S P R E N G E R   I N S T I T U U T

Haagsteeg 6, Wageningen

Tel.: 08370-5351

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CONCERNING : Unit loads of fresh produce
Study of design criteria and
conditioning of produce

SUBMITTED TO : Director Sprenger Instituut and
OECD

WRITTEN BY : Dipl.Ing. H.F.Th. Meffert

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OECD: Unit loads of fresh produce.

Study of design criteria and conditioning of produce.

SPRENGER-INSTITUUT,
Wageningen,
Netherlands.

Summary

The problem of self-heating of unit loads, depending on respiration rate, evaporation cooling, dimension and outside climate conditions is discussed on a mathematical basis. Properties of product and package turn out to be of large importance for a reasonable prediction of the behaviour of a stack with respect to mass and heat transfer in time. In an appendix an outline is given for the determination of the effective thermal diffusivity of a stack which is a very important property for both, cooling and selfheating processes. In a second appendix the product tomato is treated in detail: data of product and package are given. A model calculation is added to illustrate the practical significance of such informations for the prediction of the thermal behaviour of unit loads. This calculation has to be considered as a first approximation, further development of theory and experimental methods as well as measuring techniques is necessary.

Contents:

1. Introduction

"Unit loads", as a stable stack of individual packages, which can be handled as one piece, have got much attention from the viewpoint of low handling costs per kg as well as of the speed of the handling operation.
Pallets and other selfcontaining stacks of the same size, but also larger units as flats and containers are widely,in use now. Very important in this respect is the requirement of dimensional compatibility of package, pallet, container, truck etc. with respect to handling, stacking and stabilizing such loads, but of equal importance are the requirements for aircirculation and ventilation of the cargo during transit.

The requirements of aircirculation through the cargo create in the first place problems of space which have to be considered together with the mechanical problems of stability. The use of pallets in containers imposes some more problems of space, ventilation and stability as well as cost of handling and transportation. For West European Traffic the use of pallets in containers must be considered as essential.

Limits of the size of "unit loads" are rising from the properties of the produce as well as the package. The size of "unit loads" of respirating produce is limited by the requirements of transfer of metabolic products and the tolerable concentration of those products resulting in a rise of temperature, water vapour and CO_2-concentration above ambient conditions, and a decrease of O_2.
The "Safe Radius", the shortest distance for the heat transfer from the geometrical center of a heat generating body, is a useful yardstick in this respect [3]. Depending on the tolerable temperature difference between center of the unit and the surrounding air, on heat release and thermal conductivity, the "Safe Radius" gives the maximum of the shortest transfer distance within which the given overtemperature can be maintained.

A complication however is introduced by the cooling effect of evaporation of water from the produce.

This means that only in cases of restricted evaporation the heat of respiration can be introduced without a correction. In other cases the "Safe Radius" will give a too large value. Which means a "very Safe Radius".

As the temperature rise from heat generation depends also on time, it is necessary to deal with the transient problem.

2. Theory

2.1. Temperature field

The temperature rise in a heat generating slab at a constant rate can be described generally by:

$$\Theta = \frac{t(x,\tau) - t_0}{t_a - t_0}$$
$$= 1 + \frac{1}{2} Po \left(1 - \frac{x^2}{X^2} + \frac{2}{Bi}\right) -$$
$$- \sum_{n=1}^{\infty} \left(1 + \frac{Po}{\mu_n^2}\right) A_n \cos\left(\mu_n \frac{x}{X}\right) \exp\left(-\mu_n^2 Fo\right) \qquad (1)$$

where: Po is the Pomerantsev criterion $= \dfrac{Q X^2}{\lambda (t_a - t_0)}$

The temperature for the center of the slab (x=0) is given by the equation

$$\Theta_c = \frac{t(0,\tau) - t_0}{t_a - t_0} \qquad (2)$$
$$= 1 + \frac{1}{2} Po \left(1 + \frac{2}{Bi}\right) -$$
$$- \sum_{n=1}^{\infty} \left(1 + \frac{Po}{\mu_n^2}\right) A_n \exp\left(-\mu_n^2 Fo\right)$$

In the case of $t_a = t_o$, i.e. temperature of the body at the beginning of the proces is the same as of the surroundings (fruit packed in cartons and stacked to palletloads in a packing shed),eq.1 becomes for the center of the unit:

$$\vartheta_c = t(o,\tau - t_o$$
$$= \frac{Q\,X^2}{2\,\lambda}\left\{1 + \frac{2}{Bi} - 2\sum_{n=1}^{\infty}\frac{A_n}{\mu_n^2}\exp\left(\mu_n^2 Fo\right)\right\} \qquad (3)$$

Equation (1) consists of a cooling term:

$$\Theta_{coolg} = 1 - \sum_{n=1}^{\infty} A_n \cos\left(\mu_n \frac{x}{X}\right)\exp\left(-\mu_n^2 Fo\right) \qquad (4)$$

And a self-heating term:

$$\Theta_{heatg} = \frac{1}{2} Po\left(1 - \frac{x^2}{X^2} + \frac{2}{Bi}\right) - \qquad (5)$$
$$- Po\sum_{n=1}^{\infty}\frac{A_n}{\mu_n^2}\cos\left(\mu_n \frac{x}{X}\right)\exp\left(-\mu_n^2 Fo\right)$$

The course of temperature of any point, especially of the center, can be found by addition of the two contributions, for instance graphically.

The temperature rise at the beginning of the process is described by:

$$\frac{\Delta\vartheta}{\Delta\tau} = \frac{Q}{c\rho} \qquad (6)$$

until $Fo = \frac{D_{th}\cdot\tau}{X^2} = 0,1$

$$\therefore \tau = 0,1\,\frac{X^2}{D_{th}}$$

At the end of the process, if

$Fo > 1 \therefore \tau > \frac{X^2}{D_{th}}$,we get

$$\vartheta_c = \frac{Q\,X^2}{2\,\lambda}\left(1 + \frac{2}{Bi}\right) \qquad (7)$$

For the basic geometric bodies a relation similar to eq. 7 is valid

$$\vartheta_c = \frac{Q X^2}{m \lambda} \left(1 + \frac{2}{Bi}\right) \tag{7A}$$

where $m = 2 ; 4 ; 6$
for slab; cylinder, sphere
has to be inserted.

The solution for the rectangular parallelepiped is more difficult for the following reasons

1) The heat transfer paths are not of equal length, that means eq.: 7 is not valid in the simple form given.

2) The temperature distribution at the surface may not be uniform.

Thus: the heat flow across the surface is not uniform for inside and outside reasons.

In case of a rectangular parallepiped with uniform surface temperature ($Bi \rightarrow \infty$), an equation is valid:

$$\vartheta_c = \frac{Q X'^2}{m' \lambda} \tag{8}$$

where:

$$X' = X\left(1 + \frac{1}{Bi_x}\right)$$

$$Y' = Y\left(1 + \frac{1}{Bi_y}\right)$$

$$Z' = Z\left(1 + \frac{1}{Bi_z}\right)$$

and X' the smallest dimension, leading to an effective shape factor m' after Tchumak (see fig. 1). If all the values of Bi exceed 3, technical accuracy, i.e. a deviation of less than ca. 10%, can possibly be reached.

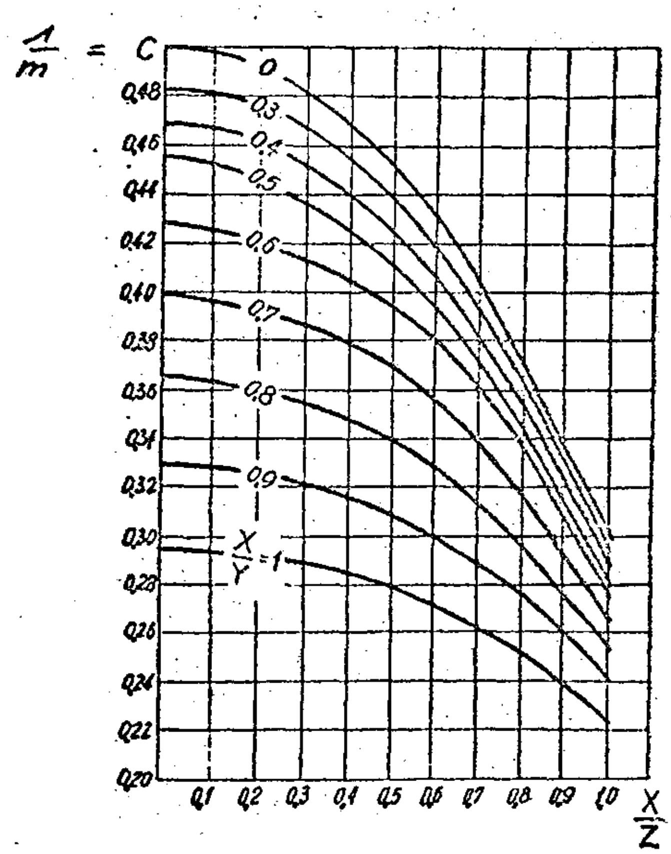

Fig.1: Shape factor $C = \frac{1}{m}$ as a function of X/Z, X/Y as parameter (after Tchumak 7).

For Bi $<$ 3 - unfortunately a practical situation - the total temperature difference can be split up into one within the package or stack and one across the surfaces. This approach does not give fully satisfying results because of the assumption uniform heat flow through the surfaces.

Non uniform temperature distribution at the surfaces create still more problems, the solution of which cannot be tackled by conventional means.

A practical approach seems to yield a relation between excess center temperature ϑ_c and shortest path of heat transfer X in the form:

$$\vartheta_c = \text{const.}\, X^2$$

Experiments with one package and different stacking methods for one product in a conventional store, yielded such a relation. The constant depends on the conditions in the hold: temperature, humidity, air velocity as indicated by the theory.

From eq. (7) The "Safe Radius" can be derived as:

$$R_\vartheta \leqslant \frac{\lambda}{k}\left(\sqrt{1 + \frac{m\, k^2 \vartheta}{\lambda\, Q_{t+\vartheta}}} - 1\right) \tag{9}$$

from eq. 8.

$$R_\vartheta \leqslant \frac{\lambda}{k}\left(\sqrt{\frac{m\, k^2 \vartheta}{\lambda\, Q_{t+\vartheta}}} - 1\right) \tag{10}$$

In order to describe the process of heating with temperature depending on heat generation actually, the heat of respiration has to be introduced at the given temperature limit and the evaporation from the produce has to be checked.

2.2. Water vapour concentration field

The evaporation depends for a great deal on the local water vapour concentration deficit, which for a slab can be found from:

$$\Gamma = \frac{c(x) - c_a}{c_{max} - c_a} = 1 - \frac{\frac{H}{D}\cosh\left(x\sqrt{\frac{E}{D}}\right)}{\frac{H}{D}\cosh\left(X\sqrt{\frac{E}{D}}\right) + \sqrt{\frac{E}{D}}\sinh\left(X\sqrt{\frac{E}{D}}\right)} \tag{11}$$

for the center condition $(x = 0)$

$$T' = 1 - \frac{\frac{H}{D}}{\frac{H}{D}\cosh\left(x\sqrt{\frac{E}{D}}\right) + \sqrt{\frac{E}{D}}\sinh\left(x\sqrt{\frac{E}{V}}\right)} \qquad (12)$$

This formula applies for infinite slabs, i.e. for rows of packages if height and length are larger than 3 x width.

If the permeability for water vapour at the surface is large, i.e. $H/_D > \sqrt{E}/_D$ than cq. 12 becomes:

$$T' = 1 - \frac{1}{\cosh\left(x\sqrt{\frac{E}{D}}\right)} \qquad (13)$$

3. Properties

In order to be able to use the relations aforementioned to predict product conditions or determine safe dimensions of unit loads, data of the involved properties of produce in package as well as of the package are necessary. At the moment data of this kind are not generally available, although part of them can be found in recent publications.

3.1. Conductivity - diffusivity

A property of particular importance is the conductivity resp. diffusivity in the package. Unfortunately there is a great lack of such data. From a large number of experiments we could derive the following rule of thumb:

$$\lambda' = (1 - \varepsilon)\lambda + \varepsilon\lambda_{air} \qquad (14)$$

The effective thermal conductivity can be found from the volume fractions and the thermal conductivity of the components. The apparent thermal conductivity of the air fraction depends on the amount of convection within the package. In tight packages with obstructed aircirculation λ_{air} can be taken as conduction only.

In a spacious package but still air tight, λ_{air} can increase 30 x due to convection.

In packages open to air penetration, a sort of apparent λ can be estimated from the amount of penetrating air:

$$\lambda_{conv} = \frac{\phi_A (c\rho)_A}{X}$$

But another approach, based on heat transfer to moving air from a heat generating bed can be expected to give a more satisfying description of the process.

Table 1 gives a roundup of experimental D_{th}.

The following conclusions can be drawn from this compilation:

Single tight packages with negligible inside circulation show low thermal diffusivity, so as to predict from D_{th} of water (nr. 1, 3, 13). Even ventilated packages with tight product packing(11, 12) show the same behaviour at low air velocities. In some cases air seems to penetrate even in closed cartons (nr.3).

Open stacks of tight packages (2) show increased D_{th} with increased air velocity. At medium air velocities the packages seem to behave like a single one in an air stream.

Tight stacks show this increase only at high air velocities (18,20,22).

Open packages exhibit much larger D_{th} which are greatly influenced by outside air velocities.

In open stacks D_{th} follows the increase of air velocity from lower values than in tight stacks (18 ,20 vs 19,21).

Values of D_{th} in the range of several hundreds are not very accurate in case they are taken from steady state overtemperature, because the temperature differences become so small that instrument deviation can play a large role.

3.2. Heat generation

The large variability of physiological data can be seen as a main characteristic of living material[8]. A calculation with maximum values will yield therefore a certain safety but such a safety should not be taken for granted.

Table 1: Preliminary values of $D_{th} \cdot 10^4 \frac{m^2}{h}$ for various commodities packing and stacking methods

	commodity	package dimensions cm (LxWxH)	exposure stack	package	product	air velocity m/sec 0	0,3	1,8	3,5	6	9
1	lettuce	cartons 55x38x9	-	0	0		5		5	5	
2	"	on pallet: 100x100x72	1	0	0		24		170		
3	"	60,5x40x16	-	0	0		6		10	14	
4	"	boxes 60x40x25		1	0		18		29	26	
5	"	small row ∞x40x∞	0	1	0		30		34	98	
6	"	double row ∞x80x∞	0	1	0		79		160	295	
7	"	wide row ∞x60x∞	0	1	0		56		97		
8	"	120x100x150	0	1	0		35		93	214	
9	"	120x100x175	1	1	0		76		260		
10	flower bulbs	crate 50x40x32	-	1	0	9					
11		carton, vent. 50x40x32		1	0	4,4					
12		39x39x39		1	0	3,4					
13		carton 39x39x39		0	0	3					
14	apple	boxes on pallet 120x120x60		0	1			7,5			
15		boxpallet 120x120x90		1	1		40			300	
16		cartons on pallet 120x120x150		0	1			25		64	
17		155x120x150		0	1			66			
18	model product	carton 40x31x14,5	0	1	1		35	48			200
19		on pallets double row ∞x240x∞	1	1	1		68	90			200

Table 1 cont'd

	commodity	package dimensions	exposure stack	exposure package	exposure product	air velocity m/sec 0	0,3	1,8	3,5	6	9
20	model product	foam plastic box 40x30x15	0	1	1		42	48			220
21		on pallets double row ∞x240x∞	1	1	1		60	115			400
22		wooden tray 43x31x13	0	1	1		44	120			800
23		on pallets double row ∞x240x∞	1	1	1		96	115			480
24		foam plastic box 40x30x150	1	1	1	10					

exposure: 0 tight
1 open (2 cm airchannels in stack)

3.3. Evaporation

Very little information is available about the rate of evaporation under controlled conditions. Therefore it is almost impossible to correct the heat generation term for evaporative heat absorption. This could be taken as a further contribution to a safety factor, but, with restricted evaporation the atmosphere in the package becomes very favourable for development of microorganisms which may contribute to the heat generation with an unpredictable amount.

Some available data are given in the attached table 2.

As far as the prediction of the developing conditions at the product are concerned, the lack of necessary data does not permit broad application of the formulas given.

Table 2 : Preliminary values of E' waterloss per occupied volume per water vapour concentration difference between product surface and surroundings.

Product	Temperature °C	Relative Humidity %	E' 1/h	kg/m³	Source (see p. 14)
Apple					
Laxton's Superb	10	70	18	525	9
		85	23		
		95	32		
James Grieve	20	75	13		9
		75	9		
Granny Smith	1,5	ca.75	1,8		2
Pear					
Packham's Triumph	1,5	ca.75	7,2	500	2
Tomato	5	75	20	635	10
			13		
	10	75	10		
			7		
	10	85	30		
			13		
Cucumber	ca.15	ca.90	12	325	

Attention: E' depends in general on R.H.

4. Experimental determination of thermal diffusivity

For the evaluation of a package or a stacking method with respect to the thermal behaviour we can recommend a simple method by measuring the cooling rate. As the temperature development in a unit load strongly is influenced by the apparent thermal diffusivity which is responsible as well for the self-heating as for the cooling down process, the diffusivity from a cooling curve can be taken as a yard-stick for comparing different packages, stacks and unit loads with respect to the thermal properties.

Two methods are available for an experimental determination of the apparent thermal diffusivity: from steady state of the heating process, and from the transient cooling process.

Hereunder the equations from 2.1. are given in terms of D_{th} with corresponding numbers.

For the initial temperature rise eq . (7) becomes:

$$\vartheta_c = \frac{Q'' X^2}{m\, D_{th}\, c\rho''} \left(1 + \frac{2}{Bi}\right) \qquad (15)$$

or

$$\vartheta_c = \frac{q'' X^2}{m\, D_{th}\, c} \left(1 + \frac{2}{Bi}\right) \qquad (15a)$$

The "Safe Radius" in terms of D_{th} is represented by:

$$R_\vartheta = \frac{\lambda}{k}\left(\sqrt{1 + \frac{m\, k^2 \vartheta}{D_{th}\, c\rho'' Q'_{t+\vartheta}}} - 1\right) \qquad (16)$$

In order to show the relation to the cooling rate in terms of halfcooling-time Z or 1/10 cooling time f, these are given below:

$$f = \frac{X^2}{D_{th}\, \beta_1^2 \log e} \qquad (17)$$

respectively:

$$Z = 0{,}3009 \frac{X^2}{D_{th}\, \beta_1^2 \log e}$$

where β_1 is a well defined function of Bi and Fo[6].

4.1. From the steady state excess temperature of the stack with self-heating:

$$D_{th} = \frac{q'' X^2}{m\, \vartheta_c} \left(1 + \frac{2}{Bi}\right) \qquad (18)$$

The determination of D_{th} according to this equation presents some difficulties:

1) the rate of heat generation must be known within reasonable limits. Values from tables are usually too crude. Special measurements have to be done but still then the rate of evaporation interferes. Therefore this

method works far better with artificial heat production than with produce.

2) steady state is at worst reached after ca. 500 hours, which makes measurements rather time consuming

4.2. From a cooling-down process

The slope of the center temperature during cooling-down or warming-up allows the determination of D_{th} most easy from logarithmic plot of temperature vs. time or even from a linear plot. (see App. I fig. I.1, I.2.). From temperature figures or plots the cooling rate can be taken and because of the interchangeability of the different expressions processed in the same way.

for 3 - dimensional heat transfer, the general case,

$$\frac{1}{f} = \frac{1}{f_x} + \frac{1}{f_y} + \frac{1}{f_z} \qquad (16)$$

for the X-coordinate is: $\xi = f_x \cdot \frac{D_{th}}{X^2}$

for the Y-coordinate is: $\eta = f_y \cdot \frac{D_{th}}{Y^2}$

for the Z-coordinate is: $\zeta = f_z \cdot \frac{D_{th}}{Z^2}$

ξ, η, ζ are taken from fig. 2

yielding:

$$D_{th} = \frac{1}{f\left(\frac{1}{\xi X^2} + \frac{1}{\eta Y^2} + \frac{1}{\zeta Z^2}\right)} \qquad (17)$$

In spite of the more complicated way of calculation the cooling method requires much less time for the experiment.

The evaluation has to rely on the middle of the cooling process, making use of the exponential course of temperature. This is the case after the bending point of the cooling curve. Towards the end of the cooling process the influence of heat generation becomes more apparent: the end temperature = air temperature cannot be reached.

The fact that the cooling-down process can easily be used for the determination of the thermal diffusivity, makes the cooling method very attractive for measurement with real produce.
Deviations have to be expected:

1) from evaporative cooling, which leads to increased D_{th},
2) from heat generation, which slows down the cooling rate, leading to smaller D_{th},
3) from the necessary assumption of thermal conductivity and heat transfer coefficient,
4) in cases of very slow cooling rates the simple method does not give the wanted information; if such cases have to be analysed a more complicated method can be derived from eq. (2) but in this case the heat generation has to be known.

Comparing the selfheating method (4.1) and the cooling method (4.2) for the experimental determination of the thermal diffusivity, experiments with model products and artificial heat generation are much simpler to evaluate. Packaging and stacking methods can be compared without interfering product properties and without preliminar assumptions. But cooling-down experiments are much shorter anyway

5. Conclusions

1. The prediction of the thermal and hygric behaviour of unit loads of living produce is at this time only possible as a first approach for a few special cases, due to lack of data from produce as well as package and stack.

2. The characterization of packaging and stacking methods with respect to thermal effects is possible by experiment. These can be performed with real produce or model product along different ways.

3. Model tests can give a reasonable impression of the thermal behaviour of stacks.

4. The characteristic "Safe Radius" can be considered as a guide line for package design and practical stacking methods.

5. The relation between inside-outside climatic conditions depends on product properties, package design, and stacking method as well as of the amount of air penetration.

6. Much more work has to be done in the field of compiling product properties, especially hygric properties.

7. Further study of the air penetration into stacks is necessary to understand the behaviour of open arrangements.

8. Further development of theory and experimental methods is needed along with suitable measuring techniques.

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7. List of Symbols

A_n	(Bi) in eq.1	
C	shape factor (fig.1)	
CR	cooling rate	$\frac{K}{h}$
D	diffusivity	$\frac{m^2}{h}$
E	evaporation rate per volume	$\frac{1}{h}$
H	permeability	$\frac{m}{h}$
Q	heat generation	$\frac{kcal}{m^3 h}$
R	safe radius	m
T	temperature	^oK
W	waterloss	$\frac{kg}{h}$
X, Y, Z	dimensions	m
Z	half/cooling/time	h

c	specific heat	$\frac{kcal}{kg\ h}$
c	concentration of water vapour	$\frac{kg}{m^3}$
f	1/10 cooling time	h
k	heat transmission coefficient	$\frac{kcal}{m^2 hK}$
m	shape factor $= \frac{1}{C}$	
q	heat generation	$\frac{kcal}{kg\ h}$
t	temperature	^oC
w	waterloss	$\frac{kg}{m^2 h}$
x	running coordinate	m

α	heat transfer coefficient	$\frac{kcal}{m^2 hk}$
β_1	function of Bi, eq.(14)	
γ	water vapour concentration difference	$\frac{kg}{m^2}$
δ	thickness	m
ε	porosity	$\frac{m^3 air}{m^3}$
λ	thermal conductivity	$\frac{kcal}{mhK}$
μ_n	f (Bi) in eq.(1)	
ρ	density	$\frac{kg}{m^3}$
τ	time	h
ϑ	temperature difference	K
$\left.\begin{matrix}\xi\\ \eta\\ \zeta\end{matrix}\right\}$	Fo (O = 0,1) for X, Y, Z axes Appendix I	
Γ	dimensionless concentration difference	
$\emptyset$	air flow rate	$\frac{m^3}{h}$
θ	dimensionless temperature difference	

Bi	Biot - number
Fo	Fourier - number
Po	Pomerantsev - number, eq (1)

Indices:

th	thermal
w	water vapour
'	bulk
"	in package/stack
c	center
o	starting point
a	ambient
1-D	one dimensional
A	air

Appendix I

Calculation of the effective thermal diffusivity $\mathcal{D}_{h}$ from experiments with packages.

In this appendix the calculations yielding $\mathcal{D}_{h}$ resp. λ and relations between the different cooling characteristics are given.

I.1. $\mathcal{D}_{h}$ from heat production rate and steady state temperature difference.

$$\vartheta_c = t_c - t_a = \frac{1}{m} \frac{q X^2}{\mathcal{D}_h c} \left(1 + \frac{2}{Bi}\right) \qquad \text{eq.I.1.}$$

yields for:

$$\mathcal{D}_h = \frac{1}{m} \frac{q X^2}{c \vartheta_c} \left(1 + \frac{2}{Bi}\right)$$

with m : shape factor

q : heat production rate $\left[\frac{\text{kcal}}{\text{kg h}} ; \frac{\text{W}}{\text{kg}}\right]$

X : shortest distance to heat exchanging surface $[\text{m}]$

t_c : center temperature $[^\circ\text{C}]$

t_a : ambient temperature $[^\circ\text{C}]$

c : specific heat $\left[\frac{\text{kcal}}{\text{kg K}} ; \frac{\text{I}}{\text{kg K}}\right]$

I.2. $\mathcal{D}_{h}$ from transient cooling

Pflug and Kopelman [6] have shown that a characteristic value f : 1/10 cooling time can be found from the cooling curve log temperature vs.time, fig. I.1. The same can be done using the linear temperature scale by determination of the time constant (fig. I.2.).

Table I.1. gives the relation between the different yardsticks for the rate of the cooling-down process, assuming an exponential relation between temperature drop and time.

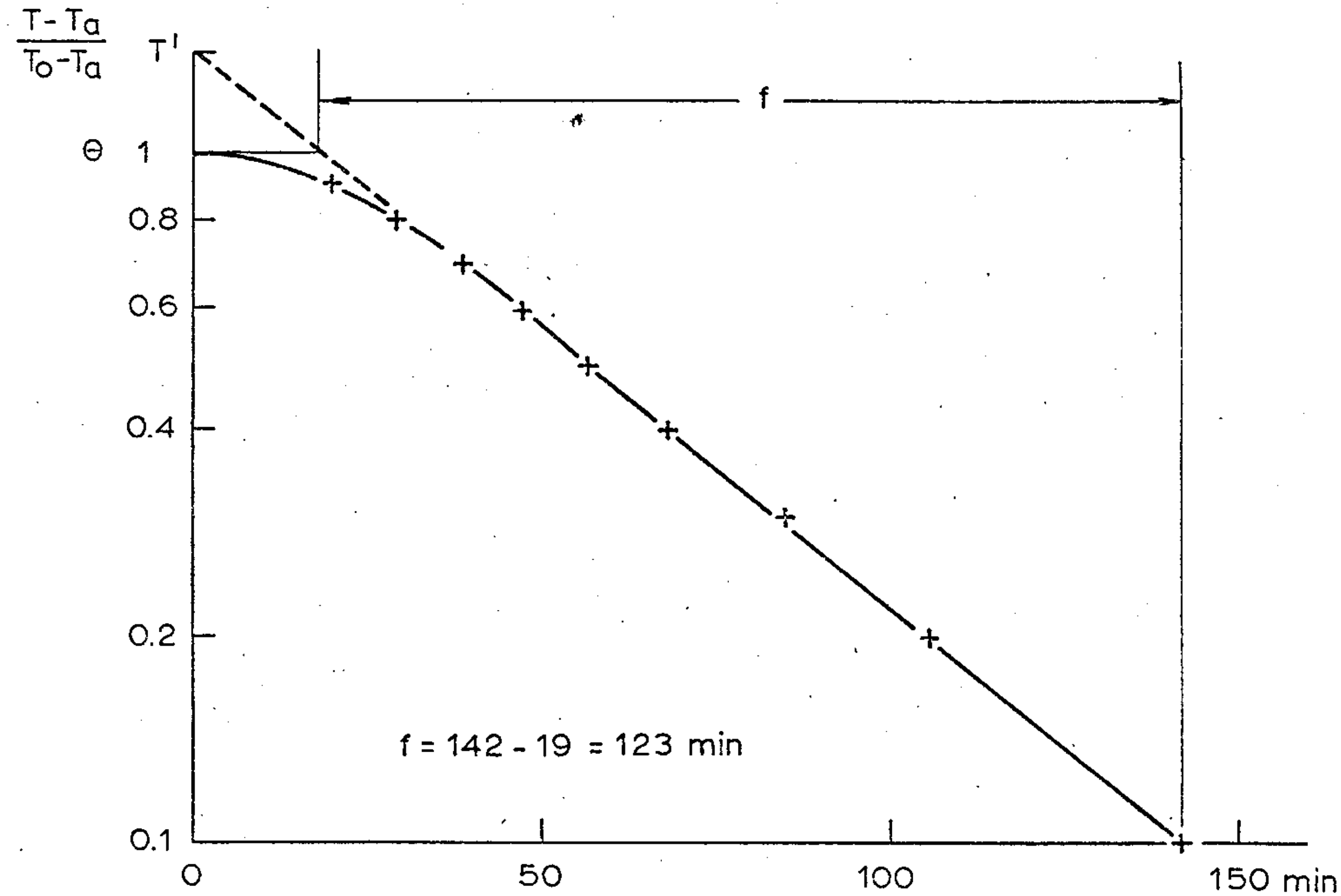


Fig. I.1. Temperature development during cooling down log θ vs. τ

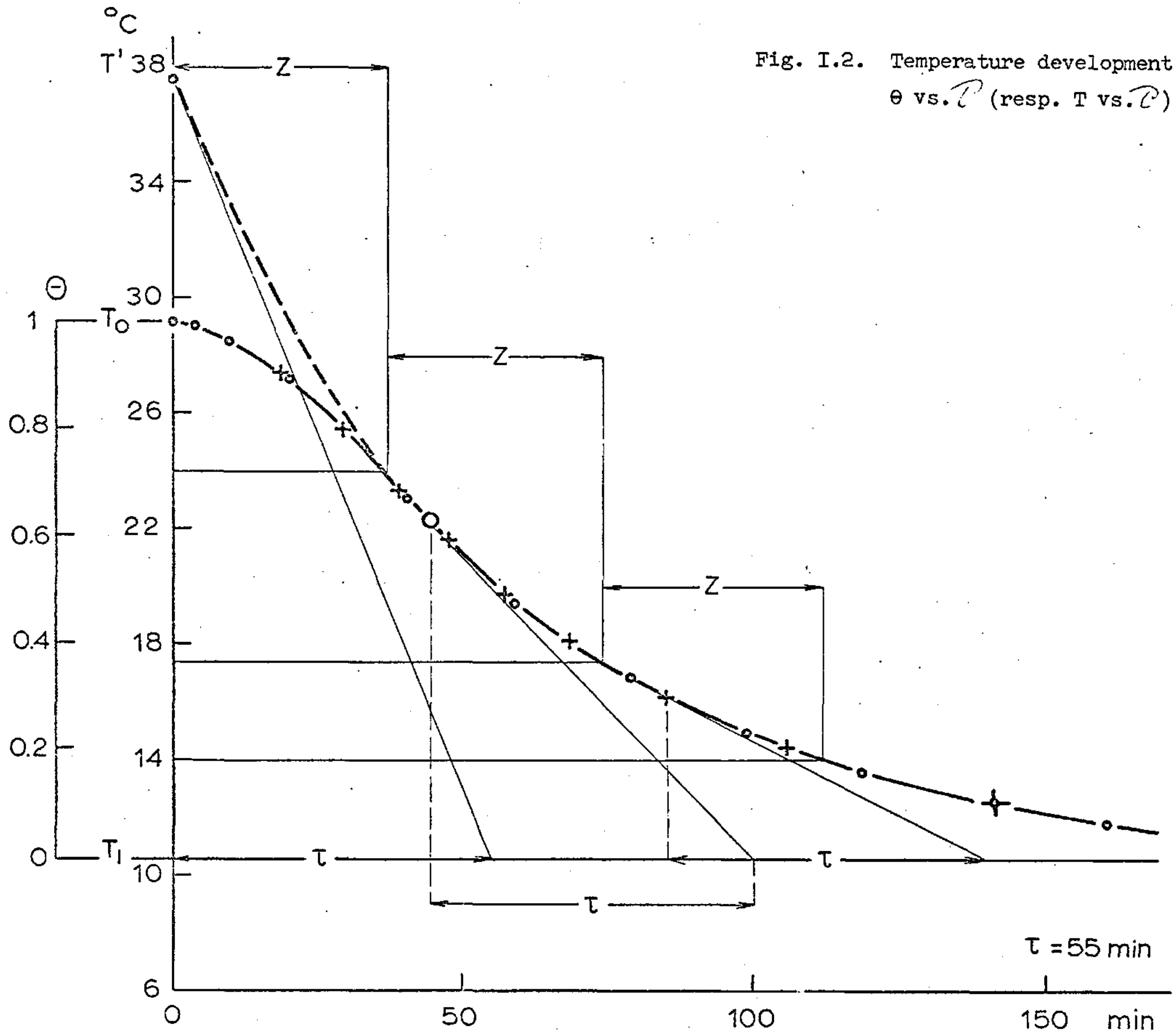


Fig. I.2. Temperature development during cooling down θ vs. τ (resp. T vs. τ)

Table I.1. Conversion table for cooling rates

	f	Z	$\frac{1}{CR}$	τ
f=-		3,32	2,303	2,303
Z	0,302	-	0,693	0,693
$\frac{1}{CR}$	$\frac{1}{2,303}$	$\frac{1}{0,693}$	-	1
τ	0,4342	1,443	1	-

f = $\frac{1}{10}$ cooling time

Z = $\frac{1}{2}$ cooling time

CR = cooling rate

τ = time constant

For the general case of three-dimensional heat transfer:

$$f = \frac{1}{\frac{1}{f_x} + \frac{1}{f_y} + \frac{1}{f_z}} \qquad \text{I.2.}$$

The relation between cooling characteristics and f is given in fig. I.3.

In the x - direction

$$\xi = f_x \frac{D_h}{x^2}$$

In the y - direction $\qquad$ I.3.

$$\eta = f_y \frac{D_h}{y^2}$$

In the z - direction

$$\zeta = f_z \frac{D_h}{z^2}$$

From I.2. and I.3. follows:

$$D_h = \frac{1}{f\left(\frac{1}{\xi x^2} + \frac{1}{\eta y^2} + \frac{1}{\zeta z^2}\right)} \qquad \text{I.4.}$$

where f : experimental $\frac{1}{10}$ cooling time (related to Z, CR, τ as indicated in table I.1.)

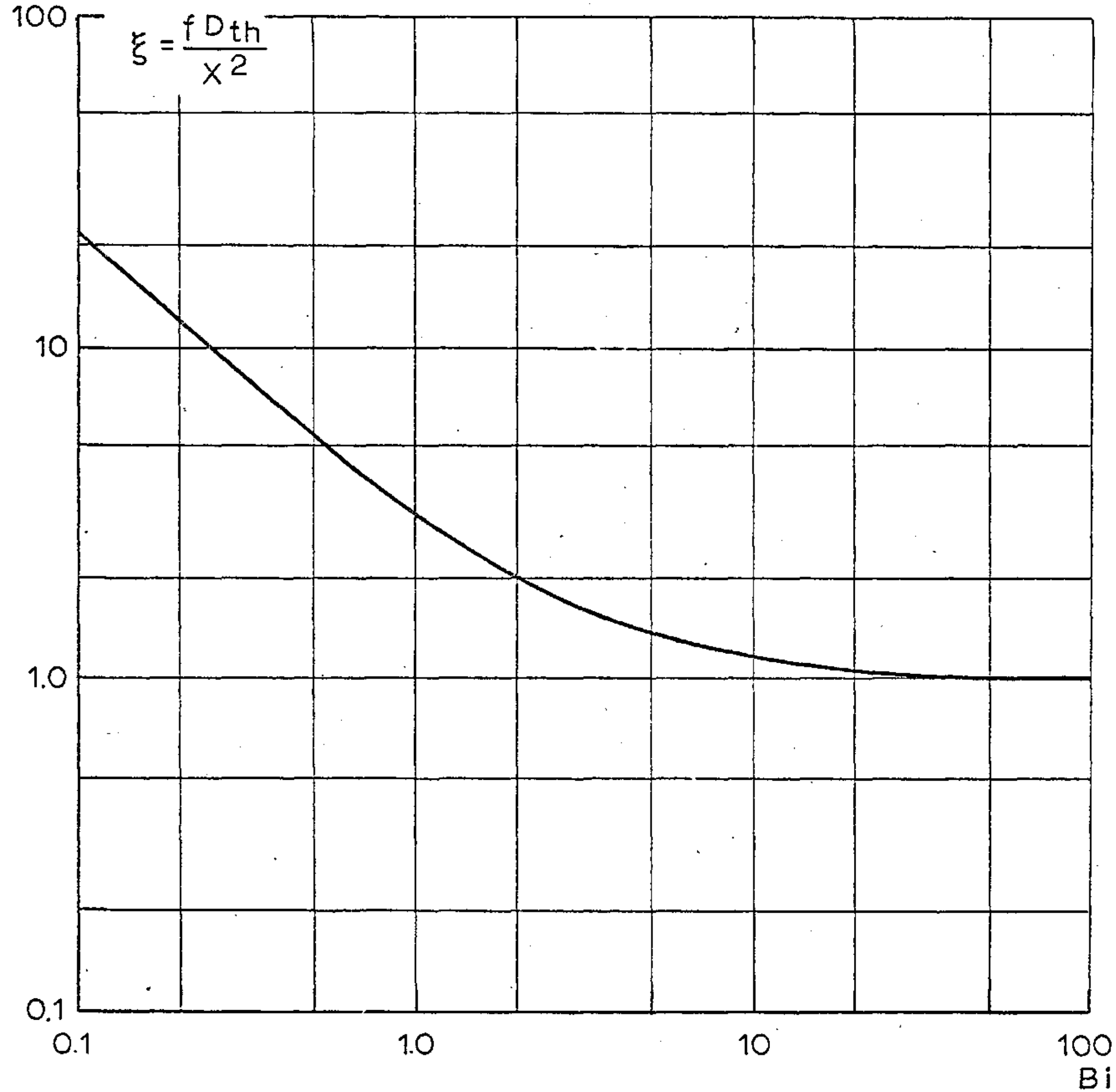


Fig. I.3. Dimensionless 1/10 cooling time Fo (Θ = 0,1) vs. Bi-number.

X, Y, Z : dimensions of the package

ξ, η, ζ : values from fig. I.4. for Bi_x, Bi_y, Bi_z

$$Bi_x = \frac{k_x X}{\lambda}$$

$$Bi_y = \frac{k_y Y}{\lambda}$$

$$Bi_z = \frac{k_z Z}{\lambda}$$

with k : heat transfer coefficient in X, Y, Z, direction

λ : thermal conductivity

As λ is also incorporated in the thermal diffusivity

$$D_{th} = \frac{\lambda}{c\rho}$$

it is necessary to check the assumed value of Bi by calculation from the value found for D_{th}.

and to recalculate if there is a reasonable deviation. This procedure gives no satisfying results with large air penetration (see under 3.1.). Another weakness is the introduction of the heat transfer coefficient, which becomes a heat transmission coefficient in case of insulating package material. This value has to be estimated for the evaluation.

Appendix II Tomato ; application of the theory

In this appendix the product tomato is treated in detail; data of product and packages are given first. The third part contains the calculations.

II.1. Product data:

1. Size: 35 mm and over but under 40 mm
   40 mm " " " " 47 mm
   47 mm " " " " 57 mm
   57 mm " " " " 67 mm
   67 mm " " " " 77 mm
   77 mm " " " " 87 mm

2. Color grades: green
   turning
   pink (pink orange)
   red

3. Freezing point: -0,6 °C

4. Bulk density: 560 kg/m³ (size 47 till 57)

5. Thermal conductivity of the product: 0,5 kcal/m h °C

6. Thermal conductivity in the package: 0,28 kcal/m h °C +)

7. Product density: circa 1000 kg/m³

8. Specific heat: 0,94 kcal/kg °C

9. Heat of respiration: kcal/ton 24 h (influence of CA, see fig.II.1)

	1 °C	12 °C	25 °C
green	270	800	2250
turning	-	-	4060
pink (pink orange)	310	1490	3050
red	220	620	1640

10. Rate of initial temperature rise: °C/h

	1 °C	12 °C	25 °C
green	0,01	0,04	0,10
turning	-	-	0,18
pink (pink orange)	0,01	0,07	0,13
red	0,01	0,03	0,07

+) without influence from convection

11. "Safe radius" for $\vartheta_c = 1^\circ C$ in package: cm

	$1^\circ C$	$12^\circ C$	$25^\circ C$
green	28,9	16,8	10,0
turning	-	-	7,5
pink (pink orange)	27,0	12,3	8,6
red	32,0	19,1	11,7

12. Evaporation: $E'' = 14 \pm 50\% \frac{1}{h}$ $(q'' = 560 \frac{kg}{m^3})$

(from respiration process) gr.10^{-3}/kg h

	$1^\circ C$	$12^\circ C$	$25^\circ C$
green	1,78	5,34	14,98
turning	-	-	30,40
pink (pink orange)	2,06	9,92	28,32
red	1,47	4,12	10,92

13. CO_2-production: gr.10^{-3}/kg h

	$1^\circ C$	$12^\circ C$	$25^\circ C$
green	4,37	13,07	36,71
turning	-	-	74,48
pink (pink orange)	5,06	24,30	49,78
red	3,61	10,09	26,75

14. Ethyleen production: gr.10^{-6}/kg.h (at $28^\circ C$)

green	0,07
turning	1,50
pink (pink orange)	2,02
red	1,67

15. Keepability: days (see following figures)

	$8^\circ C$	$12^\circ C$	$16^\circ C$	$20^\circ C$
green	-	-	-	-
turning	-	20	12	7
pink (pink orange)	-	18	10	5
red	14	10	6	3

16. Packages:
1. wooden tray
2. cartons
3. corrugated paperboard
4. plastic
5. plastic foam

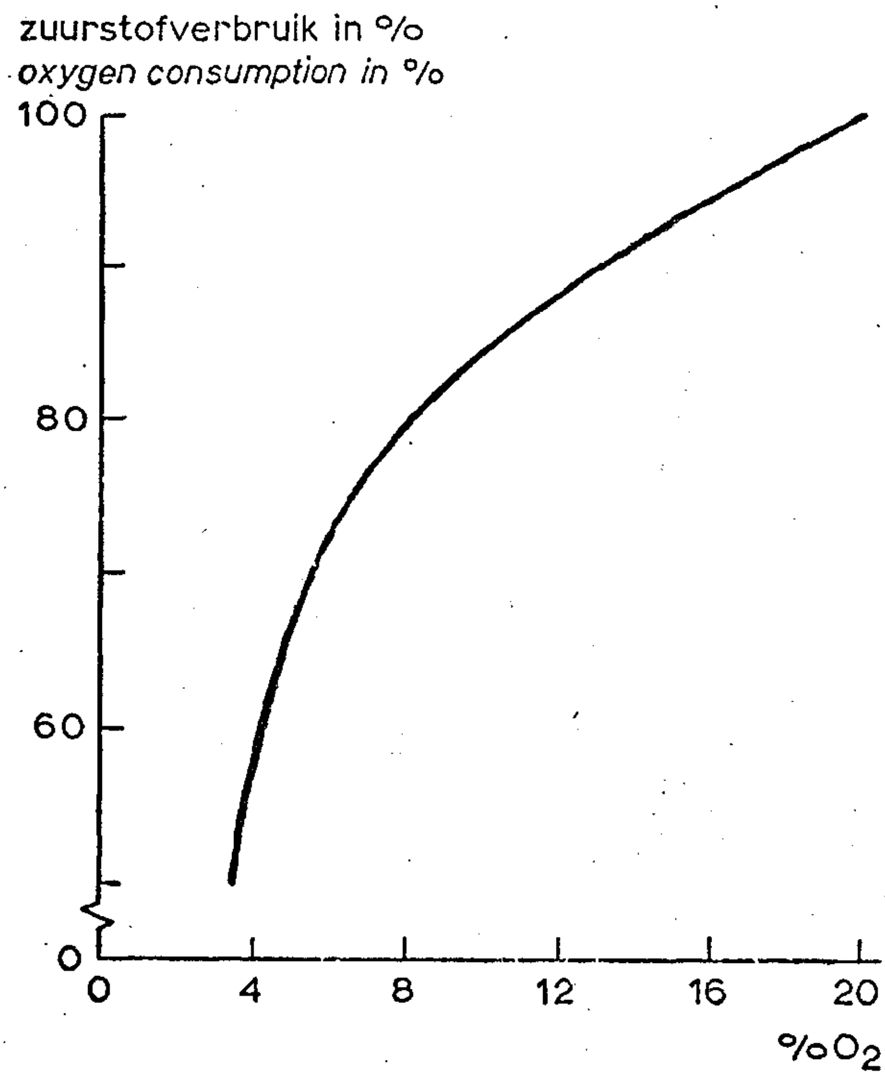


Fig. II.1.: Respiration rate of tomatoes (oxygen consumption) as a function of oxygen content of the atmosphere.

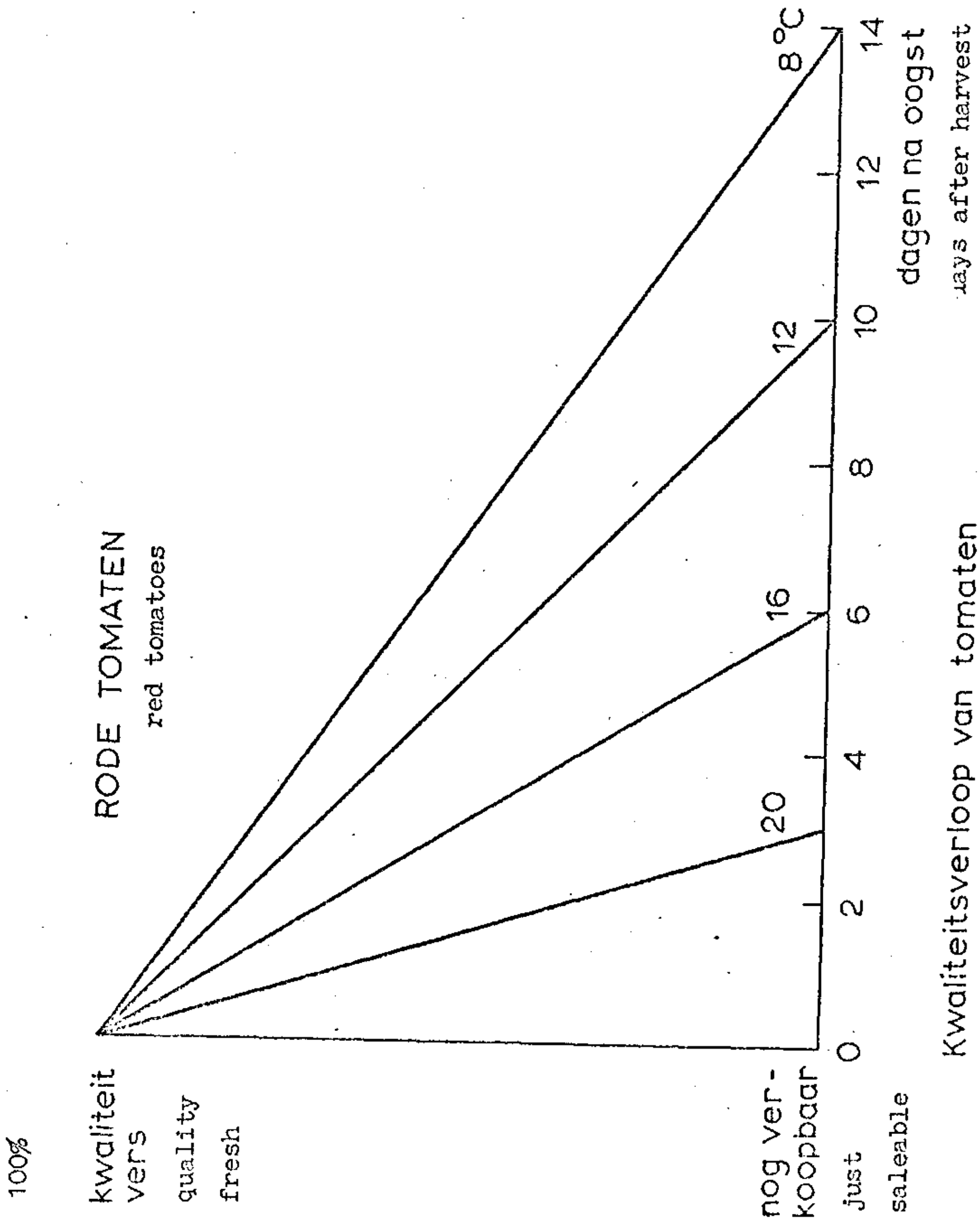
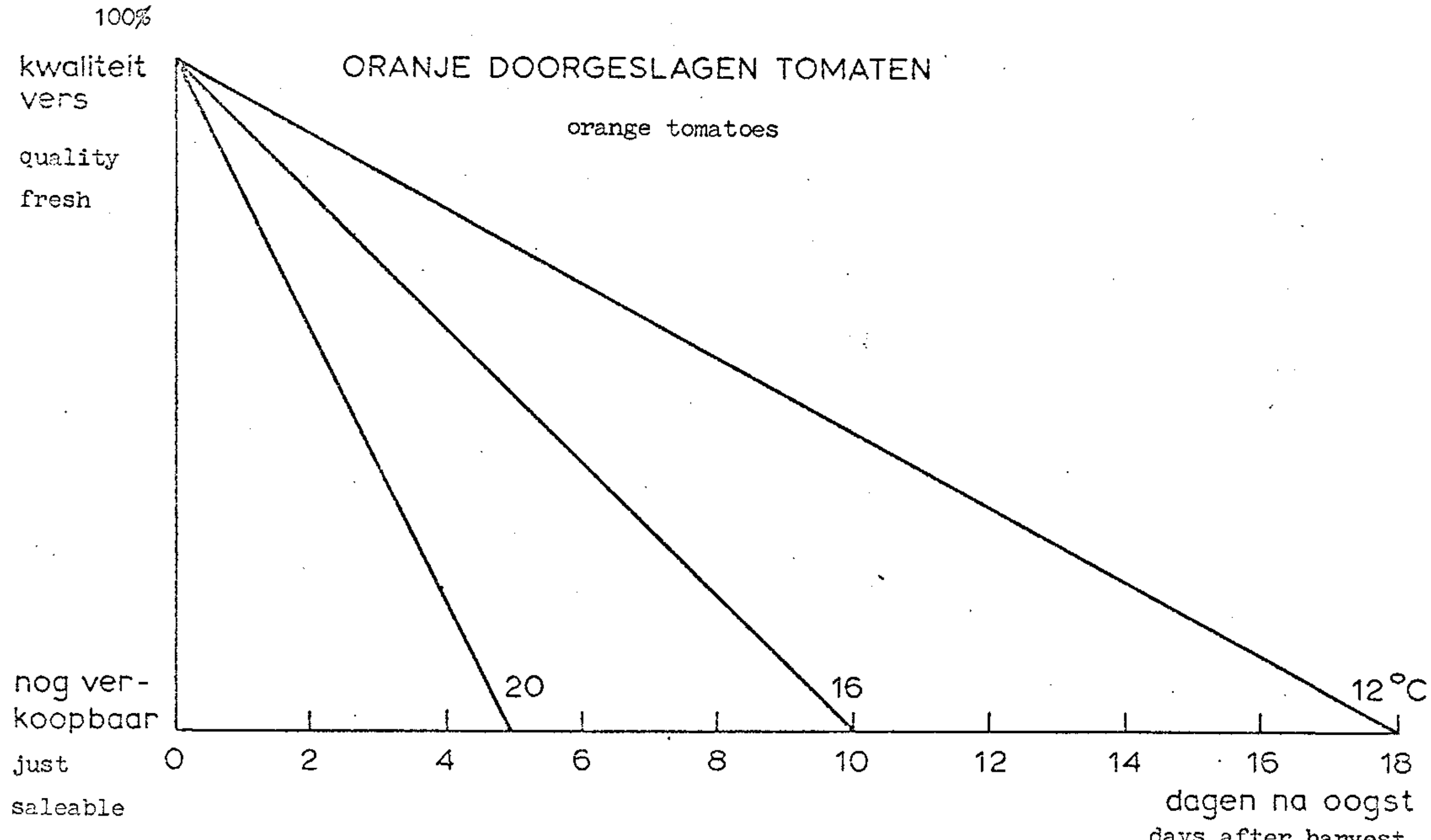


Fig. II.2 Kwaliteitsverloop van tomaten
quality decay of tomatoes



Kwaliteitsverloop van tomaten

Fig. II.3 quality decay of tomatoes

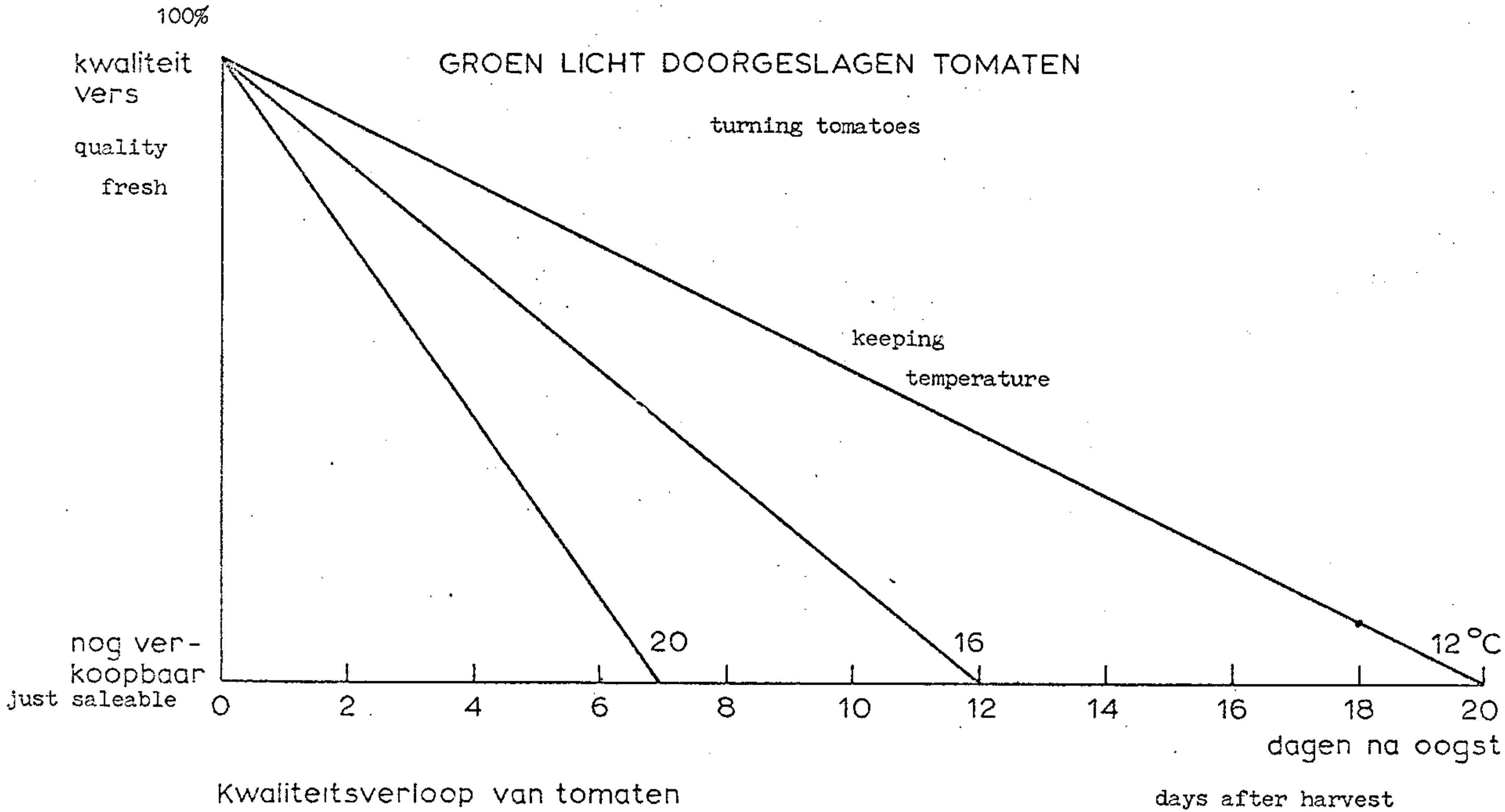
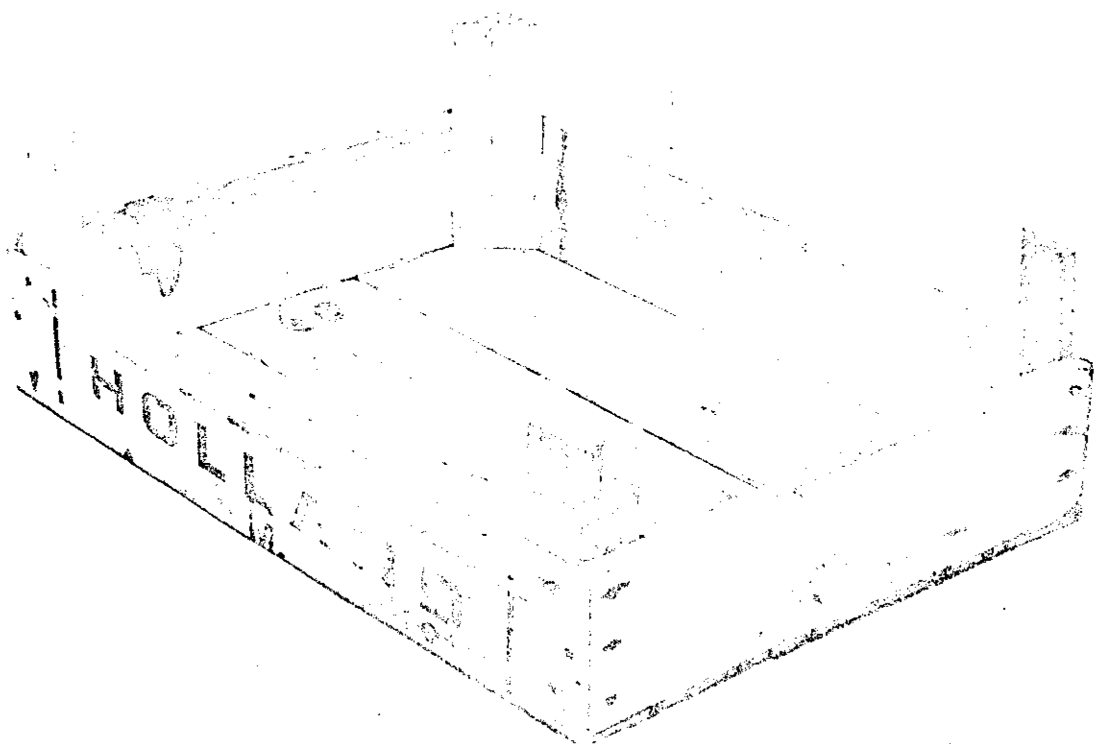


Fig. II.4 quality decay of tomatoes

II.2 Package-properties

1. Wooden tray; Package data:

dimensions	40 x 30 x 14 cm (L x W x H)
weight, tara	0,9 kg
gross volume	16,8 dm^3
net volume product weight	6 kg
product density in package	360 kg/m^3
specific weight, dry	510 kg/m^3
specific weight, wet(90% R.H.)	550 kg/m^3
specific heat	0,6 kcal/kg °C ($\pm$ 0,05)
thermal conductivity of material	0,12 kcal/m h°C ($\pm$ 0,02)
wall thickness sides and bottom	0,4, fronts 0,9 cm
k-value of package	
water vapour conductivity	
CO_2-conductivity	



II.2. 2. Cartons; Package data:

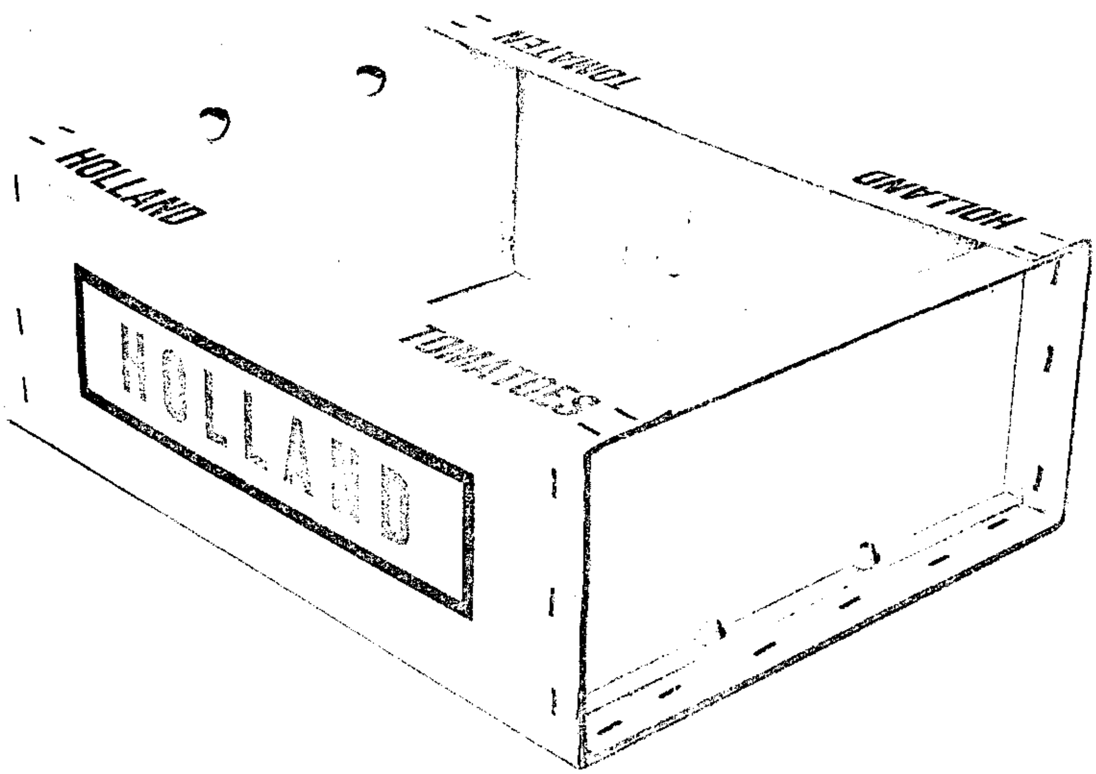
dimensions	40 x 30 x 14 cm (L x W x H)
weight, tara	0,45 kg
gross volume	16,3 dm^3
net volume product weight	6 kg
product density in package	370 kg/cm^3
specific weight, dry	1100 kg/m^3
specific weight, wet (90%)	
specific heat	0,32 kcal/kg °C
thermal conductivity of material	0,056 kcal/m h°C (± 0,001)

wall thickness sides and bottom 0,1; fronts 0,2 cm

k-value of package

water vapour conductivity

CO_2-conductivity



II.2. 3. Corrugated paperboard; Package data:

dimensions

weight, tara

gross volume

net volume product weight

product density in package

specific weight, dry

specific weight, wet (90% R.H.)

specific heat

thermal conductivity of material

wall thickness

k-value of package

water vapour conductivity

CO_2-conductivity

II.2. 4. Plastic; Package data:

dimensions

weight, tara

gross volume

net volume product weight

product density in package

specific weight, dry

specific weight, wet (90% R.H.)

specific heat

thermal conductivity of material

wall thickness

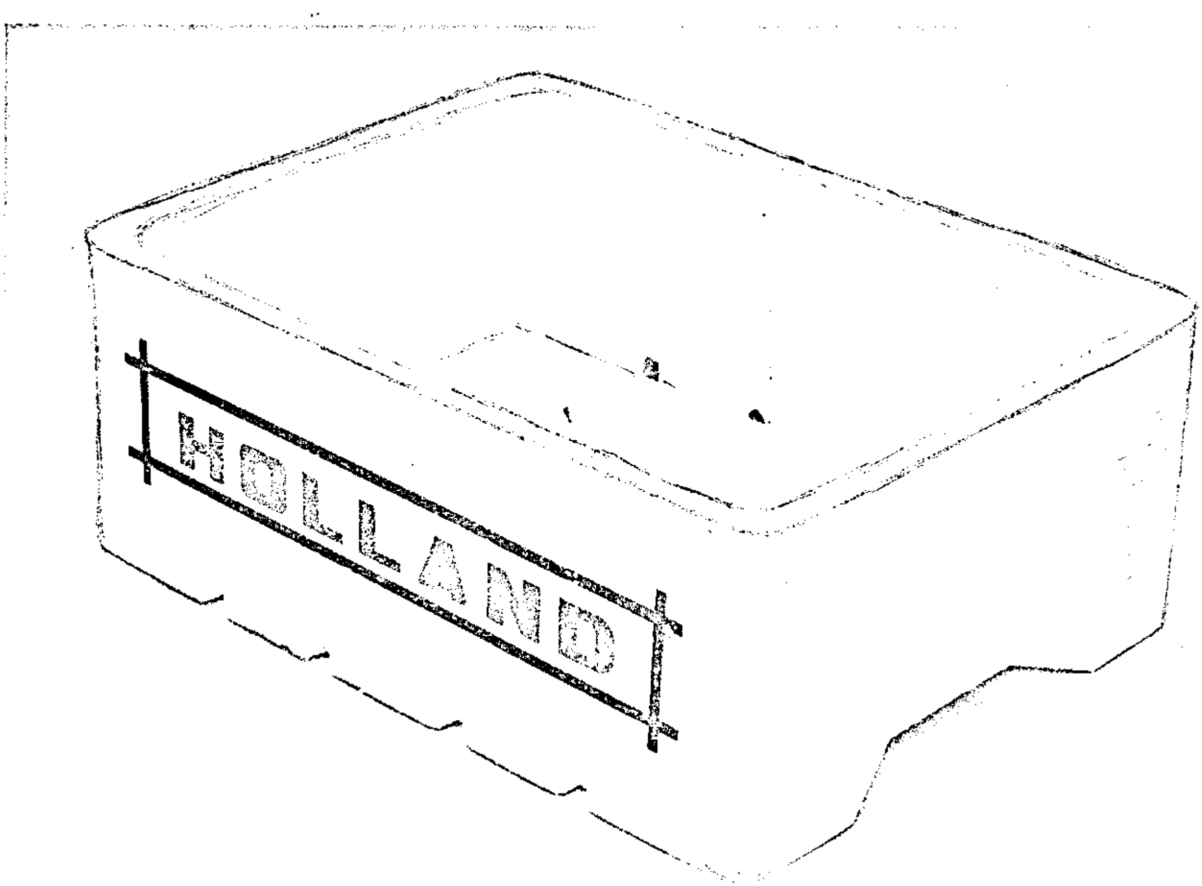
k-value of package

water vapour conductivity

CO_2-conductivity

II.2. 5. Polystyrene foam; package data :

dimensions	40 x 30 x 15 cm (L x W x H)
weight, tara	0,14 kg
gross volume	18 dm^3
net volume	14,5 dm^3
net volume product weight	6 kg
product density in package	330 kg/m^3
specific weight, dry	35 kg/m^3
specific weight, wet (90% R.H.)	
specific heat	0,33 kcal/kg °C
thermal conductivity of material	0,030 kcal/m h°C (± 0,003)
wall thickness walls 1,0; bottom 1,5 cm	
k-value of package	3 ; 2 $kcal/m^2 h °C$
water vapour conductivity : walls : 0,36 $\frac{m}{h}$	
CO_2-conductivity	



II.3. Example for the use of the given data

The aim is to determine the conditions-temperature and humidity-for storage or transport during a given time.

The basic information is the keepability of the produce as depending on time. From this information the temperature level for the wanted time has to be taken.

The second step is to find the conditions in the store, resp. vehicle/container which guarantee the wanted temperature level of the product. In doing that, the following points have to be considered:

No uniform temperature has to be expected in a hold (cold store, reefer room, container). The temperature differences in such a room consist of a couple of increments:

1) the temperature difference of the cooling air, which absorbs the total heat load of the hold, ΔT_{air}
2) the temperature difference in a package or a stack, ϑ_c (eq. 17), depending on heat generation, insulating properties of the product and the package, as well as characteristic dimensions,
3) temperature difference across aircooler if no continuous capacity control of the cooling capacity is applied,
4) response of the temperature field on the variation of air temperature of the hold in case that 3) is valid.

As a continuous capacity control is becoming normal equipment, only 1 and 2 have to be treated further.

1. The temperature gain of the air along its path through the hold is to be expressed by:

$$\Delta T_A = \frac{Q_o + Q_p}{\Phi_A \; (c_p \rho)_A}$$

where: Q_o stands for the heat load other than by respiration of produce: Q_p

$(c_p \rho)_A$: the volumetric specific heat of air: ca. 0,3 $\frac{kcal}{m^3 \, {}^oC}$

2. The steady state temperature difference between the center of resp. stack and the ambient air is represented by:

$$\vartheta_c = \frac{q\,X^2}{m \cdot D_{th} \cdot c_m}\left(1 + \frac{2}{Bi}\right) \qquad (17)$$

after a time $\tau > \frac{X^2}{D_{th}}\left(1 + \frac{2}{Bi}\right)$

If $Bi \gg 1$

$$\vartheta_c = \frac{q\,X^2}{m\,D_{th}\,c_m},$$

If $Bi \ll 1$

$$\vartheta_c = \frac{q\,X\,\rho_m'}{m \cdot k}$$

where: q heat of respiration in $\frac{\text{kcal}}{\text{kg h}}$

m a shape factor, depending on the geometric

X shortest distance from center to heat exchanging surface

D_{th} the effective thermal diffusivity (experimental)

$$Bi = \frac{k\,X}{\lambda} \quad \text{resp.} \quad \frac{k\,X}{D_{th}\,c_m\,\rho_m'}$$

k = heat transmission coefficient to surroundings

For tight packages with restricted internal aircirculation the effective thermal diffusivity D_{th} can be calculated approximately by:

$$D_{th} = \frac{\lambda''}{c \ \rho''}$$

where λ'' = thermal conductivity of product in package

= ca. $(1 - \varepsilon)\,\lambda$

with ε : porosity

$$\varepsilon = 1 - \frac{\rho''}{\rho}$$

ρ'' product density in package

ρ product density

λ = thermal conductivity of product

Till a time $\tau \leq 0{,}1 \dfrac{x^2}{D_{th}} \left(1 + \dfrac{2}{Bi}\right)$

temperature rise in the center of the stack is:

$$\frac{\Delta \vartheta}{\Delta \tau} = \frac{q}{c} \quad \left[\frac{K}{h}\right]$$

3. "Safe Radius"

If a maximum limit for the product temperature T_{max} is given the "Safe Radius" of the stack can be determined: the smallest distance for heat transfer, within which the temperature difference ϑ_c does not exeeed the given value:

$$R_{\vartheta_c} \leq \frac{\lambda''}{R} \left\{ \sqrt{1 + \frac{m\, k^2 \vartheta_c}{\lambda''\, Q_{ta} + \vartheta_c}} - 1 \right.$$

$$\vartheta_c = T_{max} - \left(t_a - \Delta T_A \right).$$

R_{ϑ} thus depends on the produce: Q, λ

on the package materiaal : k
on the stacking method : m
on the temperature conditions : t_a, ϑ_c
and ventilation: Q, λ
reflecting the influences of produce, package, stack and surroundings (see tables)

This conditions are:

t_a = 10 ; 20^oC
Q_{ta} = 530   1320 $\frac{\text{kcal}}{\text{ton 24h}}$
red   pink
(Q_1 = 1.08   1.06   -)

ϑ_c = 1 ; 2 ; 5 K
ρ'' = 350 $\frac{kg}{m^3}$
λ'' = 8.55 ; 1.67 $\frac{\text{kcal}}{\text{m h k}}$
ca. 0   ca. 0.3 m/sec. outside air velocity
k = 3 ; 6
(plastic foam);(carton)
m = 2 (row)

Table II, 1 Calculation of the "Safe radius"

λ'' kcal/m h k	K kcal/m^2hk	m —	ϑ_c K	$Q_{ta+\vartheta_c}$ kcal/ton 24h	t_a °C	R_{ϑ} m
0.55	3	2	1	570	10	0.22
				1400		0.11
			2	620		0.34
				1490		0.18
			5	770		0.54
				1700		0.32
			1	1200	20	0.13
				2400		0.07
			2	1300		0.20
				2550		0.12
			5	1640		0.33
				3050		0.21
0.55	6	2	1	570	10	0.28
				1400		0.16
			2	620		0.41
				1490		0.24
			5	770		0.61
				1700		0.39
			1	1200	20	0.18
				2400		0.11
			2	1300		0.26
				2550		0.17
			5	1640		0.40
				3050		0.27

Table II, 2 Calculation of the "Safe radius"

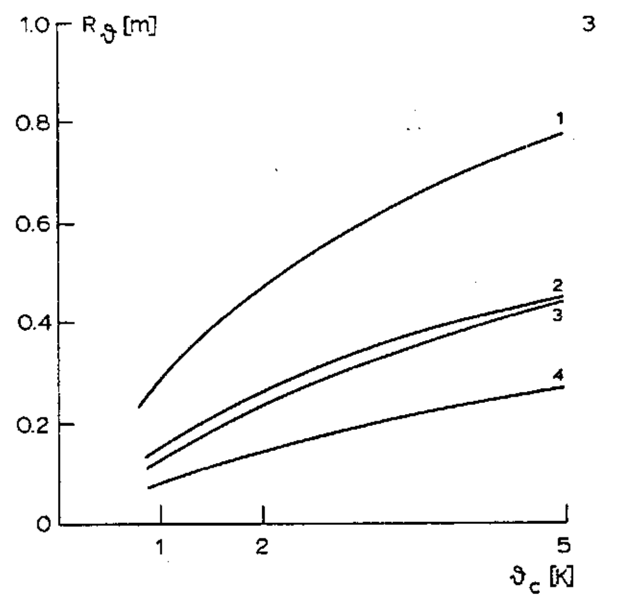
λ'' kcal/m h k	K kcal/m²hk	m —	ϑ_c K	$Q_{ta+\vartheta_c}$ kcal/ton 24h	t_a °C	R_ϑ m
1.67	3	2	1	570	10	0.29
				1400		0.13
			2	620		0.47
				1490		0.23
			5	720		0.78
				1700		0.44
			1	1200	20	0.15
				2400		0.08
			2	1300		0.26
				2550		0.14
			5	1640		0.45
				3050		0.27
1.67	6	2	1	570	10	0.41
				1400		0.21
			2	620		0.63
				1490		0.34
			5	770		0.97
				1700		0.59
			1	1200	20	0.24
				2400		0.14
			2	1300		0.38
				2550		0.23
			5	1640		0.60
				3050		0.40

fig. II.5: "Safe Radius" R_ϑ depending on excess center temperature ϑ_c for stacks of produce in stagnant ambient air $\lambda' = 0.55 \frac{kcal}{mhk}$ in different packages, at various conditions of heat generation.

	heat generation $Q_{ta.} [\frac{kcal}{ton\ 24h}]$	ambient temperature $t_a [°C]$	
1	530	10	red tomatoes
2	1120	20	
3	1320	10	pink tomatoes
4	2250	20	

Safe Radius

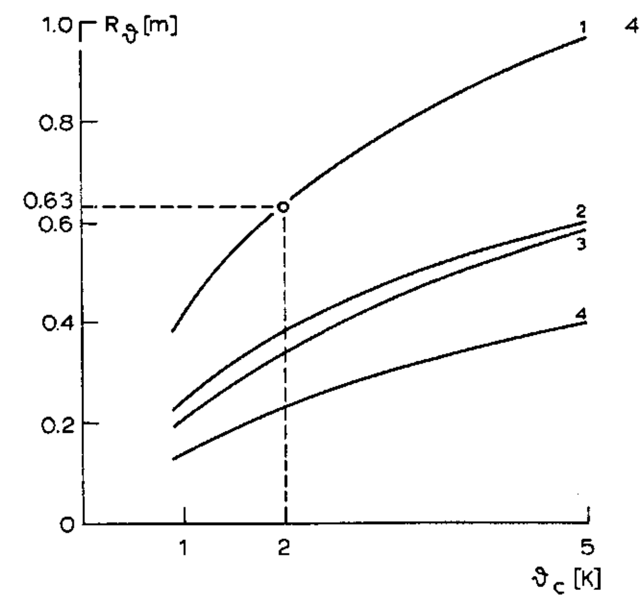
$K = 3 \frac{kcal}{m^2hk}$ - polystyrene foam box



excess center temperature

Safe Radius

$K = 6 \frac{kcal}{m^2hk}$ — carton box

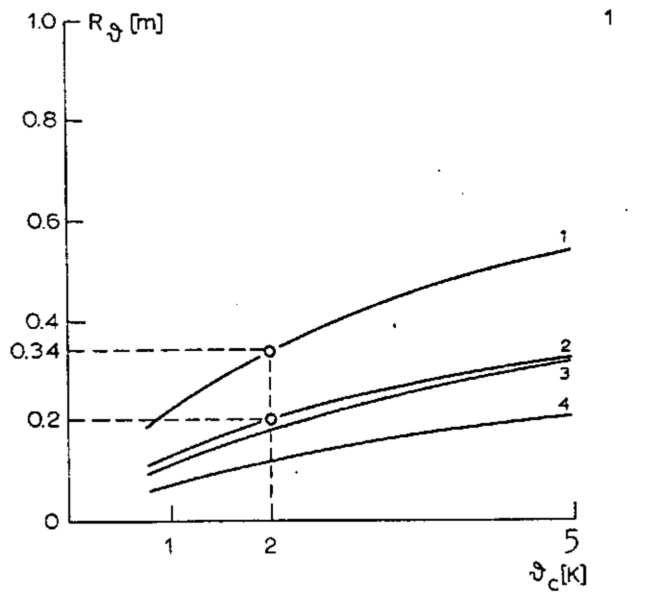


excess center temperature

fig. II. 6 : "Safe Radius" R_{ϑ} depending on excess center temperature ϑ_c for stacks of produce in slowly moving air (ca. 0,3 m/sec.) $\lambda' = 1.6 \; \frac{kcal}{m\,h\,K}$ in different packages, at various conditions of heat generation.

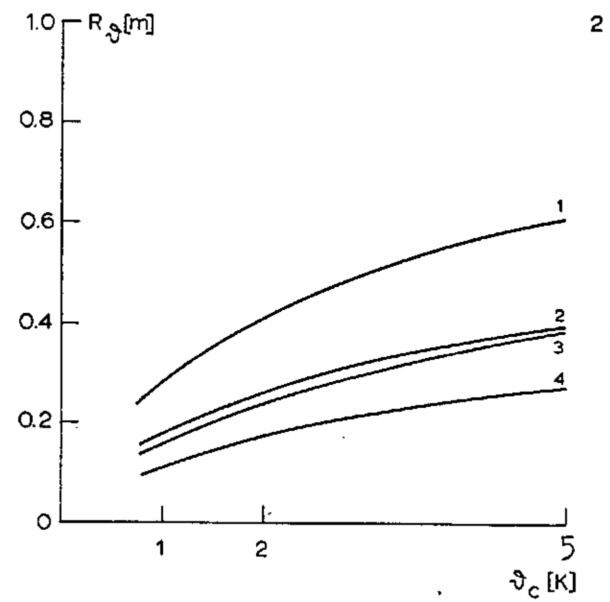
	heat generation Q_{ta} $\left[\frac{kcal}{ton\ 24h}\right]$	ambient temperature t_a [°C]	
1	530	10	red tomatoes
2	1120	20	
3	1320	10	pink tomatoes
4	2250	20	

Safe Radius $k = 3 \frac{kcal}{m^2 h K}$ - polystyrene foam box.



excess center temperature

Safe Radius $k = 6 \frac{kcal}{m^2 h K}$ - carton box



excess center temperature

Discussion

From the figures II,1&2 the increase of the "Safe Radius" with excess center temperature is obvious, also the decrease with heat generation. In order to keep the temperature difference in the stack below the dangerous value, the shortest path of heat transfer (half width of a row) must be smaller than the "Safe Radius".
Table II,3 relates the "Safe Radius" to the shortest path of heat transfer of different patterns.

The information to be derived from figures II,(1&2) and table II,3 is as follows:

Question:
If red tomatoes have to be transported during more than 2 à 3 days and the maximum temperature may not exceed 12°C at a maximum ambient temperature of 10°C, which stacking pattern has to be used?.

Table II .3: "Safe Radius" related to stacking pattern

no	$X \leq R_\varphi$ m	unit	stacking pattern
1	0.15	box 30x40	single row, lengthwise
2	0.2	box	single row, crosswise
3	0.3	box	double row, lengthwise
4	0.4	box	double row, crosswise
5	0.5	pallet 100x120	single row, lengthwise
6	0.6	pallet	single row, crosswise
7	1	pallet	double row, lengthwise
8	1.2	pallet	double row, crosswise

Answer:

Carton boxes inside resonable ventilation conditions (fig.II 1(1) may be stacked on pallets in single rows, crosswise ($X = 0.6$ m) for $X < R_{2K} = 0.63$

Polystyrene foam boxes under unfavourable ventilation conditions (fig. II,1(1) have to be stacked in single rows crosswise or double rows lengthwise in order to keep the excess center temperature below 2K : $X < R_{2K} = 0.34$

Airchannels between rows have to be at least 2 cm wide.

4. Check for evaporation:

Evaporation from the produce may reduce the net heat release. The influence of this effect can be checked by the following calculation, which is performed for too cases:

4.1. crosswise pallets rows of cartons $X = 0{,}6\,m$ at $10^{o}C$, R.H. 90% ambient temperature, v_A = ca. 0.3 m/sec.

4.2. rows of polystyrene foam boxes, crosswise $X = 0{,}2\,m$ at $t_a = 20^{o}C$ R.H. 70%, v_A = ca. 0 m/sec.

The dimensionless water vapour concentration in the center of the stack is given by eq. 14

$$T' = 1 - \frac{\frac{H}{D''}}{\frac{H}{D''}\cosh\left(X\sqrt{\frac{E''}{D''}}\right) + \sqrt{\frac{E''}{D''}}\sinh\left(X\sqrt{\frac{E''}{D''}}\right)}$$

In this equation H, E' and D' have to be inserted, whereas X is given.

4.1.1. <u>Water vapour transmission coefficiënt H</u>

The permeability of carton for water vapour can be given by

$$H_W = \frac{D}{\mu . d_W} = \frac{0{,}083}{10.0{,}001} = 8{,}3 \ \frac{m}{h}$$

The surface coefficient for water vapour transfer

$$H_S = \frac{\alpha}{c\rho} = \frac{7}{0{,}3} = 23\,\frac{m}{h}$$

The total water vapour transmission therefore is:

$$H = \frac{1}{\frac{1}{H_W} + \frac{1}{H_S}}$$

$$= \frac{1}{\frac{1}{8{,}3} + \frac{1}{23}}$$

$$\frac{1}{\underbrace{0{,}12 + 0{,}043}_{0{,}163}}$$

$$H = 6{,}15\ \frac{m}{h}$$

4.1.2. Evaporation number E''

In table 2 E for tomatoes is given, at a load density of ρ' 635 $\frac{kg}{m^3}$. Taking an average of 14 $\frac{1}{h}$, we get for ρ'' = 350 $\frac{kg}{m^3}$

$$E'' = E' \cdot \frac{\rho''}{\rho'}$$
$$= 14 \cdot \frac{360}{635} = 7.75 \frac{1}{h}$$

4.1.3. Diffusivity D''

The effective diffusivity of water vapour in the stack van be given as a function of porosity: ξ, and a convection number: ψ , which can be estimated from the thermal diffusity.

$$D'' = \psi \cdot \xi D.$$

where: $\psi = 1 - \sqrt{1-\varepsilon}$

and ε = porosity of the stack 0.65

$$\psi = 0.4.$$

and $\xi = \frac{\lambda'' - \lambda'}{\lambda_A}$

$$= \frac{1.67 - 0.28}{0.021} = 66$$

thus:

$$D'' = 0.4 \cdot 66 \cdot 0.0830 \frac{m^2}{h}$$
$$= 2.3 \frac{m^2}{h}$$

These values inserted in eq. 11
yield:

$$\Gamma = 0{,}6 = \frac{C_c - C_a}{C_{eq} - C_a}$$

which means that the maximum water vapour concentration
becomes

$$C_c = 0{,}6 \left(C_{eq} - C_a \right) + C_a$$

in this formula C_{eq} has to be taken at the center temperature $12^{o}C$ and C_a at the ambient conditions:

$$C_{s,\,12^{\circ}C} = 0.01066 \ \frac{kg}{m^3}$$

$$C_{eq} = 0.98 \cdot C_{s,\,12^{\circ}C} = 0.0105 \ \frac{kg}{m^3}.$$

$$C_a = 0.90 \cdot C_{s,\,10^{\circ}C} = 0.0084 \ \text{"}$$

$$C_{eq} - C_a = 0.0021 \ \text{"}$$

$$C_c = 0.6 \cdot 0.0021 + 0.0084$$

$$= 0.00126 + 0.0084 = 0.00968$$

The result shows relative humidity C_c/C_s, $12^{o}C$ of ca. 90%
in the center of the stack.

The water loss per kg product at the center of the stack:

$$W_c = \frac{E''}{\rho''} \cdot \left(C_{eq} - C_c \right)$$

$$\frac{7.75}{350} \cdot 0.0008 \ \frac{kg}{kg\,h}$$

$$= 0{,}017 \ \frac{g}{kg\,h}$$

and the net heat release:

$$q_{net} = q - W_c \cdot \gamma$$

$$= 0{,}026 - 0{,}017 \cdot 0.6$$

$$= 0{,}016 \ \frac{kcal}{kg \cdot h}$$

$$= 380 \ \frac{kcal}{ton \cdot 24h}$$

This qualifies the stacking pattern found from fig.
as a safe one for the chosen conditions.

4.2. Row of polystyrene foam boxes, crosswise

4.2.1. Water vapour transmission

σ = 1/30 of the sides of the polystyrene foam box is open for exchange. This opening gives the largest contribution to the water vapour transfer. For this surface, the transmission coefficient for water vapour is calculated with the wall thickness δ:

$$H_a = \frac{D_w}{\delta} = \frac{830 \cdot 10^{-4}}{0.01} = 8.3 \ \frac{m}{h}$$

The rest of the surface is covered by polystrene foam,

$$\rho_p = 35 \ \frac{kg}{m^3}$$

with a diffusion resistance coefficient of = 100, thus

$$H_w = \frac{D_w}{\mu \ \delta} = 0{,}083 \ \frac{m}{h}$$

These two contribution are working in parallel.

$$H = \sigma H_a + (1 - \sigma) H_w$$
$$= \frac{1}{30} \ 8.3 + \frac{29}{30} \ 0.083$$
$$= 0.28 + 0.08$$
$$= 0.36 \ \frac{m}{h}$$

4.2.2. Evaporation number

$E'' = 7.75$ (see p. 36)

4.2.3. Diffusivity.

$$D'' = \psi \cdot \xi \cdot D$$

$$\psi = 1 - \sqrt{1-\varepsilon}$$

$$\varepsilon = 0.53$$

$$\psi = 0.315$$

$$\xi = \frac{\lambda'' - \lambda'}{\lambda_A}$$

$$= \frac{0.55 - 0.28}{0.021} = 13$$

$$D'' = 0.315 \cdot 13 \cdot 0.0830 \frac{m^2}{h}$$

$$= 0.333 \frac{m^2}{h}$$

From eq.11 we get after inserting these values:

$$\Pi = 0.83$$

which means that the water vapour concentration in the center reaches

$$C_c = 0.83 (C_{eq} - C_a) + C_a$$

$$= 0.0101 \qquad C_c/C_s : 12^\circ C$$

The relative humidity in the center thus approaches 95% at 10°C 90% outside conditions.

The water loss:

$$W_c = \frac{E''}{\rho''} (C_{eq} - C_c)$$

$$= \frac{7.75}{350} \cdot 0.0003$$

$$= 0.0066 \frac{g}{kg\,h}$$

and

$$q_{net} = q - W_c \cdot r$$

$$= 0.026 - 0.0066 \cdot 0.6$$

$$= 0.022 \frac{kcal}{kg\,h}$$

$$= 527 \frac{kcal}{ton\ 24\,h}$$

for 20°C, 70% outside condition we can calculate the relative humidity in the center as:

$$\frac{C_c}{C_{s,22°C}} = \frac{0.83\,(C_{eq} - C_a) + C_a}{C_{22°C}}$$

$$C_{s,22°C} = 0.01942\ \frac{kg}{m^3}$$

$$C_{eq} = 0.98 \cdot C_s;22°C = 0.01902\ \frac{kg}{m^3}$$

$$C_a = 0.7 \cdot C_s;20°C = 0.01210\ \text{"}$$

$$\overline{0.00692\ \text{"}}$$

$$\frac{C_c}{C_{s;22°C}} = \frac{0.00575 + 0.01210}{0.01942} = 0.93$$

The water loss then becomes:

$$W_c = \frac{E''}{\rho''}\,(C_{eq} - C_c) = \frac{7,75}{350} \cdot 0,00107 = 0,0236\ \frac{g}{kg\,h}$$

and the net heat release:

$$q_{net} = q - W_c \cdot r = 0.064 - 0.0236 \cdot 0,6 = 0,040 - \frac{kcal}{kg \cdot h} = 960\ \frac{kcal}{ton . 24h}$$

Again indicating that the "Safe Radius" found from fig. II, 1 (1) is safe enough.

At this place one has to remember that this treatment of unit loads is only a first approximation. Further experimental and theoretical work is necessary as well as the development of suitable measuring techniques.

Wageningen, 17-6-'71.
HM/JK/HL.