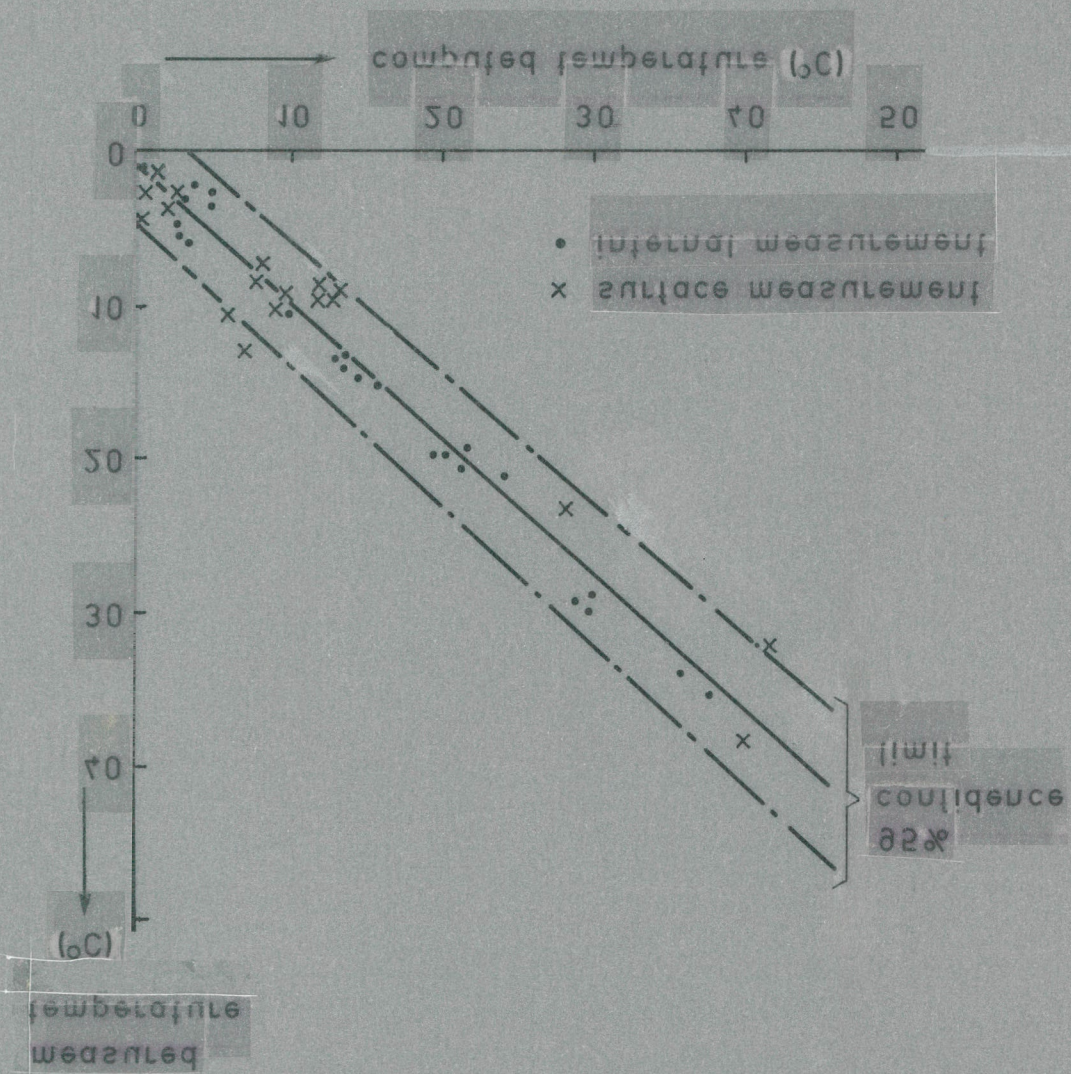
(°C)

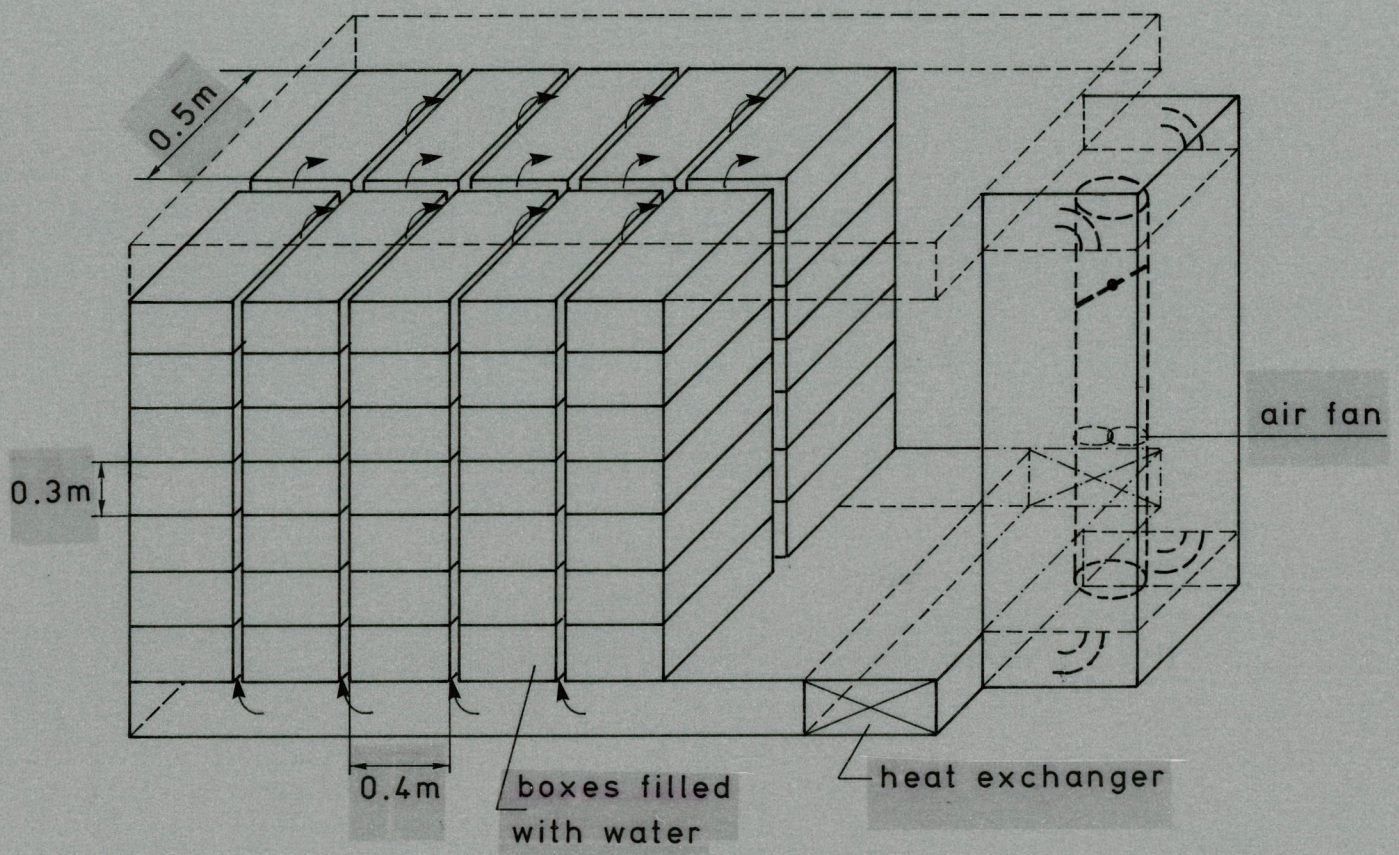


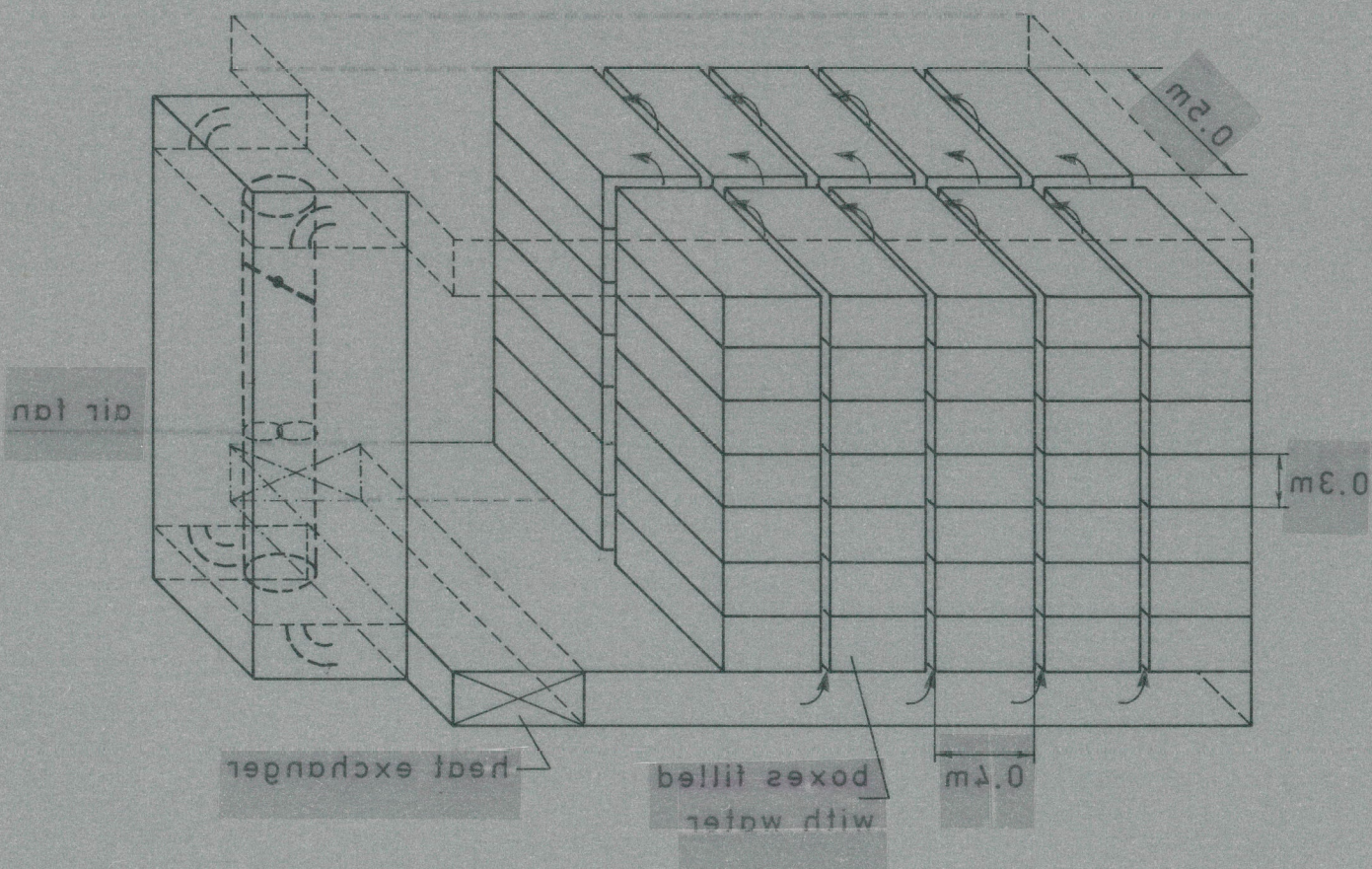
95%
confidence
limit

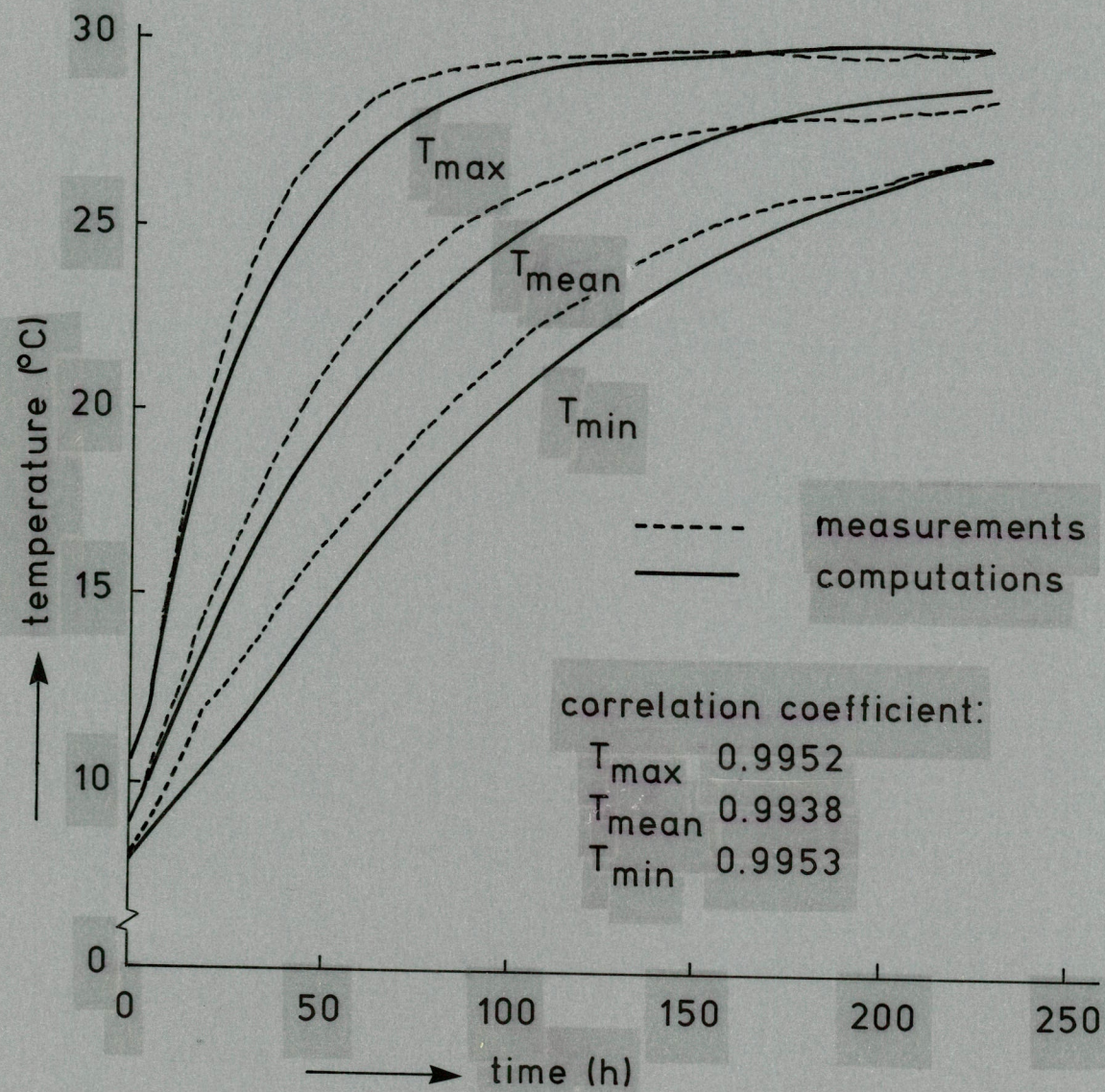
x surface measurement
• internal measurement

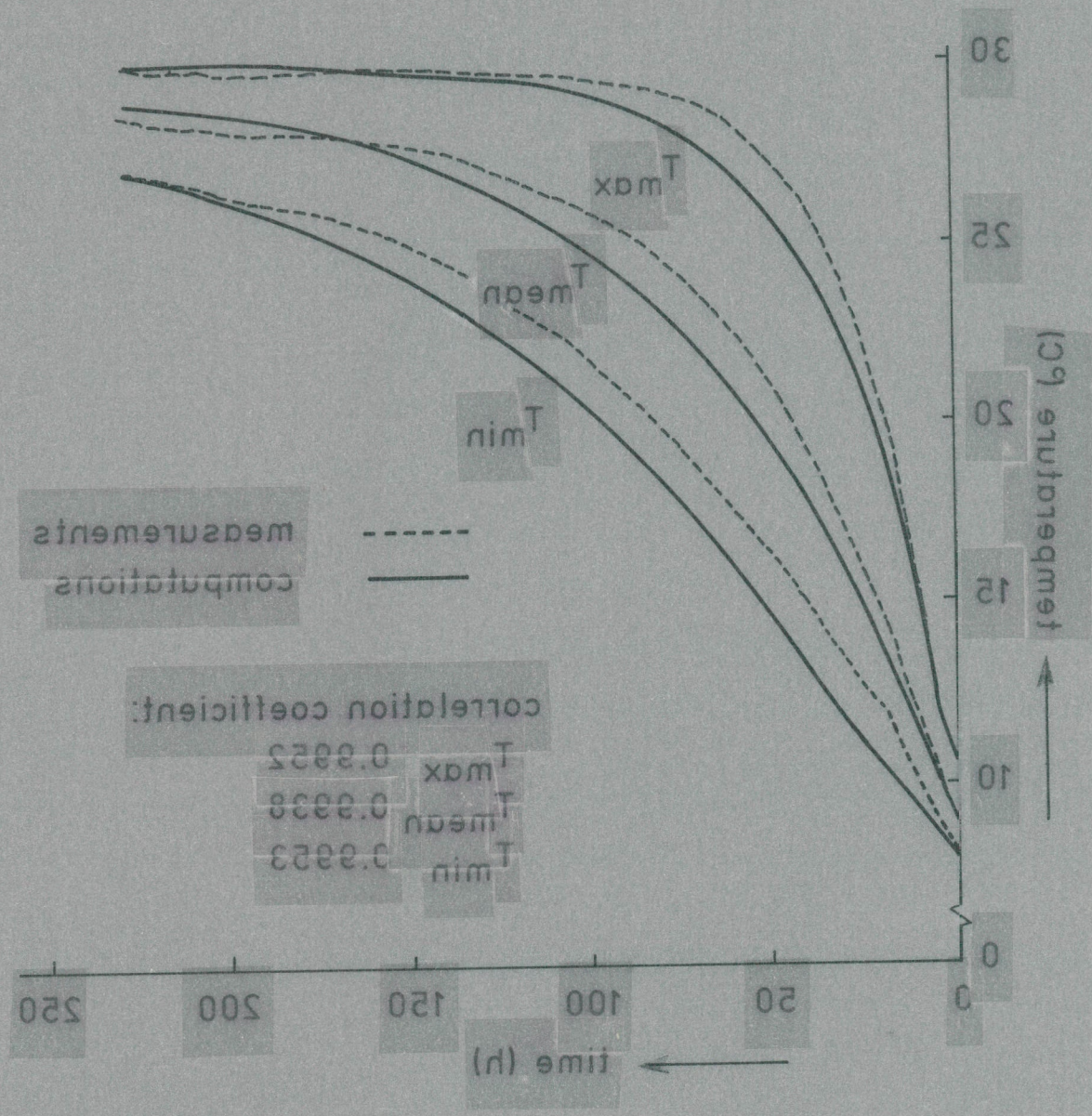
computed temperature (°C)











-  bone
-  Fat
-  meat
-  view

