How to Estimate the Heat Penetration Factors fh and fc, and the Heating Lag Factors jh and jc, required for Calculating the Sterilization or Pasteurization Times of Packaged Foods

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Summary:

The heat penetration factor fh is crucial in calculating the pasteurization or the sterilization time of packaged foods. This document explains how to calculate, or estimate, the heat penetration factor fh. Each explanation is illustrated with one or more worked examples.

For a quick reference, the next page gives an overview of the main factors which affect the heat penetration factor fh. It presents the equations to calculate the fh, and lists formula to convert a known fh to the new fh after a change in processing or packaging conditions.

Chapter 1 shows the basic equations to calculate the heat penetration factor fh of a packaged liquid or solid food. How this fh factor can be used in heat processing, is illustrated by a sterilization process calculation.

From tables with fh values in Chapter 2, a first rough estimation can be made of the heat penetration factor fh of a food product, packaged in a cylindrical metal can.
To use these tables, you need to know the product texture (solid or liquid), the packaging size (length L; diameter D), the retort conditions (rotation or still retort) and the heating medium (saturated steam, showering water, or full water).

Chapter 3 outlines the effects of the food packaging on the heat penetration factor fh: the material of the packaging (metal or glass); the shape of the packaging (cylindrical; brick; oval; cube; ball), and the packaging dimensions (length, height, width, etc), expressed as specific surface S (for a liquid food), or adapted squared specific surface S^{*2} (for a solid food), are included in the equations of the fh.

Tables of the partial heat transfer coefficients for several types of retorts, food textures and packaging materials, and equations to calculate the overall heat transfer coefficient U, are presented in Chapter 4. A list with the estimated overall heat transfer coefficients U for all types of packaged liquid foods may be of help in rapid calculations of the heat penetration factor fh. For packaged solid foods, not the overall heat transfer coefficient U, but the thermal diffusivity *a* (see Annex 3), or the thermal conductivity k of the solid is required.

Excel spreadsheet "*Heat penetration factor fh calculations.xls*" simplifies the tedious calculations of the specific surface of a food container, required to find its heat penetration factor fh. Chapter 5 explains, by means of 2 worked examples, how to use this spreadsheet to estimate the fh of both a packaged liquid food and a packaged solid food.

Several foods consist of solid food pieces, submerged in a liquid, or in a watery brine. Examples are beans in brine, sausages in brine, meat balls in gravy, etc. Chapter 6 lists equations how to calculate the heat penetration factor of such foods: first calculate the heat penetration factor of the container filled with brine only, and then add the calculated heat penetration factor of the largest solid piece of the food.

If the heat penetration factor fh of a packaged food is known, and the company wishes to change the packaging size, Chapter 7 presents size correction factors to calculate the new heat penetration factor. The size correction factor is proportional to the container's specific surface S for liquid foods, and proportional to the container's adapted squared specific surface S^{*2} for solid foods.

Chapter 8 presents packaging material correction factors for fh, in case a company intends to change the packaging material from metal to glass, or from glass to metal. The material correction factors depend also on the texture of the packaged food: solid or liquid.

Chapter 9 explains step-by-step how to obtain, from experimental heat penetration data, the penetration factors fh and fc, and the lag factors jh and jc. The experimental time-temperature data are used to construct a semi-log heating and a semi-log cooling graph, from which fh, jh, fc, and jc can be deduced. This data analysis is illustrated by an extensive example calculation, and concluded by a worked example.

Overview of factors which affect the heat penetration factor f_h

$$P_t = f_h \cdot {}^{10}\log\left(j_h \cdot \frac{T_R - T_{ih}}{T_R - T}\right) - 0.4 \cdot L$$

1) fh calculations, based on the composition and consistency of a food product:

LIQUID (convective) foods: $f_h = \frac{2.3 \cdot c_p \cdot \rho}{U \cdot S}$ [s]; $\left[\frac{1}{U} = \frac{1}{h_A} + \frac{1}{k_W/d_W} + \frac{1}{h_B} \right]$

with 4 min. < $f_{h,LIQUID}$ < 15 min.

Also: **Low viscous liquid** food: $0.4 < j_h < 1$: rotation; $j_h \approx 1$: still retort.

(Very) viscous liquid food: $1.2 < j_h < 1.8$: rotation; $j_h \approx 2$: still retort

SOLID (conductive) foods: $f_h = \frac{2.3 \cdot c_p \cdot \rho}{k \cdot S^{*2}} = \frac{2.3}{a \cdot S^{*2}}$ [s]; $[\, a = k/(c_p \cdot \rho)\,]$

with 25 min. < $f_{h,SOLID}$ < 200 min. For **solid food**: $j_h \approx 2$.

a = thermal diffusivity of the (solid) **food** [m^2/s]; $0.11 \cdot 10^{-6}\ m^2/s \le a \le 0.19 \cdot 10^{-6}\ m^2/s$.

Packaged LIQUID food, containing submerged SOLID PIECES:

$f_{h,\text{ liquid food with submerged solid}} = f_{h,\text{package with liquid only}} + f_{h,\text{ one submerged solid piece}}$.

2) Change in retort temperature T_R and/or change in initial food temperature T_{ih}

does not affect f_h, nor does it affect the lag factors j_h and j_c.

3) Change in packaging SIZE does not affect the lag factors j_h and j_c.

Change in packaging size, however, does affect f_h:

$f_{h,\text{ NEW packaging size}}$ = **Size conversion factor** $\cdot\ f_{h,\text{ OLD packaging size}}$

in which, for **packaged LIQUID foods: size conversion factor** = $S_{OLD\ Size}/S_{NEW\ Size}$;

and, for **packaged SOLID foods: size conversion factor** = $S^{*2}_{OLD\ Size}/S^{*2}_{NEW\ Size}$

Cylinder	$S_{Cylinder} = 2/H + 4/D$	$S^{*2}_{Cylinder} = 9.93/H^{*2} + 23.2/D^{*2}$
Brick	$S_{Brick} = 2/H + 2/L + 2/W$	$S^{*2}_{Brick} = 14.2 \cdot (1/H^{*2} + 1/L^{*2} + 1/W^{*2})$
Cube	$S_{Cube} = 6/D$	$S^{*2}_{Cube} = 42.6/D^{*2}$
Oval	$S_{Oval} = 2/H + 2/(BD) + 2/(SD)$	-
Sphere; ball	$S_{Ball} = 6/D$	$S^{*2}_{Ball} = 39.5/D^{*2}$

For **SOLID** foods, packaged in **GLASS**, * means: add 2x glass wall thickness to D*, H*, L*, W*.

4) Effect of change in packaging MATERIAL:

Changing from METAL packaging to GLASS packaging:

LIQUID: New $f_{h,Liquid,\ Glass} = \frac{S_{Metal}}{S_{Glass}} \cdot f_{h,Liquid,\ Metal} + \frac{2.3 \cdot c_p \cdot \rho}{S_{Glass}} \cdot \frac{d_{W,Glass}}{k_{W,Glass}}$

SOLID: New $f_{h,Solid,\ Glass} = \frac{S^{*2}_{Metal}}{S^{*2}_{Glass}} \cdot f_{h,Solid,\ Metal}$

Changing from GLASS packaging to METAL packaging:

LIQUID: New $f_{h,Liquid,\ Metal} = \frac{S_{Glass}}{S_{Metal}} \cdot f_{h,Liquid,\ Glass} - \frac{2.3 \cdot c_p \cdot \rho}{S_{Metal}} \cdot \frac{d_{W,Glass}}{k_{W,Glass}}$

SOLID: New $f_{h,Solid,\ Metal} = \frac{S^{*2}_{Glass}}{S^{*2}_{Metal}} \cdot f_{h,Solid,\ Glass}$

1. How do both the heat penetration factor f_h, and the heating lag factor j_h, affect the sterilization or pasteurization time? The sterilization time equation.

The pasteurization or sterilization time P_t of a packaged food product can be calculated by:

$$P_t = f_h \cdot {}^{10}\log\left(j_h \cdot \frac{T_R - T_{ih}}{T_R - T}\right) - 0.4 \cdot L \quad (1)$$

the sterilization or pasteurization equation.

Equations to calculate the heat penetration factor f_h are:

for **LIQUID** (= convective) foods:	for **SOLID** (= conductive) foods:
$f_h = \frac{2.3 \cdot c_p \cdot \rho}{U \cdot S}$ [s]	$f_h = \frac{2.3 \cdot c_p \cdot \rho}{k \cdot S^{*2}} = \frac{2.3}{a \cdot S^{*2}}$ [s]
For equation of S: see table 4.	For equation of S^{*2}: see table 4.
$\frac{1}{U} = \frac{1}{h_A} + \frac{1}{k_W/d_W} + \frac{1}{h_B}$ [(s m² °C)/J]	$a = k/(c_p \cdot \rho)$ [m²/s] ; usually $a \approx 1.1 \cdot 10^{-7}$ m²/s to $1.9 \cdot 10^{-7}$ m²/s. For some values of a: see Annex 3.
For values of h_A, k_W/d_W, and h_B: see tables 5, 6 and 7.	
4 min. < $f_{h,LIQUID}$ < 15 min.	**25 min. < $f_{h,SOLID}$ < 200 min.**
$0.8 < j_h < 1.2$ liquid food; rotation $1.0 < j_h < 1.4$ liquid food; still retort $1.2 < j_h < 1.8$ viscous food; rotation $1.6 < j_h < 2.0$ viscous food; still retort	$1.6 < j_h < 2.0$ viscous food; still retort $j_h = 2.0$ solid food

Table 1: Equations and estimated values of heat penetration factor f_h and heating lag factor j_h for liquid and solid foods.

Sources: Leniger (1975: 314); Lewis (1990: 308); Mohr (1988); Rahman (1995: 358 + 389); Holdsworth (1997:127; 130-138); Holdsworth (2007). In case of very flat cans (H < 3 cm), no rotation: see Mohr (1988).

in which

P_t Pasteurization or sterilization time of a packaged **food product** [s]; [min.];
= time from the moment the steam in the retort is switched on, to the moment the steam is switched off, and the cooling water is switched on.
Sometimes P_t is called the "*operator's process time*".

f_h Heat penetration factor of the **food product** [s]; [min.].
A high value of fh means that the food in the can heats up very slowly.
See tables 1, 2, and 3 to estimate values of fh.

j_h Heating lag factor of the **food product** [-].
Cylindrical packaging material: $0.4 \leq jh \leq 2.0$. Liquid foods: $jh \approx 0.8$ (rotation) to $jh \approx 1.4$ (still); viscous foods: $jh \approx 1.2$ (rotation) to $jh \approx 2.0$ (still); solid foods: $jh \approx 2.0$.
Ball shaped packaging material: maximum theoretical value of jh = 2.0.
Brick shaped packaging material: maximum theoretical value of jh = 2.1.
Cube shaped packaging material: maximum theoretical value of jh = 1.6.

T_R Retort temperature = **equipment** pasteurization or sterilization temperature [°C].

T_{ih} Initial temperature of the **food product** at the start of the heating process = food temperature at the moment the steam is switched on [°C].

T Core temperature of the **food product** at the start of the cooling stage [°C].

L Come-up time C.U.T. of **retort** = time required to bring retort to T_R [s]; [min.].

c_p Specific heat of **food product** = Joules required to increase the temperature of 1 kg of food product by 1 ºC. [J/(kg ºC)]

For water and food products with a very low % of dry matter: cp = 4200 J/(kg ºC).
For meats with high % of fat: cp ≈ 3000 J/(kg ºC).
For pure "dry matter" such as proteins, sugars, starches, salts: cp ≈ 2000 J/(kg ºC).
A table with specific heats of many different food products, and a computer program to calculate the specific heat cp of a composed food: see FYSCONST 2.0.xls, downloadable from Academia.edu or ResearchGate.net.

ρ Density of **food product** = mass of 1 m^3 of the food product [kg/m^3].

For water and food products with a very low % of dry matter: ρ ≈ 1000 kg/m^3.
Concentrated apple juice: 30% dry matter: ρ = 1124 kg/m^3; 64% dry m.: ρ = 1312 kg/m^3.
For a computer program to calculate the density ρ of a composed food: see FYSCONST 2.0.xls, downloadable from Academia.edu or at ResearchGate.net.

U Overall heat transfer coefficient **from heating medium in retort to slowest heating point ("coldest core") of food** product [J/(s m^2 ºC)]; [W/(m^2 K)].

For estimated values of the overall heat transfer coefficient U of liquid packaged foods: see table 8.

h_A Surface heat transfer coefficient **from retort heating medium to outer wall of packaging**; also named film heat transfer coefficient [J/(s m^2 ºC)]; [W/(m^2 K].

For numerical values of hA: see table 5.

k_W Thermal conductivity of the **wall of the packaging material** [J/(s m ºC)]; [W/(m K].

For values of thermal conductivity of several packaging materials: see table 6.

h_B Heat transfer coefficient **from inner wall of packaging to center (= "slowest heating point") of food product** [J/(s m^2 ºC)]; [W/(m^2 K)].

For numerical values of hB: see table 7.

k Thermal conductivity of the **food product** [J/(s m ºC)]; [W/(m K)].

For a computer program to calculate the thermal conductivity of a composed food: see FYSCONST 2.0.xls, downloadable from Academia.edu or at ResearchGate.net.

d_W Wall thickness of **packaging material** [m].

For values of wall thickness dw of several packaging materials: see table 6.

S Specific surface of packaging (can; jar; etc.) of **liquid food** product [m^2/m^3]

S = (Surface area of packaging A)/(Volume of packaging V); S = Area/Volume = A/V.
See equations in table 4 to calculate S of a packaged liquid food product.

S^{*2} Adapted squared specific surface area of packaging of **solid food product** [m^4/m^6].

When using glass packaging: increase internal diameter and internal height each by 2xglass wall thickness d_W. Example:
Diameter glass jar = $D_{JAR,INTERNAL} + 2xd_W$; Height glass jar = $H_{JAR,INTERNAL} + 2xd_W$.
See equations in table 4 to calculate S^{*2} of a packaged solid food product.

a Thermal diffusivity of the (solid) **food product**; $a = k/(c_p \cdot \rho)$ [m^2/s].

For **solid** food products: $a \approx 1.1 \cdot 10^{-7}$ m^2/s to $1.9 \cdot 10^{-7}$ m^2/s. See also Annex 3.
For a computer program to calculate the thermal diffusivity *a* of a food from its components: see FYSCONST 2.0.xls, downloadable from Academia.edu or at ResearchGate.net.

As can be seen from the equations of the f_h in table 1 above, ...

1) f_h depends on the **type of product**: c_P, ρ, k, and *a*, all are food product properties; also important for heat penetration is the viscosity η of the food;

2) f_h depends on the **dimensions** and the **shape of the packaging**: S and S^{*2} can be calculated from the shape (cylinder; brick; cube; ball; oval), and the diameter D, the width W, and the height H of the packaging;

3) f_h depends on the **packaging material:** metal, glass, or plastic (i.e. f_h depends on the conductivity of the packaging wall k_W), and on the **wall thickness** d_W (incorporated the calculation of the overall heat transfer coefficient U). S^{*2}, in the heat penetration factor equation of solid foods, also is related to the packaging material;

4) f_h depends on the **heating medium in the retort:** saturated steam, showering water, full water immersion; steam+air;
The retort heating medium affects the overall heat transfer coefficient U, via the surface heat transfer coefficient from retort medium to outer side of the packaging wall;

5) f_h depends on the **headspace in the packaging**, on the **rotation frequency** (which affects the internal and external heat transfer surface coefficient), and the **rotation axis** of the packaging.

A simple test to decide whether or not a packaged food behaves as a liquid:

1. Put the food in a transparent (glass) jar.
2. Make sure that there is a head space of at least 1 cm between food and lid.
3. Close the lid, and slowly turn the jar upside down once.
4. If you notice that the heat space gas bubble is easily moving through the food, the packaged food probably will behave as a liquid (milk, condensed milk, etc.) during retorting, or as a liquid with solid pieces (peas or carrots in a can with brine, etc.).
5. If the head space gas bubble does not, or only with great difficulty, passes through the food, the packaged food probably will behave as a solid (apple sauce, tomato paste, meat, etc.) during retorting.

Example calculation 1: *Effect of f_h on pasteurization or sterilization time P_t*
Food in cylindrical cans of 1000 ml has an initial temperature of T_{ih} = 4 ºC, and is to be sterilized in a saturated steam retort. Come up time of the retort L = 3 min. Retort temperature T_R = 123 ºC. Heat penetration factor f_h = 7.0 min. Heating lag factor j_h = 1.0.

1a) From table 1, deduce whether the food in the can is a solid or a liquid.

1b) Using equation (1), calculate the sterilization time P_t required for the slowest heating point (= coldest core) in the food to reach T = 122 ºC.

1c) If the heat penetration factor of a cylindrical can would have been f_h = 3.5 min. (in stead of f_h = 7 min.), what will be the sterilization time P_t required for the food to reach the temperature T = 122 ºC in its slowest heating point (= coldest core)?

1d) Comparing answers 1b and 1c, it can be concluded: Reduction of the f_h will __________ (reduce/increase) the sterilization time P_t.

1e) Verify the required sterilization time P_t of answer 1c) by using computer program STUMBO.exe. (Computer program Stumbo.exe is obtainable on CD-ROM from j.w.mrouweler@freeler.nl).

Worked Answer 1:
Answer 1a) *Deduce whether the food in the can is a solid or a liquid:*
* Deduction 1: Consider the value of the f_h:
Given: the heat penetration factor f_h of the canned food f_h = 7.0 min.
According to table 1, canned liquid foods have a f_h of 4 min. < $f_{h,LIQUID}$ < 15 min.;
while canned solid foods have a f_h of 25 min. < $f_{h,SOLID}$ < 200 min.
Thus a can with a f_h = 7.0 min. most likely will be filled with a liquid food.
* Deduction 2: Consider the value of j_h:
Given: The j_h of the canned food is j_h = 1.0
According to table 1, a liquid food has a j_h of $0.8 \le j_h \le 1.4$, and a canned viscous food in a rotating retort has a j_h of $1.2 \le j_h \le 1.8$ (table 1).
Canned solid foods, however, have a j_h = 2.0 according to table 1.
Thus the can with a j_h = 1.0 most likely will be filled with a liquid food.
Conclusion: According to the values of f_h = 7.0 min. and j_h = 1.0, the food in the can most likely is a **liquid food.**

Answer 1b) *Calculate the sterilization time P_t required for the food to reach T = 122 ºC:*
The equation for the sterilization time P_t of a **liquid** (convection type) food is:

$$P_t = f_h \cdot {}^{10}\log(j_h \cdot \frac{T_R - T_{ih}}{T_R - T}) - 0.4 \cdot L$$

(see equation (1) at start of Chapter 1)

in which (all given):
f_h = 7.0 min.;
j_h = 1.0;
T_{ih} = 4 ºC;
T_R = 123 ºC;
T = 122 ºC;
L = 3 min.

Substitution in the above equation for P_t results in:

$$P_t = 7.0 \cdot {}^{10}\log(1.0 \cdot \frac{123 - 4}{123 - 122}) - 0.4 \cdot 3 = 7.0 \cdot {}^{10}\log(1.0 \cdot \frac{119}{1}) - 1.2$$

$$= 7.0 \cdot {}^{10}\log 119 - 1.2 = 7.0 \cdot 2.076 - 1.2 = 13.3 \text{ min.}$$

At time **P_t = 13.3 min.** after the steam was turned on, the food in the can reaches a product core temperature of T = 122 ºC.

N.B.: Because in the equation the value of f_h is substituted in minutes, as a result also the resulting P_t will be in minutes!

Answer 1c) *Assume that f_h = 3.5 min., calculate the sterilization time P_t required for the food to reach T = 122 ºC:*
The equation for the sterilization time P_t of a **liquid** (convection type) food is:

$$P_t = f_h \cdot {}^{10}\log(j_h \cdot \frac{T_R - T_{ih}}{T_R - T}) - 0.4 \cdot L$$

(see equation (1) at start of Chapter 1)

in which (all given):
f_h = 3.5 min.;
j_h = 1.0;
T_{ih} = 4 ºC;
T_R = 123 ºC;
T = 122 ºC;
L = 3 min.

Substitution in the above equation results in:

$$P_t = 3.5 \cdot {}^{10}\log(1.0 \cdot \frac{123 - 4}{123 - 122}) - 0.4 \cdot 3 = 3.5 \cdot {}^{10}\log(1.0 \cdot \frac{119}{1}) - 1.2$$

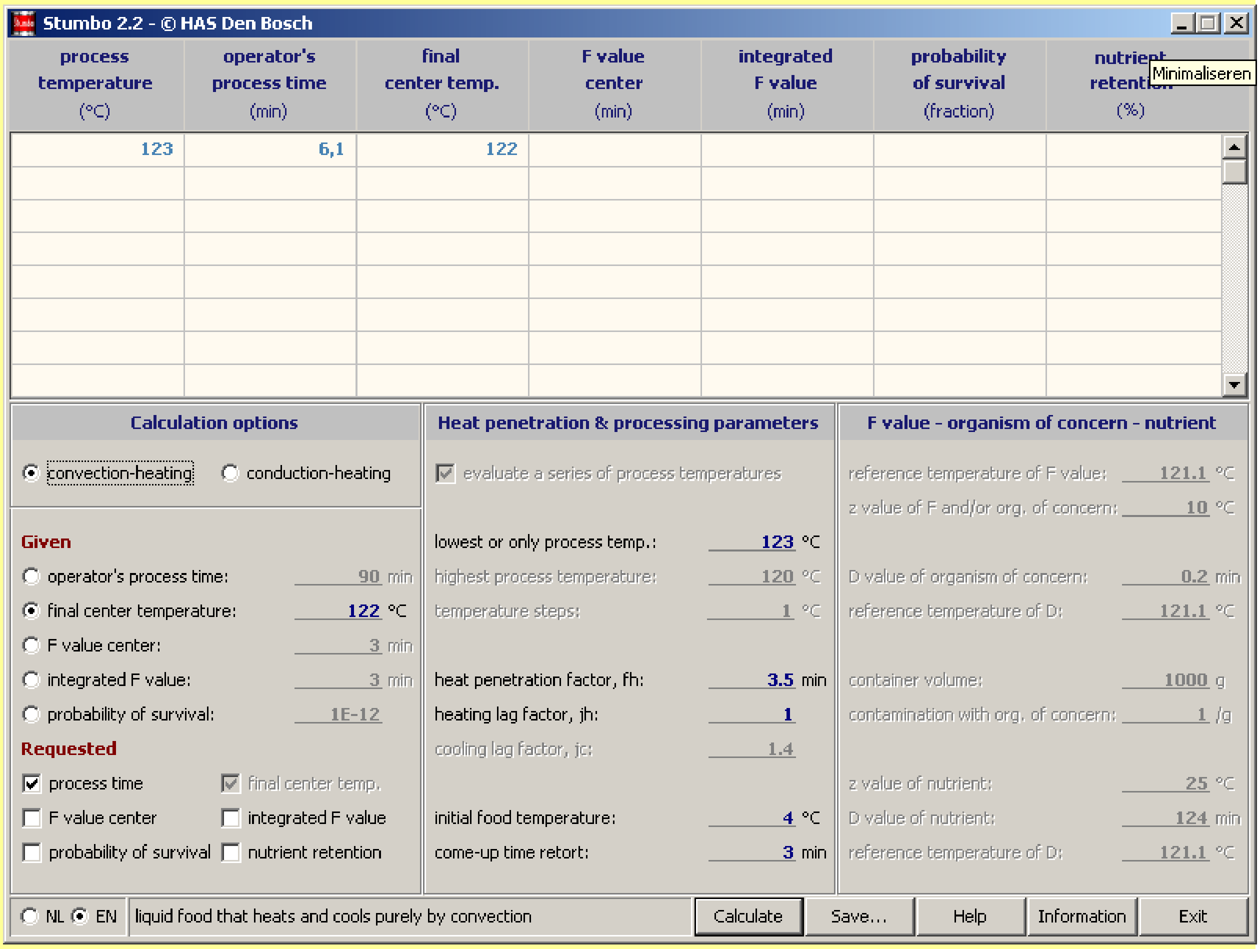
$$= 3.5 \cdot {}^{10}\log 119 - 1.2 = 3.5 \cdot 2.076 - 1.2 = 6.1 \text{ min.}$$

At **P_t = 6.1 min.** after the steam was turned on, the food in the can reaches a product core temperature of T = 122 ºC.

Answer 1d) *Comparing answers 1b (f_h = 7 min.; P_t = 13.3 min.) and 1c (f_h = 3.5 min.; P_t = 6.1 min.), it can be concluded:* Reduction of f_h will **reduce** the sterilization time P_t.

Answer 1e) *Verification of answer 1c (sterilization time P_t) by program STUMBO.exe:*

(**Answer 1e)** Continued**)**



Result:
[See grey section in the Stumbo screen print:] If the packaged food is *convection-heating* (= a liquid), and if given is that the food product should get a *final center temperature* of T = 122 ºC, while the *lowest or only process temp.* (= retort temperature) T_R = 123 ºC, then [white section in screen print] an *operator's process time* P_t = 6.1 min. is needed.
This P_t = 6.1 min. is **exactly equal** to the manually calculated sterilization time P_t = 6.1 min. of answer 1c).

2. Estimating the heat penetration factor f_h of a packaged food from tables

Table 2: Some typical f_h-values for products in cylindrical cans, processed in **STATIC** retorts using steam heating. (Adapted from Holdsworth (1997: 127); Holdsworth & Simpson (2007: 157)

Can size D x H [mm]	Volume [cm^3 = ml]	CONDUCTION heating (SOLID) **fh** [min.]	CONVECTION heating (LIQUID) f_h [min.]
68.3 x 54.0	198	25	4.0
68.3 x 77.8	285	34	4.5
68.3 x 101.6	372	39	5.0
76.2 x 62	283	34	4.5
76.2 x 115.3	526	47	4.5
77.8 x 115.9	551	52	5.5
87.3 x 114.3	684	62	6.0
103.2 x 119.1	996	83	7.0
157.2 x 177.8	3451	198	11.0

Table 3: Some f_h-values for **CONDUCTIVE** (= **SOLID**) products in cylindrical cans, in commercial sterilization processes. (adapted from Holdsworth (1997: 188))

Product	Container size DxH [mm]	Volume [cm^3= ml]	Thermal diffusivity *a* [m^2/s]	**fh** [min.]
Spag. hoops/tom. sauce	U8 73x 61	230	$2.50 \cdot 10^{-7}$	22.2
Corned beef	76x 51	185	$1.73 \cdot 10^{-7}$	28.5
Mushroom soup, cream	A1 65x101	315	$1.58 \cdot 10^{-7}$	37.0
Carrot purée	A1 65x101	315	$1.58 \cdot 10^{-7}$	37.0
Celeriac purée	A1 65x101	315	$1.50 \cdot 10^{-7}$	39.0
White wine sauce	UT 73x115	445	$1.64 \cdot 10^{-7}$	46.0
Pet food	UT 73x115	445	$1.57 \cdot 10^{-7}$	48.0
Spaghetti in tomato sauce	A2½ 99x119	850	$2.50 \cdot 10^{-7}$	49.0
Chicken supr. sauce	UT 73x115	445	$1.54 \cdot 10^{-7}$	49.0
Mackerel+tom. sauce	UT 73x115	445	$1.49 \cdot 10^{-7}$	50.8
Beans+tomato sauce	UT 73x115	445	$1.46 \cdot 10^{-7}$	51.5
Stewed steak	UT 73x115	445	$1.45 \cdot 10^{-7}$	52.0
Chili con carne	UT 73x115	445	$1.44 \cdot 10^{-7}$	52.2
Minced beef	UT 73x115	445	$1.37 \cdot 10^{-7}$	55.0
Beans+tomato sauce	A2 83x114	580	$1.46 \cdot 10^{-7}$	64.6

Example calculation 2: *estimation of f_h and j_h from tables 1, 2 and 3:*
445 grams of a solid food in a cylindrical can with size Diameter x Height = 73 mm x 115 mm (sometimes called an UT can) is heated in a static retort. Make an estimation of the f_h value and of the j_h value of the canned food, using tables 1, 2, and 3.

Worked answer 2: According to table 3 above, cans with 445 ml of solid foods and size DxH = 73x115mm have heat penetration values from f_h = 46.0 min. ("white wine sauce") to f_h = 55.0 min. ("minced beef"). Thus depending on the composition (viscosity) of the food in the can, the f_h will be 46 min. ≤ f_h ≤ 55 min., with values near f_h = 46 min. if the food is viscous, to values near f_h = 55 min. if the food is a real solid.

According to table 2, cans of 526 ml of solid food have a f_h = 47 min., and cans of 551 ml of solid food have an f_h = 52 min. Although the can volumes (526 ml and 551 ml) are about 20% larger than the 445 ml, the f_h values are within the range 46 min. ≤ f_h ≤ 55 min.

According to table 1, a solid food has a heating lag factor of j_h = 2.0.

Conclusions:
- the food will have a **f_h values within the range of 46 min. ≤ f_h ≤ 55 min.**
- the food has a **heating lag factor of j_h = 2.0.**

Example calculation 3: *estimation of f_h and j_h from tables:*
Cylindrical cans, containing about 1000 ml of food. are heated in a static retort.
3a) Estimate, by using tables 1-2-3, the f_h and the j_h in case the food is real solid product.
3b) Estimate, by using tables 1-2-3, the f_h and the j_h for a liquid food such as apple juice.

Worked answer 3:
Answer 3a) *Estimate the values of f_h and j_h if the food product is a solid:*
Cylindrical cans containing 1000 ml of **solid**: According to table 2 a can with 996 ml of solid has a f_h = 83 min. According to table 3, a can with 850 ml "spaghetti in tomato sauce" has a f_h = 49.0 min; a can with 590 ml of "beans in tomato sauce" (table 3) has a f_h = 64 min. Most likely the "spaghetti in tomato sauce", according to its relatively low f_h, does not behave as a pure solid. So probably the best estimation will be **f_h = 83 min.**
The heating lag factor for a solid food (table 1) will be **j_h = 2.0.**

Answer 3b) *Estimate the values of f_h and j_h if the food product is a liquid:*
Cylindrical cans containing 1000 ml of **liquid**: According to table 2 a can with 996 ml of liquid has a f_h = 7.0 min.
The heating lag factor j_h for a liquid food in a still retort (table 1) will be 1.0 < j_h < 1.4.

3. Effect of the packaging size, the packaging material, and the food texture (solid or liquid) on the heat penetration factor f_h of a packaged food product

Table 1 lists the following equations to calculate the heat penetration factor f_h:

for **LIQUID** (= convective) foods:	for **SOLID** (= conductive) foods:
$$f_h = \frac{2.3 \cdot c_p \cdot \rho}{U \cdot S} \quad [s]$$	$$f_h = \frac{2.3 \cdot c_p \cdot \rho}{k \cdot S^{*2}} = \frac{2.3}{a \cdot S^{*2}} \quad [s]$$
For equations of S: see table 4.	For equations of S^{*2}: see table 4.
$$\frac{1}{U} = \frac{1}{h_A} + \frac{1}{k_W/d_W} + \frac{1}{h_B} \quad [(s\ m^2\ {}^oC)/J]$$	$a = k/(cp \cdot \rho)$ [m^2/s] usually $a \approx 1.1 \cdot 10^{-7}\ m^2/s$ to $1.9 \cdot 10^{-7}\ m^2/s$. (see Annex 3 for a values of some foods).
For values of h_A, k_W/d_W, and h_B: tables 5-6-7	
4 min. < $f_{h,LIQUID}$ < 15 min.	**25 min. < $f_{h,SOLID}$ < 200 min.**

For explanation of symbols: see Chapter 1.

As can be concluded from the equations above, the effect of the packaging size, of the packaging material, and of the food texture, on f_h, are included in the specific surface S or S^{*2}.

Table 4: Equations to calculate the specific surface S of packaged liquid foods, and the adapted squared specific surface S^{*2} of a packaged solid foods.

D = internal diameter; H = internal height; L = internal length; W = internal width; BD = biggest internal diameter; SD = smallest internal diameter; d_W = thickness of glass wall = 2.5 mm = $2.5 \cdot 10^{-3}$ m.

In equations below: D, H, L, W, BD, BL, d_W, are all in [m].

Shape of packaging	**LIQUID** (convection type) product: S [m^2/m^3]	**SOLID** (conduction type) product: S^{*2} [m^4/m^6]. If **GLASS** packaging: $H^{*2} = (H + 2 \cdot d_W)^2$; $D^{*2} = (D + 2 \cdot d_W)^2$; $L^{*2} = (L + 2 \cdot d_W)^2$; $W^{*2} = (W + 2 \cdot d_W)^2$.
Cylinder	S = 2/H + 4/D	$S^{*2} = 9.93/H^{*2} + 23.2/D^{*2}$ [1])
Brick	S = 2/H + 2/L + 2/W	$S^{*2} = 14.2 \cdot (1/H^{*2} + 1/L^{*2} + 1/W^{*2})$
Cube	S = 6/D	$S^{*2} = 42.6/D^{*2}$
Oval	S = 2/H + 2/(BD) + 2/(SD)	-
Sphere; ball	S = 6/D	$S^{*2} = 39.5/D^{*2}$

[1]) Derived from Holdsworth & Simpson (2007), p. 159 equation 5.8.

N.B. 1: The superscript * at H, D, W, and S in case of solid foods is only to remind you that in case of **glass** packaging material the internal Height, the internal Diameter, the internal Width, and the internal Height each has to be increased by 2x the glass wall thickness d_W.
Thus H*, D*, L*, and W* are *adapted* sizes.

N.B. 2: In case of solid foods in metal cans or in plastic pouches, the wall thickness d_W is so small, and the thermal conductivity is so high (see table 6), that the heat transfer through the walls is very rapid compared to the heat transfer from retort to outer wall of the can h_A, and the heat transfer from inner wall to core of the food h_B. Thus in case of metal or plastic, the wall thickness does NOT notably influence the overall heat transfer coefficient U.

N.B. 3: In case of solid foods the superscript ^{2} at H^{*2}, D^{*2}, L^{*2}, and W^{*2} means that the (adapted) sizes each have to be squared.

In liquid foods, the effect of the packaging material on f_h is already incorporated in the factor (k_W/d_W) of the overall heat transfer coefficient U: U depends on the packaging wall thickness d_W, and on the packaging thermal conductivity k_W (metal, glass; plastic). See also table 6.

Example calculation 4: *calculation of S and S^{*2}; effect of packaging material:*
4a) Calculate the specific surface S of a cylindrical metal can with diameter D = 9.9 cm and a height H of 11.9 cm, containing a liquid (= convection heating) food.
4b) Calculate the adapted squared specific surface S^{*2} of a cylindrical metal can with diameter D = 9.9 cm and a height H of 11.9 cm, containing a solid (= conduction heating) food.
4c) Calculate the adapted squared specific surface S^{*2} of a cylindrical glass jar with internal diameter D_{int} = 9.9 cm and an internal height H_{int} of 11.9 cm, glass wall thickness d_W = 2.5 mm, containing a solid (= conduction heating) food.
4d) In Annex 3, find the thermal diffusivity *a* of Celeriac purée.
4e) Calculate the heat penetration factor f_h for a solid food with thermal diffusivity a = 0.-$1.5 \cdot 10^{-7}$ m^2/s in a cylindrical metal can with diameter D = 9.9 cm and a height H of 11.9 cm; use the S^{*2} findings from answer 4b).

Worked answer 4:
Answer 4a) *Calculate the specific surface S of a cylindrical metal can with liquid food:*
According to table 4, for a liquid food in a cylindrical metal can, the equation for the specific surface S = 2/H + 4/D.
Given: H = 11.9 cm = 0.119 m; D = 9.9 cm = 0.099 m
Substitution in equation S = 2/H + 4/D results in S = (2/0.119) + (4/0.099) = 57.2 m^2/m^3.
So the specific surface S of the metal can with liquid food is **S = 57.2 m^2/m^3**.

Answer 4b) *Calculate the adapted squared specific surface S^{*2} of a cylindrical metal can with solid food:*
According to table 4, for a solid food in a cylindrical metal can, the equation for the adapted squared specific surface is: $S^{*2} = 9.93/H^{*2} + 23.2/D^{*2}$.
In case of metal cans, the wall material is made of a very conductive, very tiny layer of metal. So NO addition of d_W is required.
Given: H = 11.9 cm = 0.119 m; so $H^{*2} = 0.119^2 = 0.01416\ m^2$.
D = 9.9 cm = 0.099 m; so $D^{*2} = 0.099^2 = 0.009801\ m^2$.
Substitution in equation $S^{*2} = 9.93/H^{*2} + 23.2/D^{*2}$ results in
$S^{*2} = [9.93/(0.119^2)] + [23.2/(0.099^2)] = [9.93/0.01416] + [23.2/0.009801] = 3068$.
So the adapted specific surface of the metal can with solid food is **$S^{*2} = 3068\ m^4/m^6$**.

Answer 4c) *Calculate the adapted squared specific surface S^{*2} of a cylindrical glass jar with solid food:*
According to table 4, for a solid food in a cylindrical glass jar, the equation for the adapted squared specific surface $S^{*2} = 9.93/H^{*2} + 23.2/D^{*2}$.
Glass: so $H^{*2} = (H_{int} + 2 \cdot d_W)^2$; and $D^{*2} = (D_{int} + 2 \cdot d_W)^2$.
Given: H = 11.9 cm = 0.119 m; and d_W = 2.5 mm = 0.0025 m;
so $H^{*2} = (0.119 + 2 \cdot 0.0025)^2 = 0.124^2 = 0.015376\ m^2$.
D = 9.9 cm = 0.099 m; and d_W = 2.5 mm = 0.0025 m;
so $D^{*2} = (0.099 + 2 \cdot 0.0025)^2 = 0.104^2 = 0.010816\ m^2$.
Substitution in equation $S^{*2} = 9.93/H^{*2} + 23.2/D^{*2}$ results in
$S^{*2} = [9.93/(0.015376)] + [23.2/(0.010816)] = 645.8 + 2144.9 = 2791$
So the adapted specific surface of the glass jar with solid food is **$S^{*2} = 2791\ m^4/m^6$**.

Answer 4d) According to Annex 3, celeriac purée has an ***a* = $1.5 \cdot 10^{-7}\ m^2/s$.**

Answer 4e) According to table 1, the heat penetration factor of a solid food in a cylindrical can is: $f_h = 2.3 \cdot c_P \cdot \rho/(k \cdot S^{*2}) = 2.3/(a \cdot S^{*2})$.
We know: $S^{*2} = 3068\ m^4/m^6$; see answer 4b);
a = thermal diffusivity = $1.5 \cdot 10^{-7}\ m^2/s$ (given).
Substitution of the values of S^{*2} and *a* in equation $f_h = 2.3/(a \cdot S^{*2})$ results in:
$f_h = 2.3/(a \cdot S^{*2}) = 2.3/(1.5 \cdot 10^{-7} \cdot 3068)$ = **4998 seconds = 83.3 min. = f_h**.

The specific surface S, the adapted squared specific surface S^{*2}, and the heat penetration factor f_h can also be calculated by Excel spreadsheet **"*Heat penetration factor fh calculations.xls*"**. For example calculations with that spreadsheet: see Chapter 5.

4. Effect of the partial heat transfer coefficients, and of the overall heat transfer coefficient U, on the heat penetration factor f_h of a packaged food product

4.1 Values of the partial heat transfer coefficients h_A, k_W/d_W, and h_B

Heat (= Joules), travelling from the retort medium to the slowest heating point ("coldest core") of a packaged food, will encounter 3 times a heat resistance (see Figure 1):

1) The Joules first have to travel **from the retort medium to the outer wall of the packaging.** That number of Joules depends on the **film heat transfer coefficient h_A**, or **surface heat transfer coefficient h_A**. Table 5 lists average values of the film heat transfer coefficient, which depends on the composition of the retort medium, and on the degree of turbulence of the retort medium (caused by rotation of the package, or by using a pump or a fan in the heat transfer medium).

As can be seen from table 5, saturated condensing steam causes the highest film heat transfer coefficient: h_A = 12 000 J/(s m^2 ºC). However, s small fraction of air in the steam already drastically reduces the heat transfer: reason is that the non-condensing air envelopes the food package with an isolating air layer, which hinders penetration of the condensing steam.

Spraying water over packaged food, usually in a pressurized air atmosphere, also produces a rather good film heat transfer coefficient: h_A ≈ 5 000 J/(s m^2 ºC). Stagnant water such as in an immersion bath, without turbulence, has a rather low film heat transfer coefficient.

Table 5: Approximate values for the film heat transfer coefficient **h_A from retort medium to the outer wall of the packaging** [J/(s m^2 ºC)]; [W/(m^2 K]. [1]) Earle (1983: Chapter 5).

Heat transfer medium	Film heat transfer coefficient **h_A** from retort medium to outer wall of packaging
Condensing steam	
Saturated condensing steam:	12 000 [J/(s m^2 ºC)] [1])
Condensing steam with 3% of air:	3 500 [J/(s m^2 ºC)] [1])
Condensing steam with 6% of air:	1 200 [J/(s m^2 ºC)] [1])
Water	
Water (spray; showering retort):	5 000 [J/(s m^2 ºC)]
Water (boiling):	4 000 [J/(s m^2 ºC)]
Water (forced convection; rotating retort; fan):	3 000 [J/(s m^2 ºC)]
Water (free convection; still retort):	1 500 [J/(s m^2 ºC)]
Water (stagnant; immersion bath);	800 J/(s m2 ºC)]
Air	
Air (frying oven; forced convection; fan):	20 - 120 [J/(s m^2 ºC)]
Air (flowing; 3m/s):	30 [J/(s m^2 ºC)]
Air (stagnant):	6 [J/(s m^2 ºC)] [1])

2) Joules from the retort medium, arriving at the outer wall of the packaging material, next have to pass **through the wall of the packaging material**. The heat transfer through that wall will be much faster (see table 6) if the wall of the packaging material has a high thermal conduction k_W (e.g. aluminum and plated metal; column 2 of table 6), and if the wall thickness d_W is very small (plated metal; aluminum; plastic; column 3 of table 6). Thus the heat transfer depends on the **quotient k_W/d_W** (column 4 of table 6). Thus joules will pass much more rapidly through the wall of a metal can than through the wall of a glass jar.

Table 6: Heat transfer by conduction **through the wall of packaging material**

Material	Thermal conductivity k_W [J/(s m ºC)];	Wall thickness d_W [mm]	Coefficient **k_W/d_W** [J/(s m^2 ºC)];
Plated metal (cans)	60	0.23	260 000
Glass (jars; bottles)	0.7	2.5	280
Alumina (cans)	280	0.2	1 400 000
Plastic/compound (bottles; pouches)	1.4	0.05	28 000

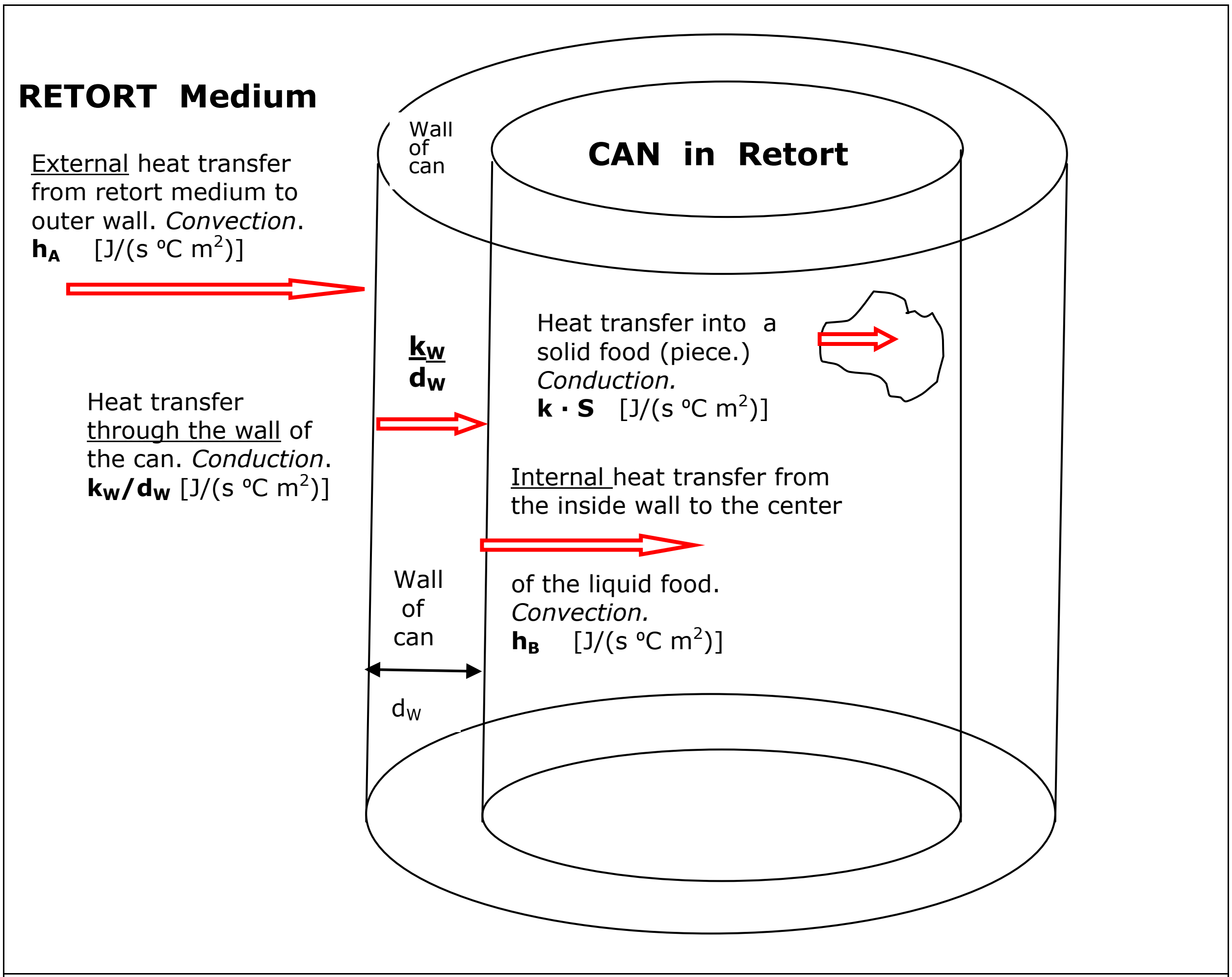


Figure 1: Heat transfer from the retort medium to the slowest heating point of a packaged food.

During heating, Joules (= heat) will travel ....
- from the retort medium (steam; showering water, etc.) to the outside wall of the container;
- from the outside wall, through the wall (metal; glass) of the container, to the inside wall;
- from the inside wall of the container to the coldest center of the liquid or solid food.

In case of a liquid food containing solid pieces, Joules also will travel ....
- from the liquid food to the outside of the submerged food pieces;
- from the outside into the solid food pieces, to the coldest centre in the food piece.

For approximate values the partial heat transfer coefficients **h_A**: see table 5; **k_W/d_W**: see table 6; **h_B**: see table 7.

For estimated values of the overall heat transfer coefficient **U** from the retort medium to the slowest heating point of a liquid food product: see table 8.

3) Joules, arriving at the inner side of the packaging wall, next have to travel **from the inner wall to the centre of the food**. This **inner heat transfer coefficient h_B** primarily depends on the consistency of the food (liquid, viscous, or solid); see table 7 and fig. 1.

In case of a ***liquid food***, the heat transfer from the inside packaging wall to the centre of the food will be more rapid if there is more turbulence: e.g. rotation, and/or low food viscosity.

In case of a ***solid food***, the heat transfer from the inside packaging wall to the centre of the food will be more rapid if the food has a higher thermal conductivity k, and the distance to the food centre is smaller (i.e. the adapted squared specific surface S^{*2} is smaller).

Table 7: Approximate values of the heat transfer coefficient h_B from the inner wall of the packaging to the coldest center of the food product [J/(s m² °C)]; [W/(m² K].

Food properties	Retort properties	Inner heat transfer coefficient h_B [J/(s m² °C)]; [W/(m² K].	Food examples
Very low viscosity liquid foods	NO rotation (free convection)	1 500 J/(s m² °C)	Canned liquids such as milk, single strength juices and lemonades, beer,
	Rotation (forced convection)	3 000 J/(s m² °C)	
Viscous foods	Rotation (forced convection)	500 - 1000 J/(s m² °C)	Porridge, sauces; cream soups; fruit syrups and concentrates,
	No rotation (conduction + convection	100 - 500 J/(s m² °C)	
Very viscous foods	Rotation (forced convection)	40 - 50 J/(s m² °C)	Glucose syrup 84 °Brix
	No rotation (conduction)	Behaves as solid food; k·S = 10 - 30 J/(s m² °C)	
Solid foods	Conduction	k·S = 10 - 30 J/(s m² °C)	Cheese, canned meats canned spinach.

4.2 The overall heat transfer coefficient U, and its effect on f_h

In case of a **liquid food**, the total heat transfer from the retort medium, trough the wall of the packaging material, to the coldest centre of the food, depends on the **overall heat transfer coefficient U**:

$$\frac{1}{\mathbf{U}} = \frac{1}{h_A} + \frac{1}{k_W/d_W} + \frac{1}{h_B} \quad [(\text{s m}^2\ {}^\circ\text{C})/\text{J}]$$

(for values of h_A, k_W/d_W, and h_B: see tables 5, 6, and 7; for estimated values of U_{LIQUID}: see table 8).

For a **liquid food**, the **overall heat transfer coefficient U** can also be roughly **estimated** from table 8.

If the specific surface S of the packaging is known, if also the overall heat transfer coefficient U is known, and both the food properties specific heat c_P and food density ρ are known, then the heat penetration factor f_h of a packaged **liquid** food can be calculated by (see table 1):

$$\mathbf{f_{h,LIQUID}} = \frac{\mathbf{2.3 \cdot c_p \cdot \rho}}{\mathbf{U \cdot S}} \quad [\text{s}]$$

In case of a **solid food**, the total heat transfer from the retort medium, through the wall of the packaging material, to the centre of the food strongly depends on the thermal conductivity k of the solid food, and on the dimensions of the packaging material, incorporated in S^{*2}.
If k, c_P, ρ, and the adapted squared specific surface of the packaging S^{*2} are known, the heat penetration factor f_h of a packaged **solid food** can be calculated by (see table 1):

$$\mathbf{f_{h,SOLID}} = \frac{\mathbf{2.3 \cdot c_p \cdot \rho}}{\mathbf{k \cdot S^{*2}}} = \frac{\mathbf{2.3}}{\mathbf{a \cdot S^{*2}}} \quad [\text{s}]$$

Equations to calculate S and of S^{*2} can be found in table 4.
S and S^{*2} can also be calculated by the Excel spreadsheet "*Heat penetration factor fh calculations.xls*". For worked examples see Chapter 5.

Values of the thermal diffusivity *a* of several foods can be found in Annex 3.

Table 8: **ESTIMATED** overall heat transfer coefficient U for **liquid foods** in several retort types.

Viscosity of packaged liquid food	**Packaging material**. Rotation or still retort. *Retort heating medium.*	**Estimated** Overall Heat Transfer Coefficient U
Very low viscous liquid food (watery). *Canned liquids such as milk, single strength juices, vegetable juices, lemonades, beer, etc.*	**In metal can**. Rotating retort. *Retort medium = saturated condensing steam.*	U ≈ **2375** J/(s m^2 °C)
	In metal can. Rotating retort. *Retort medium = showering water.*	U ≈ **1850** J/(s m2 °C)
	In metal can. Still retort; no rotation. *Retort medium = saturated condensing steam.*	U ≈ **1325** J/(s m2 °C)
	In metal can. Still retort; no rotation. *Retort medium = showering water.*	U ≈ **1150** J/(s m2 °C)
	In metal can. Still retort; no rotation. *Retort medium = full water.*	U ≈ **750** J/(s m2 °C)
	In glass jar or bottle. Rotating retort. *Retort medium = saturated condensing steam or showering water*	U ≈ **240** J/(s m^2 °C)
	In glass jar or bottle. Still retort; no rotation. *Retort medium = saturated condensing steam or showering water.*	U ≈ **225** J/(s m2 °C)
	In glass jar or bottle. Still retort; no rotation. *Retort medium = full water.*	U ≈ **200** J/(s m2 °C)
Viscous liquid food *Porridge, sauces; cream soups; fruit syrups and fruit concentrates, etc*	**In metal can**. Rotating retort. *Retort medium = saturated condensing steam.*	U ≈ **480** J/(s m2 °C)
	In metal can. Rotating retort. *Retort medium = showering water.*	U ≈ **450** J/(s m2 °C)
	In metal can. Still retort; no rotation. *Retort medium = saturated condensing steam or showering water.*	U ≈ **100** J/(s m2 °C)
	In glass jar or bottle. Rotating retort. *Retort medium = saturated condensing steam or showering water*	U ≈ **175** J/(s m2 °C)
	In glass jar or bottle. Still retort; no rotation. *Retort medium = saturated condensing steam or showering water.*	U ≈ **70** J/(s m2 °C)
Very viscous food *Glucose syrup 84 ºBrix*	**In can, glass jar or bottle.** Rotating retort. *Retort medium = saturated steam or showering water.*	U ≈ **35** J/(s m2 °C)
	In can, glass jar or bottle. Still retort; no rotation. *Retort medium = saturated steam or showering water or full water.*	Use equations for a **SOLID** food

Example calculation 5: *calculation of $f_{h\ LIQUID}$ from equations:*
Full cream milk with 3.5 mass% of fat, filled in a cylindrical glass jar of internal diameter 8.73 cm and internal height 11.43 cm, has a specific heat of c_p = 3890 J/(kg ºC), a thermal conductivity of k = 0.58 J/(s m ºC), a density of ρ = 1028 kg/m³, and a thermal diffusivity of $a = 0.145 \cdot 10^{-6}$ m²/s. Thickness of the jar glass walls d_W = 2.5 mm.
Make an estimated calculation of the heat penetration factor of such a glass jar with full cream milk in a rotating showered water retort.

Worked answer 5:
According to table 1, for a liquid in a glass jar, the equations are:

$f_h = \dfrac{2.3 \cdot c_p \cdot \rho}{U \cdot S}$ [s]	$\dfrac{1}{U} = \dfrac{1}{h_A} + \dfrac{1}{k_W/d_W} + \dfrac{1}{h_B}$ [(s m² ºC)/J]

And according to table 4, for a cylinder with liquid, S is S = 2/H + 4/D

Calculation of the **overall heat transfer coefficient U** requires h_A, k_W/d_W, and h_B.

h_A = film heat transfer coefficient from retort medium to outside of jar.
According to table 5, h_A of a showered water retort is: h_A = 5 000 J/(s m² ºC).
k_W/d_W = heat transfer through glass wall.
According to table 6, for glass packaging k_W/d_W = 280 J/(s m² ºC).
h_B = heat transfer coefficient from inside of glass wall to centre of milk jar.
According to table 7, for a low viscosity liquid in a rotating retort (= forced convection), the heat transfer coefficient h_B = 3 000 J/(s m² ºC).
Substitution of h_A, k_W/d_W, and h_B in the equation of the overall heat transfer coefficient U results in

$$\frac{1}{U} = \frac{1}{5000} + \frac{1}{280} + \frac{1}{3000} = 0.0002 + 0.00357 + 0.00333 = 0.00410$$

Thus **<u>U = 1/0.00410 = 244 J/(s m² ºC).</u>**
(*<u>General rule</u>*: U is <u>always</u> smaller than the smallest value of h_A, k_W/d_W, and h_B)

Calculation of the **specific surface S** of a <u>liquid</u> in a cylindrical glass jar requires H and D.
(in case of a **liquid** in a glass packaging, NO addition of the glass wall diameter d_W is required when calculating S; d_W is already included in the value of U).
H = internal height; H = 11.43 cm = 0.1143 m.
D = internal diameter; D = 8.73 cm = 0.0873 m.
Substitution of H and D in the equation of the specific surface S results in:
S = 2/H + 4/D = 2/0.1143 + 4/0.0873 = 17.50 + 45.87 = **63.32 m²/m³ = S**.

To calculate the **heat penetration factor f_h** of a liquid in a packaging, the equation is

$$f_h = \frac{2.3 \cdot c_p \cdot \rho}{U \cdot S} \quad [s] \quad (\text{table 1})$$

in which:
c_p = 3890 J/(kg ºC) (given);
ρ = 1028 kg/m³ (given);
U = 244 J/(s m² ºC) (calculated above)
S = 63.32 m²/m³ (calculated above)

Substitution in the equation for f_h results in:

$$f_h = \frac{2.3 \cdot c_p \cdot \rho}{U \cdot S} = \frac{2.3 \cdot 3890 \cdot 1028}{244 \cdot 63.32} = \frac{9197516}{15460} = \underline{\textbf{595 seconds = 9.9 min.}}$$

<u>Estimated</u> heat penetration factor $f_{h,\ LIQUID}$ of a glass jar of full cream milk in a rotating showered water retort: **<u>f_h = 9.9 min.</u>**

Example calculation 6: *calculation of $f_{h\ SOLID}$ from equations:*
Lean meat, filled in a brick shaped plated metal can of internal length L = 9.0 cm, internal width W = 8.5 cm, and internal height H = 4.4 cm, has a specific heat of c_P = 3630 J/(kg ºC), a thermal conductivity of k = 0.51 J/(s m ºC), and a density of ρ = 1067 kg/m^3.
6a) Estimate the heating lag factor j_h of the can with lean meat food product, using table 1.
6b) Make an estimated calculation of the heat penetration factor f_h of such a can with lean meat in a saturated steam retort.

Worked answer 6:
Answer 6a) Lean meat is a solid food.
So, according to table 1, a solid food product has a **heating lag factor j_h = 2.0**.

Answer 6b) Lean meat is a solid food.
So, according to table 1 and table 4, for a solid food in a brick-shaped metal can, the following equations apply:

$$f_h = \frac{2.3 \cdot c_p \cdot \rho}{k \cdot S^{*2}} \quad [s] \qquad \text{(table 1)}$$

and $$S^{*2} = 14.2 \cdot (1/H^{*2} + 1/L^{*2} + 1/W^{*2}) \quad [m^4/m^6] \qquad \text{(table 4)}$$

Factors in these equation for f_h:
- c_P = 3630 J/(kg ºC) (given);
- ρ = 1067 kg/m^3 (given);
- k = 0.51 J/(s m ºC) (given);
- S^{*2}: has to be calculated.

Calculation of S^{*2}: As the packaging material is metal, and NOT glass, addition of $2 \cdot d_W$ to the internal dimensions H, L and W of the packaging material is not required.

So: H = 4.4 cm = 0.044 m (given); thus $H^{*2} = 0.044^2 = 0.001936\ m^2$;
L = 9.0 cm = 0.090 m (given); thus $L^{*2} = 0.090^2 = 0.0081\ m^2$;
W = 8.5 cm = 0.085 m (given); thus $D^{*2} = 0.085^2 = 0.007225\ m^2$.
Substitution in $S^{*2} = 14.2 \cdot (1/H^{*2} + 1/L^{*2} + 1/W^{*2})$ results in
$S^{*2} = 14.2 \cdot (1/0.001936 + 1/0.0081 + 1/0.007225) = 14.2 \cdot (778.4) =$
$= S^{*2} = 11053\ m^4/m^6$.

Substitution of the values of c_P, ρ, k, and S^{*2} in the equation

$$f_h = \frac{2.3 \cdot c_p \cdot \rho}{k \cdot S^{*2}}$$

results in

$$f_h = \frac{2.3 \cdot 3630 \cdot 1067}{0.51 \cdot 11053} = \frac{8908383}{5637} = 1580 \text{ seconds} = 26.3 \text{ min.}$$

Estimated heat penetration factor $f_{h,\ SOLID}$ of lean meat in a brick-shaped metal package in a saturated steam retort: **f_h = 26.3 min.**

The specific surface S, the adapted squared specific surface S^{*2}, and the heat penetration factor f_h can also be calculated by Excel spreadsheet ***"Heat penetration factor fh calculations.xls"***, downloadable from the sites Academia.edu and ResearchGate.net.
For some example calculations with that Excel spreadsheet: see Chapter 5

5. Excel program "*Heat penetration factor fh calculations.xls*" calculates the heat penetration factor f_h, and the specific surface S and S^{*2}, of packaged foods

In Example calculation 5, the value of $f_{h\ LIQUID}$ was manually calculated.
This Chapter 5 will show that a more rapid computer calculation is possible.

Example calculation 5 stated: *Full cream milk with 3.5 mass% of fat, filled in a cylindrical glass jar of diameter 8.73 cm and height 11.43 cm, has a specific heat of c_p = 3890 J/(kg ºC), a thermal conductivity of k = 0.58 J/(s m ºC), a density of ρ = 1028 kg/m^3. Thickness of the jar glass walls d_W = 2.5 mm. Calculate the heat penetration factor of such a jar with full cream milk in a rotating showered water retort.*

Now we will use Excel program "*Heat penetration factor fh calculations.xls*" to calculate the heat penetration factor f_h of the cylindrical glass jar of full cream milk.

- Start Excel program "*Heat penetration factor fh calculations.xls*"
  (downloadable from Academia.edu or ResearchGate.net).
  For a screen print of the Excel program: see at the next 2 pages.

- At "**INPUT OF THE PHYSICAL PROPERTIES OF THE FOOD**", in the yellow cells,
type: Specific heat food product Cp = 3890 J/(kg ºC);
Density food product ρ = 1028 kg/m^3;
Thermal conductivity food product k product = 0.58 J/(s m ºC).

- The food product full cream milk is a **liquid**; thus in the spreadsheet you have to include a value in the cell of the "Overall het transfer coefficient U".
  * In answer 5), the value of U was calculated: **U = 244 J/(s m^2 ºC).**

  * From table 8 (= table 3 in the Excel spreadsheet), a rough estimation can be made of the value of U of a glass jar with full cream milk (very low viscous liquid) in a rotating showered water retort:
  For a very low viscous food in a glass jar or glass bottle, in a rotating retort with heating medium saturated steam or showering water, an rough estimation of the overall heat transfer coefficient is: **U ≈ 240 J/(s m^2 ºC).**
  [This rough estimation is in **very good agreement** with the calculated U = 244 J/(s m^2 ºC) in answer 5)].

In the spreadsheet, let us use the calculated value of U: **U = 244 J/(s m^2 ºC).**

- At "**INPUT OF THE SHAPE AND DIMENSIONS OF THE PACKAGED FOOD PRODUCT**",
  The package shape of the food product is **cylinder**, thus in the spreadsheet fill up section **a)**: **CYLINDER SHAPED PACKAGED PRODUCT**.

  Use the yellow cells on the left side ("LIQUID"), to insert the given package dimensions:
  Product diameter D_{CYL} = 8.73 cm = 0.0873 m.
  Product height H_{CYL} = 11.43 cm = 0.1143 m.
  Thickness glass wall dw = XXXXXXXX.
  In a liquid food, the thickness of the glass wall has already been included in the value of U, the overall heat transfer coefficient. So at "thickness glass wall dw =" NO value should be inserted.

Results: See computer print below, at section ***a) CYLINDER SHAPED PACKAGED PRODUCT "$_{CYL}$"***, at the **left** hand column Liquid (for the milk is a liquid):

The computer calculates the specific surface S_{CYL} = 63.32 m^2/m^3.
(This S_{CYL} = 63.32 m^2/m^3 is exactly equal to manually calculated S = 63.32 m^2/m^3 in answer 5).

Next the computer calculates the heat penetration factor **fh_{CYL} = 595 s** (= 9.9 min.).
(This fh_{CYL} = 595 s is exactly equal to manually calculated fh = 595 s in answer 5).

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Heat penetration factor	**LIQUID** food product	**SOLID** food product
	$fh = \frac{2.3 \cdot Cp \cdot \rho}{U \cdot S}$	$fh = \frac{2.3 \cdot Cp \cdot \rho}{k \cdot S^{*2}}$

INPUT OF THE PHYSICAL PROPERTIES OF THE FOOD PRODUCT:

pale yellow = input cell

pale blue = calculation results

Specific heat food product **Cp** =	3890	J/(kg °C)
Density food product **ρ** =	1028	kg/m^3
Thermal conductivity food product **k** =	0.58	J/(s m °C)

In case of <u>LIQUID</u> foods: Overall heat transfer coefficient **U** = 244 $J/(s\ m^2\ °C)$;

INPUT OF THE SHAPE AND DIMENSIONS OF THE PACKAGED FOOD PRODUCT:

a) CYLINDER SHAPED PACKAGED PRODUCT "CYL":

Liquid: $S_{CYL} = 2/H_{CYL} + 4/D_{CYL}$

Product diameter D_{CYL} =	0.0873	m
Product height H_{CYL} =	0.1143	m
Thickness glass wall dw =	XXXXXXXX	
Specific Surface S_{CYL} =	**63.3168277**	m^2/m^3
Max. volume of package V =	0.68382406	liters

Solid: $S^{*2}_{CYL} = 9{,}93/H^{*2}_{CYL} + 23{,}2/D^{*2}_{CYL}$

diam. D_{CYL} =	0.102	m
height H_{CYL} =	0.112	m
glass dw =	0	in **meters**!!! [1])
S^{*2}_{CYL} =	3021.52509	m^4/m^6
Max. volume V=	0.91471968	Liters

[1]) Usually, glass wall thickness dw = 0.0025 m (= 2.5 mm)

RESULTS:

<u>LIQUID</u> food heat penetration factor

fh_{CYL} = **595.33522** seconds.

<u>SOLID</u> food heat penetration factor

fh_{CYL} = 5248.2722 seconds.

b) BRICK SHAPED PACKAGED PRODUCT "BR":

Liquid: $S_{BR} = 2/H_{BR} + 2/L_{BR} + 2/W_{BR}$

Product heigth H_{BR} =	0.05	m
Product lenght L_{BR} =	0.12	m
Product width W_{BR} =	0.1	m
Specific Surface S_{BR} =	76.6666667	m^2/m^3
Max. volume of package V =	0.6	liters

Solid: $S^{*2}_{BR} = 14{,}2 \cdot (1/H^{*2}_{BR} + 1/L^{*2}_{BR} + 1/W^{*2}_{BR})$

height H_{BR} =	0.044	m
length L_{BR} =	0.09	m
width W_{BR} =	0.085	m
S^{*2}_{BR} =	11053.1951	m^4/m^6
Max. volume V=	0.3366	liters

RESULTS:

***LIQUID* food heat penetration factor**			***SOLID* food heat penetration factor**		
fh_{BR} =	491.67049	seconds.	fh_{BR} =	1434.6789	seconds.

c) CUBE SHAPED PACKAGED PRODUCT "CUBE":

Liquid: $S_{CUBE} = 6/D_{CUBE}$			**Solid:** $S^{*2}_{CUBE} = 42,6/D^{*2}_{CUBE}$		
Diameter D_{CUBE} =	0.11	m	diam. D_{CUBE} =	0.08	m
Specific Surface S_{CUBE} =	54.5454545	m^2/m^3	S^{*2}_{CUBE} =	6656.25	m^4/m^6
Max. volume of package V =	1.331	liters	*Max. volume V*=	0.512	liters

RESULTS:

***LIQUID* food heat penetration factor**			***SOLID* food heat penetration factor**		
fh_{CUBE} =	691.07019	seconds.	fh_{CUBE} =	2382.3904	seconds.

d) OVAL SHAPED PACKAGED PRODUCT "OV":

Liquid: $S_{OV} = 2/H_{OV} + 2/(BD) + 2/(SD)$

Product heigth H_{OV} =	0.03	m
Biggest diameter BD =	0.1	m
Smallest diameter SD =	0.07	m
Specific Surface S_{OV} =	115.238095	m^2/m^3

RESULTS:

***LIQUID* food heat penetration factor**		
fh_{OV} =	327,1031	seconds.

e) SPHERE = BALL SHAPED PRODUCT "BALL":

Liquid: $S_{BALL} = 6/D_{BALL}$			**Solid:** $S^{*2}_{BALL} = 39,5/D^{*2}_{BALL}$		
Product diameter D_{BALL} =	0.04	m	diam. D_{BALL} =	0.06	m
Specific Surface S_{BALL} =	150	m^2/m^3	S^{*2}_{BALL} =	10972.2222	m^4/m^6
Max. volume of package V =	0.03349333	liters	*Max. volume V*=	0.11304	liters

RESULTS:

***LIQUID* food heat penetration factor**			***SOLID* food heat penetration factor**		
fh_{BALL} =	251.29825	seconds.	fh_{BALL} =	1445.2666	seconds.

Example calculation 7: *Computer calculation of $f_{h\ SOLID}$; sterilization time P_t:*
Lean meat, filled in a brick shaped plated metal can of length L = 9.0 cm, width W = 8.5 cm, and height H = 4.4 cm, has a specific heat of c_P = 3630 J/(kg °C), a thermal conductivity of k = 0.51 J/(s m °C), and a density of ρ = 1067 kg/m^3.
The heating lag factor j_h of the can with solid lean meat food product j_h = 2.0.
7a) Use Excel program "*Heat penetration factor fh calculations.xls*" to calculate the heat penetration factor f_h if the brick shaped metal can is sterilized in a saturated steam retort.

7b) The **i**nitial temperature of the food in the can, at the start of the **h**eating process, is T_{ih} = 22 °C.
The retort temperature = sterilization temperature will be T_R = 122 °C.
The come-up time C.U.T. of the saturated steam retort is L = 6 min.
The product temperature at the start of the cooling phase should be T = 118 °C.
Calculate the required sterilization time P_t; use the P_t equation (1) above table 1.

7c) Verify the manually calculated sterilization time P_t of answer 7b) by using computer program STUMBO.exe (STUMBO.exe is available on CD-ROM from j.w.mrouweler@freeler.nl).

Worked answer 7:
Answer 7a: Use Excel program *"Heat penetration factor fh calculations.xls"* to calculate the heat penetration factor f_h of solid lean meat in a brick shaped metal can, sterilized in saturated steam.

- Start Excel program *"Heat penetration factor fh calculations.xls"*.

- At "**INPUT OF THE PHYSICAL PROPERTIES OF THE FOOD**", in the yellow cells, type
  Specific heat food product Cp = 3630 J/(kg °C);
  Density food product ρ = 1067 kg/m^3;
  Thermal conductivity food product k product = 0.51 J/(s m °C)

As the food product is a **solid**, there is no need to include a value in the cell of the "Overall heat transfer coefficient U".

- At "**INPUT OF THE SHAPE AND DIMENSIONS OF THE PACKAGED FOOD PRODUCT**",
  The package shape of the food product is **brick**, thus **fill up section b)**:
  As lean meat is a solid, use the yellow cells on the right side ("SOLID"), to include the package dimensions:
    Product height H_{BR} = 4.4 cm = 0.044 m.
    Product length L_{BR} = 9.0 cm = 0.09 m.
    Product width W_{BR} = 8.5 cm = 0.085 m.

Results: (See computer print below at section ***b) BRICK SHAPED PACKAGED PRODUCT "$_{BR}$"***, at the right hand column Solid):

The computer then calculates the specific surface S^{*2}_{BR} = 11053 m^4/m^6
(this is exactly equal to manually calculated S^{*2} 11053 m^4/m^6 in answer 6b).

Next the computer calculates heat penetration factor brick **fh_{BR} = 1580 s (= = 26.3 min.)**
(this is exactly equal to manually calculated f_h = 1580 s = 26.3 min. in answer 6b).

See section ***b) BRICK SHAPED PACKAGED PRODUCT "$_{BR}$"*** in the screenprint below:

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Heat penetration factor	LIQUID food product	SOLID food product
	$fh = \frac{2.3 \cdot Cp \cdot \rho}{U \cdot S}$	$fh = \frac{2.3 \cdot Cp \cdot \rho}{k \cdot S^{*2}}$

INPUT OF THE PHYSICAL PROPERTIES OF THE FOOD PRODUCT:

pale yellow = input cell

pale blue = calculation results

Specific heat food product **Cp** =	3630	J/(kg °C)
Density food product **ρ** =	1067	kg/m³
Thermal conductivity food product **k** =	0.51	J/(s m °C)
In case of LIQUID foods: Overall heat transfer coefficient **U** =		J/(s m² °C); **see table 3**

INPUT OF THE SHAPE AND DIMENSIONS OF THE PACKAGED FOOD PRODUCT:

a) CYLINDER SHAPED PACKAGED PRODUCT "CYL":

Liquid: $S_{CYL} = 2/H_{CYL} + 4/D_{CYL}$

Solid: $S^{*2}_{CYL} = 9{,}93/H^{*2}_{CYL} + 23{,}2/D^{*2}_{CYL}$

Liquid			Solid		
Product diameter D_{CYL} =	0083	m	diam. D_{CYL} =	0.102	m
Product height H_{CYL} =	0.114	m	height H_{CYL} =	0.112	m
Thickness glass wall dw =	XXXXXXXX		glass dw =	0	in **meters**!!! [1])
Specific Surface S_{CYL} =	65.7366307	m²/m³	S^{*2}_{CYL} =	3021.52509	m⁴/m⁶
Max. volume of package V =	0.61649661	liters	*Max. volume V*=	0.91471968	Liters

[1]) Usually, glass wall thickness dw = 0.0025 m (= 2.5 mm)

RESULTS:

LIQUID food heat penetration factor fh_{CYL} =	#DEEL/0!	seconds.	***SOLID food heat penetration factor*** fh_{CYL} =	5780.9937	seconds.

b) BRICK SHAPED PACKAGED PRODUCT "BR":

Liquid: $S_{BR} = 2/H_{BR} + 2/L_{BR} + 2/W_{BR}$

Solid: $S^{*2}_{BR} = 14{,}2 \cdot (1/H^{*2}_{BR} + 1/L^{*2}_{BR} + 1/W^{*2}_{BR})$

Liquid			Solid		
Product heigth H_{BR} =	0.05	m	height H_{BR} =	0.044	m
Product lenght L_{BR} =	0.12	m	length L_{BR} =	0.09	m
Product width W_{BR} =	0.1	m	width W_{BR} =	0.085	m
Specific Surface S_{BR} =	76.6666667	m²/m³	S^{*2}_{BR} =	**11053.1951**	m⁴/m⁶
Max. volume of package V =	0.6	liters	*Max. volume V*=	0.3366	liters

RESULTS:

LIQUID food heat penetration factor fh_{BR} =	#DEEL/0!	seconds.	***SOLID food heat penetration factor*** fh_{BR} =	**1580.3048**	seconds.

c) CUBE SHAPED PACKAGED PRODUCT "CUBE":

Liquid: $S_{CUBE} = 6/D_{CUBE}$			**Solid**: $S*^2_{CUBE} = 42,6/D*^2_{CUBE}$		
Diameter D_{CUBE} =	0.11	m	diam. D_{CUBE} =	0.08	m
Specific Surface S_{CUBE} =	54.5454545	m^2/m^3	$S*^2_{CUBE}$ =	6656.25	m^4/m^6
Max. volume of package V =	1.331	liters	*Max. volume V*=	0.512	liters

RESULTS:

***LIQUID* food heat penetration factor** fh_{CUBE} =	#DEEL/0!	seconds.	***SOLID* food heat penetration factor** fh_{CUBE} =	2624.213	seconds.

d) OVAL SHAPED PACKAGED PRODUCT "OV":

Liquid: $S_{OV} = 2/H_{OV} + 2/(BD) + 2/(SD)$

Product heigth H_{OV} =	0.03	m
Biggest diameter BD =	0.1	m
Smallest diameter SD =	0.07	m
Specific Surface S_{OV} =	115.238095	m^2/m^3

RESULTS:

***LIQUID* food heat penetration factor** fh_{OV} =	#DEEL/0!	seconds.

e) SPHERE = BALL SHAPED PRODUCT "BALL":

Liquid: $S_{BALL} = 6/D_{BALL}$			**Solid**: $S*^2_{BALL} = 39,5/D*^2_{BALL}$		
Product diameter D_{BALL} =	0.04	m	diam. D_{BALL} =	0.06	m
Specific Surface S_{BALL} =	150	m^2/m^3	$S*^2_{BALL}$ =	10972.2222	m^4/m^6
Max. volume of package V =	0.03349333	liters	*Max. volume V*=	0.11304	liters

RESULTS:

***LIQUID* food heat penetration factor** fh_{BALL} =	#DEEL/0!	seconds.	***SOLID* food heat penetration factor** fh_{BALL} =	1591.9672	seconds.

Answer 7b) *Calculate the required sterilization time P_t;*
According to equation (1) above table 1, the equation for the pasteurization or sterilization time P_t is:

$$P_t = f_h \cdot {}^{10}\log\left(j_h \cdot \frac{T_R - T_{ih}}{T_R - T}\right) - 0.4 \cdot L$$

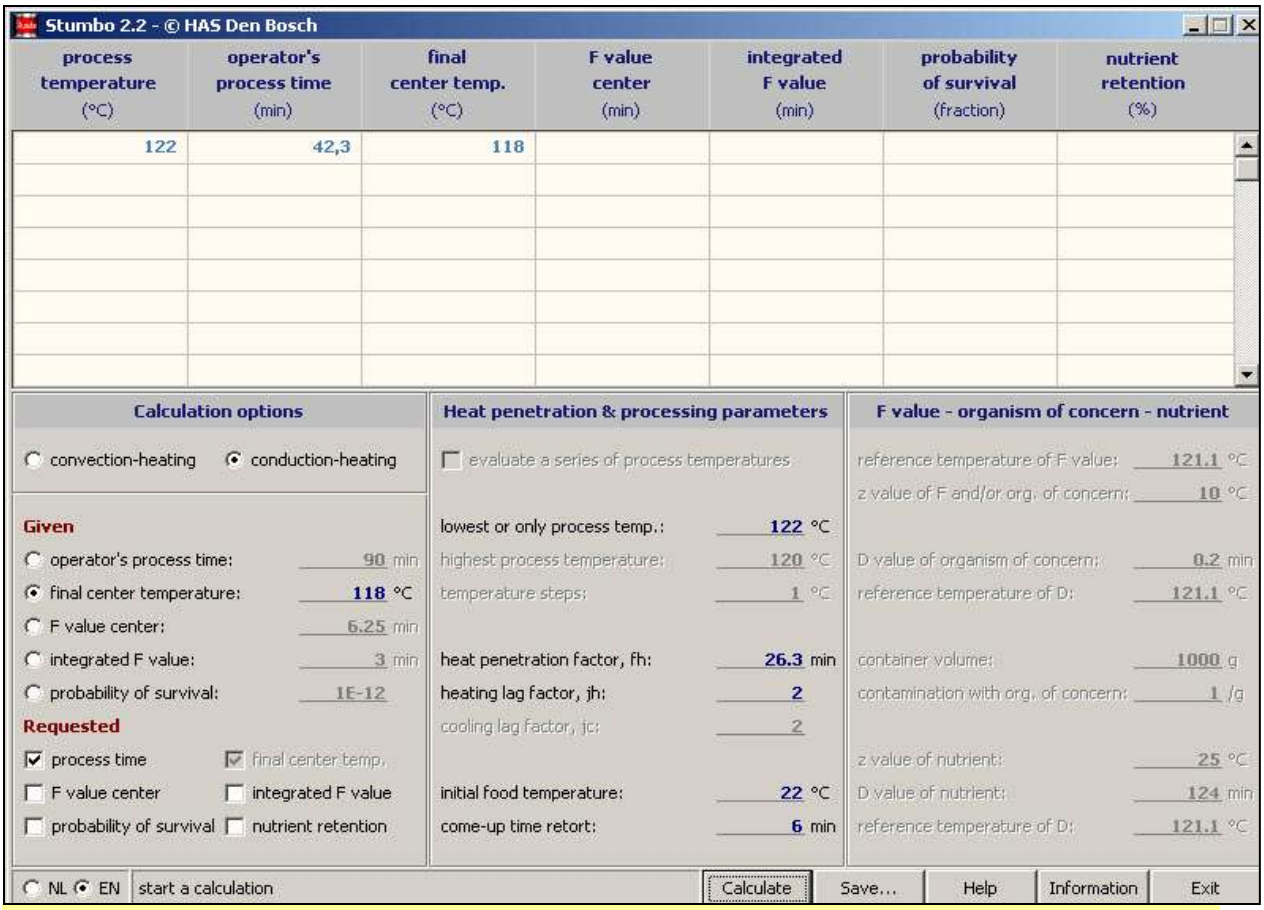
in which
f_h = 26.3 min. (see worked answer 7a);
j_h = 2.0 (given)
T_R = sterilization temperature =122 °C (given)
T_{ih} = initial temperature of product in retort at start of process = 22 °C (given);
T = core temperature of food product at moment of steam off/cooling water on = 118 °C (given);
L = Come-up time of retort = 6 min. (given).

Substitution of f_h, j_h, T_R, T_{ih}, T and L in equation (1) of sterilization time P_t results in:

$$P_t = 26.3 \cdot {}^{10}\log(2.0 \cdot \frac{122 - 22}{122 - 118}) - 0.4 \cdot 6 = 26.3 \cdot {}^{10}\log(2 \cdot 100/4) - 2.4$$

So the sterilization time **P_t = 42.3 min.**

Answer 7c) *Verification of the manually calculated sterilization time P_t = "operator's process time", by using the computer program STUMBO.exe*:
- After start of STUMBO.exe, at bottom left of STUMBO 2.2: select language (•)EN.
- At **Calculation options**: select (•) "conduction heating", as lean meat is a solid.
- At **Given**: select (•) "final center temperature"; insert the temperature 118
- At **Requested**: put a tick at "process time"; remove the other ticks.
- At **Heat penetration & processing parameters:**
  - remove the tick at "evaluate a series of process temperatures";
  - at "lowest or only process temperature": insert 122 (= given retort temperature);
  - at "heat penetration factor, fh": insert 26.3 (see worked answer 7a);
  - at "heating lag factor, jh": insert 2 (given);
  - at "initial food temperature": insert 22 (given);
  - at "come-up time retort": insert 6 (given).
- Next press button "Calculate" (at the bottom in the middle).
  This results in:



As can be seen from the **STUMBO.exe** print screen above:
A conduction heating food, which should get a final center temperature of T = 118 ºC, which is processed at a retort temperature of T_R = 122 ºC, which has a heat penetration factor f_h = 26.3 min., a heating lag factor j_h = 2, an initial food temperature T_{ih} = 22 ºC, and with retort come-up time L = 6 min., has to be sterilized during **operator's process time of P_t = 42.3 min.**

This is exactly equal to the manual calculated P_t = 42.3 min. of answer 7b).

6. Heat penetration factor f_h for a packaged liquid food, containing solid pieces

Several packaged food products contain solid pieces, submerged in the liquid. Examples of such packaged foods are: meat balls in soup or in gravy, sausages in water or in brine, gherkins or sliced cucumbers in vinegar, cherries in a sugar solution, sliced pineapple in syrup, etc. The heat penetration factor f_h of such foods can be estimated by assuming:

$$f_{h,\text{ can of liquid food with submerged solid}} = f_{h,\text{ can full of liquid only}} + f_{h,\text{ one submerged solid piece}}$$

For example: in case of canned meat balls in gravy, the equation for f_h would be:

$$f_{h,\text{ can of solid meat balls in liquid gravy}} = f_{h,\text{ can filled with gravy only}} + f_{h,\text{ one solid meat ball}}$$

or

$$f_{h,\text{ can of solid meat balls in liquid gravy}} = \frac{2.3 \cdot C_{p,gravy} \cdot \rho_{gravy}}{S_{\text{can of gravy}} \cdot U_{\text{can of gravy}}} + \frac{2.3 \cdot C_{p,ball} \cdot \rho_{ball}}{S^{*2}_{\text{one ball}} \cdot k_{ball}}$$

For an explanation of the symbols used: see Chapter 1.

Example calculation 8: *calculate the f_h for liquid foods with solid pieces:*

8a) Estimate the heat penetration factor f_h of a cylindrical glass jar, with internal diameter x height = 7.0 cm x 10 cm, thickness of glass wall 2.5 mm, filled with small cylindrical sausages (D x H = 1.6 cm x 9.0 cm). The sausages are submerged in a watery brine. The jars will be sterilized in a full water still retort.
(Physical) properties of the low viscous watery brine in the jar, are:

- density ρ_{brine} = 1014 kg/m^3;
- specific heat $C_{p,brine}$ = 4120 J/(kg ºC);
- overall heat transfer coefficient regarding a glass jar with low viscous brine, in a full water still retort: $U_{\text{jar with brine}}$ = 200 J/(s ºC m^2) (see table 8).

Physical properties of each of the sausages, are:

- density $\rho_{sausage}$ = 1040 kg/m^3;
- specific heat $C_{p,sausage}$ = 3300 J/(kg ºC);
- thermal conductivity $k_{sausage}$ = 0.48 J/(s m ºC).

8b) Verify each of the 2 manually estimated f_h values of answer 8a), i.e. the f_h of the glass jar with brine, and the f_h of a solid cylindrical sausage, by using Excel spreadsheet "*Heat penetration factor fh calculations.xls*".

Worked answer 8:

Answer 8a: The heat penetration factor f_h of a packaged liquid food with solid pieces is:

$$f_{h,\text{ jar of liquid food with submerged solid}} = f_{h,\text{ jar with liquid only}} + f_{h,\text{largest submerged solid pieces}}.$$

For a jar with solid cylindrical sausages, submerged in a liquid brine, this equation is:

$$f_{h,\text{ jar with sausages in brine}} = \frac{2.3 \cdot C_{p,brine} \cdot \rho_{brine}}{S_{\text{jar with brine}} \cdot U_{\text{jar with brine}}} + \frac{2.3 \cdot C_{p,sausage} \cdot \rho_{sausage}}{S^{*2}_{sausage} \cdot k_{sausage}}$$

in which

$C_{p,brine}$ = 4120 J/(kg ºC) (given);
ρ_{brine} = 1014 kg/m^3 (given)
$S_{\text{jar with brine}}$ = ????????????
$U_{\text{jar with brine}}$ = 200 J/(s ºC m^2) (given);
$C_{p,sausage}$ = 3300 J/(kg ºC) (given);
$\rho_{sausage}$ = 1040 kg/m^3 (given);
$S^{*2}_{sausage}$ = ????????????
$k_{sausage}$ = 0.48 J/(s m ºC) (given).

Calculation of $S_{\text{jar with brine only}}$:

Glass jar: $D_{internal}$ = 7.0 cm = 0.07 m; $H_{internal}$ = 10 cm = 0.10 m.
Specific surface of a cylindrical glass jar, filled with liquid brine (see table 4):
$S_{\text{jar with brine only}} = 2/H + 4/D = 2/0.10 + 4/0.07 = 77\ m^2/m^3$.

Calculation of $S^{*2}_{sausage}$:

Sausage: D = 1.6 cm = 0.016 m; H = 9 cm = 0.09 m.
Squared specific surface S^{*2} of one cylindrical solid sausage (see table 4):
$S^{*2}_{sausage} = 9.93/H^{*2} + 23.2/D^{*2} = 9.93/(0.09^2) + 23.2/(0.016^2) =$
$= 1225.9 + 90625 = 91\,851\ m^4/m^6 = S^{*2}_{sausage}$.

Substitution of all factors in the equation above results in:

$$f_{h,\text{ jar with sausages in brine}} = \frac{2.3 \cdot 4120 \cdot 1014}{77 \cdot 200} + \frac{2.3 \cdot 3300 \cdot 1040}{91\,851 \cdot 0.48} =$$

= 624 seconds + 179 seconds = 803 seconds.

$f_{h,\text{ jar with sausages in brine}}$ = 803 seconds = 13.4 min.

Answer 8b: *Verification of the manually estimated f_h value of the* ***cylindrical glass jar with brine****:*

(only part of the Excel spreadsheet "*Heat penetration factor fh calculations.xls*" is reproduced)

Calculation of $f_{h,liquid}$ of the cylindrical glass jar with brine:

INPUT OF THE PHYSICAL PROPERTIES OF THE FOOD PRODUCT:

Specific heat food product **Cp** =	4120	J/(kg °C)
Density food product **ρ** =	1014	kg/m^3
Thermal conductivity food product **k** =		J/(s m °C)
In case of LIQUID foods: Overall heat transfer coefficient **U** =	200	$J/(s\ m^2\ °C)$; **see table 3**

INPUT OF THE SHAPE AND DIMENSIONS OF THE PACKAGED FOOD PRODUCT:

a) CYLINDER SHAPED PACKAGED PRODUCT "CYL":

Liquid: $S_{CYL} = 2/H_{CYL} + 4/D_{CYL}$			**Solid:** $S^{*2}_{CYL} = 9{,}93/H^{*2}_{CYL} + 23{,}2/D^{*2}_{CYL}$		
Product diameter D_{CYL} =	0.07	m	diam. D_{CYL} =		m
Product height H_{CYL} =	0.1	m	height H_{CYL} =		m
Thickness glass wall dw =	XXXXXX		glass dw =		in **meters**!!
Specific Surface S_{CYL} =	77.1428571	m^2/m^3	S^{*2}_{CYL} =		m^4/m^6
Max. volume of package V =	0.38465	liters	*Max. volume V*=		liters

RESULTS:

LIQUID food heat penetration factor			***SOLID food heat penetration factor***		
fh_{CYL} =	622.78378	seconds.	fh_{CYL} =		seconds.

The Excel file "*Heat penetration factor fh calculations.xls*" above calculates for the cylindrical glass jar a specific surface $S_{\text{Glass Jar}} = 77.1\ m^2/m^3$, and a separate f_h value for the cylindrical glass jar with brine of **f_{hCYL} = 623 seconds**. Which is almost exactly equal to manually calculated $S_{\text{jar with brine only}} = 77\ m^2/m^3$, and the manually estimated $f_{h,\text{jar with brine}}$ = 624 seconds in answer 8a).

Answer 8b *(continued):*

*Verification of the manually estimated f_h value of a **solid cylindrical sausage**:*

(only part of the Excel spreadsheet "*Heat penetration factor fh calculations.xls*" is reproduced)

Calculation of the $f_{h,solid}$ of one cylindrical sausage:

INPUT OF THE PHYSICAL PROPERTIES OF THE FOOD PRODUCT:

Specific heat food product **Cp** =	3300	J/(kg °C)
Density food product **ρ** =	1040	kg/m³
Thermal conductivity food product **k** =	0.48	J/(s m °C)
In case of <u>LIQUID</u> foods: Overall heat transfer coefficient **U** =		J/(s m² °C); **see table 3**

INPUT OF THE SHAPE AND DIMENSIONS OF THE PACKAGED FOOD PRODUCT:

a) CYLINDER SHAPED PACKAGED PRODUCT "CYL":

Liquid: $S_{CYL} = 2/H_{CYL} + 4/D_{CYL}$			**Solid:** $S^{*2}_{CYL} = 9{,}93/H^{*2}_{CYL} + 23{,}2/D^{*2}_{CYL}$		
Product diameter D_{CYL} =		m	diam. D_{CYL} =	0.016	m
Product height H_{CYL} =		m	height H_{CYL} =	0.09	m
Thickness glass wall dw =	XXXXXX		glass dw =	0	in **meters**!!
Specific Surface S_{CYL} =		m²/m³	S^{*2}_{CYL} =	91850.9259	m⁴/m⁶
Max. volume of package V =		liters	*Max. volume V*=	0.0180864	liters

RESULTS

Liquid Food heat penetration factor			***Solid food heat penetration factor***		
fh_{CYL} =		seconds.	fh_{CYL} =	179.04011	seconds.

For **<u>one</u>** cylindrical solid sausage, the Excel file "*Heat penetration factor fh calculations.xls*" calculates S^{*2}_{CYL} = 91 851 m⁴/m⁶, and the (separate) f_h value for one cylindrical solid sausages of f_{hCYL} = 179 seconds. Which is exactly equal to manually calculated $S^{*2}_{sausage}$ = 91 851 m⁴/m⁶ in answer 8a), and the manually estimated $f_{h,sausage}$ = 179 seconds in answer 8a).

7. Effect of a CHANGE in processing conditions, or in packaging size, on the heat penetration factor f_h of a packaged food

7.1 Neither a change in retort temperature T_R, nor a change in initial food temperature T_{ih}, does affect the heat penetration factor f_h or the heating lag factor j_h

During processing, sometimes the retort temperature T_R has to be adapted.
In other cases, sometimes the initial product temperature T_{ih} has changed; for example when there is an obstruction at the supplying belt to the retort, and the packaged food cools down or increases in temperature before entering the retort.
These situations require recalculation of the sterilization or pasteurization time P_t.

> Neither the heat penetration factor f_h, nor the heating lag factor j_h, depend on the initial food temperature T_{ih}, nor on the retort temperature T_R.
> So after such a changes in process conditions, f_h and j_h need not to be recalculated.
>
> Only a very large change in **c**ome **u**p **t**ime C.U.T. = L of the retort does influence the values of f_h, j_h and j_C.

7.2 A change in packaging size strongly affects f_h; use size conversion factor

A change in the size of the packaging of a liquid food ..... (Stumbo (1973: 193-198))
- * strongly influences the heat penetration factor f_h;
- * does NOT, or only very slightly, change the heating lag factors j_h and j_C.

Table 9: Conversion of the heat penetration factor f_h when package size changes.

Liquid foods: f_h is proportional to 1/S; S = normal specific surface of packaging (table 4).
$\mathbf{S}_{OLD}/\mathbf{S}_{NEW}$ = ***size conversion factor*** for **liquid** foods.

$$f_{h,\text{ liquid NEW packaging size}} = \frac{\mathbf{S}_{\text{ OLD packaging size}}}{\mathbf{S}_{\text{ NEW packaging size}}} \cdot f_{h,\text{ liquid OLD packaging size}}$$

Solid foods; highly viscous foods: f_h is proportional to $1/S*^2$; $S*^2$ = adapted squared specific surface (see table 4).
$\mathbf{S*^2}_{OLD}/\mathbf{S*^2}_{NEW}$ = ***size conversion factor*** for **solid** foods.

$$f_{h,\text{ solid NEW packaging size}} = \frac{\mathbf{S*^2}_{\text{ OLD packaging size}}}{\mathbf{S*^2}_{\text{ NEW packaging size}}} \cdot f_{h,\text{ solid OLD packaging size}}$$

See also **Table 4**: Equations to calculate the specific surface S of packaged liquid foods, and the adapted squared specific surface $S*^2$ of packaged solid foods.

D = internal diameter; H = internal height; L = internal length; W = internal width; BD = biggest internal diameter; SD = smallest internal diameter; d_W = thickness of glass wall = 2.5 mm = $2.5 \cdot 10^{-3}$ m.
In the equations below: D, H, L, W, BD, SD, d_W, are all in [m].

Shape of	**LIQUID** (convection type) product: S [m^2/m^3]	**SOLID** (conduction type) product: $S*^2$ [m^4/m^6]. If **GLASS** packaging: $H*^2 = (H + 2 \cdot d_W)^2$; $D*^2 = (D + 2 \cdot d_W)^2$; $L*^2 = (L + 2 \cdot d_W)^2$; $W*^2 = (W + 2 \cdot d_W)^2$.
Cylinder	S = 2/H + 4/D	$S*^2 = 9.93/H*^2 + 23.2/D*^2$
Brick	S = 2/H + 2/L + 2/W	$S*^2 = 14.2 \cdot (1/H*^2 + 1/L*^2 + 1/W*^2)$
Cube	S = 6/D	$S*^2 = 42.6/D*^2$
Oval	S = 2/H + 2/(BD) + 2/(SD)	-
Sphere; ball	S = 6/D	$S*^2 = 39.5/D*^2$

Example calculation 9: *Effect on f_h of a change in packaging size of a **liquid** food:*
A company produces green beans in brine, packaged in a cylindrical can 1 with internal D x H = 73 mm x 103 mm; these cans 1 have a heat penetration factor of f_h = 5.4 min.
The company considers to use a new cylindrical can 2, which has an internal diameter 163 mm, and an internal height of 156 mm.

9a) Calculate the new heat penetration factor $f_{h,NEW}$ if the green beans in brine are processed in a can 2 of internal diameter 163 mm, and an internal height of 156 mm.
9b) The value of the size conversion factor from can 1 to can 2 is: _______________.
9c) What will be the effect of the change in packaging size on the heating lag factor j_h?

Worked answer 9:
Answer 9a) *Calculate the new heat penetration factor after change of can size:*
To find the proper f_h conversion equation, we first have to find out: do green beans in brine behave like a liquid or like a solid?
* 1st test: when turning a glass jar with green beans in brine and headspace slowly upside down once, the head space bubble will easily passes through the content of the jar (see the "simple test" in Chapter 1).
So green beans in brine will behave as a liquid food (with solid pieces) during retorting.
* 2nd test: according to table 1, for a packaged liquid food the value of f_h is:
4 min. < $f_{h,LIQUID}$ < 15 min. [for a solid food: 25 min. < $f_{h,SOLID}$ < 200 min.].
The given value of the heat penetration factor of the green beans in brine is f_h = 5.4 min.
This indicates that green beans in brine will behave as a liquid food (with solid pieces).
Conclusion: green beans in brine will behave like a liquid food.
According to Table 9: $f_{h,liquid}$ is proportional to 1/S; in which S = specific surface of packaging. So:

$$f_{h,\text{ liquid NEW packaging size}} = \frac{S_{\text{OLD packaging size}}}{S_{\text{NEW packaging size}}} \cdot f_{h,\text{ liquid OLD packaging size}}$$

in which
$f_{h,\text{ liquid OLD packaging size}}$ = 5.4 min. (given)
$S_{\text{OLD packaging size}} = 2/H_{OLD} + 4/D_{OLD} = 2/0.103 + 4/0.073$ (see table 4);
so $S_{\text{OLD packaging size}} = 74.2\ m^2/m^3$.
$S_{\text{NEW packaging size}} = 2/H_{NEW} + 4/D_{NEW} = 2/0.156 + 4/0.163$;
so $S_{\text{NEW packaging size}} = 37.4\ m^2/m^3$.

Substitution in the f_h conversion equation above results in:

$$f_{h,\text{ liquid NEW packaging size}} = \frac{74.2}{37.4} \cdot 5.4 = 1.98 \cdot 5.4 = 10.7 \text{ min.}$$

So **$f_{h,\text{ liquid NEW packaging size}}$ = 10.7 min.**

Answer 9b) *The size conversion factor for a liquid food from size OLD to size NEW is*:

$$\text{Size conversion factor liquid food} = \frac{S_{\text{OLD packaging size}}}{S_{\text{NEW packaging size}}}$$ (see table 9).

In answer 9a) we found: $S_{\text{OLD packaging size}} = 74.2\ m^2/m^3$.
$S_{\text{NEW packaging size}} = 37.4\ m^2/m^3$.
So the liquid food **size conversion factor from can OLD to can NEW = 74.2/37.4 = 1.98.**

Answer 9c) *Will be change in packaging size affect the heating lag factor j_h?*
At the top of chapter 7.2 it says: "A change in packaging size, does NOT, or only very slightly, change the heating lag factors j_h and j_C.
So the change in packaging size of this liquid food does not change j_h and j_C.

Example calculation 10: *Effect on f_h of a change in packaging size of **solid** foods:*
During heat processing of luncheon meat in cylindrical metal can L of internal D x H = 73 mm x 138 mm, the heat penetration is f_h = 60 minutes.
In the future, the company considers heat processing of luncheon meat in cylindrical metal cans M with internal size D x H = 163 mm x 156 mm.
10a) Calculate the "size conversion factor" for the size conversion from metal can L to metal can M.
10b) Calculate the new heat penetration factor of luncheon meat in metal can M.
10c) A different solid food showed a heat penetration factor of f_h = 220 min. in metal can M. What would be the heat penetration factor of that solid food in the smaller metal can L?

Worked answer 10:
Answer 10a) The **size conversion factor** for conversion of solid food packages is (see table 9):

$$\text{Size conversion factor solid food from can OLD to can NEW} = \frac{S^{*2}\ \text{OLD packaging size}}{S^{*2}\ \text{NEW packaging size}}$$

For cylindrical metal can L = "OLD" with solid food and internal sizes D = 73 mm and H = 138 mm, the equation for S^{*2} is: $S^{*2} = 9.93/H^{*2} + 23.2/D^{*2}$ (see table 4).
Because the cans are made of metal, no glass wall thickness need to be considered.
So $S^{*2} = 9.93/0.138^2 + 23.2/0.073^2 = 4875\ m^4/m^6$ for can L.
For metal can M = "NEW", with solid food and internal sizes D = 163 mm and H = 156 mm, $S^{*2} = 9.93/H^{*2} + 23.2/D^{*2} = 9.93/0.156^2 + 23.2/0.163^2 = 1281\ m^4/m^6$ (can M).
Substitution in the size conversion equation above, results in:

$$\text{Size conversion factor solid food from can L to can M} = \frac{S^{*2}\ \text{OLD packaging size}\ \mathbf{L}}{S^{*2}\ \text{NEW packaging size}\ \mathbf{M}} =$$

$$= \frac{4875}{1281} =$$ **3.81 = Size conversion factor solid food from can L to can M.**

Answer 10b) *Calculate the new heat penetration factor of luncheon meat in cylindrical metal can M:*

$$f_{h,\ \text{solid NEW packaging size}} = \frac{S^{*2}\ \text{OLD packaging size}}{S^{*2}\ \text{NEW packaging size}} \cdot f_{h,\ \text{solid OLD packaging size}}$$ (table 9).

or

$$f_{h,\ \text{solid NEW packaging size}} = \text{Size conversion factor solid foods} \cdot f_{h,\ \text{solid OLD packaging size}}$$

in which

Size conversion factor solid food from L to M = 3.81 (see answer 10a above);

$f_{h,\ \text{solid OLD packaging size}}$ = 60 min. (given)

So **$f_{h,\ \text{solid NEW packaging size M}}$ = 3.81 · 60 = 229 min.**

Answer 10 c) *Calculate the heat penetration factor of a "different" solid food in the smaller metal can L.*
The size of the cylindrical metal can of the "different" solid food goes from size M to size L; so the size change is the inverse from L to M.
Thus the size conversion factor is also inverted = 1/(size conversion factor from L to M).
So size conversion factor for the "different food" is 1/3.81 = 0.262.
Thus the $f_{h,\ \text{different solid NEW packaging size}} = 0.262 \cdot f_{h,\ \text{solid OLD packaging size}}$,
or **$f_{h,\ \text{different solid NEW packaging size}}$ = 0.262 · 220 = 57.6 min.**

8. Effect on f_h of change in material (glass; metal) of the packaging:
$f_{h,\ LIQUID}$ requires considerable correction; $f_{h,\ SOLID}$ shows a smaller change

8.1 How does a change in type of packaging material affects the f_h of LIQUID PRODUCTS?

Table 10: Conversion of the heat penetration factor f_h of a **liquid** food product if the packaging **material** changes: from metal to glass, or from glass to metal.

Liquid (convection type) products
Change **from metal** packaging **to glass** packaging: $$\text{New } f_{h,Liquid,\ Glass} = \frac{S_{Metal}}{S_{Glass}} \cdot f_{h,Liquid,\ Metal} + \frac{2.3 \cdot c_P \cdot \rho}{S_{Glass}} \cdot \frac{d_{W,Glass}}{k_{W,Glass}}$$
Change **from glass** packaging **to metal** packaging: $$\text{New } f_{h,Liquid,\ Metal} = \frac{S_{Glass}}{S_{Metal}} \cdot f_{h,Liquid,\ Glass} - \frac{2.3 \cdot c_P \cdot \rho}{S_{Metal}} \cdot \frac{d_{W,Glass}}{k_{W,Glass}}$$

Kopelman (1981: 234); Reichert (1985: 32); May (1997: 55-56)

in which:

$f_{h,Liquid,\ Glass}$ f_h value of the liquid food product in glass packaging; [s];

$f_{h,Liquid,\ Metal}$ f_h value of the liquid food product in metal packaging; [s];

S_{Metal} Specific surface of the metal packaging, based on its inside dimensions; [m^2/m^3];
See table 4 for equations of S. See Chapter 3 for calculation of S.

S_{Glass} Specific surface of the glass packaging, based on its inside dimensions; [m^2/m^3];
See table 4 for equations of S. See chapter 3 for calculation of S.

c_P Specific heat of the liquid food product; [J/(kg·°C)].
A table with specific heats of many different food products, and a computer program to calculate the specific heat cp of a composed food: see FYSCONST 2.0.xls, downloadable from Academia.edu or ResearchGate.net.

ρ Density of the liquid food product; [kg/m^3].
For a computer program to calculate the density ρ of a composed food: see FYSCONST 2.0.xls, downloadable from Academia.edu or at ResearchGate.net.

$d_{W,Glass}$ Thickness of the glass wall of the packaging material; [m];
Usually dw,glass = 2.5 mm = $2.5 \cdot 10^{-3}$ m. Range: $2.1 \cdot 10^{-3}$ m < dw,glass < $3.1 \cdot 10^{-3}$ m.

$k_{W,\ Glass}$ Thermal conductivity of the glass wall of the packaging material [J/(s m ºC)]; [W/(m K].
Usually $k_{W,\ Glass} \approx 0.7$ J/(s m ºC). Range: 0.7 J/(s m °C) < $k_{W,\ Glass}$ < 1.2 J/(s m °C).

If only the packaging material of a liquid food changes, but the shape and the internal dimensions of the packaging materials do NOT change,
thus if $S_{Metal} = S_{Glass}$, then **always** $f_{h,\ Liquid,\ Glass} > f_{h,\ Liquid,\ Metal}$.
This can be deduced from the equations in table 10:

from metal to glass packaging: "new" $f_{h,Liquid,\ Glass} = 1 \cdot f_{h,Liquid,\ Metal}$ **+** correction factor;

from glass to metal packaging: "new" $f_{h,Liquid,\ Metal} = 1 \cdot f_{h,Liquid,\ Glass}$ **-** correction factor.

Neither the heating lag factor j_h, nor the cooling lag factor j_C of a liquid food will be influenced by a change in packaging material.

Example calculation 11: *Effect of change in packaging material on f_h of liquid product:*
A metal can with internal D x H = 163 mm x 141 mm contains 57 sausages of each 30 g, and diameter d = 10 mm, in 1232 grams of a watery brine.
When sterilized in a rotary retort (30 rotations per minute), the heat penetration factor of that metal can with contents is f_h = 7.1 min.
The company considers to use cylindrical glass jars, type 82RTO.FD130, internal D x H = 83.9 mm x 191.5 mm, with 18 sausages of each 30 g, and diameter d = 10 mm, in 390 grams of watery brine, to be sterilized in a rotary retort (30 rotations per minute).
For glass: wall thickness of glass jars: d_W = 3.1 mm;
thermal conductivity glass = 1.15 J/(s m °C) = 1.15 W/(m °C).
For brine: c_P = 4184 J/(kg °C);
density ρ = 1000 kg/m³.
Estimate the heat penetration factor f_h of the smaller cylindrical glass jar.
(from Reichert (1985: 32)).

Worked answer 11:
* First we should find out whether the product "sausages in brine" will behave like a liquid or like a solid.
Sausages in brine will behave like a liquid (= convection type) food product. This can be deduced from the rather low heat penetration factor of f_h = 7.1 min.
Compare to the usual $f_{h,LIQUID}$ of a liquid: 4 min. < $f_{h,LIQUID}$ < 15 min. See table 1.
[If the product would behave like a solid, then 25 min. < $f_{h,SOLID}$ < 200 min.]

* For a liquid product of which the packaging material is changed from metal to glass, the conversion equation is (see table 10):

$$\text{New } f_{h,Liquid,\,Glass} = \frac{S_{Metal}}{S_{Glass}} \cdot f_{h,Liquid,\,Metal} + \frac{2.3 \cdot c_P \cdot \rho}{S_{Glass}} \cdot \frac{d_{W,Glass}}{k_{W,Glass}}$$

in which:
$S_{Metal} = S_{CYLINDER} = 2/H_{Metal\ Can} + 4/D_{Metal\ Can}$ (see table 4, for a liquid food in cylinder);
$H_{Metal\ Can}$ = 141 mm = 0.141 m (given);
$D_{Metal\ Can}$ = 163 mm = 0.163 m (given);
So $S_{Metal} = 2/H_{Metal\ Can} + 4/D_{Metal\ Can}$ = 2/0.141 + 4/0.163 = 38.7 m²/m³.
$S_{Glass} = S_{CYLINDER} = 2/H_{Glass\ Jar} + 4/D_{Glass\ Jar}$ (see table 4, for a liquid food in cylinder);
$H_{Glass\ Jar}$ = 191.5 mm = 0.1915 m (given);
$D_{Glass\ Jar}$ = 83.9 mm = 0.0839 m (given);
$S_{Glass} = 2/H_{Glass\ Jar} + 4/D_{Glass\ Jar}$ = 2/0.1915 + 4/0.0839 = 58.1 m²/m³.
$f_{h,Liquid,\,Metal}$ = 7.1 min. = 426 s (given).
c_p = specific heat of brine c_p = 4184 J/(kg °C) (given);
ρ = density of brine ρ = 1000 kg/m³ (given);
$d_{W,Glass}$ = glass wall thickness = $d_{W,Glass}$ = 3.1 mm = 0.0031 m (given);
$k_{W,Glass}$ = 1.15 J/(s m °C) (given).

Substitution of all factors in the equation for the new $f_{h,Glass}$ above results in:

$$\text{New } f_{h,Liquid,\,Glass} = \frac{S_{Metal}}{S_{Glass}} \cdot f_{h,Liquid,\,Metal} + \frac{2.3 \cdot c_P \cdot \rho}{S_{Glass}} \cdot \frac{d_{W,Glass}}{k_{W,Glass}}$$

$$= \frac{38.7}{58.1} \cdot 426 + \frac{2.3 \cdot 4184 \cdot 1000}{58.1} \cdot \frac{0.0031}{1.15}$$

$$= 284 + 446 = 730 \text{ s} = 12.2 \text{ min.}$$

So the new $f_{h,Liquid,\,Glass}$ = 730 s = 12.2 min.
[Reichert (1985: p 32) finds new $f_{h,Glass}$ = 11.9 min.]

Compare this new $f_{h,Liquid,\,Glass}$ = 12.2 min. of the smaller jar, to the original $f_{h,Liquid,\,Metal}$ = 7.1 min. of the larger can: an f_h increase of 70%, despite the reduced size of the jar!
Thus change from metal to glass considerably increases $f_{h,Liquid}$.

8.2 How does a change in packaging material affect the f_h of SOLID PRODUCTS?

Table 11: Conversion of the heat penetration factor f_h of a **solid** food product if the packaging **material** changes: from metal to glass, or from glass to metal.

Solid (conduction type) products
Change **from metal** packaging **to glass** packaging. $$\text{New } f_{h,Solid,\,Glass} = \frac{S^{*2}_{Metal}}{S^{*2}_{Glass}} \cdot f_{h,Solid,\,Metal}$$
Change **from glass** packaging **to metal** packaging. $$\text{New } f_{h,Solid,\,Metal} = \frac{S^{*2}_{Glass}}{S^{*2}_{Metal}} \cdot f_{h,Solid,\,Glass}$$

In which

$f_{h,Solid,\,Glass}$ f_h value of the solid food product in glass packaging; [s];

$f_{h,Solid,\,Metal}$ f_h value of the solid food product in metal packaging; [s];

S^{*2}_{Metal} Adapted squared specific surface of the metal packaging, based on its inside dimensions only; [m^4/m^6];
See table 4 for equations of S^{*2}. See Chapter 3 for calculation of S^{*2}.

S^{*2}_{Glass} Adapted squared specific surface of the glass packaging, based on its inside dimensions, **each with addition of 2x glass wall thickness**; [m^4/m^6];
See table 4 for equations of S^{*2}. See Chapter 3 for calculation of S^{*2}.

When comparing table 11 (equations on a solid food) to table 10 (equations on a liquid food), in the conversion equations of a solid food the extra "addition correction factor" or "subtraction correction factor" is absent.
Reason: in a glass packed solid food, the heat transfer resistance of the glass wall has already been incorporated in the S^{*2}: the addition of 2x the glass wall thickness d_W to the product dimensions thus does account for the extra heat transfer resistance of glass.
In a metal packed solid food, however, the heat transfer resistance of the highly conductive, very thin metal wall, is neglectible; so an extra correction is not necessary.

Example calculation 12: *effect of change in packaging material of solid foods:*
A cylindrical glass jar with a solid (conduction type) food has internal dimensions of D x H = 103.2 mm x 119.1 mm. The glass wall thickness d_W of the jar is d_W = 3.1 mm.
In a static, steam heating, retort, the heat penetration factor of the solid food in the glass jar is $f_{h,Solid,\,glass}$ = 85 min.
The company decides to process the solid food in metal cans of the same internal sizes as the glass jar, in the same retort.
a) Estimate the heat penetration factor of a the solid food in a cylindrical metal can with internal dimensions of D x H = 103.2 mm x 119.1 mm, at the same retorting conditions.
b) Use Excel program "*Heat penetration factor fh calculations.xls*", to verify the adapted squared specific surface S^{*2} of the cylindrical glass jar, and of the cylindrical metal can, calculated in answer 12a.

Worked answer 12:
Answer 12a) If the packaging material of a solid food is changed from glass to metal, the new $f_{h,Solid,\,Metal}$ will be (see table 11):

$$f_{h,Solid,\,Metal} = \frac{S^{*2}_{Glass}}{S^{*2}_{Metal}} \cdot f_{h,Solid,\,Glass}$$

in which

$f_{h,Solid,\ Glass}$ = 85 min = 5100 s (given)

$f_{h,Solid,\ Metal}$ = ?????

S^{*2}_{Glass}: Cylindrical glass jar: $S^{*2}_{Glass} = 9.93/H^{*2} + 23.2/D^{*2}$ [m^4/m^6]; (see table 4)

with $H_{Glass} = H + 2xd_{W,Glass}$ = 119.1 mm + 2x3.1 mm = 125.3 mm = 0.1253 m;
so $H^{*2} = 0.1253^2 = 0.01570$ [m^2];

and $D_{Metal} = D + 2xd_{W,Glass}$ = 103.2 mm + 2x3.1 mm = 109.4 mm = 0.1094 m;
so $D^{*2} = 0.1094^2 = 0.01197$ [m^2];

Thus $S^{*2}_{Glass} = 9.93/H^{*2} + 23.2/D^{*2} = 9.93/0.01570 + 23.2/0.01197 = 2571$;
so S^{*2}_{Glass} = 2571 m^4/m^6.

S^{*2}_{Metal}: Cylindrical metal can: $S^{*2}_{Metal} = 9.93/H^{*2} + 23.2/D^{*2}$ [m^4/m^6]; (see table 4)

with H_{Metal} = 119.1 mm = 0.1191 m; so $H^{*2} = 0.1191^2 = 0.01418$ [m^2];

and D_{Metal} = 103.2 mm = 0.1032 m; so $D^{*2} = 0.1032^2 = 0.01065$ [m^2];

In case of metal packaging: do <u>NOT</u> add d_W to H and D.

Thus $S^{*2}_{Metal} = 9.93/H^{*2} + 23.2/D^{*2} = 9.93/0.01418 + 23.2/0.01065 = 2879$;
so S^{*2}_{Metal} = 2879 m^4/m^6.

Substitution of $f_{h,Solid,\ Glass}$, S^{*2}_{Glass}, and S^{*2}_{Metal} in the equation of $f_{h,Solid,\ Metal}$ results in:

$$f_{h,Solid,\ Metal} = \frac{S^{*2}_{Glass}}{S^{*2}_{Metal}} \cdot f_{h,Solid,\ Glass} = \frac{2571}{2879} \cdot 5100 = 4556 \text{ s} = 75.9 \text{ min.}$$

<u>So the cylindrical metal can will have a $f_{h,Solid,\ Metal}$ = 75.9 min.</u>

Compare this to the $f_{h,Solid,\ glass}$ = 85 min. of the solid product in a glass jar.

Answer 12b) Verification of the adapted squared specific surface $\mathbf{S^{*2} = 2571}$ **m^4/m^6** of the cylindrical glass jar with internal dimensions of D x H = 103.2 mm x 119.1 mm and glass wall thickness d_W = 3.1 mm by Excel program "*Heat penetration factor fh calculations.xls*", section a) Cylinder shaped packaged product SOLID (right hand side):

Heat Penetration Factor fh Calculations for Liquid and Solid Foods

Version 1.6

LIQUID food product	**SOLID** food product
$fh = \frac{2.3 \cdot Cp \cdot \rho}{U \cdot S}$	$fh = \frac{2.3 \cdot Cp \cdot \rho}{k \cdot S^{*2}}$

INPUT OF THE PHYSICAL PROPERTIES OF THE FOOD PRODUCT:

Specific heat food product **Cp** = [ ] J/(kg °C)

Density food product **ρ** = [ ] kg/m^3

Thermal conductivity food product **k** = [ ] J/(s m °C)

In case of <u>LIQUID</u> foods: Overall heat transfer coefficient **U** = [ ] J/(s m^2 °C); **see table 3**

INPUT OF THE SHAPE AND DIMENSIONS OF THE PACKAGED FOOD PRODUCT:

a) CYLINDER SHAPED PACKAGED PRODUCT "$_{CYL}$":

Liquid: $S_{CYL} = 2/H_{CYL} + 4/D_{CYL}$

Product diameter D_{CYL} = [ ] m

Product height H_{CYL} = [ ] m

Thickness glass wall dw = XXXXXX

Specific Surface S_{CYL} = [ ] m^2/m^3

Solid: $S^{*2}_{CYL} = 9{,}93/H^{*2}_{CYL} + 23{,}2/D^{*2}_{CYL}$

diam. D_{CYL} = 0.1032 m

height H_{CYL} = 0.1191 m

glass dw = 0.0031 in **meters**

S^{*2}_{CYL} = **2570.9248** m^4/m^6

Excel program "*Heat penetration factor fh calculations.xls*" calculates a $S*^2_{CYL}$ **= 2571** m^4/m^6, which is exactly equal to the manually calculated $S*^2_{Glass}$ =2571 m^4/m^6, found in answer 12a).

Verification of the adapted squared specific surface $\mathbf{S*^2_{Metal} = 2879\ m^4/m^6}$ of the cylindrical **metal** can with internal dimensions of D x H = 103.2 mm x 119.1 mm, by Excel program "*Heat penetration factor fh calculations.xls*", results in:

Heat Penetration Factor fh Calculations for Liquid and Solid Foods

Version 1.6

LIQUID food product	**SOLID** food product
$fh = \frac{2.3 \cdot Cp \cdot \rho}{U \cdot S}$	$fh = \frac{2.3 \cdot Cp \cdot \rho}{k \cdot S*^2}$

INPUT OF THE PHYSICAL PROPERTIES OF THE FOOD PRODUCT:

Specific heat food product **Cp** =		J/(kg °C)
Density food product **ρ** =		kg/m^3
Thermal conductivity food product **k** =		J/(s m °C)
In case of LIQUID foods: Overall heat transfer coefficient **U** =		J/(s m^2 °C); **see table 3**

INPUT OF THE SHAPE AND DIMENSIONS OF THE PACKAGED FOOD PRODUCT:

a) CYLINDER SHAPED PACKAGED PRODUCT "CYL":

Liquid: $S_{CYL} = 2/H_{CYL} + 4/D_{CYL}$			**Solid:** $S*^2_{CYL} = 9{,}93/H*^2_{CYL} + 23{,}2/D*^2_{CYL}$		
Product diameter D_{CYL} =		m	diam. D_{CYL} =	0.1032	m
Product height H_{CYL} =		m	height H_{CYL} =	0.1191	m
Thickness glass wall dw =	XXXXXXXX		glass dw =		in **meters**!
Specific Surface S_{CYL} =		m^2/m^3	$S*^2_{CYL}$ =	**2878.39929**	m^4/m^6

Excel program "*Heat penetration factor fh calculations.xls*" calculates a $S*^2_{CYL}$ **= 2878** m^4/m^6, which is (almost) exactly equal to the manually calculated $S*^2_{Glass}$ =2879 m^4/m^6, found in answer 12a).

9. How to find the heat penetration factor f_h and the heating lag factor j_h from experimental heat penetration measurements of packaged foods

9.1 Record the temperatures of retort and product at small time intervals

Probably the best way to estimate the (heat) penetration factors f_h and f_C, and the (heating) lag factors j_h and j_C, is by measuring the heat penetration in the slowest heating point (= "coldest core") of the packaged product. At the same time, time-temperature measurements of the retort medium should be recorded.
Holdsworth & Simpson (2007), p. 145 - 151 discuss in detail how to perform heat penetration measurements.
Make sure that the following times are exactly known: time "Steam On"; time "Retort at sterilization temperature"; time "Steam Off/Cooling Water ON"; time "Cooling Water Off".

This chapter 9 deals with the analysis of experimental heat penetration measurements. And how these measurements can be used to find the penetration and lag factors.

Annex 1 shows example time-temperature measurements of the heating medium in a still batch retort, and of two canned solid products, 1 and 2, at intervals of 1 minute. In Figure 2 the temperature profile of retort medium and canned food #1 are presented.

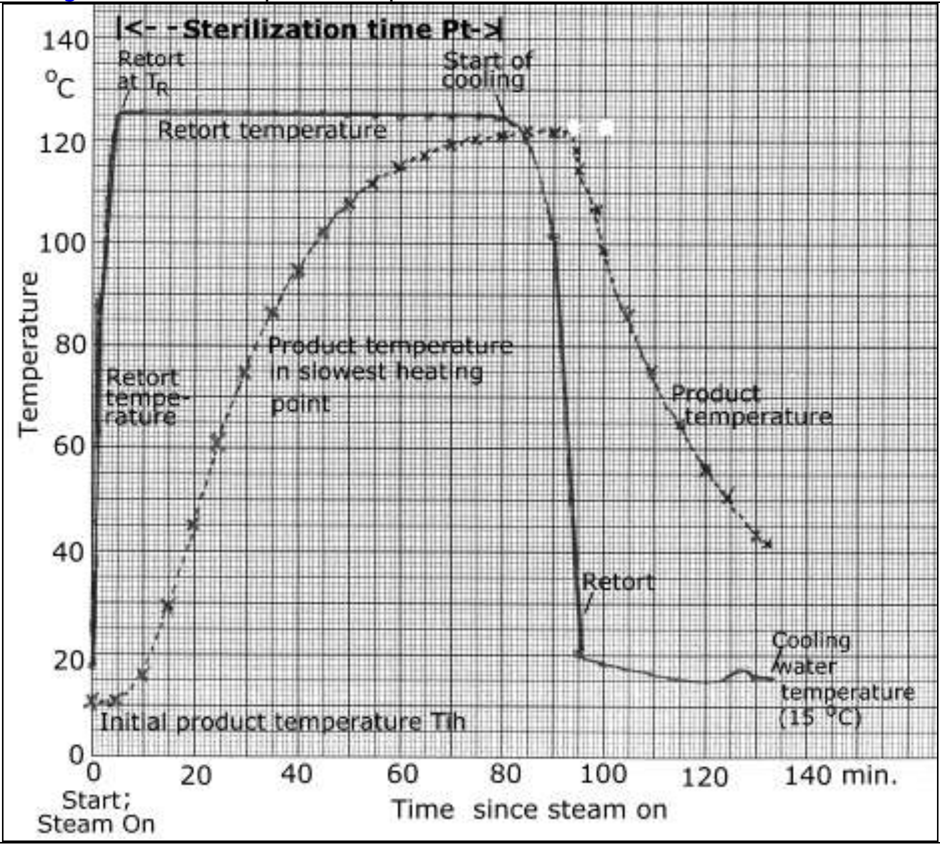


Figure 2: Time-temperature profile of the temperature of a still retort (saturated steam for heating; cold water for immersion cooling), and of solid product #1, measured in its slowest heating point. For time-Temperature data, see Annex 1.

Key information about the process:

- "Steam On" at time t = 0 min.
- Initial product temperature at moment "Steam On": T_{ih} = 9.7 ºC.
- At time t = 5 min. the retort medium has reached the required retort temperature T_R = 124 ºC; so the Come Up Time C.U.T. of the retort is L = 5 min.
- "Steam Off; Cooling Water ON" was at time t = 79 min.; so the sterilization time P_t = 79 min. - 5 min. (C.U.T.) = 74 min. = P_t.
- Product temperature at time "Steam Off; Cooling Water On" is: T = 120.9 ºC.
- Cooling water temperature T_W = 15 ºC.
- At time t = 124 min. the "Cooling Water was turned Off", so the Process was over.

9.2 Analysis of the heating data: the semi-log heat penetration graph; f_h ; j_h

By putting the **PRODUCT** temperature - time data in a semi log heat penetration graph, the heat penetration factor f_h and the heating lag factor j_h can be found.

Step 1: Compile a table with at least 15-20 time-temperature data of both retort and product: from time "Steam On" to time "Steam Off; Cooling water on". If possible, the time interval between the data should be constant.

Table 12 lists some 18 time-temperature measurements, at intervals of 3 min., derived from the heating part of Annex 1.

Table 12: HEATING PART OF STERILIZATION PROCESS (Source: Annex 1): Time-temperature measurements of the retort medium (for heating": saturated condensing steam; for cooling: immersion in cold water), and of 2 solid products, 1 and 2, measured in their slowest heating point, or coldest core. (Intended) retort temperature T_R = 124 ºC.

HEATING				
Date/Time	Retort	Product 1	Product 2	Comments
3 min. time steps	ºC	ºC	ºC	
25-10-2013 00:00:00	17.2	T_{ih} = 9.7 [1])	10.1	t = 0; "Steam On"; start process
25-10-2013 00:03:00	105.5	10.4	11.1	At time t = 5 min. (not shown) the retort reached the intended retort temperature T_R = 124 ºC.
25-10-2013 00:06:00	126.6	11.1	12.4	
25-10-2013 00:09:00	125.9	14.2	17.8	
25-10-2013 00:12:00	125.6	20.6	29.3	
25-10-2013 00:15:00	125.6	29.3	40.4	
25-10-2013 00:18:00	125.4	38.8	50.8	
25-10-2013 00:21:00	125.3	48.6	60.4	
25-10-2013 00:24:00	125.1	57.7	68.9	
25-10-2013 00:27:00	125.1	66.3	75.9	
25-10-2013 00:30:00	125	74.4	82.3	
25-10-2013 00:33:00	124.8	81.6	88.3	
25-10-2013 00:36:00	124.8	87.7	93.5	
25-10-2013 00:39:00	124.8	93.1	98.1	
25-10-2013 00:42:00	124.7	97.7	102.1	
25-10-2013 00:45:00	124.6	101.8	105.6	
25-10-2013 00:48:00	124.6	105.3	108.5	
25-10-2013 00:51:00	124.6	108.2	111	
25-10-2013 00:54:00	124.6	110.7	113.2	
25-10-2013 00:57:00	124.5	112.8	114.9	
25-10-2013 01:00:00	124.3	114.6	116.4	
25-10-2013 01:03:00	124.5	116.1	117.7	
25-10-2013 01:06:00	124.5	117.4	118.8	
25-10-2013 01:09:00	124.5	118.4	119.6	
25-10-2013 01:12:00	124.5	119.3	120.4	
25-10-2013 01:15:00	124.3	120.1	121	
25-10-2013 01:18:00	124.1	120.7	121.5	
25-10-2013 **1:19:00**	124.3	T_{ic} = 120.9 [2])	121.7	**Steam Off; Cooling Water On**

[1]) Tih = **i**nitial **h**eating temperature of food; [2]) T_{ic} = **i**nitial **c**ooling temperature of food at "Steam Off; Cooling On".

Step 2: Use semi log graph paper for a graphical presentation. For empty semi log paper: see Annex 2. Semi log paper has one logarithmic side, and one linear side (See figure 3A). The log part should have 3 decimal steps, so should go from 1 to 1000 (= 10^3). Next put the semi-log graph paper upside down (invert the paper). See figure 3B. Thus at the vertical log scale, 1 is at the top, and 1000 (= 10^3) is at the bottom.

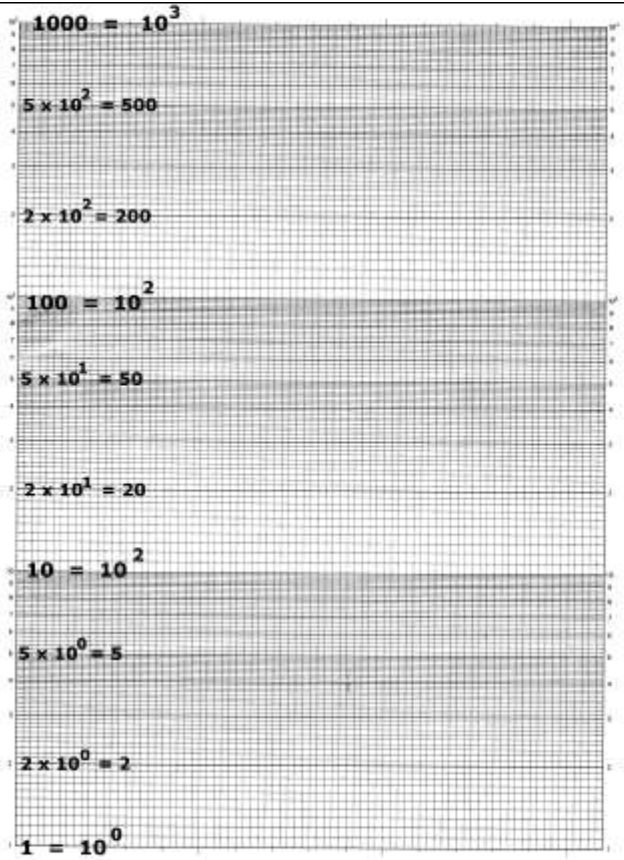


Figure 3A: Semi log paper. Vertical scale has 3 log sections; 1 = 10^0 at bottom; 1000 = 10^3 at top. Horizontal axis: linear SCALE.

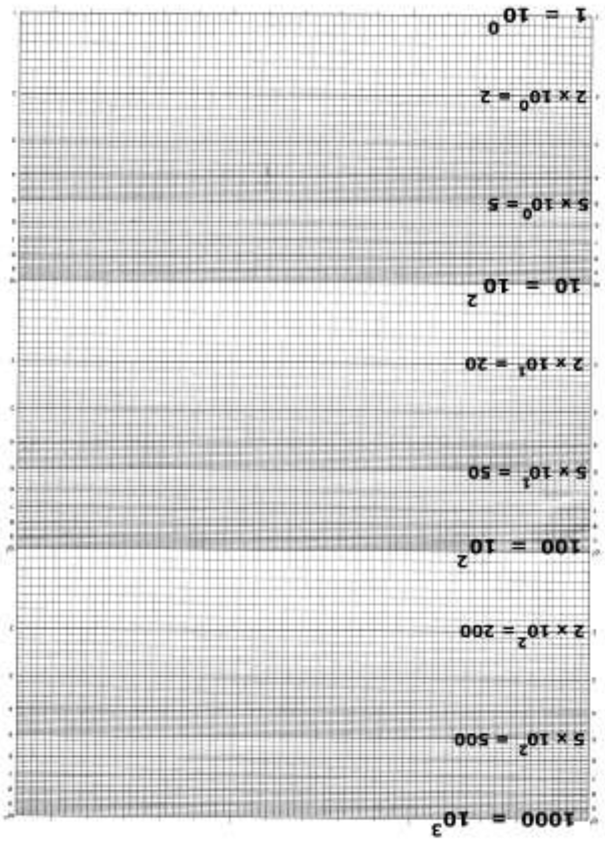


Figure 3B: Inverted semi log paper: 1 = 10^0 at top; 1000 =10^3 at bottom. Vertical scale has 3 log sections. Horizontal axis: linear SCALE.

Step 3: The log temperature scale (vertical, left):
At the **inverted** semi log paper, the temperatures will be put at the left hand vertical log scale.
At the top left, at number **1** on the log scale, write at scale number 1: "**Retort temperature T_R MINUS 1**".
As the retort temperature in this example is T_R = 124 ºC, at the top left, so at scale number 1, write 124 MINUS 1 = 124 - 1 = ***123 ºC*** (**= T_R - 1**).
Also: at the left log scale, at number **5**, write the result of (Retort temperature T_R - 5) = 124 - **5** = 119 ºC.
See figure 4.

Repeat this process to insert as many as possible converted numbers on the vertical scale.
So at number 10 write T_R - 10 = 124 - 10 = 114 ºC;
at number 15 write T_R - 15 = 124 - 15 = 109 ºC;
at number 20 write 124 - 20 = 104 ºC, etc. etc.

Figure 5 shows the vertical product temperature scale of the inverted semi log graph.
When drawing the heat penetration graph later, it will be helpful if you have converted as many vertical numbers as possible.

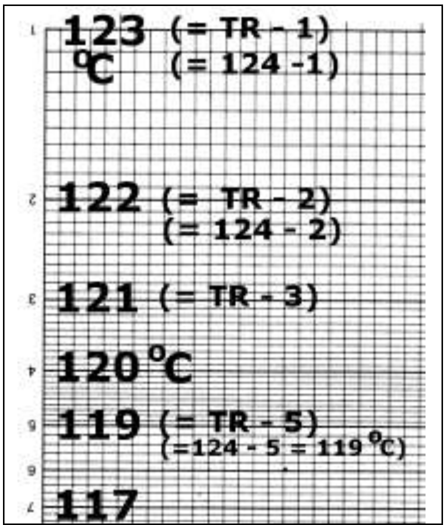


Figure 4: How to find the correct product temperature numbers on the vertical scale of the inverted semi log paper. A small section of the graph is reproduced here. See also table 12.

Step 4: The linear time scale (horizontal, bottom):
A semi-log heating graph will record the product temperatures during the heating part of the process. So from moment t = 0 min. ("Steam On") to moment "Steam Off; Cooling water ON". Thus at the linear horizontal bottom scale of the inverted log paper, write down the minutes of the heating section.

Start with t = 0 min. at the left bottom corner of the graph paper: "Steam On". According to table 12, the moment "Steam Off; Cooling Water On" is at time 1 h 19 min., so at 79 min. Thus the horizontal linear scale should at least cover the time period from t = 0 min. to t = 79 min. See figure 5.

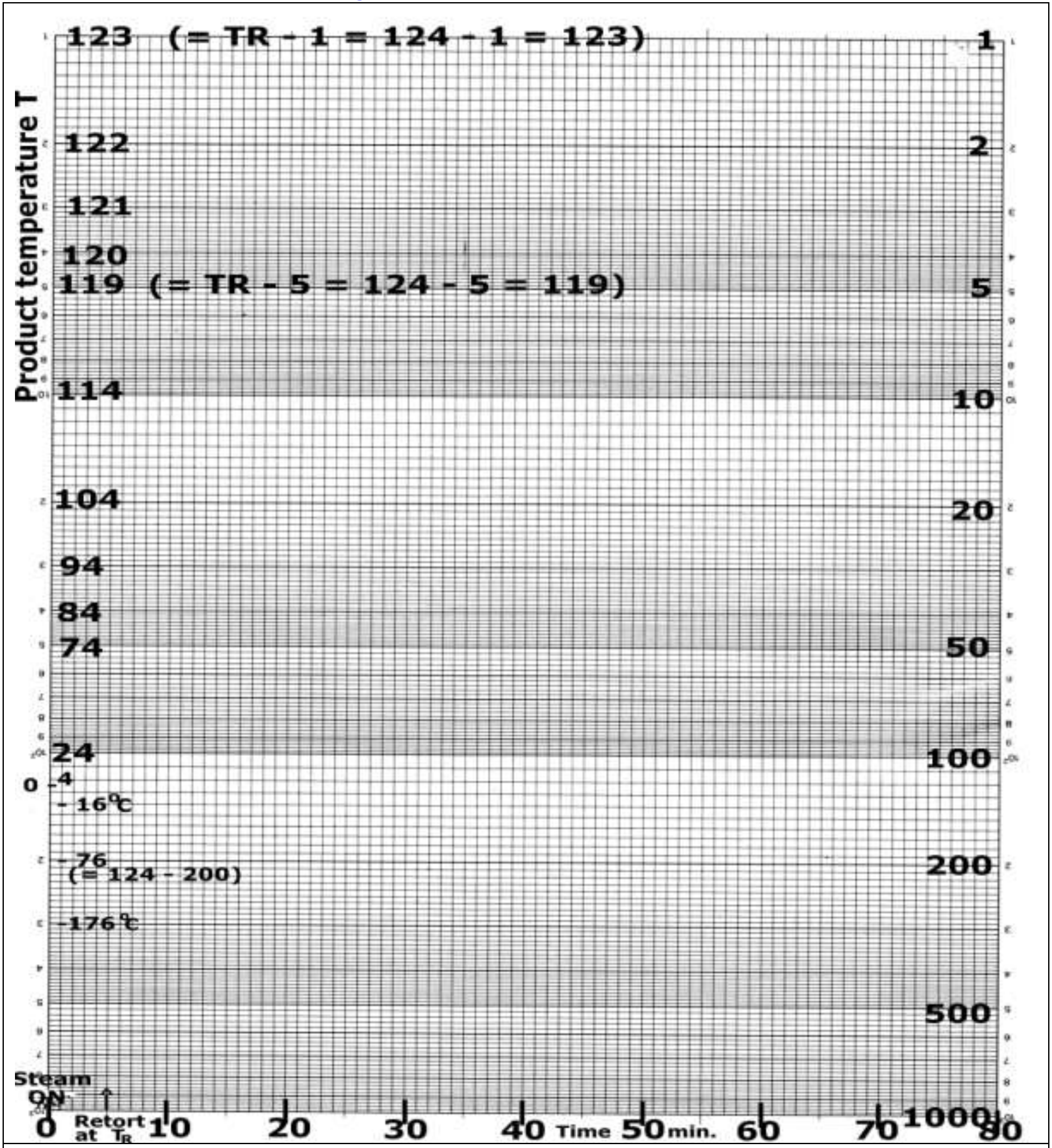


Figure 5: Vertical scale: product temperatures in a semi-log heating graph.
At left hand scale, as many as possible product converted temperatures [ºC]. See also at table 12. Actual retort temperature T_R = 124 ºC. At scale number 1: T_R - 1 = 123 ºC
Horizontal scale: time of heating, from "Steam On", at t =0 min., to "Cooling On" at t = 79 min. Linear scale.

Step 5: Next include the actual **product** temperatures of product 1 (see table 12) in the inverted semi-log heating graph.
Start with the **i**nitial **h**eating temperature T_{ih} of food 1 is: T_{ih} = 9.7 ºC (= product temperature at time t = 0, so at time "Steam On"). Next include the other points. In figure 6, all product time-temperature points are indicated with an X.

You will notice that from a certain time onward the plotted points will be on an (almost) straight line.

> ***Do not use product temperatures that are within 5 ºC from the retort temperature. As T_R = 124 ºC, stop including readings from T = 119 ºC onward). Reason: A product temperature close to the retort temperature will be affected by fluctuations in the retort temperature, and thus will not be on the straight line any more.***

Draw a straight line through the higher time-temperature points; extend that straight line to time t = 0 min. For the extension part of the straight line, use a broken line. See figure 6.

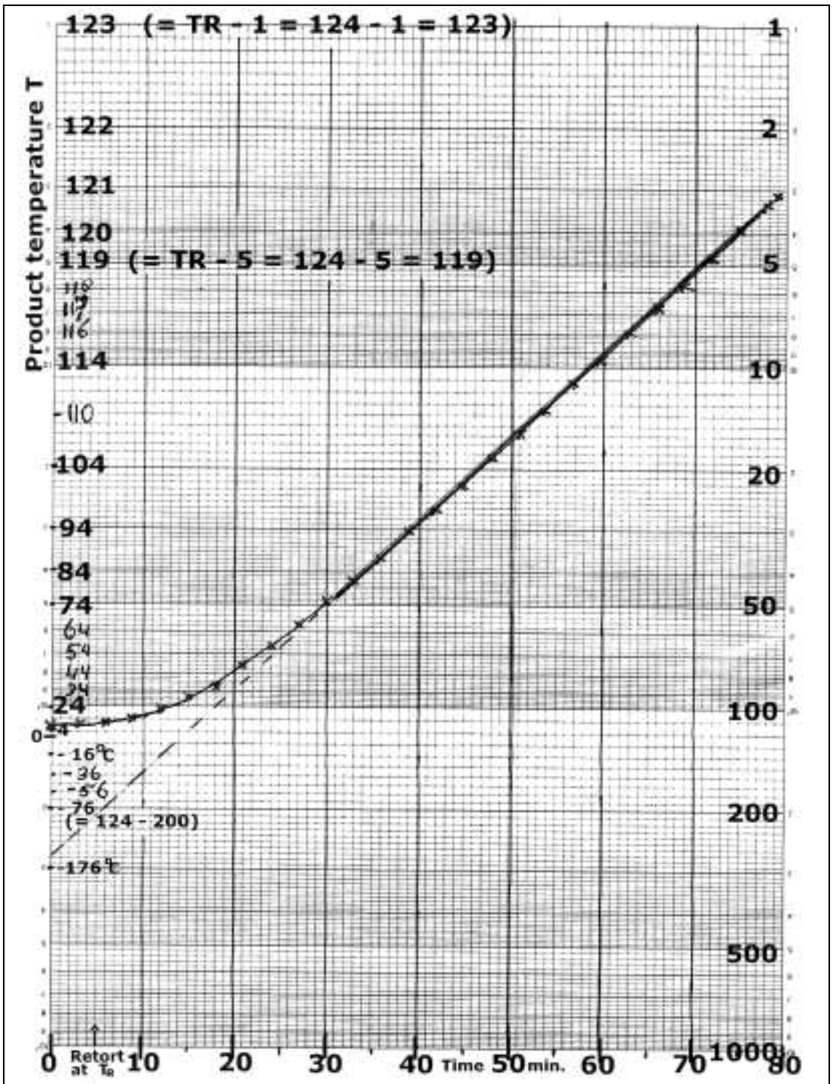


Figure 6: Semi log heating graph of product 1 (table 12).

* Do NOT use temperatures above T_R - 5 ºC = 124 - 5 = 119 ºC!
* The straight line through the higher time-temperature findings is extended to time t = 0 min. (use broken line for the extension).

Step 6: From now on, only use the straight product temperature line. **Ignore the bended part of the product graph at the left side.**

Using the **right** hand vertical log scale, mark a **one log** (= a 10-fold) temperature cycle on the **straight** line. So mark two points on that straight line which are a ten-fold temperature change apart, if measured on the right hand scale.
For example: from 10 to 100 at the **right** hand scale is one log cycle; thus mark points 10 and 100 on the straight line (see fig. 7).
Also: from from 5 to 50 on the right hand log scale is one log cycle: so you could mark points 5 and 50. Etc.

In figure 7, on the straight line, marks are placed at temperature points 10 and 100. The distance between these two points is one log cycle.

> *N.B.: make sure that the 100 mark is at the straight line, and NOT at the bended part of the semi log heating graph!*

Next, at the horizontal time axis, read the **time** required for the product to make such a one log temperature cycle:

At T = 10 (10 on the right hand scale), the time t = 58 min.
At T = 100 (100 at the right hand scale), the time t 18 = min.
So a one log temperature cycle requires a time of 58 - 18 = 40 min.

The time a packaged food requires for a one log temperature cycle, is called the **heat penetration factor f_h.** So in fig. 7, **f_h = 40 min.**

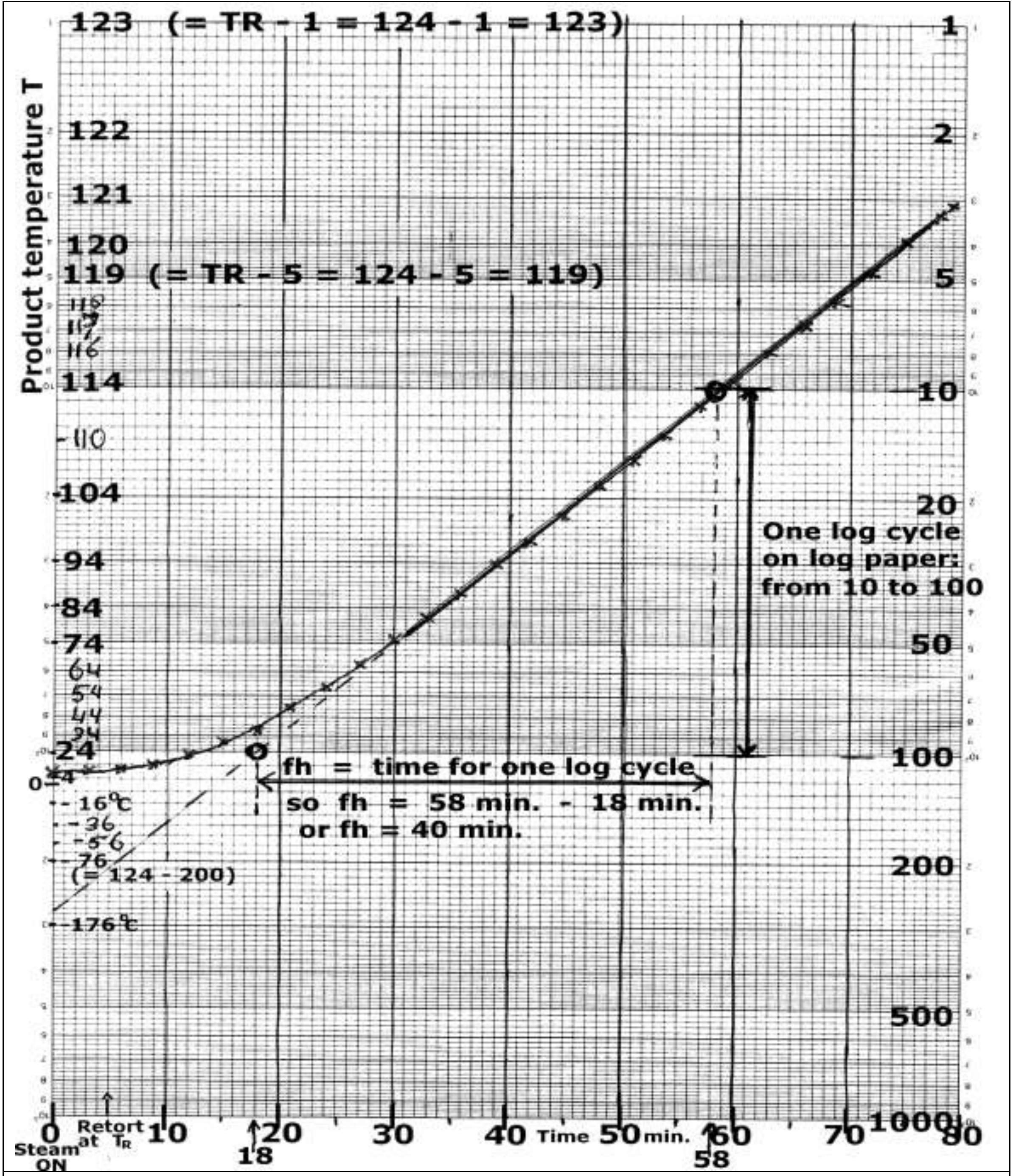


Figure 7: How to find the heat penetration factor f_h from the experimental semi log heat penetration graph:
On the straight section of the heating graph, mark a one log temperature cycle; use the right hand log scale. Example: a 1 log temperature cycle goes from temperature 10 at log scale (at time t = 58 min.) to temperature 100 at log scale (at time t = 18 min.). Heat penetration factor f_h = time needed for a one log temperature cycle, so f_h = 58 - 18 = 40 min.

Step 7: How to find the **heating lag factor j_h**? (see fig. 8).

- At time "Retort at T_R", so at Come Up Time L = 5 min., go 40% of L to the left (so go 0.4 x L = 2 min. to the left). That new time on the horizontal scale, so time L - 0.4·L = 5 - 0.4·5 = 3 min. is called the *pseudo initialheating time* [or the *corrected zero time* or the *pseudo zero heating time]* of the process.

- From the **p**seudo **i**nitial **h**eating time, draw a vertical line to the (extended) straight line of the food temperature (see fig. 8). The intersection of these lines, at temperature $T_{pih} \approx$ - 114 ºC, is called the **p**seudo **i**nitial **h**eating temperature T_{pih}.

- In the definition equation of the heating lag factor j_h,

$$j_h = \frac{T_R - T_{pih}}{T_R - T_{ih}}$$

now all 3 factors are known:
T_R = sterilizing retort temperature = 124 ºC;
T_{pih} = pseudo initial heating temperature = - 114 ºC;
T_{ih} = initial heating temperature = 9.7 ºC (see table 12).
So substitution in the equation for j_h results in: j_h = 2 (see below).

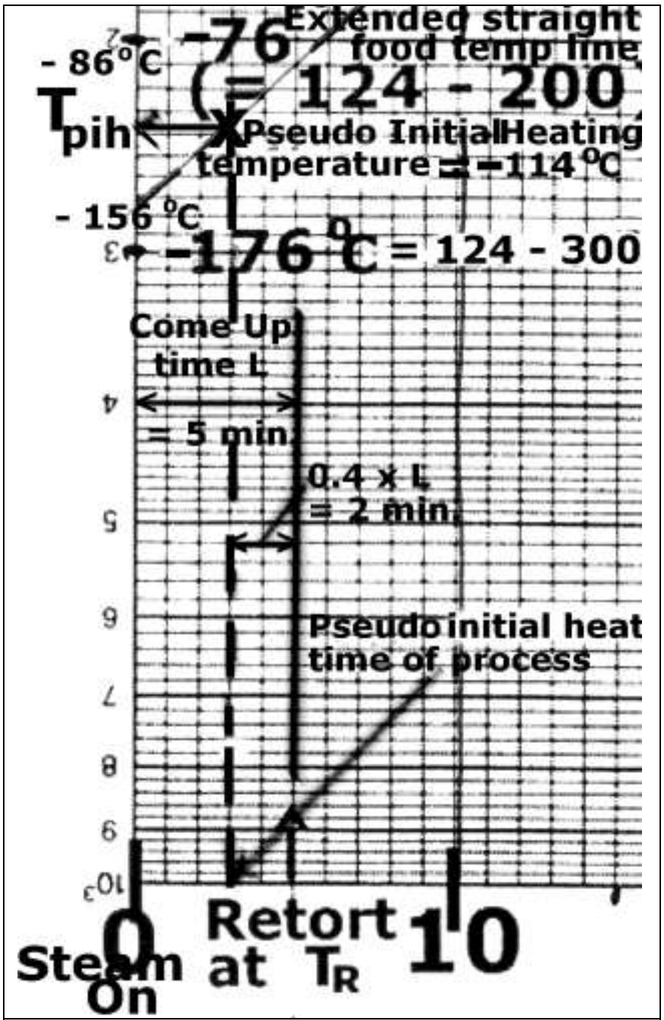


Figure 8: Finding the pseudo initial heating temperature T_{pih}:

- At time "Retort at T_R", so at moment come up time L = 5 min., go 40% of L to the left. So go 0.4 x L = 0.4x5 = 2 min. to the left. This time, thus L - 0.4xL = 5 - 2 = 3 min. is called the "pseudo initial heating time".

- A vertical line through the pseudo initial heating time intersects the extended straight food temperature line at T = - 114 ºC. This T = - 114 ºC is called the **p**seudo **i**nitial **h**eating temperature T_{pih}.

Definition: $$j_h = \frac{T_R - T_{pih}}{T_R - T_{ih}} = \frac{124 - (-114)}{124 - 9.7} = \frac{238}{114.3} = 2; \text{ so } j_h = 2$$

The graphical approach to find f_h and j_h from the semi log heating graph, as presented in steps 1 to 7 above, has been summarized in figure 9.

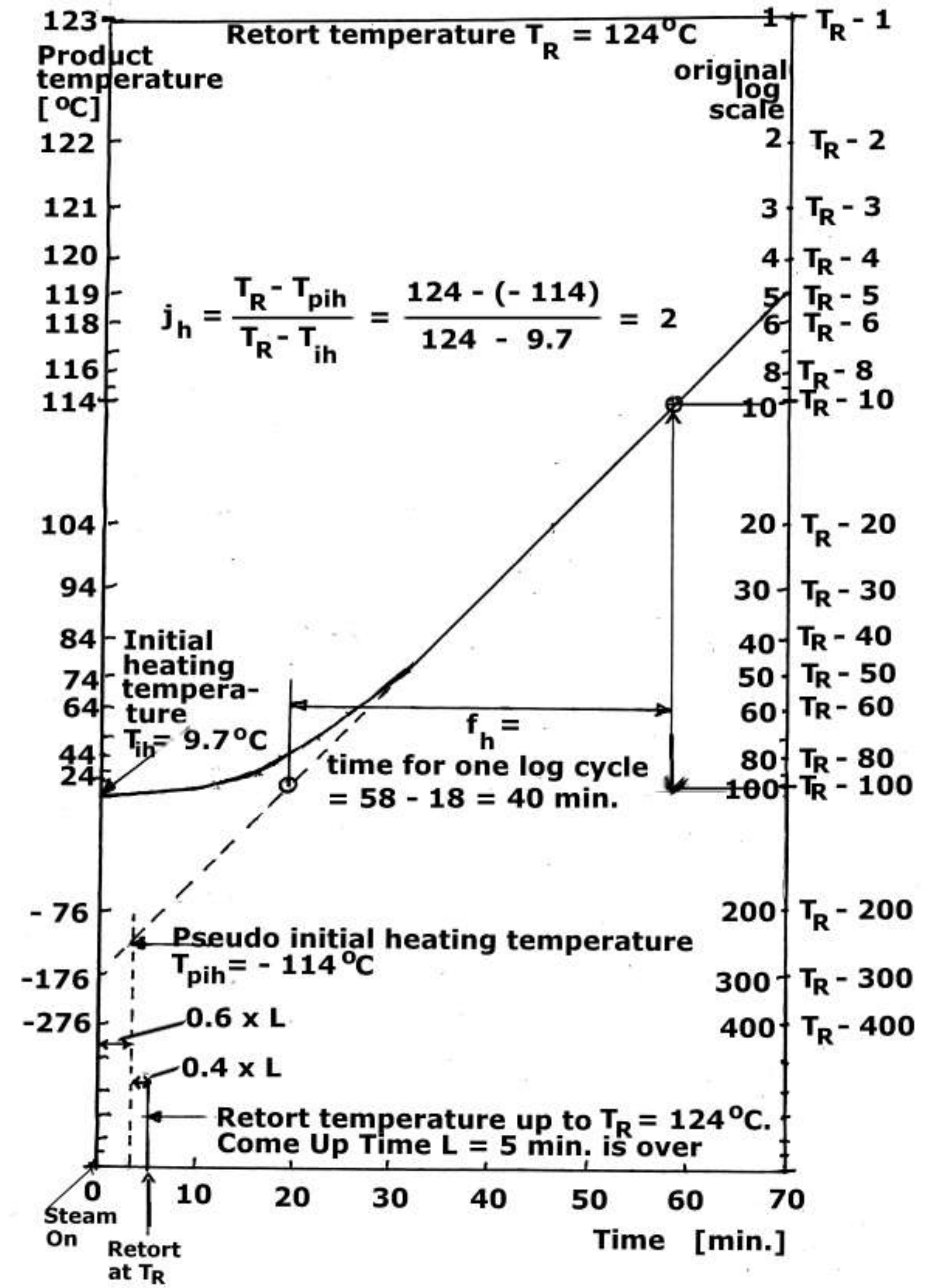


Figure 9: SUMMARY: how to use the semi-logarithmic **heat penetration graph** to find the numerical values of the heat penetration factor f_h and the heating lag factor j_h from the experimental heat penetration measurements of table 12 and Annex 1.

See also Holdsworth and Simpson (2007: p 156); C.R. Stumbo (1973: p. 137-141).

9.3 Analysis of the cooling data: the semi-log cooling graph; f_C ; j_C

To find the cooling penetration factor f_C, and the cooling lag factor j_C from experimental heating and cooling data, the procedure is more or less similar to that of chapter 9.2:

Step 1: Compile a table with cooling data of retort and product from Annex 1. Collect data from time "Steam Off; Cooling Water On" to time "Cooling Water Off". See table 13.

Table 13: COOLING PART OF STERILIZATION PROCESS (source: Annex 1).
Time-temperature measurements of the retort medium (for heating: saturated condensing steam; for cooling immersion in cold water), and of 2 solid products, 1 and 2, measured in their "slowest heating point" or coldest core. Cooling water temperature T_W = 15 ºC.

COOLING					
Date/Time	Cooling	Retort	Product 1	Product 2	Comments
3 min. time steps	time	ºC	ºC	ºC	
25-10-2013 01:19:00	0	124.3	T_{ic} = 120.9 [2])	121.7	Steam Off; Cooling Water On
25-10-2013 01:22:00	3	120.1	121.4	121.9	
25-10-2013 01:25:00	6	119.9	121.8	121.9	
25-10-2013 01:28:00	9	114.3	122	121.3	
25-10-2013 01:31:00	12	50.4	121.7	120.8	
25-10-2013 01:34:00	15	23.4	117.8	117.6	
25-10-2013 01:37:00	18	19.4	109.1	109.4	
25-10-2013 01:40:00	21	18	99.9	99.8	
25-10-2013 01:43:00	24	17.2	90.6	90.5	
25-10-2013 01:46:00	27	16.7	83.2	82.3	
25-10-2013 01:49:00	30	16.2	76.4	74.9	
25-10-2013 01:52:00	33	15.9	70.2	68.4	
25-10-2013 01:55:00	36	15.6	64.5	62.5	
25-10-2013 01:58:00	39	15.4	59.4	57.4	
25-10-2013 02:01:00	42	15.3	54.7	52.7	
25-10-2013 02:04:00	45	15.2	50.5	48.7	Cooling Water Off; end of Process

[2]) Tic = **i**nitial **c**ooling temperature of food at time "Steam Off; Cooling Water ON".

Step 2: Use semi log graph paper for a graphical presentation. The log part of the paper should have 3 decimal steps, so should go from 1 to 1000 (= 10^3).
For the cooling graph, keep the paper upright: thus at the vertical log scale, 1 is at the bottom, and 1000 (= 10^3) is at the top. See fig. 10.

Step 3: How to set up the log temperature scale (vertical, left)?
At the semi log paper, the product temperatures are put at the left hand vertical log scale.
At the bottom left, thus at the original number **1** on the log scale, write:
Cooling water temperature T_W PLUS 1.

> *As the cooling water temperature in this example is T_W = 15 ºC, thus at the bottom left, so at number 1, write **Tw plus 1** = 15 + 1 = **16 ºC**.*
> Other example: at the left log scale, at original number 5, write the result of (Retort temperature T_W + 5) = 15 + 5 = **20** ºC. See figure 10.

Repeat this process to include as many as possible converted numbers on the vertical log scale. So at the original log scale number 10 write T_W + 10 = 15 + 10 = 25 ºC;
at the original log scale number 15 write T_W + 15 = 15 + 15 = 30 ºC;
at the number log scale number 20 write 15 + 20 = 35 ºC; etc.

Figure 10 shows the vertical product temperature scale of the semi log cooling graph. When drawing the cooling graph, it will be helpful if you have converted as many original vertical log scale numbers as possible.

Step 4: How to set up the linear time scale (horizontal, bottom)?
A semi-log cooling graph will record the product temperatures during the cooling part of the process. So from moment "Steam Off; Cooling Water On" to moment "Cooling Water Off". Thus at the linear horizontal bottom scale of the cooling graph, write the minutes of the cooling section (see table 13).
Also register:
t = 0 min.: Steam Off; Cooling Water ON;
t = 45 min.: Cooling Water Off.
These times have been included in figure 10.

Step 5: Now include the **product** temperatures of product 1 (see table 13) in the semi-log cooling graph.
The **i**nitial **c**ooling temperature T_{ic} of food 1 at moment "Steam Off; Cooling Water On" is: $\mathbf{T_{ic} = 120.9}$ **ºC**.
So point {t = 0 min.; T = 120.9 ºC} will be the first point of the cooling graph.
Next draw the other time-temperature readings from the cooling section (table 13).
See fig. 11.

Do not use product temperature readings that are within 5 ºC from the cooling water temperature. As T_W = 15 ºC, stop including readings from T = 20 ºC onward).
Reason: A product temperature close to the cooling water temperature will be affected by fluctuations in that T_W, and thus will not be on the straight line any more.

You will notice that from a certain time onward the plotted points will be on an (almost) straight line.

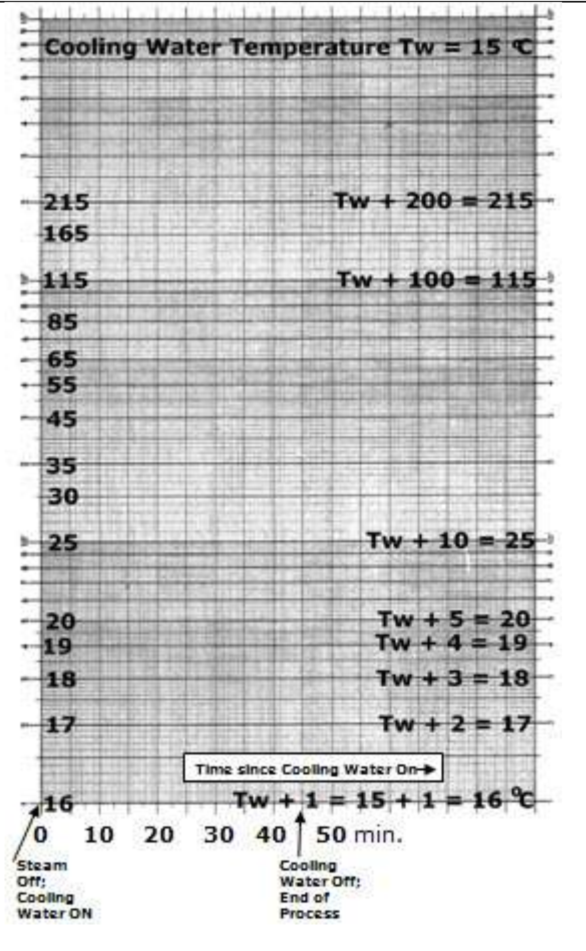


Figure 10: Temperatures and times at upright semi log cooling graph, if cooling water temperature T_W = 15 ºC.

Vertical scale: 3 log sections; 1 at bottom; 1000 at top. Horizontal axis: linear.

In cooling graph:
1 at log scale = cooling water temperature **plus** 1.
So number 1 at log scale actually is 15 + 1 = 16 ºC.
Also:
4 at log scale = cooling water temperature **plus** 4.
So number 4 at log scale actually is 15 + 4 = 19 ºC.

Draw a straight line through the higher time-temperature points. Extend by a broken line that straight line at both ends: to time t = 0 min. = time "Cooling Water On" until it intersects with the left vertical axis, and to its intersection at the right vertical axis.

The intersection of the extended straight product temperature line and time t = 0 = time "Cooling Water On" is called the **pseudo initial cooling temperature** $\mathbf{T_{pic}}$ of the product. "Pseudo" means: "corrected", or "virtual". According to fig. 10, $\mathbf{T_{pic} \approx 210}$ **ºC**.
At time t = 0 = time "Cooling Water On", the real **i**nitial **c**ooling product temperature T_{ic} = 120.9 ºC (see table 13).
Both "initial" temperatures T_{ic} = 120.9 ºC and T_{pic} = 210 ºC have been indicated in fig. 11.

Step 6: How to find the cooling lag factor j_C (see fig. 11)?

The definition of j_C is:

$$j_C = \frac{T_W - T_{pic}}{T_W - T_{ic}} \quad \text{(see below)}$$

From step 5 above, and from figure 11, we know already all factors in the j_C equation:

* T_W = cooling water temperature: T_W = 15 ºC;

* T_{ic} = **i**nitial **c**ooling temperature of product: T_{ic} = 120.0 ºC;

* T_{pic} =**p**seudo **i**nitial **c**ooling temperature of product: T_{pic} = 210 ºC.

Substitution of these 3 factors in the definition equation of j_C (see below), results in a cooling lag factor of **j_C = 1.84**.

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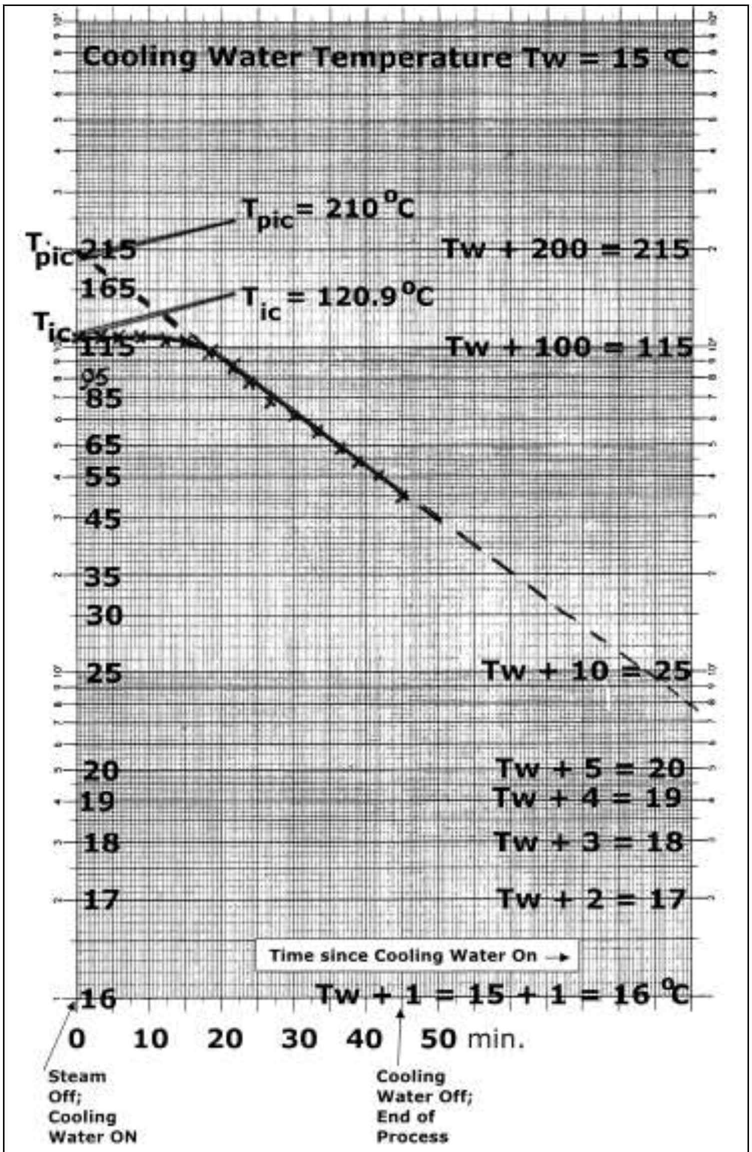


Figure 11: Semi log cooling graph of product 1 (for data: see table 13).

At time "Cooling Water On", so at t = 0 in the cooling graph, the actual product **i**nitial **c**ooling temperature **T_{ic} = 120.9 ºC**. See table 13 at time t = 0 min.
The extended straight product cooling line intersects the line through time t = 0 = time "Cooling Water On" (= left vertical scale) at the temperature of about 210 ºC. This intersection temperature is called the **p**seudo **i**nitial **c**ooling temperature **T_{pic} = 210 ºC**.

Definition: $$j_C = \frac{T_W - T_{pic}}{T_W - T_{ic}} = \frac{15 - 210}{15 - 120.9} = \frac{-195}{-105.9} = 1.84; \text{ so } \mathbf{j_C = 1.84}$$

Step 7: From now on, only use the straight product temperature line. **Ignore the left side bended part of the product cooling graph.**

Using the **right** hand vertical log scale, mark a **one log** (= a 10-fold) temperature cycle on the straight line. So mark two points on that straight line which are a ten-fold temperature change apart, if measured on the right hand scale.
For example: from 100 to 10 at the **right** hand scale is one log cycle; thus mark points 100 and 10 on the straight line (see fig. 12).

In figure 12, on the straight product line, marks are placed at temperature points 100 and 10. The distance between these two points is one log cycle.

N.B.: make sure that the 100 mark is at the straight line, and NOT at the bended part of the semi log product cooling graph!

Next, at the bottom horizontal time scale, read the time required for the product to make such a one log temperature cycle:
At T = 100 on the right hand scale, the time t = 79 min.
At T = 10 at the right hand scale, the time t = 17.5 = min.
So a one log temperature cycle requires
f_C = 79 - 17.5 = 61.5 min.
Or **f_C = 61.5 min.**

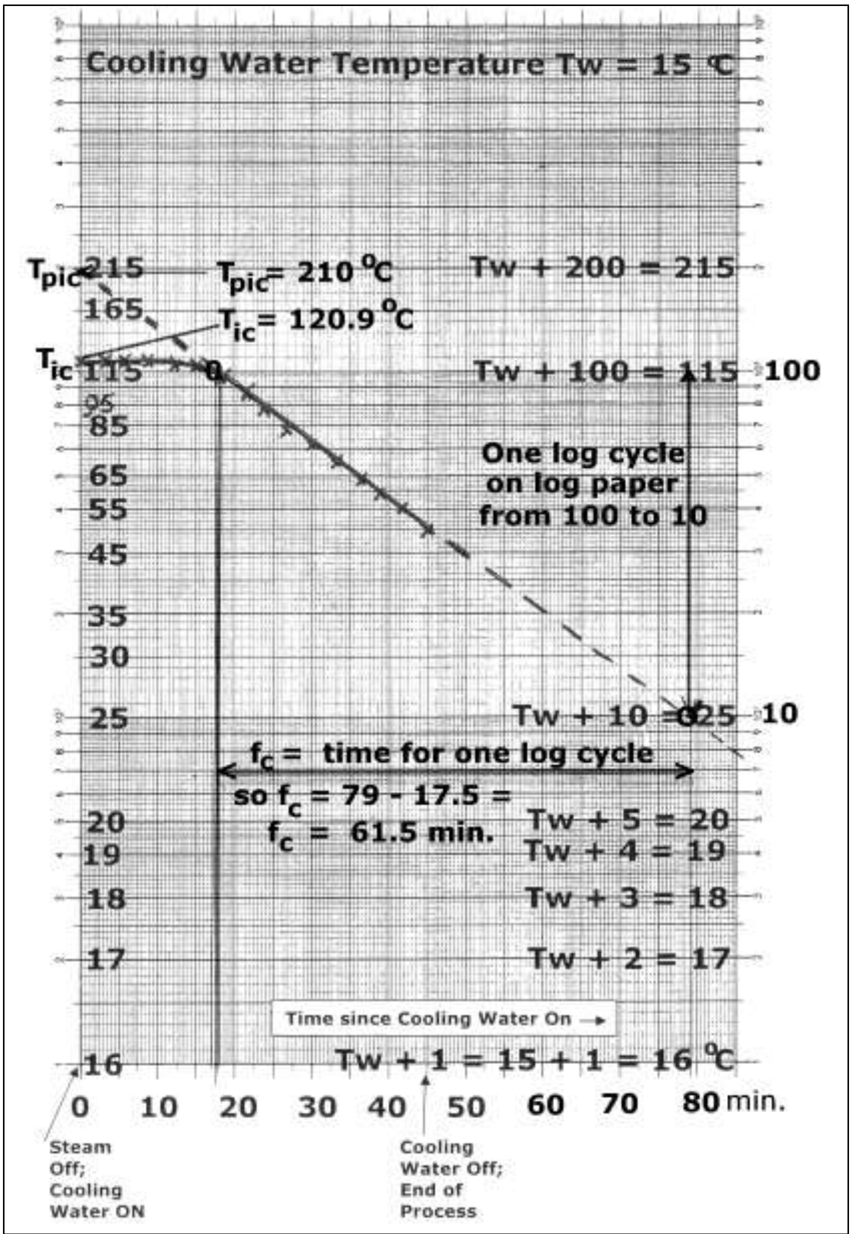


Figure 12: How to find the cooling penetration factor f_C from the experimental semi log cooling graph:

On the straight section of the product cooling graph, mark a one log temperature cycle; use the right hand log scale. So a one log temperature cycle goes from temperature 100 (at time t = 79 min.) to temperature 10 (at time t = 17.5 min.).
Cooling penetration factor f_C = time needed for a one log temperature cycle, so f_C = 79 - 17,5 = 61.5 min.

The graphical approach to find f_C and j_C from the semi log cooling graph, as presented in steps 1 to 7 above, has been summarized in figure 13.

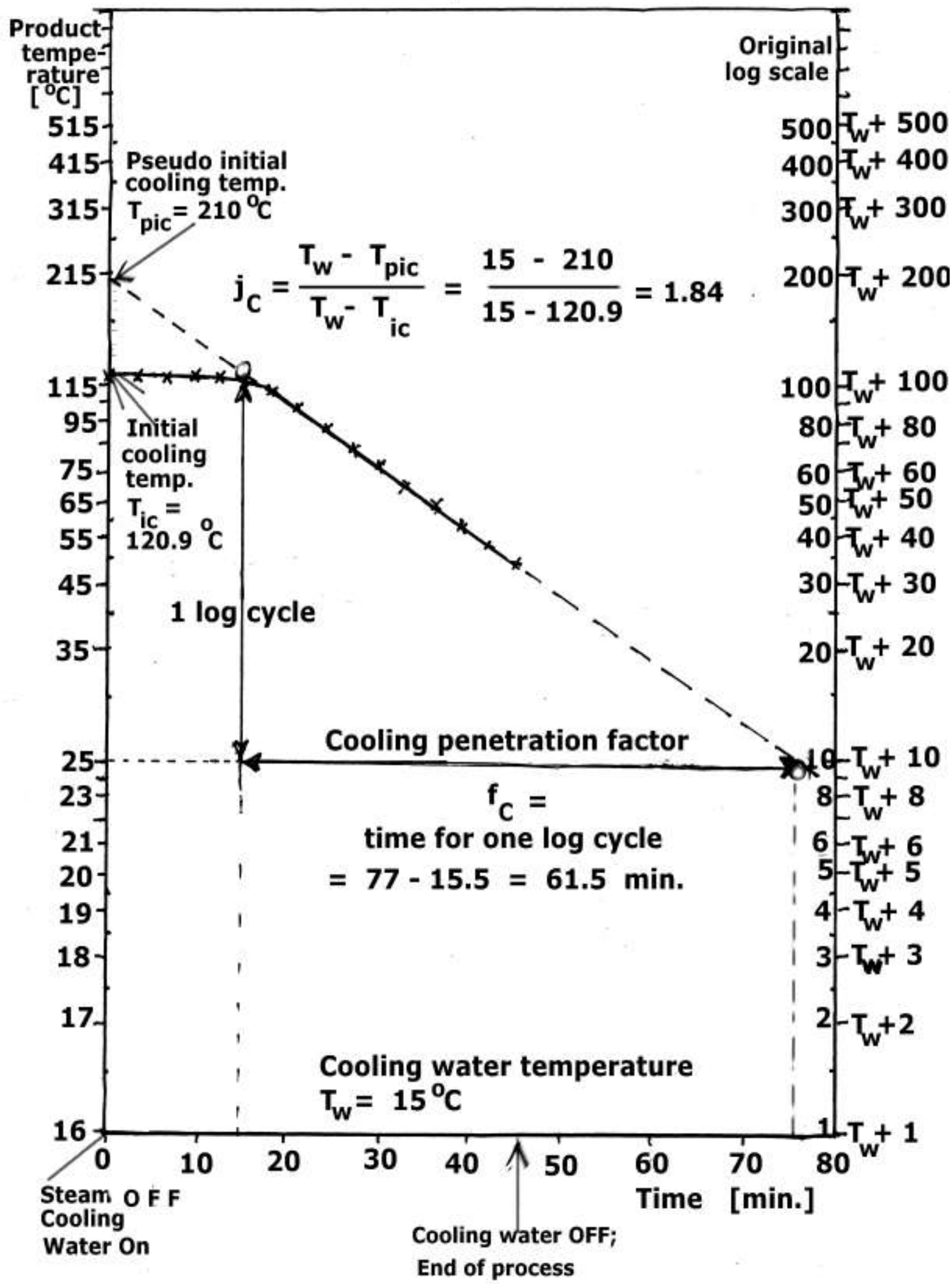


Figure 13: SUMMARY: how to use the semi-logarithmic **cooling graph**, to find the numerical values of the cooling penetration factor f_C and the cooling lag factor j_C from the experimental cooling penetration measurements of table 13 and Annex 1.

See also Holdsworth and Simpson (2007: p 157); C.R. Stumbo (1973: p. 137-141).

Example Calculation 13:

A solid food, packaged in cylindrical metal A2 cans of internal Diameter x Height = 83 mm x 114 mm, is sterilized in a saturated steam retort.
Sterilization temperature T_R = 119 ºC; cooling water temperature T_W = 20 ºC.
At intervals of 10 min., both the retort temperature, and the food temperature in its slowest heating point, have been registered; see table 14 below:

Table 14: Heating time and temperature of both the retort and of a canned solid food product in its slowest heating point, registered at intervals of 10 min..

time	Retort temp	Product temp	Comments
h:mm:ss	ºC	ºC	
0:00:00	30	55	Steam On
0:10:00	119	56	Retort at sterilization temp. T_R = 119 ºC
0:20:00	119	65	
0:30:00	119	77	
0:40:00	119	88	
0:50:00	119	98	
1:00:00	119	105	
1:10:00	119	109.4	
1:20:00	119	112.5	
1:30:00	119	114.7	
1:40:00	119	116	
1:50:00	119	117	Steam Off; Cooling Water On
2:00:00	20	114	
2:10:00	20	94	
2:20:00	20	74	
2:30:00	20	56	
2:40:00	20	44	
2:50:00	20	36	Cooling Water Off; End of process

13a) Conclude from the table 14 above:
13a-1) the initial food temperature at heating T_{ih} = ____________ ºC.
13a-2) the come up time of the retort L = ______________ min.
13a-3) the sterilization time P_t = __________________ min.
13a-4) the initial food temperature at start of cooling T_{ic} = ____________ ºC.

13b From table 1, table 2, and table 3,
13b-1) make a first estimation of the heat penetration factor f_h = ______________ min.
13b-2) Make a first estimation of the food heating lag factor j_h = ________.

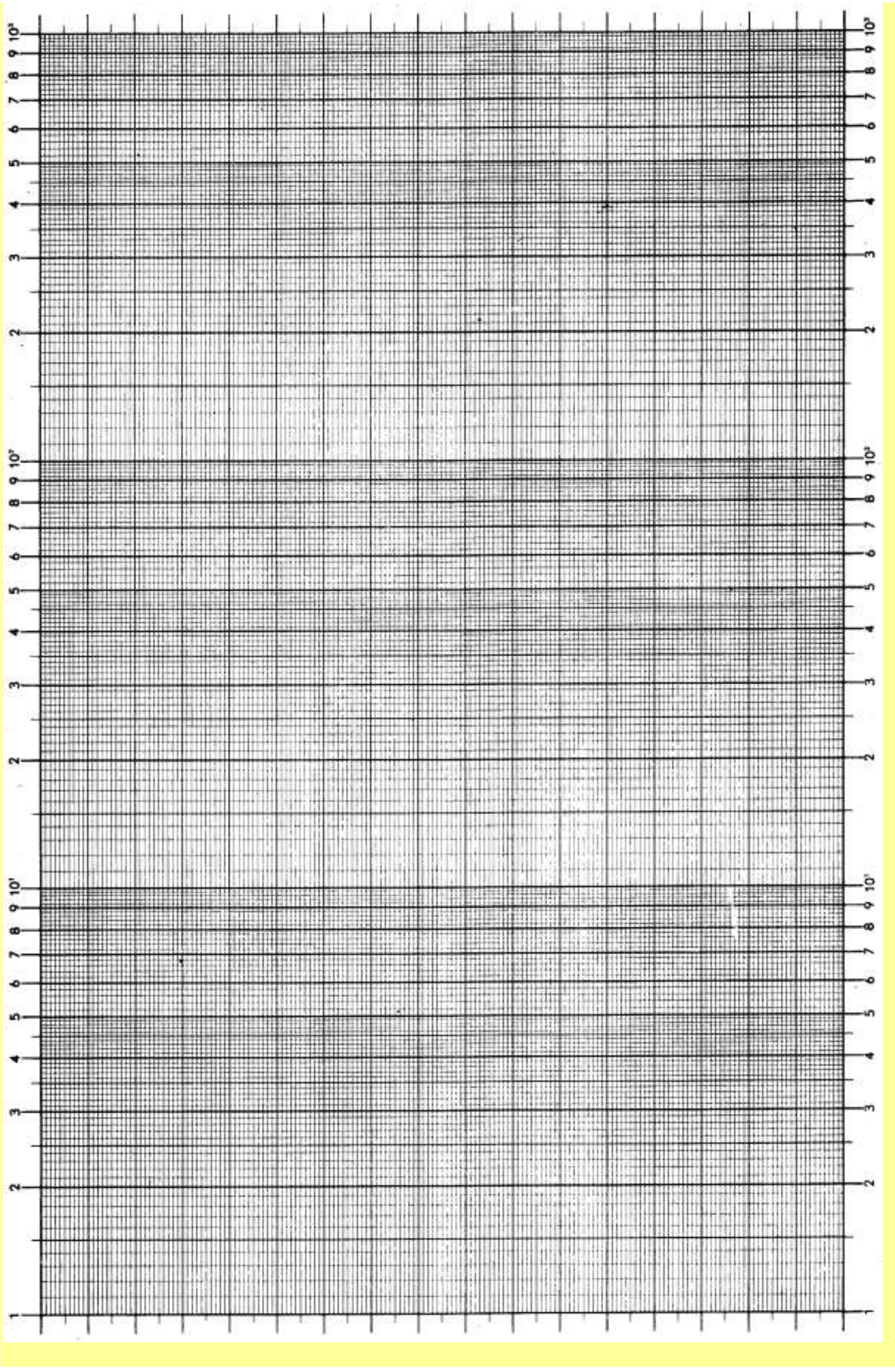
13c) Construct a semi-logarithmic heat penetration graph (graph paper at next pages) and calculate ......
13c-1) the experimental heat penetration factor f_h = ______________________ min.

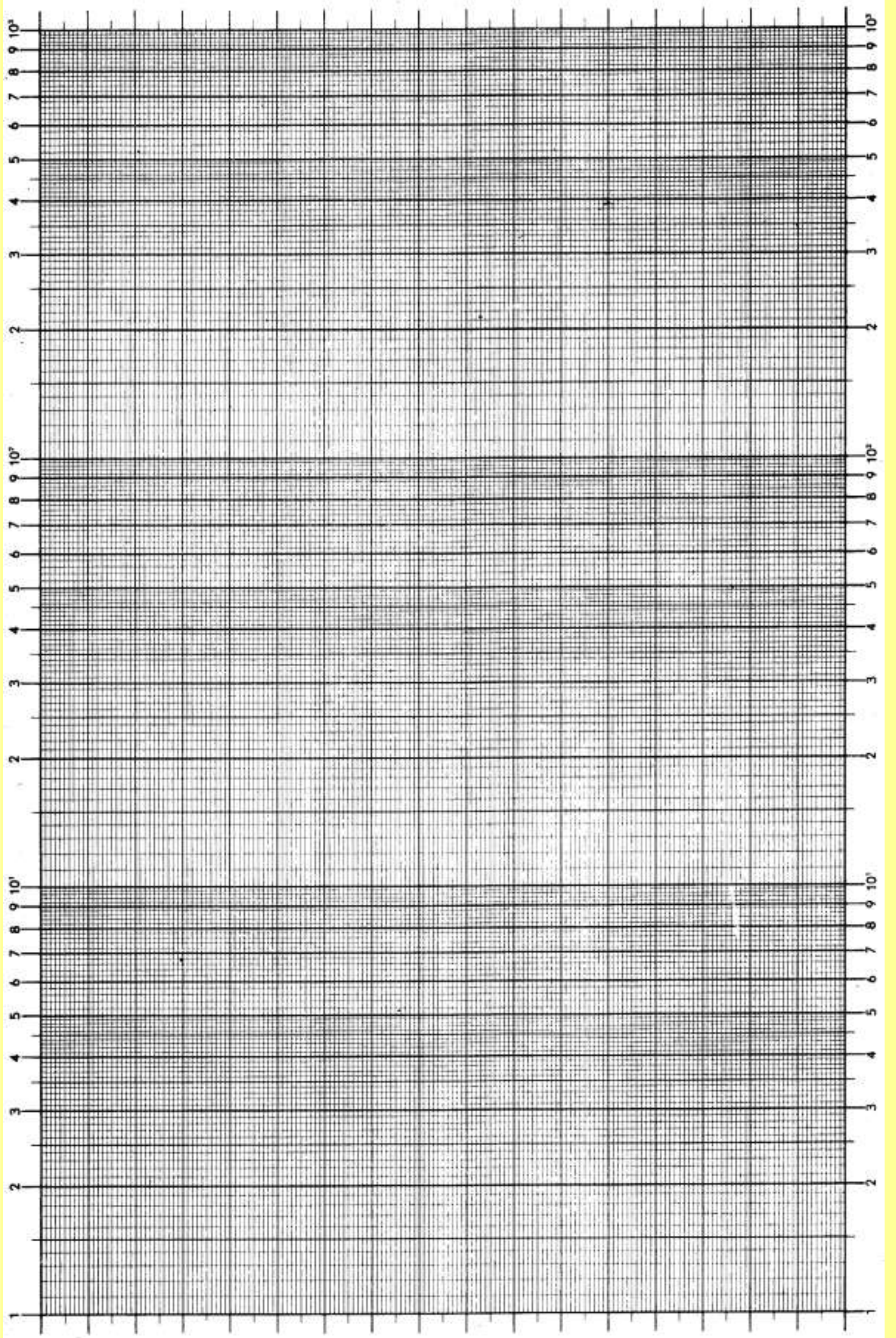
13c-2) the experimental heating lag factor j_h = _____________________.

13c-3) Compare and contrast the experimental f_h and j_h values of answers 13c-1) and 13c-2) with the estimated f_h and j_h values of answers 13b-1) and 13b-2).

13d) Construct a semi-logarithmic cooling graph (graph paper at next pages) and calculate ...
13d-1) the experimental cooling penetration factor f_c = ______________________ min.

13d-2) the experimental cooling lag factor j_c = _____________________.





Worked answers 13:

Answer 13a) Conclude from the table 14:

Answer 13a-1) the initial food temperature at heating **T_{ih} = 55 ºC.**

*The **i**nitial food temperature at **h**eating Tih is the temperature in the slowest heating point of the food at the moment "Steam On". See table 14 at time t = 0.*

Answer 13a-2) the come up time of the retort **L = 10 min.**

The Come Up Time L of a retort is the time, needed for the retort to reach the sterilization temperature T_R. So the time between "Steam ON" and "Retort at T_R"

Answer 13a-3) the sterilization time **P_t = 1 h 50 min. - 10 min. = 1h 40 min. = 100 min..**

The sterilization time is the time during which the retort is at sterilization temperature. So the time between "Retort at TR" and the moment "Steam Off; Cooling Water ON".

Answer 13a-4) the initial food temperature at start of cooling **T_{ic} = 117 ºC**.

*The **i**nitial food temperature at **c**ooling Tic is the temperature in the slowest heating point of the food at the moment "Steam Off; Cooling Water On".*

Answer 13b) From table 1, table 2, and table 3,

Answer 13b-1) make a first estimation of the heat penetration factor: **f_h = 64 - 65 min.**

In table 3, dealing with SOLID foods, a can A2 (DxH = 83 x 114 mm) with beans in tomato sauce has a f_h = 64.6 min.

Answer 13b-2) Make a first estimation of the food heating lag factor: **j_h = 2.**

*According to Table 1, a solid food has a j_h of about j_h = 2***.**

Answer 13c) For the (inverted!) semi-logarithmic heat penetration graph: see fig. 14. From that graph it can be concluded that

Answer 13c-1) the experimental heat penetration factor: **f_h = 59 min.**

This f_h is somewhat lower than the estimated f_h = 64-65 min. of answer 13b-1.

Answer 13c-2) the experimental heating lag factor: **j_h = 1.83.**

This j_h is somewhat lower than the estimated j_h = 2 of answer 13b-2.

Answer 13c-3): see Italic remarks at answers 13c-1) and 13c-2)

Answer 13d) For the semi-logarithmic cooling graph: see fig. 15. From that graph it can be concluded that

13d-1) the experimental cooling penetration factor: **f_c = 56.5 min.**

13d-2) the experimental cooling lag factor: **j_c = 1.96.**

In figure 16, the experimental findings from table 14 (as Excel file) have been used to produce two semi log graphs, and to find the values of f_h, j_h, f_c and j_c by using computer program Ball.exe.

Conclusion: The values of f_h and j_h, derived from the manually produced semi log heating graph in figure 14, and the values of f_c and j_c, derived from the manually produced semi log cooling graph in figure 15, are **almost identical** to the findings by computer program Ball.exe, presented in figure 16.

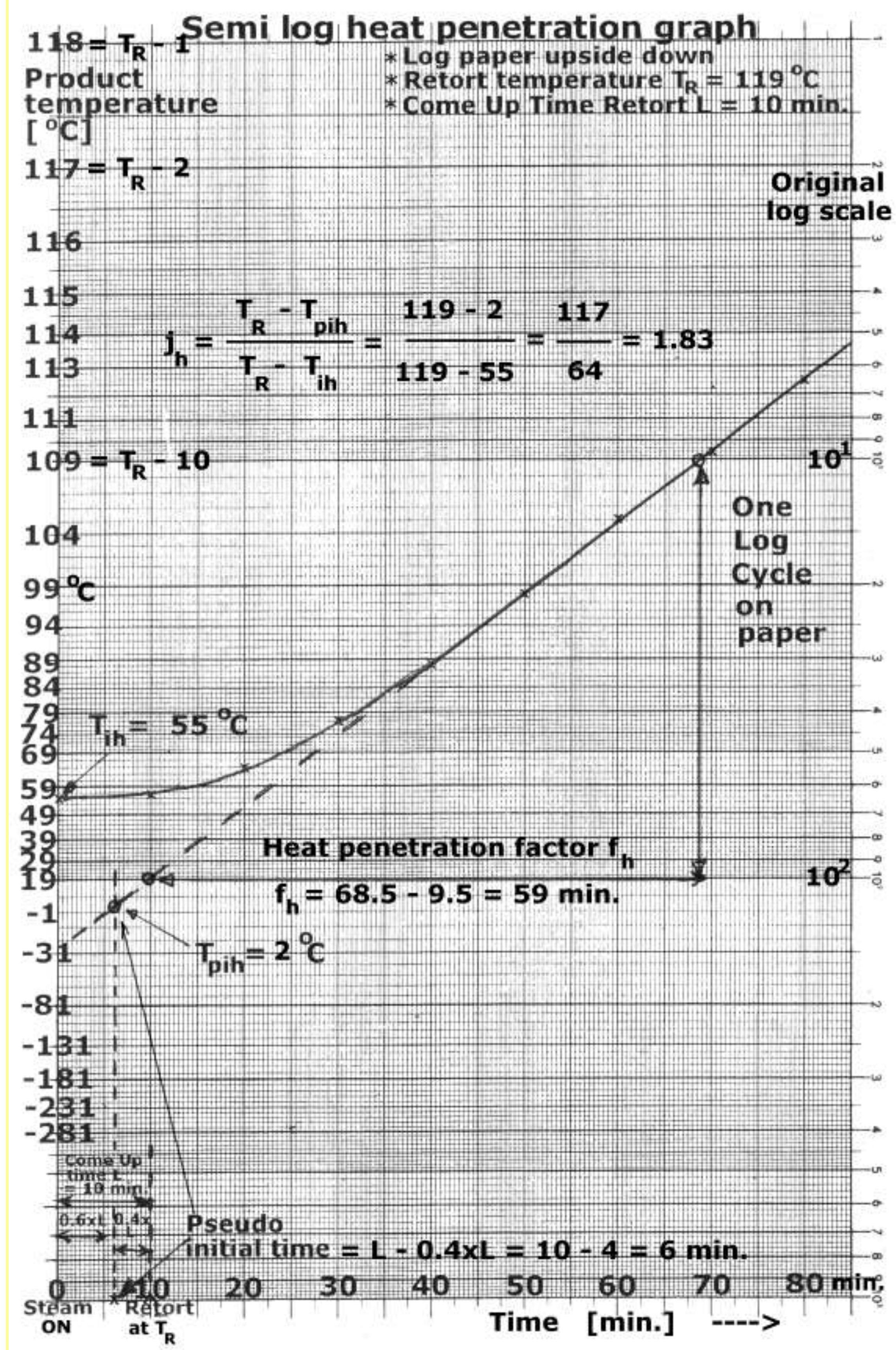


Fig. 14: Answer **13c)** Semi-log heat penetration graph. f_h ≈ 59 min.; j_h ≈ 1.83.

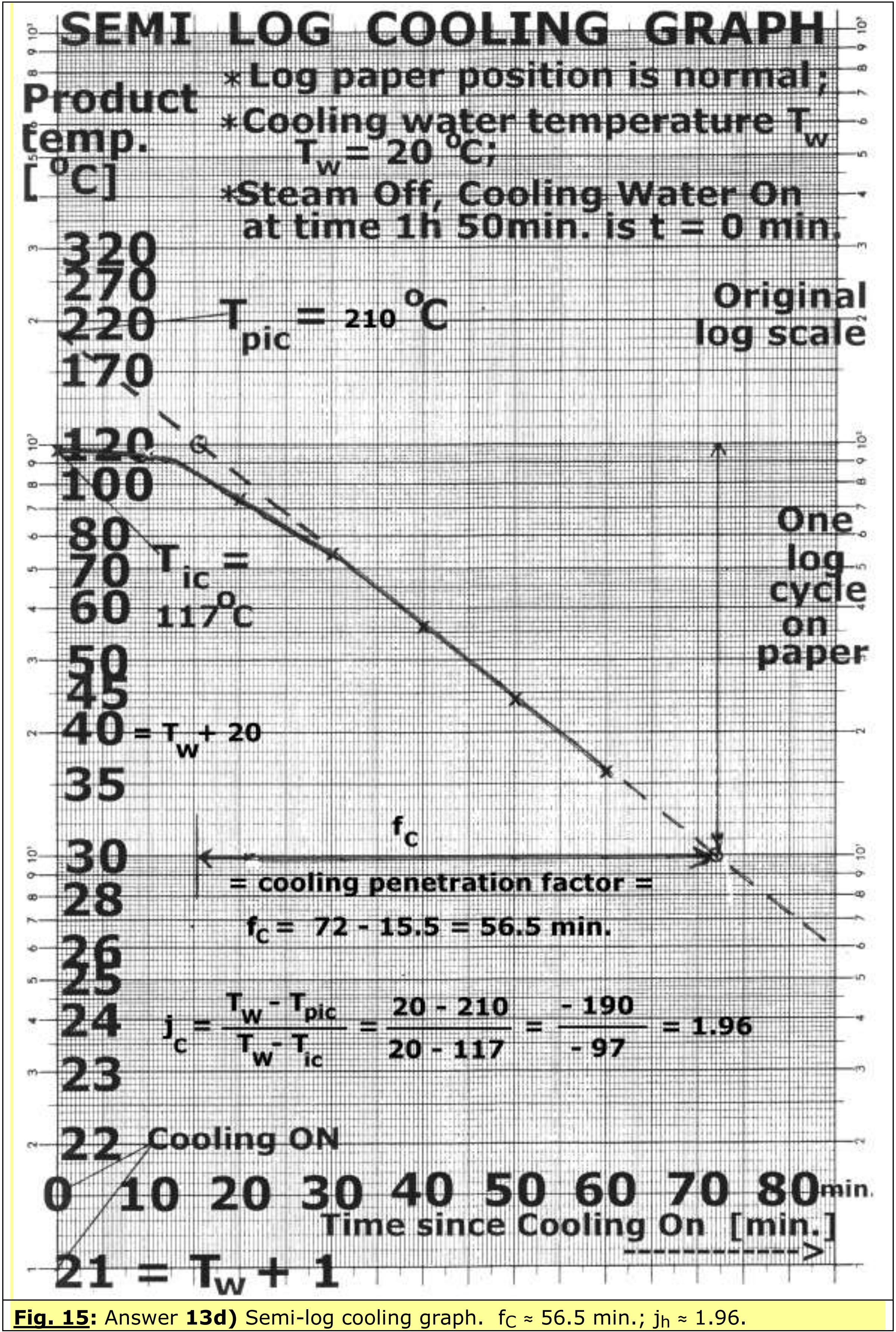


Fig. 15: Answer **13d)** Semi-log cooling graph. $f_C \approx 56.5$ min.; $j_h \approx 1.96$.

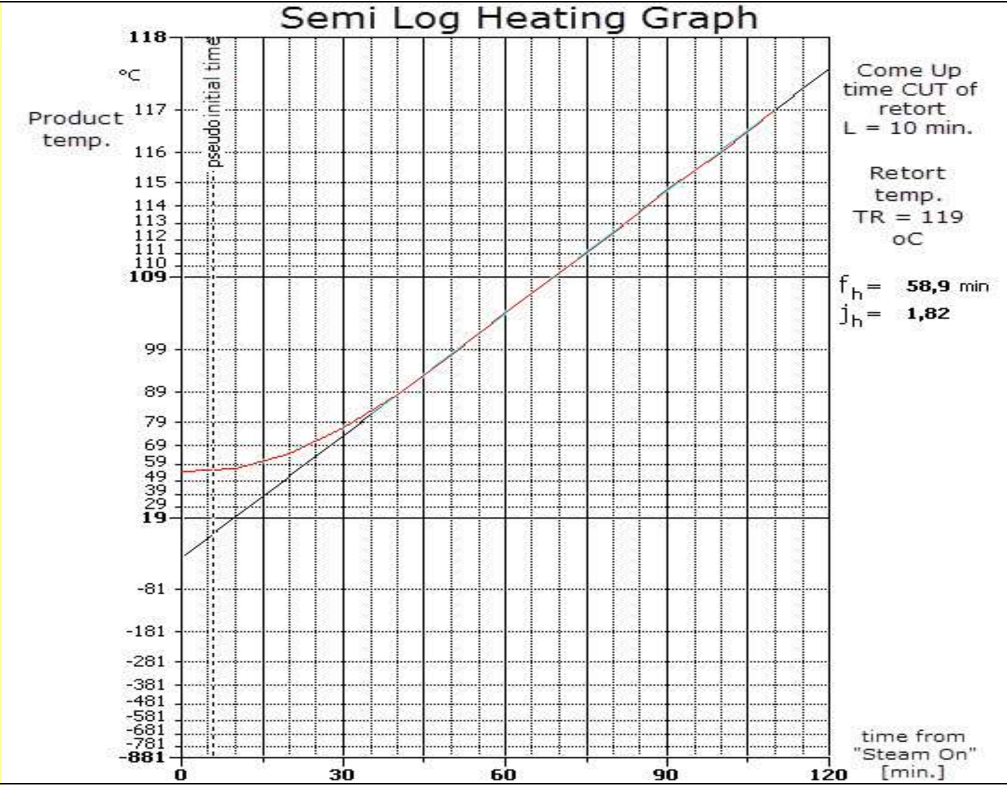


Fig. 16A: Semi log product heating graph, constructed from table 14 by computer program Ball.exe, which also calculated: f_h = 58.9 min.; j_h = 1.82.

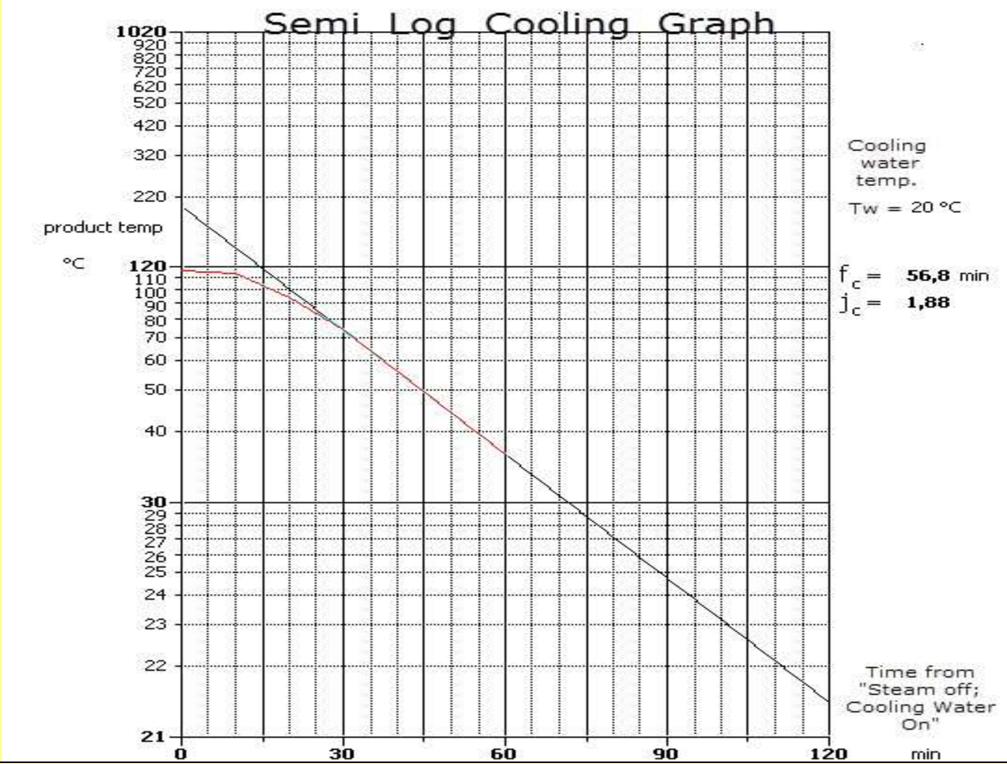


Fig. 16B: Semi log product cooling graph, constructed from table 14 by computer program Ball.exe, which also calculated: f_c = 56.8 min.; j_c = 1.88.

Fig. 16: Verification of answers **13c)** and **13d)**, by using computer program BALL.exe.

* Ball.exe calculated (semi log heating graph fig. 16A above): f_h = 58.9 min.; j_h = 1.82;
in fig. 14) it was found that: $f_h \approx$ 59 min.; $j_h \approx$ 1.83.
These values match almost perfectly.

* Ball.exe calculated (semi log cooling graph fig. 16B above): f_c = 56.8 min.; j_c = 1.88;
in fig. 15) it was found that: $f_c \approx$ 56.6 min.; $j_c \approx$ 1.96.
These values match rather well.

(courtesy Frits Eckenhausen, HAS University of Applied Sciences; 's-Hertogenbosch, NL)

ANNEX 1: Time-temperature measurements of Example Calculation 13

Time-temperature measurements of ......
- the retort medium (saturated condensing steam for heating; immersion in cold water for cooling), and
- of 2 solid products, 1 and 2, measured in their slowest heating point.

Analysis of process data:

Start process = "Steam On", at time t = 00:00:00 [h:m:s] = t = 0 min.
Initial **product** temperature at start (t = 0 min.) of process: $T_{ih,1}$ = 9.7 ºC
$T_{ih,2}$ = 10.1 ºC
Retort temperature = sterilization temperature: $T_R \approx$ 124 ºC
Time for retort medium to reach T_R, so come up time CUT: L = 5 min.
"Steam Off and Cooling Water On": at time 1 h 19 min. = 79 min.
Thus sterilization time P_t = 79 min - 5 min. come up time = 74 min.
Product temperature at end of sterilization time (at t = 1h 19 min.): T1 = 120.9 ºC.
T2 = 121.7 ºC.
Temperature of the cooling water T_W = 15 ºC.
"Cooling Water Off", so end of the total process: at time 2h 04 min. = 124 min.

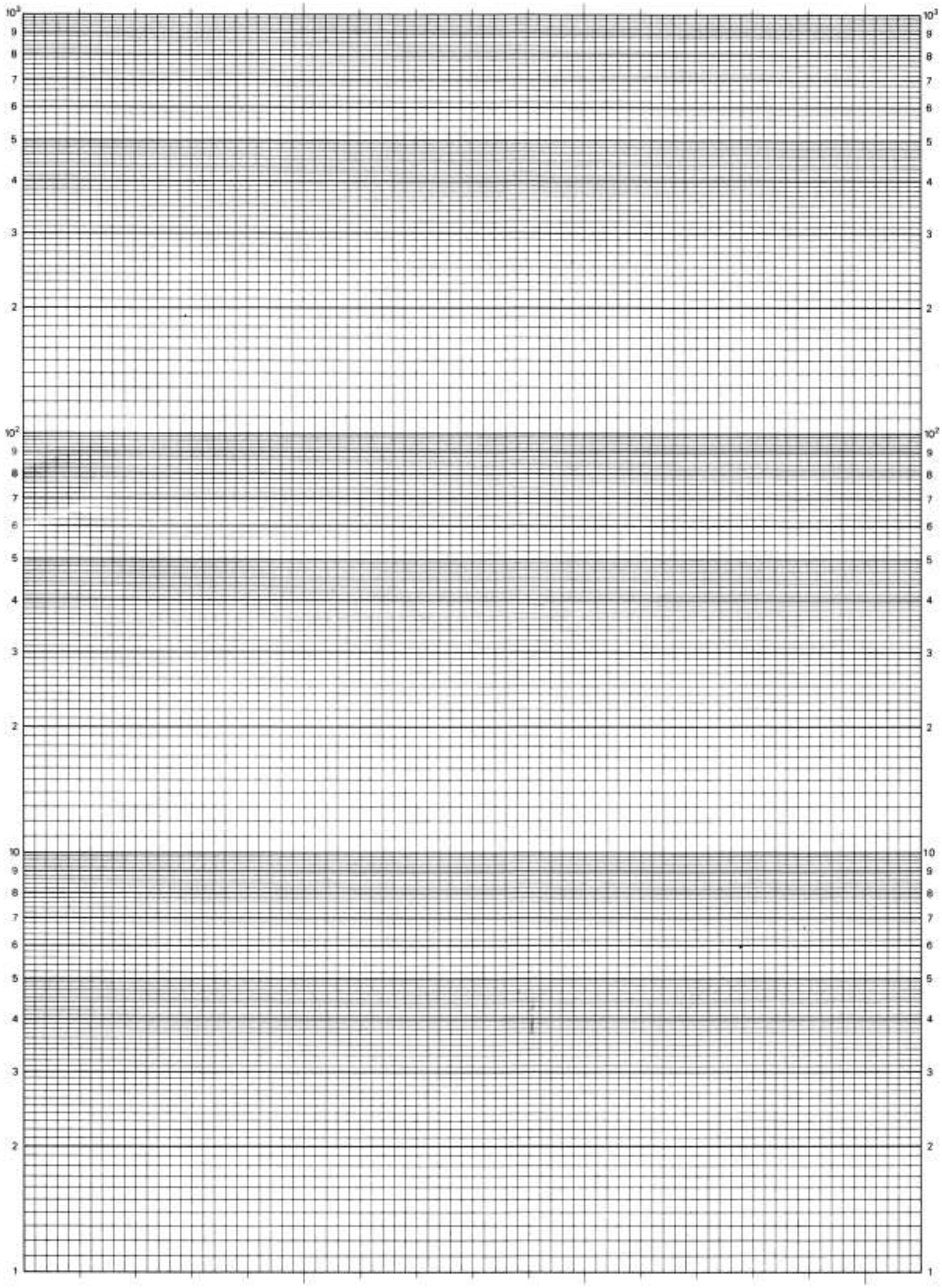
Date/Time	Retort	Product 1	Product 2	Comments
	ºC	ºC	ºC	
24-10-2013 23:58:00	19.2	9.5	10.2	Temperature sensors started
24-10-2013 23:59:00	17.5	9.6	10.1	
25-10-2013 00:00:00	17.2	9.7	10.1	t = 0; Steam On; start process;
25-10-2013 00:01:00	87.3	9.8	10	
25-10-2013 00:02:00	100.3	10.2	10.5	
25-10-2013 00:03:00	105.5	10.4	11.1	
25-10-2013 00:04:00	118.6	10.5	11.3	
25-10-2013 00:05:00	124.4	10.7	11.6	Retort at retort temperature TR
25-10-2013 00:06:00	126.6	11.1	12.4	
25-10-2013 00:07:00	127.2	11.7	13.5	
25-10-2013 00:08:00	126.7	12.7	15.3	
25-10-2013 00:09:00	125.9	14.2	17.8	
25-10-2013 00:10:00	125.1	16	21.3	
25-10-2013 00:11:00	125.3	18.2	25.4	
25-10-2013 00:12:00	125.6	20.6	29.3	
25-10-2013 00:13:00	125.4	23.3	33.1	
25-10-2013 00:14:00	125.5	26.2	36.8	
25-10-2013 00:15:00	125.6	29.3	40.4	
25-10-2013 00:16:00	125.3	32.4	43.9	
25-10-2013 00:17:00	125.3	35.6	47.4	
25-10-2013 00:18:00	125.4	38.8	50.8	
25-10-2013 00:19:00	125.4	42.2	54	
25-10-2013 00:20:00	125.3	45.4	57.2	
25-10-2013 00:21:00	125.3	48.6	60.4	
25-10-2013 00:22:00	125.2	51.7	63.3	
25-10-2013 00:23:00	125.2	54.7	66.2	
25-10-2013 00:24:00	125.1	57.7	68.9	
25-10-2013 00:25:00	125.2	60.6	71.3	
25-10-2013 00:26:00	125.1	63.5	73.6	

Date/Time	Retort	Product 1	Product 2	Comments
	ºC	ºC	ºC	
25-10-2013 00:27:00	125.1	66.3	75.9	
25-10-2013 00:28:00	125	69.1	78.1	
25-10-2013 00:29:00	125	71.8	80.2	
25-10-2013 00:30:00	125	74.4	82.3	
25-10-2013 00:31:00	125	76.9	84.4	
25-10-2013 00:32:00	124.9	79.3	86.4	
25-10-2013 00:33:00	124.8	81.6	88.3	
25-10-2013 00:34:00	124.7	83.7	90.1	
25-10-2013 00:35:00	124.9	85.7	91.9	
25-10-2013 00:36:00	124.8	87.7	93.5	
25-10-2013 00:37:00	124.8	89.6	95.1	
25-10-2013 00:38:00	124.8	91.3	96.7	
25-10-2013 00:39:00	124.8	93.1	98.1	
25-10-2013 00:40:00	124.8	94.7	99.5	
25-10-2013 00:41:00	124.8	96.3	100.8	
25-10-2013 00:42:00	124.7	97.7	102.1	
25-10-2013 00:43:00	124.8	99.2	103.3	
25-10-2013 00:44:00	124.6	100.5	104.5	
25-10-2013 00:45:00	124.6	101.8	105.6	
25-10-2013 00:46:00	124.5	103.1	106.6	
25-10-2013 00:47:00	124.6	104.2	107.6	
25-10-2013 00:48:00	124.6	105.3	108.5	
25-10-2013 00:49:00	124.6	106.3	109.4	
25-10-2013 00:50:00	124.5	107.3	110.2	
25-10-2013 00:51:00	124.6	108.2	111	
25-10-2013 00:52:00	124.5	109.1	111.8	
25-10-2013 00:53:00	124.4	109.9	112.5	
25-10-2013 00:54:00	124.6	110.7	113.2	
25-10-2013 00:55:00	124.6	111.5	113.8	
25-10-2013 00:56:00	124.5	112.2	114.4	
25-10-2013 00:57:00	124.5	112.8	114.9	
25-10-2013 00:58:00	124.6	113.4	115.5	
25-10-2013 00:59:00	124.5	114.1	115.9	
25-10-2013 01:00:00	124.3	114.6	116.4	
25-10-2013 01:01:00	124.5	115.1	116.9	
25-10-2013 01:02:00	124.4	115.6	117.3	
25-10-2013 01:03:00	124.5	116.1	117.7	
25-10-2013 01:04:00	124.4	116.6	118.1	
25-10-2013 01:05:00	124.3	117	118.5	
25-10-2013 01:06:00	124.5	117.4	118.8	
25-10-2013 01:07:00	124.4	117.7	119.1	
25-10-2013 01:08:00	124.6	118.1	119.4	
25-10-2013 01:09:00	124.5	118.4	119.6	
25-10-2013 01:10:00	124.3	118.8	119.9	
25-10-2013 01:11:00	124.4	119.1	120.1	
25-10-2013 01:12:00	124.5	119.3	120.4	
25-10-2013 01:13:00	124.4	119.6	120.6	
25-10-2013 01:14:00	124.3	119.9	120.8	
25-10-2013 01:15:00	124.3	120.1	121	
25-10-2013 01:16:00	124.2	120.3	121.2	

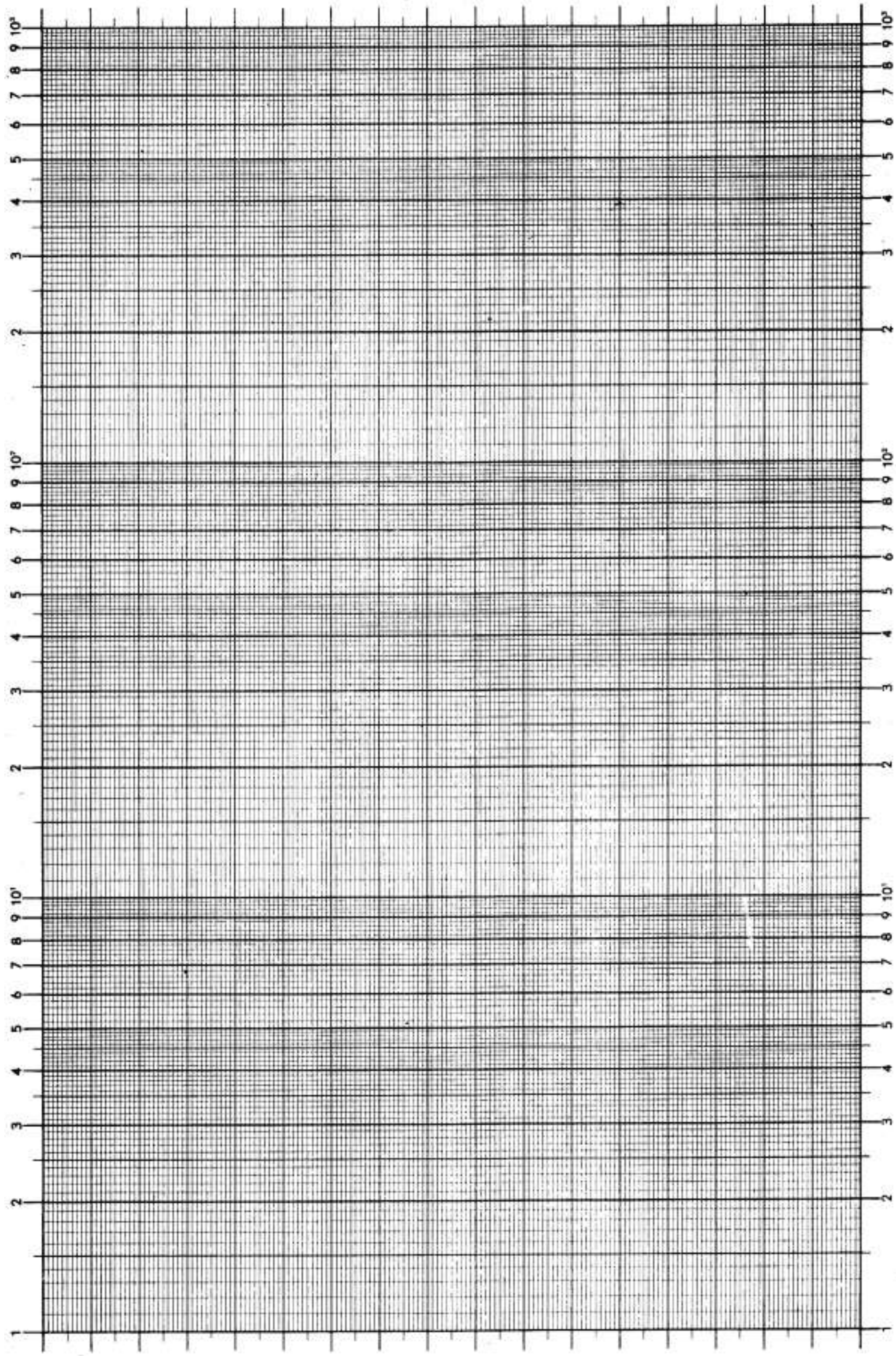
Date/Time	Retort	Product 1	Product 2	Comments
	ºC	ºC	ºC	
25-10-2013 01:17:00	124.4	120.5	121.3	
25-10-2013 01:18:00	124.1	120.7	121.5	
25-10-2013 01:19:00	124.3	120.9	121.7	Steam Off; Cooling Water On
25-10-2013 01:20:00	122.4	121.1	121.8	
25-10-2013 01:21:00	120.4	121.3	121.9	
25-10-2013 01:22:00	120.1	121.4	121.9	
25-10-2013 01:23:00	119.6	121.6	121.9	
25-10-2013 01:24:00	119.5	121.7	121.8	
25-10-2013 01:25:00	119.9	121.8	121.9	
25-10-2013 01:26:00	119.7	121.9	122	
25-10-2013 01:27:00	114.1	121.7	121.2	
25-10-2013 01:28:00	114.3	122	121.3	
25-10-2013 01:29:00	109	121.8	121.3	
25-10-2013 01:30:00	102.1	121.8	121.1	
25-10-2013 01:31:00	50.4	121.7	120.8	
25-10-2013 01:32:00	33.2	121.1	120.4	
25-10-2013 01:33:00	26.8	119.8	119.4	
25-10-2013 01:34:00	23.4	117.8	117.6	
25-10-2013 01:35:00	21.7	114.6	115.2	
25-10-2013 01:36:00	20.3	111.7	112.5	
25-10-2013 01:37:00	19.4	109.1	109.4	
25-10-2013 01:38:00	18.8	106.4	106.3	
25-10-2013 01:39:00	18.3	103.5	103	
25-10-2013 01:40:00	18	99.9	99.8	
25-10-2013 01:41:00	17.5	96.2	96.6	
25-10-2013 01:42:00	17.5	93.2	93.5	
25-10-2013 01:43:00	17.2	90.6	90.5	
25-10-2013 01:44:00	16.9	88.2	87.7	
25-10-2013 01:45:00	16.9	85.7	84.9	
25-10-2013 01:46:00	16.7	83.2	82.3	
25-10-2013 01:47:00	16.3	80.9	79.7	
25-10-2013 01:48:00	16.2	78.6	77.3	
25-10-2013 01:49:00	16.2	76.4	74.9	
25-10-2013 01:50:00	16	74.3	72.7	
25-10-2013 01:51:00	16.1	72.3	70.5	
25-10-2013 01:52:00	15.9	70.2	68.4	
25-10-2013 01:53:00	15.8	68.3	66.4	
25-10-2013 01:54:00	15.6	66.3	64.3	
25-10-2013 01:55:00	15.6	64.5	62.5	
25-10-2013 01:56:00	15.5	62.8	60.7	
25-10-2013 01:57:00	15.4	61	59.1	
25-10-2013 01:58:00	15.4	59.4	57.4	
25-10-2013 01:59:00	15.4	57.8	55.8	
25-10-2013 02:00:00	15.3	56.2	54.2	
25-10-2013 02:01:00	15.3	54.7	52.7	
25-10-2013 02:02:00	15.2	53.2	51.3	
25-10-2013 02:03:00	15.3	51.9	50	
25-10-2013 02:04:00	15.2	50.5	48.7	Cooling Water Off; End of Process
25-10-2013 02:05:00	16.6	49.2	47.5	
25-10-2013 02:06:00	16.9	47.9	46.3	

Date/Time	Retort	Product 1	Product 2	Comments
	ºC	ºC	ºC	
25-10-2013 02:07:00	17.4	46.7	45.1	
25-10-2013 02:08:00	18.1	45.5	44	
25-10-2013 02:09:00	18.4	44.4	42.9	
25-10-2013 02:10:00	15.8	43.4	41.9	
25-10-2013 02:11:00	15.9	42.3	29.6	
25-10-2013 02:12:00	16.4	41.3	17.6	

ANNEX 2:
Semi log paper with 3 log sections



Annex 2 (continued): Semi log paper with 3 log sections



ANNEX 3:
Thermal Diffusivity *a* of some Food Products

Annex 3: Thermal diffusivities *a* of some food products $a = k/(c_p \cdot \rho)$			
Food product	Thermal diffusivity *a* [m^2/s]	Remarks	Reference
	Fruit, fruit juices, fruit products		
Apple	$1.44 \cdot 10^{-7}$		Noordervliet (1982)
Apple	$1.50 \cdot 10^{-7}$	T = 27 to -18 ºC	Rahman (1995: 373)
Apple, whole, McIntosh	$0.77 \cdot 10^{-7}$	T = 32 - 0 ºC	Rahman (1995: 373)
Apple, Crab	$1.30 \cdot 10^{-7}$	T = 16 - 0 ºC	Rahman (1995: 373)
Apple, whole, Cox	$1.34 \cdot 10^{-7}$	T = 20 - 4 ºC	Rahman (1995: 373)
Apple, whole, Jonathan	$1.20 \cdot 10^{-7}$	T = 27 - 4 ºC	Rahman (1995: 373)
Apple, whole, RD (85% water)	$1.37 \cdot 10^{-7}$	T = 0 to -30 ºC	Rahman (1995: 373)
Apple, whole, RD	$1.37 \cdot 10^{-7}$	T = 29 - 1 ºC	Rahman (1995: 373)
Apple, whole, GD	$1.46 \cdot 10^{-7}$	T = 20 - 4 ºC	Rahman (1995: 373)
Apple, whole, Red Delicious	$1.37 \cdot 10^{-7}$	T = 0 - 30 ºC	Singh (1992: 254)
Apple, flesh, RD	$1.11 \cdot 10^{-7}$		Rahman (1995: 373)
Apple juice	$1.32 \cdot 10^{-7}$	13% dry matter	Noordervliet (1982)
Apple juice	$1.31 \cdot 10^{-7}$	30% dry matter	Noordervliet (1982)
Apple juice	$1.30 \cdot 10^{-7}$	64% dry matter	Noordervliet (1982)
Apple, pulp, GD	$1.50 \cdot 10^{-7}$	T = 4 - 26 ºC	Rahman (1995: 373)
Apple pulp (Golden Delicious)	$1.50 \cdot 10^{-7}$ - $1.62 \cdot 10^{-7}$	T = 29 ºC	Holdsworth (2007:18)
Apple pulp (88.6% water)	$1.345 \cdot 10^{-7}$	T = 10 ºC	Rahman (1995: 383)
Apple pulp (88.6% water)	$1.350 \cdot 10^{-7}$	T = 20 ºC	Rahman (1995: 383)
Apple pulp (88.6% water)	$1.430 \cdot 10^{-7}$	T = 25 ºC	Rahman (1995: 383)
Apple pulp (88.6% water)	$1.505 \cdot 10^{-7}$	T = 40 ºC	Rahman (1995: 383)
Apple pulp (88.6% water)	$1.422 \cdot 10^{-7}$	T = 50 ºC	Rahman (1995: 383)
Apple sauce	$1.61 \cdot 10^{-7}$	T = 105 ºC	Holdsworth (2007:18)
Apple sauce (37% water)	$1.05 \cdot 10^{-7}$	T = 5 ºC	Singh (1992: 254)
Apple sauce (37% water)	$1.12 \cdot 10^{-7}$	T = 65 ºC	Singh (1992: 254)
Apple sauce (80% water)	$1.22 \cdot 10^{-7}$	T = 5 ºC	Singh (1992: 254)
Apple sauce (80% water)	$1.40 \cdot 10^{-7}$	T = 65 ºC	Singh (1992: 254)
Applesauce (75.7% water)	$1.49 \cdot 10^{-7}$	T = 21 - 50 ºC	Rahman (1995: 373)
Apple sauce	$1.67 \cdot 10^{-7}$	T = 26-129 ºC	Singh (1992: 254)
Avocado (flesh)	$1.27 \cdot 10^{-7}$	T = 20 ºC	Rahman (1995: 373)
Avocado (flesh)	$1.32 \cdot 10^{-7}$	T = 20 ºC	Rahman (1995: 373)
Avocado (flesh), Lula	$1.05 \cdot 10^{-7}$	T = 24 - 3 ºC	Rahman (1995: 373)
Avocado (flesh)	$1.24 \cdot 10^{-7}$	T = 24 ºC	Singh (1992: 254)
Avocado (seed), Lula	$1.10 \cdot 10^{-7}$	T = 24 - 3 ºC	Rahman (1995: 373)
Avocado (seed)	$1.29 \cdot 10^{-7}$	T = 24 ºC	Singh (1992: 254)
Avocado (whole)	$1.54 \cdot 10^{-7}$	T = 41 - 3 ºC	Rahman (1995: 373)
Avocado (whole)	$1.54 \cdot 10^{-7}$	T = 24 ºC	Singh (1992: 254)
Banana	$1.44 \cdot 10^{-7}$		Noordervliet (1982)
Banana (flesh)	$1.46 \cdot 10^{-7}$	T = 20 ºC	Rahman (1995: 373)
Banana (flesh)	$1.37 \cdot 10^{-7}$	T = 20 ºC	Rahman (1995: 373)
Banana (flesh; 76% water)	$1.18 \cdot 10^{-7}$	T = 5 ºC	Singh (1992: 254)
Banana (flesh; 76% water)	$1.42 \cdot 10^{-7}$	T = 65 ºC	Singh (1992: 254)

Annex 3: Thermal diffusivities *a* of some food products $a = k/(c_p \cdot \rho)$			
Food product	Thermal diffusivity *a* [m^2/s]	Remarks	Reference
Berry	$1.40{\cdot}10^{-7}$		Noordervliet (1982)
Blackberry	$1.27{\cdot}10^{-7}$	T = 27 to -18 ºC	Rahman (1995: 373)
Cherries, tart, flesh	$1.32{\cdot}10^{-7}$	T = 30 - 0 ºC	Singh (1992: 254)
Grape juice	$0.85{\cdot}10^{-7}$	T = -37.8 to -19.4 ºC	Rahman (1995: 375)
Grape juice	$0.99{\cdot}10^{-7}$	T = -40 t0 -27 ºC	Rahman (1995: 375)
Grapefruit, Marsh, flesh (88% water)	$1.27{\cdot}10^{-7}$		Singh (1992: 254)
Grapefruit, Marsh, albedo (72.2% water)	$1.09{\cdot}10^{-7}$		Singh (1992: 254)
Grapefruit, Marsh, flesh	$1.23{\cdot}10^{-7}$	T = 31 ºC	Rahman (1995: 373)
Grapefruit, Marsh, whole	$0.92{\cdot}10^{-7}$	T = 40 - 10 ºC	Rahman (1995: 373)
Grapefruit, Marsh, whole	$0.94{\cdot}10^{-7}$	T = 46 - 0 ºC	Rahman (1995: 373)
Grapefruit, Marsh, whole	$0.92{\cdot}10^{-7}$	T = 27 - 2 ºC	Rahman (1995: 373)
Grapefruit, Marsh, rind	$1.20{\cdot}10^{-7}$	T = 27 ºC	Rahman (1995: 373)
Grapefruit	$1.45{\cdot}10^{-7}$		Noordervliet (1982)
Grapefruit	$1.20{\cdot}10^{-7}$	T = 16 - 0 ºC	Rahman (1995: 373)
Grapefruit, whole	$0.84{\cdot}10^{-7}$	T = 36 - 0 ºC	Rahman (1995: 373)
Lemon, Eureka, whole	$1.07{\cdot}10^{-7}$	T = 40 - 0 ºC	Rahman (1995: 373)
Lemon, whole	$1.07{\cdot}10^{-7}$	T = 40 ºC	Singh (1992: 254)
Melon	$1{,}44{\cdot}10^{-7}$		Noordervliet (1982)
Orange	$1.43{\cdot}10^{-7}$		Noordervliet (1982)
Orange	$1.30{\cdot}10^{-7}$	T = 16 - 0 ºC	Rahman (1995: 373)
Orange, Valencia, whole	$0.94{\cdot}10^{-7}$	T = 40 - 0 ºC	Rahman (1995: 373)
Orange, Navel, whole	$1.07{\cdot}10^{-7}$	T = 40 - 0 ºC	Rahman (1995: 373)
Peach	$1.11{\cdot}10^{-7}$		Rahman (1995: 373)
Peach, several, whole	$1.39{\cdot}10^{-7}$	T = 27 - 4 ºC	Rahman (1995: 374)
Peach, whole	$1.39{\cdot}10^{-7}$	T = 27.4 ºC	Singh (1992: 254)
Pear	$1.43{\cdot}10^{-7}$		Noordervliet (1982)
Plum	$1.42{\cdot}10^{-7}$		Noordervliet (1982)
Strawberry	$1.47{\cdot}10^{-7}$	T = 27 to -18 ºC	Rahman (1995: 374)
Strawberry	$1.43{\cdot}10^{-7}$		Noordervliet (1982)
Strawberry, flesh (92% water)	$1.27{\cdot}10^{-7}$	T = 5 ºC	Singh (1992: 254)
Vegetables and vegetable products			
Beans, baked	$1.68{\cdot}10^{-7}$	T = 4 - 122 ºC	Singh (1992: 254)
Beans, green beans	$1.43{\cdot}10^{-7}$		Noordervliet (1982)
Beans, Lima,	$1.24{\cdot}10^{-7}$	T = 27 to -18 ºC	Rahman (1995: 373)
Beans, Lima bean, pureed	$1.80{\cdot}10^{-7}$	T = 26-122 ºC	Singh (1992: 254)
Beans in tomato sauce	$1.46{\cdot}10^{-7}$		Holdsworth (2007:245)
Beetroot	$1.42{\cdot}10^{-7}$		Noordervliet (1982)
Cabbage	$1.43{\cdot}10^{-7}$		Noordervliet (1982)
Carrot	$1.40{\cdot}10^{-7}$	T = 20 ºC	Rahman (1995: 373)
Carrot	$1.55{\cdot}10^{-7}$	T = 20 ºC	Rahman (1995: 373)
Carrot	$1.42{\cdot}10^{-7}$		Noordervliet (1982)

Annex 3: Thermal diffusivities *a* of some food products $a = k/(c_p \cdot \rho)$

Food product	Thermal diffusivity *a* [m^2/s]	Remarks	Reference
Carrot	$1.70 \cdot 10^{-7}$		Noordervliet (1982)
Carrots	$1.82 \cdot 10^{-7}$ - $1.88 \cdot 10^{-7}$	T = 138 ºC	Holdsworth (2007:18)
Carrot purée	$1.58 \cdot 10^{-7}$		Holdsworth (2007:245)
Celeriac purée	$1.50 \cdot 10^{-7}$		Holdsworth (2007:245)
Celery tube	$1.45 \cdot 10^{-7}$		Noordervliet (1982)
Cucumber	$1.42 \cdot 10^{-7}$		Noordervliet (1982)
Cucumber, flesh	$1.39 \cdot 10^{-7}$	T = 20 ºC	Rahman (1995: 373)
Cucumber, flesh	$1.41 \cdot 10^{-7}$	T = 20 ºC	Rahman (1995: 373)
Lima beans: see Beans, Lima			
Mushrooms in brine	$1.18 \cdot 10^{-7}$		Holdsworth (2007:18)
Mushroom soup, cream	$1.58 \cdot 10^{-7}$		Holdsworth (2007:245)
Onion	$1.44 \cdot 10^{-7}$		Noordervliet (1982)
Onion, whole	$1.41 \cdot 10^{-7}$	T = 20 - 4 ºC	Rahman (1995: 373)
Pea, English	$1.24 \cdot 10^{-7}$	T = 27 to -18 ºC	Rahman (1995: 374)
Peas	$1.40 \cdot 10^{-7}$		Noordervliet (1982)
Pea, pureed	$1.82 \cdot 10^{-7}$	T = 26-128 ºC	Singh (1992: 254)
Pea purée	$1.59 \cdot 10^{-7}$		Holdsworth (2007:18)
Pea purée	$1.54 \cdot 10^{-7}$		Holdsworth (2007:18)
Potato (78% water)	$1.39 \cdot 10^{-7}$ - $1.46 \cdot 10^{-7}$	T = 60 - 100 ºC	Holdsworth (2007:18)
Potato	$1.42 \cdot 10^{-7}$ - $1.96 \cdot 10^{-7}$	T = 42.9 ºC	Holdsworth (2007:18)
Potato	$1.43 \cdot 10^{-7}$		Noordervliet (1982)
Potato, whole	$1.77 \cdot 10^{-7}$	T = 26 to -6 ºC	Rahman (1995: 374)
Potato, Pungo, whole	$1.31 \cdot 10^{-7}$		Rahman (1995: 374)
Potato, several, flesh	$1.70 \cdot 10^{-7}$	T = 25 ºC	Rahman (1995: 374)
Potato, Irish, flesh	$1.23 \cdot 10^{-7}$	T = 27 to -18 ºC	Rahman (1995: 374)
Potato, Excel, flesh	$1.17 \cdot 10^{-7}$	T = 24 - 91 ºC	Rahman (1995: 374)
Potato, flesh	$1.53 \cdot 10^{-7}$	T = 20 ºC	Rahman (1995: 374)
Potato, flesh	$1.48 \cdot 10^{-7}$	T = 20 ºC	Rahman (1995: 374)
Potato, flesh	$1.70 \cdot 10^{-7}$	T = 25 ºC	Singh (1992: 254)
Potato, mashed, cooked (78% water)	$1.23 \cdot 10^{-7}$	T = 5 ºC	Singh (1992: 254)
Potato, mashed, cooked (78% water)	$1.45 \cdot 10^{-7}$	T = 65 ºC	Singh (1992: 254)
Potato purée	$(1.30 \pm 0.04) \cdot 10^{-7}$		Holdsworth (2007:18)
Rutabaga	$1.34 \cdot 10^{-7}$	T = 48 ºC	Singh (1992: 254)
Rutabaga, whole	$1.34 \cdot 10^{-7}$	T = 48 - 0 ºC	Rahman (1995: 374)
Seaweed, cooked (75.9% water)	$1.90 \cdot 10^{-7}$	T = 56 - 110 ºC	Rahman (1995: 369)
Squash, whole	$1.10 \cdot 10^{-7}$	T = 16 - 0 ºC	Rahman (1995: 374)
Squash, whole	$1.71 \cdot 10^{-7}$	T = 47 ºC	Singh (1992: 254)
Squash, green, whole	$1.71 \cdot 10^{-7}$	T = 47 - 0 ºC	Rahman (1995: 374)
Squash, several, flesh	$1.56 \cdot 10^{-7}$	T = 25 ºC	Rahman (1995: 374)
Sugar beet, flesh	$1.26 \cdot 10^{-7}$	T = 14 - 60 ºC	Rahman (1995: 374)
Sweet potato, whole, Goldrush	$1.06 \cdot 10^{-7}$	T = 35 ºC	Rahman (1995: 374)
Sweet potato, whole, Goldrush	$1.39 \cdot 10^{-7}$	T = 55 ºC	Rahman (1995: 374)
Sweet potato, whole, Goldrush	$1.91 \cdot 10^{-7}$	T = 70 ºC	Rahman (1995: 374)

Annex 3: Thermal diffusivities *a* of some food products $a = k/(c_p \cdot \rho)$			
Food product	Thermal diffusivity *a* [m^2/s]	Remarks	Reference
Sweet potato, whole	$1.20 \cdot 10^{-7}$	T = 42 - 0 ºC	Rahman (1995: 374)
Sweet potato, whole	$1.06 \cdot 10^{-7}$	T = 35 ºC	Singh (1992: 254)
Sweet potato, whole	$1.39 \cdot 10^{-7}$	T = 55 ºC	Singh (1992: 254)
Sweet potato, whole	$1.91 \cdot 10^{-7}$	T = 70 ºC	Singh (1992: 254)
Sweet potato, flesh, Centennial	$1.32 \cdot 10^{-7}$	T = 116 ºC	Rahman (1995: 374)
Tomato, whole	$1.51 \cdot 10^{-7}$	T = 7 - 23 ºC	Rahman (1995: 374)
Tomato	$1.44 \cdot 10^{-7}$		Noordervliet (1982)
Tomato, Ace var.	$1.22 \cdot 10^{-7}$ - $1.88 \cdot 10^{-7}$	T = 42.9 ºC	Holdsworth (2007:18)
Tomato, Cherry, pulp	$1.48 \cdot 10^{-7}$	T = 4 -26 ºC	Rahman (1995: 374)
Tomato, Cherry tomato pulp	$1.46 \cdot 10^{-7}$ - $1.50 \cdot 10^{-7}$	T = 26 ºC	Holdsworth (2007:18)
Tomato ketchup	$(1.20 \pm 0.02) \cdot 10^{-7}$		Holdsworth (2007:18)
Tomato, pulp	$1.48 \cdot 10^{-7}$	T = 4.26 ºC	Singh (1992: 254)
Tomato purée	$1.28 \cdot 10^{-7}$	6% dry matter	Noordervliet (1982)
Tomato purée	$1,42 \cdot 10^{-7}$	20% dry matter	Noordervliet (1982)
Meat and meat products			
Beef; lean	$1.35 \cdot 10^{-7}$		Noordervliet (1982)
Beef; fat	$1.43 \cdot 10^{-7}$		Noordervliet (1982)
Beef, chuck (66% water)	$1.23 \cdot 10^{-7}$	T = 40-65 ºC	Singh (1992: 254)
Beef, round (71% water)	$1.33 \cdot 10^{-7}$	T = 40-65 ºC	Singh (1992: 254)
Beef, tongue (68% water)	$1.32 \cdot 10^{-7}$	T = 40-65 ºC	Singh (1992: 254)
Beef purée	$1.75 \cdot 10^{-7}$		Holdsworth (2007:18)
Beef, ground	$10.04 \cdot 10^{-7}$	T = -35 to -24 ºC	Rahman (1995: 370)
Beef, ground	$6.08 \cdot 10^{-7}$	T = -17 to -27 ºC	Rahman (1995: 370)
Beef, ground	$4.43 \cdot 10^{-7}$	T = -22 to -7 ºC	Rahman (1995: 370)
Corned beef	$1.73 \cdot 10^{-7}$		Holdsworth (2007:245)
Corned beef (65% water)	$1.32 \cdot 10^{-7}$	T = 5 ºC	Singh (1992: 254)
Corned beef (65% water)	$1.18 \cdot 10^{-7}$	T = 65 ºC	Singh (1992: 254)
Frankfurters (73.4% water)	$2.36 \cdot 10^{-7}$	T = 58-109 ºC	Rahman (1995: 369)
Ham, smoked (64% water)	$1.18 \cdot 10^{-7}$	T = 5 ºC	Singh (1992: 254)
Ham, smoked (64% water)	$1.38 \cdot 10^{-7}$	T = 40 - 65 ºC	Singh (1992: 254)
Ham, processed	$0.94 \cdot 10^{-7}$		Holdsworth (2007:18)
Ham salami	$1.52 \cdot 10^{-7}$		Holdsworth (2007:18)
Hamburgers, lean	$1.33 \cdot 10^{-7}$		Noordervliet (1982)
Hamburgers, fat	$1.45 \cdot 10^{-7}$		Noordervliet (1982)
Lard (0% water)	$0.61 \cdot 10^{-7}$	T = 0 - 25 ºC	Rahman (1995: 370)
Meat (74% water)	$1.46 \cdot 10^{-7}$	T = 0 - 50 ºC	Rahman (1995: 375)
Meat croquette (74% water)	$1.98 \cdot 10^{-7}$	T = 59-115 ºC	Rahman (1995: 369)
Meat croquette	$(1.98 \pm 0.22) \cdot 10^{-7}$	T = 59-115 ºC	Holdsworth (2007:18)
Meat, ground	$1.26 \cdot 10^{-7}$ - $1.82 \cdot 10^{-7}$	T = 20 ºC	Holdsworth (2007:18)
Meat hash	$1.52 \cdot 10^{-7}$		Holdsworth (2007:18)
Meat paste (69.2% water)	$1.177 \cdot 10^{-7}$	T = 10 ºC	Rahman (1995: 383)
Meat paste (69.2% water)	$1.272 \cdot 10^{-7}$	T = 20 ºC	Rahman (1995: 383)
Meat paste (69.2% water)	$1.382 \cdot 10^{-7}$	T = 25 ºC	Rahman (1995: 383)
Meat paste (69.2% water)	$1.325 \cdot 10^{-7}$	T = 40 ºC	Rahman (1995: 383)

Annex 3: Thermal diffusivities *a* of some food products $a = k/(c_p \cdot \rho)$			
Food product	Thermal diffusivity *a* [m^2/s]	Remarks	Reference
Meat paste (69.2% water)	$1.412 \cdot 10^{-7}$	T = 50 ºC	Rahman (1995: 383)
Meat paste (69.2% water)	$2.053 \cdot 10^{-7}$	T = 75 ºC	Rahman (1995: 383)
Meat products, heated, lean	$1.32 \cdot 10^{-7}$		Noordervliet (1982)
Meat products, heated, fat	$1,45 \cdot 10^{-7}$		Noordervliet (1982)
Meat sauce	$(1.46 \pm 0.05) \cdot 10^{-7}$	T = 69-112 ºC	Holdsworth (2007:18)
Meat sauce (77.3% water)	$1.46 \cdot 10^{-7}$	T = 60 - 112 ºC	Rahman (1995: 369)
Meat snacks; lean	$1.35 \cdot 10^{-7}$		Noordervliet (1982)
Meat snacks, fat	$1.41 \cdot 10^{-7}$		Noordervliet (1982)
Minced beef	$1.37 \cdot 10^{-7}$		Holdsworth (2007:245)
Organs meat; lean	$1.38 \cdot 10^{-7}$		Noordervliet (1982)
Organs meat; fat	$1.35 \cdot 10^{-7}$		Noordervliet (1982)
Pork; lean	$1.24 \cdot 10^{7}$ - $1.29 \cdot 10^{-7}$		Noordervliet (1982)
Pork; fat	$1.44 \cdot 10^{7}$		Noordervliet (1982)
Pork purée	$1.94 \cdot 10^{-7}$		Holdsworth (2007:18)
Steak, stewed	$1.45 \cdot 10^{-7}$		Holdsworth (2007:245)
Poultry and poultry products; eggs			
Chicken, complete	$1.32 \cdot 10^{-7}$		Noordervliet (1982)
Chicken, breast meat	$1.28 \cdot 10^{-7}$		Noordervliet (1982)
Chicken, leg meat	$1.31 \cdot 10^{-7}$		Noordervliet (1982)
Chicken, skin	$1.30 \cdot 10^{-7}$		Noordervliet (1982)
Chicken supreme sauce	$1.54 \cdot 10^{-7}$		Holdsworth (2007:245)
Duck	$1.31 \cdot 10^{-7}$		Noordervliet (1982)
Egg white (87.5% water)	$1.46 \cdot 10^{-7}$	T = 0 - 50 ºC	Rahman (1995: 375)
Egg, white	$1.36 \cdot 10^{-7}$		Noordervliet (1982)
Egg, whole, no shell	$1.34 \cdot 10^{-7}$		Noordervliet (1982)
Egg, yolk	$1.27 \cdot 10^{-7}$		Noordervliet (1982)
Turkey, breast meat	$1.30 \cdot 10^{-7}$		Noordervliet (1982)
Turkey, leg meat	$1.30 \cdot 10^{-7}$		Noordervliet (1982)
Turkey, skin	$1.27 \cdot 10^{-7}$		Noordervliet (1982)
Fish and fish products			
Abalone, cooked (68.5% water)	$1.85 \cdot 10^{-7}$	T = 56-108 ºC	Rahman (1995: 369)
Clam, cooked (75.1% water)	$1.96 \cdot 10^{-7}$	T = 51-108 ºC	Rahman (1995: 369)
Cod	$1.50 \cdot 10^{-7}$	T = 5 - 25 ºC	Rahman (1995: 382)
Cod	$1.31 \cdot 10^{-7}$	T = 5 ºC	Rahman (1995: 382)
Cod	$1.34 \cdot 10^{-7}$	T = 25 ºC	Rahman (1995: 382)
Codfish (81% water)	$1.22 \cdot 10^{-7}$	T = 5 ºC	Singh (1992: 254)
Codfish (81% water)	$1.42 \cdot 10^{-7}$	T = 65 ºC	Singh (1992: 254)
Cod mince, fillet (81% water)	$1.52 \cdot 10^{-7}$	T = 22 - 50 ºC	Rahman (1995: 370)
Cod fillet	$1.20 \cdot 10^{-7}$	T = 5 ºC	Rahman (1995: 382)
Cod fillet	$1.40 \cdot 10^{-7}$	T = 25 ºC	Rahman (1995: 382)
Fish, lean	$1.27 \cdot 10^{-7}$		Noordervliet (1982)
Fish fillet, lean	$1.29 \cdot 10^{-7}$		Noordervliet (1982)
Fish paste (71.8% water)	$1.220 \cdot 10^{-7}$	T = 10 ºC	Rahman (1995: 383)
Fish paste (71.8% water)	$1.180 \cdot 10^{-7}$	T = 20 ºC	Rahman (1995: 383)
Fish paste (71.8% water)	$1.337 \cdot 10^{-7}$	T = 25 ºC	Rahman (1995: 383)

Annex 3: Thermal diffusivities *a* of some food products $a = k/(c_p \cdot \rho)$			
Food product	Thermal diffusivity *a* [m^2/s]	Remarks	Reference
Fish paste (71.8% water)	$1.353 \cdot 10^{-7}$	T = 40 ºC	Rahman (1995: 383)
Fish paste (71.8% water)	$1.360 \cdot 10^{-7}$	T = 50 ºC	Rahman (1995: 383)
Fish paste (71.8% water)	$1.930 \cdot 10^{-7}$	T = 75 ºC	Rahman (1995: 383)
Halibut (76% water)	$1.47 \cdot 10^{-7}$	T = 40-65 ºC	Singh (1992: 254)
Herring, fresh; summer	$1.20 \cdot 10^{-7}$		Noordervliet (1982)
Herring fillets	$1.20 \cdot 10^{-7}$		Noordervliet (1982)
Herring, brined	$1.18 \cdot 10^{-7}$		Noordervliet (1982)
Mackerel, fresh	$1.23 \cdot 10^{-7}$		Noordervliet (1982)
Mackerel (77.4% water)	$1.408 \cdot 10^{-7}$	T = 0 ºC	Rahman (1995: 376)
Mackerel (77.4% water)	$1.519 \cdot 10^{-7}$	T = 10 ºC	Rahman (1995: 376)
Mackerel (77.4% water)	$1.793 \cdot 10^{-7}$	T = 20 ºC	Rahman (1995: 376)
Mackerel (77.4% water)	$2.070 \cdot 10^{-7}$	T =3 0 ºC	Rahman (1995: 376)
Mackerel	$1.20 \cdot 10^{-7}$	T = 5 ºC	Rahman (1995: 382)
Mackerel	$1.30 \cdot 10^{-7}$	T = 25 ºC	Rahman (1995: 382)
Mackerel in tomato sauce	$1.49 \cdot 10^{-7}$		Holdsworth (2007:245)
Shrimps, peeled	$1.00 \cdot 10^{-7}$		Noordervliet (1982)
Tuna fish in oil	$1.64 \cdot 10^{-7}$	T = 115 ºC	Holdsworth (2007:18)
Milk and milk products; egg and egg products			
Butter, unsalted	$1.08 \cdot 10^{-7}$		Noordervliet (1982)
Butter	$0.92 \cdot 10^{-7}$	T = 20 ºC	Walstra (2006: 756)
Buttermilk	$1.47 \cdot 10^{-7}$		Noordervliet (1982)
Cheese, Edam , young, 40^+ (≥ 40% fat in dry matter)	$1.30 \cdot 10^{-7}$		Noordervliet (1982)
Cheese, Gouda, young; 48^+ (≥ 48% fat in dry matter)	$1.22 \cdot 10^{-7}$		Noordervliet (1982)
Cheese, hard; semi-hard	$1.07 \cdot 10^{-7}$ - $1.32 \cdot 10^{-7}$	T = 20 ºC	Walstra (2006: 756)
Cheese, Leiden, young, 20^+ (≥ 20% fat in dry matter)	$1.24 \cdot 10^{-7}$		Noordervliet (1982)
Cheese, Processed, 48^+ (≥ 48% fat in dry matter)	$1.24 \cdot 10^{-7}$		Noordervliet (1982)
Cream (20% fat)	$1.05 \cdot 10^{-7}$	T = 20 ºC	Walstra (2006: 756)
Cream (40% fat)	$1.04 \cdot 10^{-7}$		Noordervliet (1982)
Dutch custard (vla)	$1.37 \cdot 10^{-7}$		Noordervliet (1982)
Milk (3,2% fat)	$1.44 \cdot 10^{-7}$		Noordervliet (1982)
Milk (3.5% fat)	$1.45 \cdot 10^{-7}$		Noordervliet (1982)
Milk	$1.30 \cdot 10^{-7}$		Walstra (2006: 756)
Milk, Coffee milk = Condensed milk, not sweetened, 9% fat; 31% milk dry matter	$2.06 \cdot 10^{-7}$		Noordervliet (1982)
Milk, Condensed milk, sweetened, 9% fat; 31% milk dry matter	$1.85 \cdot 10^{-7}$		Noordervliet (1982)
Milk, evaporated	$1.30 \cdot 10^{-7}$	T = 20 ºC	Walstra (2006: 756)
Milk fat; 100% fat	$4.35 \cdot 10^{-7}$	T = 20 ºC	Walstra (2006: 756)
Skim milk (< 0.1 % fat)	$1.39 \cdot 10^{-7}$		Noordervliet (1982)
Skim milk (< 0.1 % fat)	$1.37 \cdot 10^{-7}$	T = 20 ºC	Walstra (2006: 756)
Yoghurt (86.2% water; 1.1% fat)	$1.32 \cdot 10^{-7}$	T = 10 ºC	Rahman (1995: 383)

Annex 3: Thermal diffusivities *a* of some food products $a = k/(c_p \cdot \rho)$			
Food product	Thermal diffusivity *a* [m^2/s]	Remarks	Reference
Yoghurt (86.2% water; 1.1% fat)	$1.40 \cdot 10^{-7}$	T = 20 ºC	Rahman (1995: 383)
Yoghurt (86.2% water; 1.1% fat)	$1.37 \cdot 10^{-7}$	T = 25 ºC	Rahman (1995: 383)
Yoghurt (86.2% water; 1.1% fat)	$1.46 \cdot 10^{-7}$	T = 30 ºC	Rahman (1995: 383)
Yoghurt (86.2% water; 1.1% fat)	$1.33 \cdot 10^{-7}$	T = 40 ºC	Rahman (1995: 383)
Yoghurt (86.2% water; 1.1% fat)	$1.43 \cdot 10^{-7}$	T = 50 ºC	Rahman (1995: 383)
Composed meals			
Beans, cooked, with corn and diced squash (68.3% water)	$1.83 \cdot 10^{-7}$	T = 56 - 113 ºC	Rahman (1995: 369)
Chicken & rice	$(1.93 \pm 0.21) \cdot 10^{-7}$	T = 65 - 113 ºC	Holdsworth (2007:18)
Chicken with rice (75.1% water)	$1.93 \cdot 10^{-7}$	T = 65 - 113 ºC	Rahman (1995: 369)
Chicken with diced potatoes + carrots (73.7% water)	$1.70 \cdot 10^{-7}$	T = 72 - 109 ºC	Rahman (1995: 369)
Chicken+potatoes+carrots	$(1.70 \pm 0.03) \cdot 10^{-7}$	T = 72 - 109 ºC	Holdsworth (2007:18)
Chicken with peas and diced potatoes and carrots (67.6% water)	$1.65 \cdot 10^{-7}$	T = 63 - 109 ºC	Rahman (1995: 369)
Chickenpeas, cooked, +pork sausage	$(1.90 \pm 0.03) \cdot 10^{-7}$	T = 71 - 114 ºC	Holdsworth (2007:18)
Chickpeas, cooked, with pork sausages (81.4% water)	$2.24 \cdot 10^{-7}$	T = 71-114 ºC	Rahman (1995: 369)
Chili con carne	$1.44 \cdot 10^{-7}$		Holdsworth (2007:245)
Clams, cooked, with rice (80.1% water)	$1.98 \cdot 10^{-7}$	T = 60 - 114 ºC	Rahman (1995: 369)
French beans and chicken purée	$1.62 \cdot 10^{-7}$		Holdsworth (2007:18)
Lentils, cooked, with rice (77.8% water)	$1.64 \cdot 10^{-7}$	T = 64 - 114 ºC	Rahman (1995: 369)
Meat, chopped, with tomato and diced potatoes (66.4% water)	$1.57 \cdot 10^{-7}$	T = 65-106 ºC	Rahman (1995: 369)
Meat+tomatoes+potatoes	$(1.57 \pm 0.20) \cdot 10^{-7}$	T = 65 - 106 ºC	Holdsworth (2007:18)
Meat+potatoes+carrots	$(1.77 \pm 0.15) \cdot 10^{-7}$	T = 58 - 113 ºC	Holdsworth (2007:18)
Meat, chopped, with diced potatoes and carrots (82.1% water)	$1.77 \cdot 10^{-7}$	T = 56 - 113 ºC	Rahman (1995: 369)
Mixed vegetables and beef purée	$1.63 \cdot 10^{-7}$		Holdsworth (2007:18)
Lasagne (73.6% water)	$1.32 \cdot 10^{-7}$ - $1.70 \cdot 10^{-7}$	T = 60 - 100 ºC	Holdsworth (2007:18)
Pea and potato purée	$1.48 \cdot 10^{-7}$		Holdsworth (2007:18)
Spagetti hoops in tomato sauce	$2.50 \cdot 10^{-7}$		Holdsworth (2007:245)
Spagetti in tomato sauce	$2.50 \cdot 10^{-7}$		Holdsworth (2007:245)
Other food products			
Acetic acid	$5.06 \cdot 10^{-7}$		Several
Blood, cooked bovine blood (74% water)	$1.62 \cdot 10^{-7}$	T = 58-104 ºC	Rahman (1995: 369)
Dough (bread),(43.5 % water)	$1.450 \cdot 10^{-7}$	T = 23 ºC	Rahman (1995: 378)

Annex 3: Thermal diffusivities *a* of some food products $a = k/(c_p \cdot \rho)$			
Food product	Thermal diffusivity *a* [m^2/s]	Remarks	Reference
Dough (bread),(46.1 % water)	$1.630 \cdot 10^{-7}$	T = 19 °C	Rahman (1995: 378)
Dough (wheat),(42 % water)	$1.770 \cdot 10^{-7}$	T = 28 °C	Rahman (1995: 378)
Dough (wheat),(44.4 % water)	$2.375 \cdot 10^{-7}$		Rahman (1995: 378)
Dough (wheat),(44.8 % water)	$1.916 \cdot 10^{-7}$		Rahman (1995: 379)
Dough (wheat),(45.1 % water)	$1.916 \cdot 10^{-7}$		Rahman (1995: 378)
Dough (rye),(45.9 % water)	$2.434 \cdot 10^{-7}$		Rahman (1995: 378)
Dough (rye),(53.6 % water)	$1.875 \cdot 10^{-7}$		Rahman (1995: 379)
Dough (rye),(53.9 % water)	$1.875 \cdot 10^{-7}$		Rahman (1995: 379)
Dough, biscuit (4,1% water)	$(0.800 - 1.200) \cdot 10^{-7}$		Rahman (1995: 380)
Dough, biscuit (8.5% water)	$(0.800 - 1.200) \cdot 10^{-7}$		Rahman (1995: 380)
Dough, Tortilla	$(1.050 - 3.080) \cdot 10^{-7}$	T = 55 - 75 °C	Rahman (1995: 380)
Ethanol	$0.99 \cdot 10^{-7}$		Several
Ice	$11.82 \cdot 10^{-7}$	T = 0 °C	Singh (1992: 254)
Mayonaise (18% water)	$1.07 \cdot 10^{-7}$	T = 0 - 50 °C	Rahman (1995: 375)
NaCl solution (78% water)	$1.28 \cdot 10^{-7}$		Several
Petfood	$1.57 \cdot 10^{-7}$		Holdsworth (2007:245)
Saccharose solution (80% water)	$1.32 \cdot 10^{-7}$		Several
Sucrose solution (60% water)	$1.39 \cdot 10^{-7}$	T = 50 - 90 °C	Rahman (1995: 375)
Sucrose solution (60% water)	$1.35 \cdot 10^{-7}$	T = 30 - 65 °C	Rahman (1995: 375)
Sucrose solution (60% water)	$1.14 \cdot 10^{-7}$	T = 0 - 35 °C	Rahman (1995: 375)
Swede, whole	$1.38 \cdot 10^{-7}$	T = 20 - 4 °C	Rahman (1995: 374)
Water	$1.48 \cdot 10^{-7}$	T = 30 °C	Singh (1992: 254)
Water	$1.60 \cdot 10^{-7}$	T = 65 °C	Singh (1992: 254)
Water	$1.338 \cdot 10^{-7} - 1.713 \cdot 10^{-7}$	T = 0 - 100 °C	Holdsworth (2007:18)
White wine sauce	$1.64 \cdot 10^{-7}$		Holdsworth (2007:245)

Example calculation Annex 3: ***Use of the thermal diffusivity a to calculate the heat penetration factor f_h of a solid food.***
An cylindrical UT metal can (DxH = 73mm x 115 mm) is filled with chili con carne, a composed meal. Chili con carne in cylindrical cans behaves as a solid during heat processing in a still retort.
a) Chapter 3 presents equations on the effect of food packaging material, dimensions, and shape on the heat penetration factor f_h.
a-1) Give the equation for calculating the heat penetration factor f_h of a solid food:
a-2) The equation of the "specific surface" of a solid food in a cylindrical metal can is:
b) In Annex 3 above, find a value of the thermal diffusivity *a* of the composed meal chili con carne.
c) Calculate the heat penetration factor f_h of the cylindrical UT metal can (DxH = 73mm x 115 mm; internal dimensions) with chili con carne.
d) Compare your f_h calculation of answer c) with the chili con carne f_h value in table 3.

Worked answers:
Answer a-1) The equation for calculating the heat penetration factor f_h of a solid food:

$$f_h = \frac{2.3 \cdot c_p \cdot \rho}{k \cdot S^{*2}} = \frac{2.3}{a \cdot S^{*2}} \quad [s]$$

(see Chapter 3).

Answer a-2) The equation of the "specific surface" of a solid food in a cylindrical metal can is: $\mathbf{S^{*2} = 9.93/H^{*2} + 23.2/D^{*2}}$ (see table 4).

Answer b) The thermal diffusivity a of chili con carne can be found in Annex 3, section composed meals: ***a* = 1.44·10⁻⁷ m²/s**

Answer c) Calculation of the heat penetration factor fh of the cylindrical UT metal can (DxH = 73mm x 115 mm) with chili con carne:

$$f_h = \frac{2.3 \cdot c_p \cdot \rho}{k \cdot S^{*2}} = \frac{2.3}{a \cdot S^{*2}} \quad [s] \; ; \quad \text{with } S^{*2} = 9.93/H^{*2} + 23.2/D^{*2}$$

Of the fh equation, only use the part with the thermal diffusivity *a*:

$$f_h = \frac{2.3}{a \cdot S^{*2}} \quad [s] \; ;$$

in which

$a = 1.44 \cdot 10^{-7}$ m^2/s (answer b)

$S^{*2} = 9.93/H^{*2} + 23.2/D^{*2}$

in which: H = 115 mm = 0.115 m (given)

D = 73 mm = 0.073 m (given)

In a **metal** can, the thickness d_W of the metal wall can be neglected

Substitution of D and H in $S^{*2} = 9.93/H^{*2} + 23.2/D^{*2}$ results in:

$S^{*2} = 9.93/H^{*2} + 23.2/D^{*2} = 9.93/(0.115)^2 + 23.2/(0.073)^2 = 751 + 4354 = 5104.$

So $S^{*2} = 5104$ m^4/m^6.

Substitution of S^{*2} and *a* in the equation for fh results in:

$$f_h = \frac{2.3}{a \cdot S^{*2}} = \frac{2.3}{1.44 \cdot 10^{-7} \cdot 5104} = \frac{2.3}{7350 \cdot 10^{-7}} = 3129 \text{ s} = 52.2 \text{ min.}$$

So **fh = 52.2 min**.

Answer d) Compare the fh calculation of answer c) with the fh value listed in table 3. According to Table 3, for chili con carne in a metal UT can (DxH = 73mm x 115 mm) in a still retort: fh = 52.2 min.

This is **exactly the fh value = 52.2 min., calculated in answer c**.

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Ch. 3: Kinetics of thermal resistance: pH; a_W. Denaturation rate; decimal reduction; z; food quality.
Ch. 4: Sterilization, pasteurization and cooking criteria. F; F_0; lethal rates; integrated F-value F_S. Cooking values C; C_S; minimally processed foods; process achievement standards.
Ch. 5: Heat penetration in packaged foods: process characteristics; product characteristics; experimental determination of heat penetration: thermocouples and model systems. Graphical analysis of heat penetration measurements (semi-log heating + cooling plot); factors affecting heat penetration and heat penetration factor fh; broken heating curve. Thermal process simulation of non-symmetric foods in vacuum pouches.
Ch. 6: Process evaluation techniques: F-value graphically and numerically; analytical methods; Patashnik. Ball; Gillespy; broken curve; worked examples. Hayakawa. Other methods. Mass average sterilizing values. Factors affecting F. Microbiological methods. Guide to Sterilization values. Computerized process calculations.
Ch. 7: Quality optimization: C values; tables
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Convection: products with viscosities not greatly different from water heated in a non-agitated mode (e.g. juices; thin soups, and small particles in liquid such as peas in brine, etc.) and products with a higher viscosity for agitated processes (e.g., thick soups; cream style corn, etc.). Formulas for conversion from metal->metal (or pouches), from metal to glass and vice versa.
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