WORKSHOP ON OPTIMIZING GLASS MELTING

Reinhard Conradt
Department of Mineral Engineering, RWTH Aachen Univbersity, Germany

Department of Materials Science, Faculty of Science, Chulalongkorn University
&
Department of Science Service
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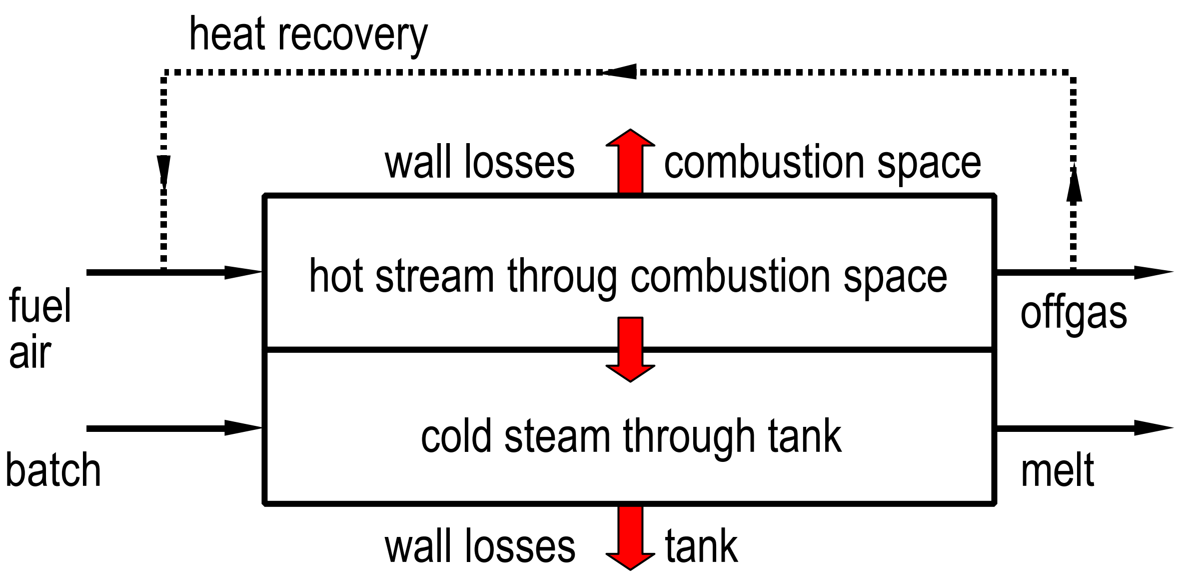
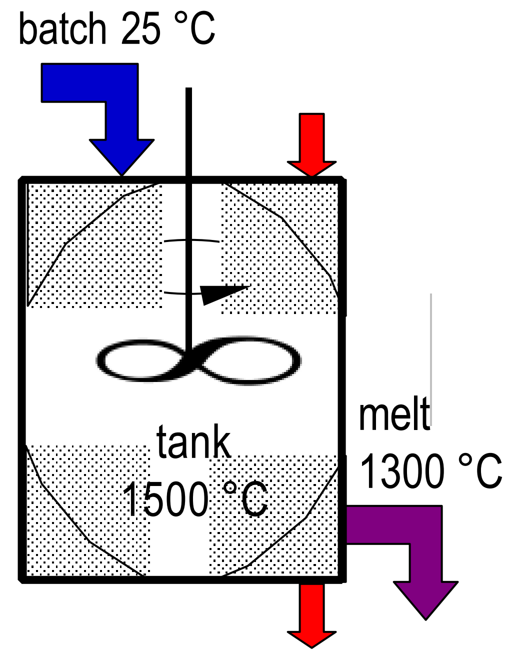
conradt@ghi.rwth-aachen.de

fundamentals

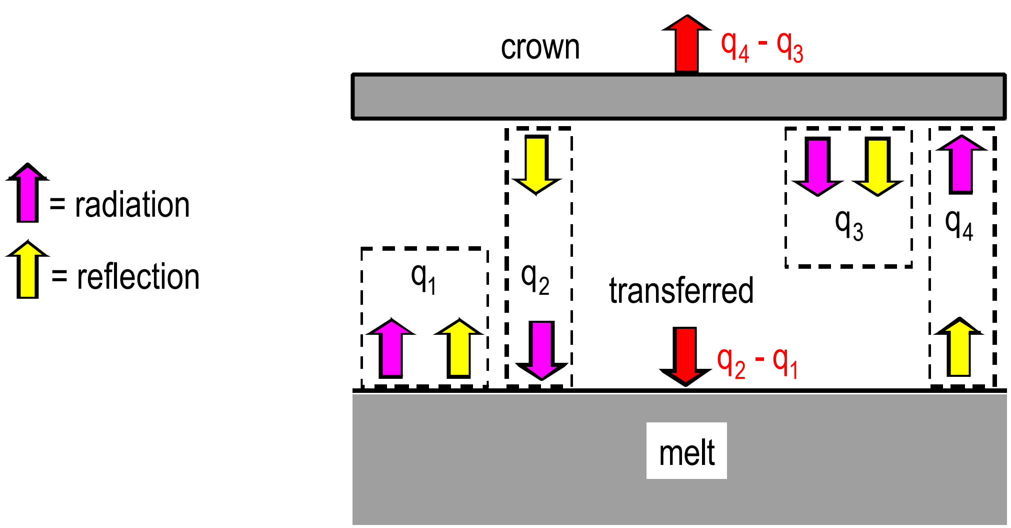
power station and heat exchanger

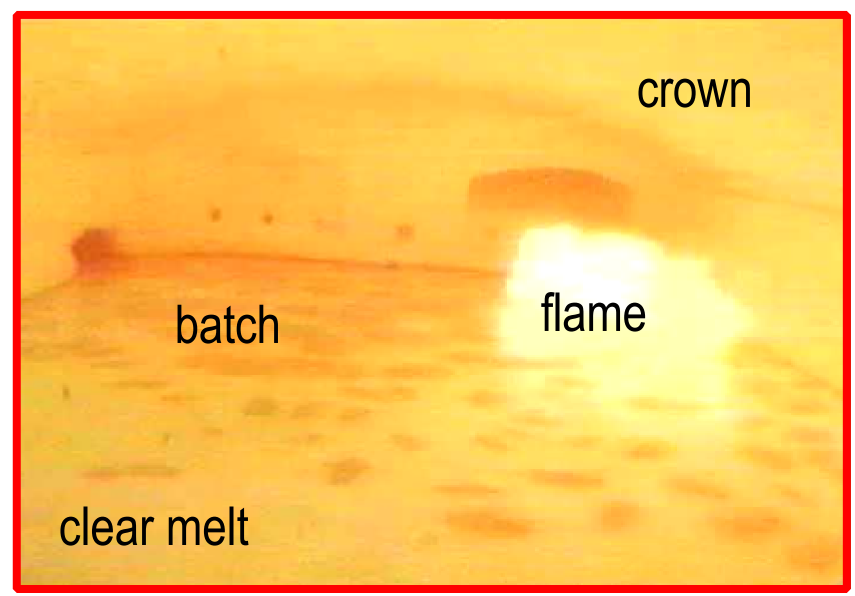


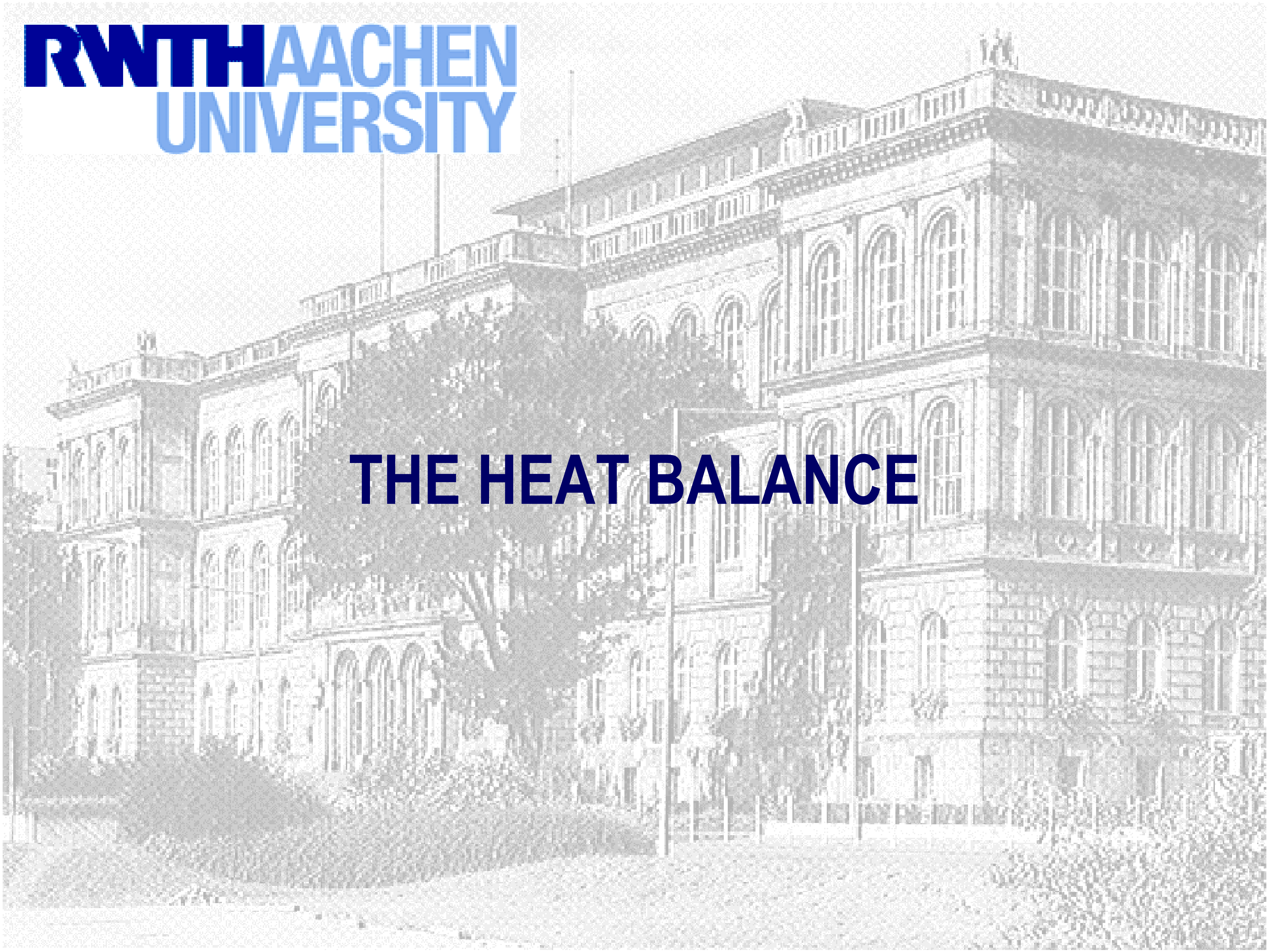
chemical reactor



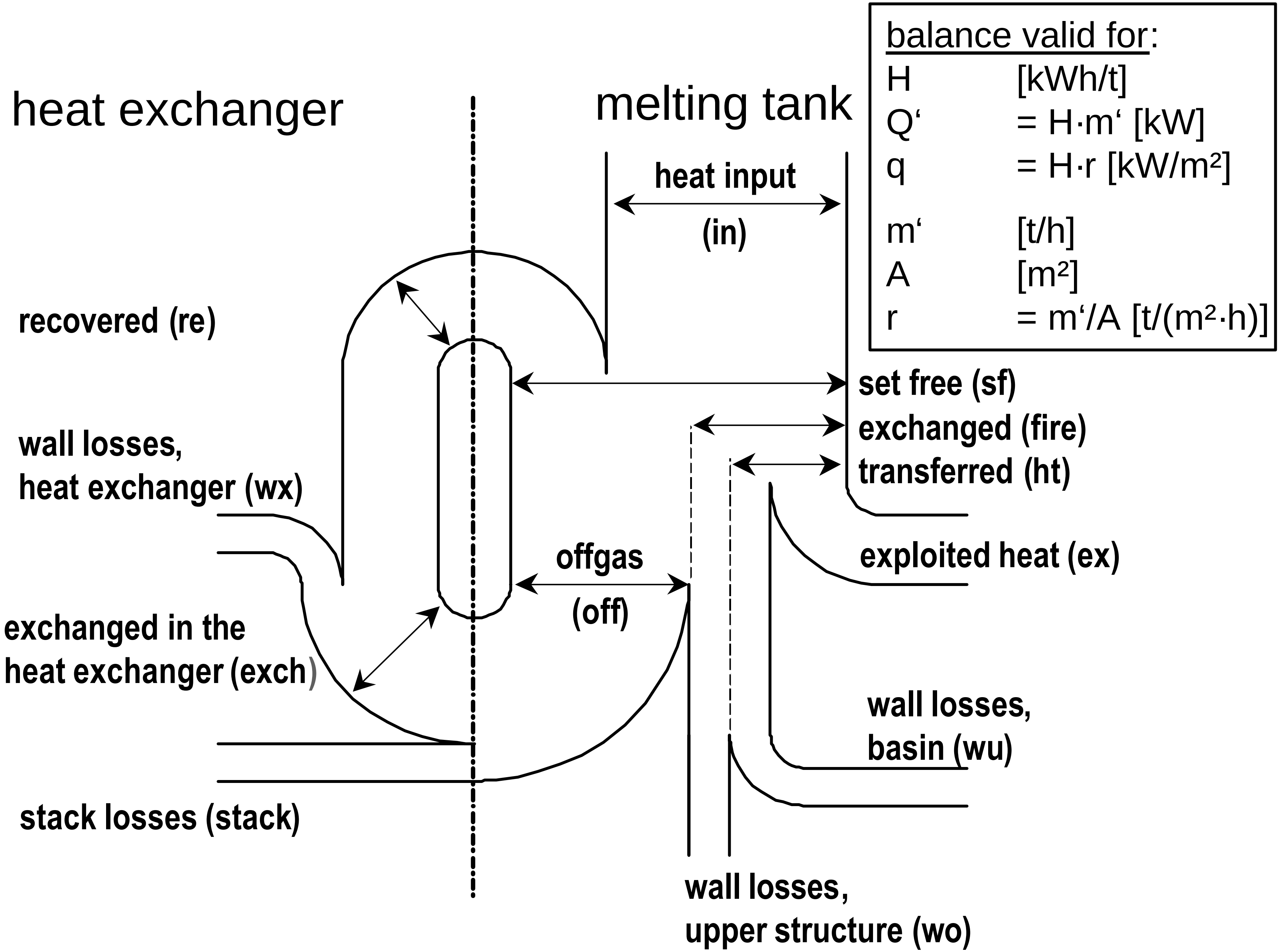
radiative heat exchange



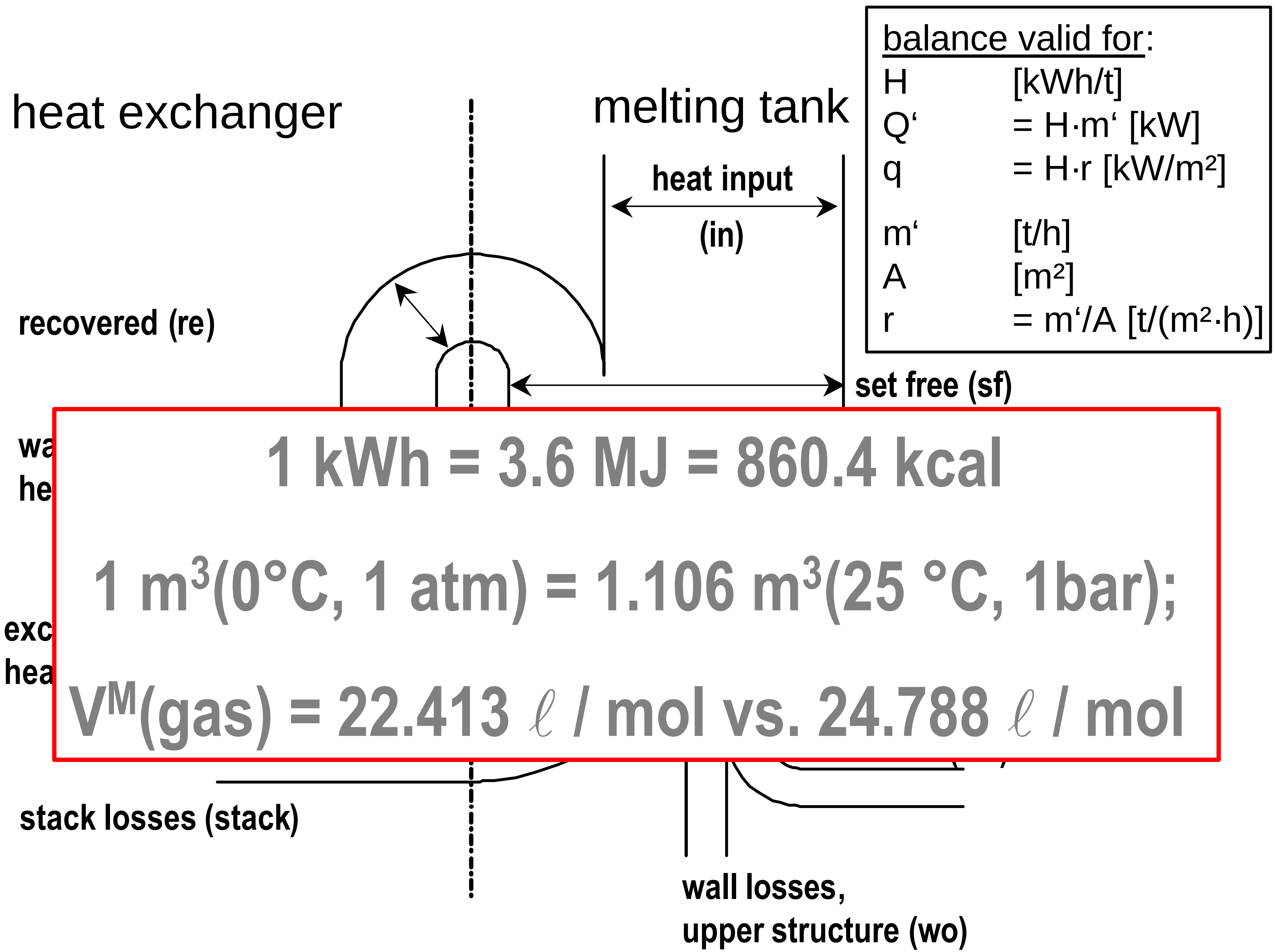




THE HEAT BALANCE



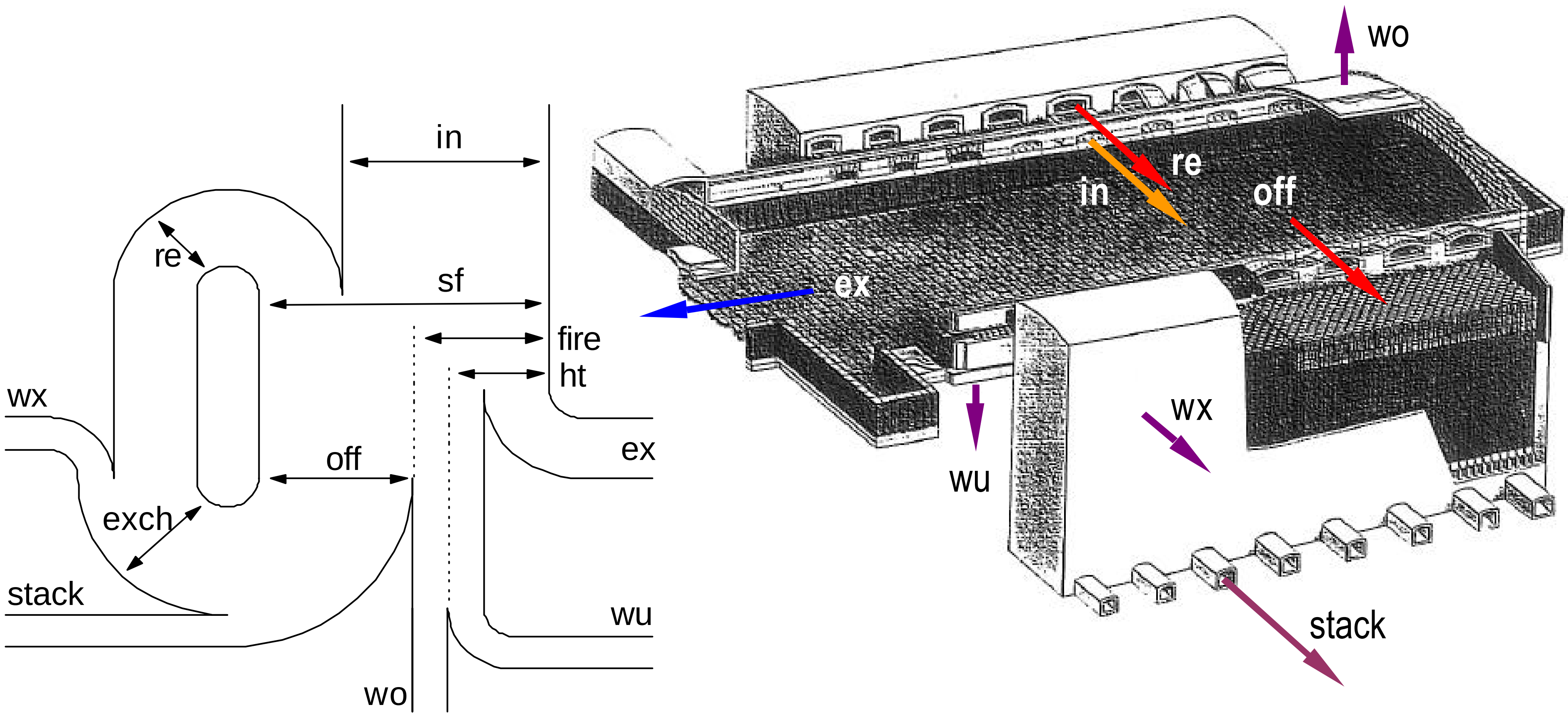
heat exchanger
melting tank
balance valid for:
H [kWh/t]
Q‘ = H·m‘ [kW]
q = H·r [kW/m²]
m‘ [t/h]
A [m²]
r = m‘/A [t/(m²·h)]
heat input
(in)
recovered (re)
set free (sf)
exchanged (fire)
transferred (ht)
wall losses,
heat exchanger (wx)
exploited heat (ex)
offgas
(off)
exchanged in the
heat exchanger (exch)
wall losses,
basin (wu)
stack losses (stack)
wall losses,
upper structure (wo)



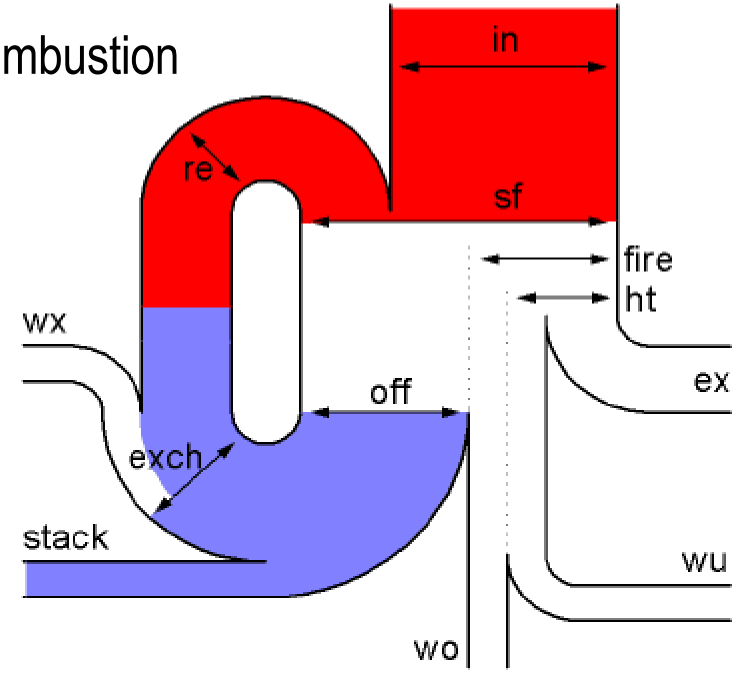
1 kWh = 3.6 MJ = 860.4 kcal

$1\ m^3(0°C,\ 1\ atm) = 1.106\ m^3(25\ °C,\ 1 bar)$;

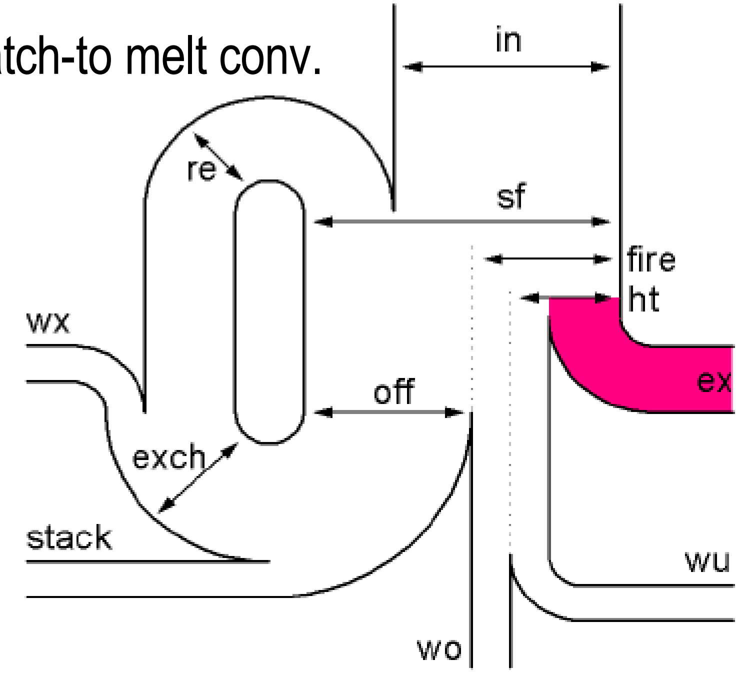
$V^M(gas) = 22.413\ \ell\ /\ mol$ vs. $24.788\ \ell\ /\ mol$


in
re
sf
fire
ht
wx
off
ex
exch
stack
wu
wo
wo
re
in
off
ex
wu
wx
stack

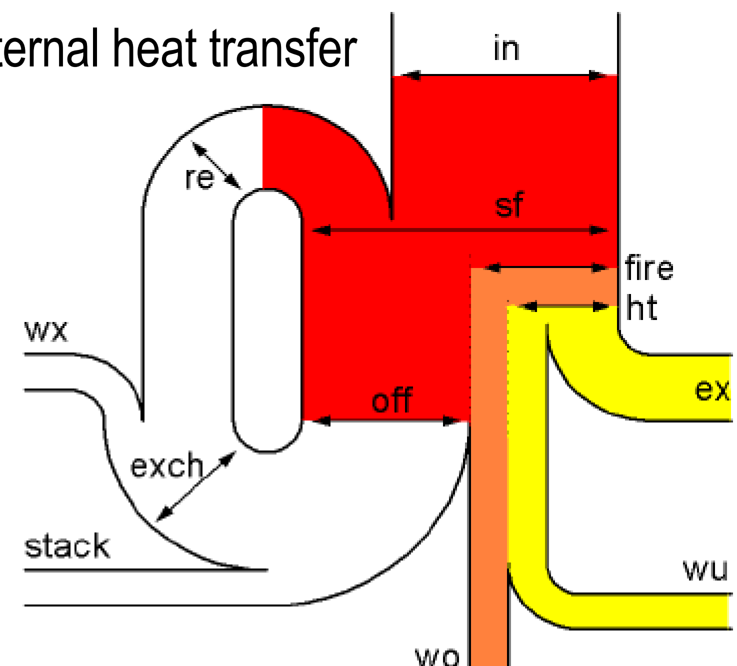
combustion



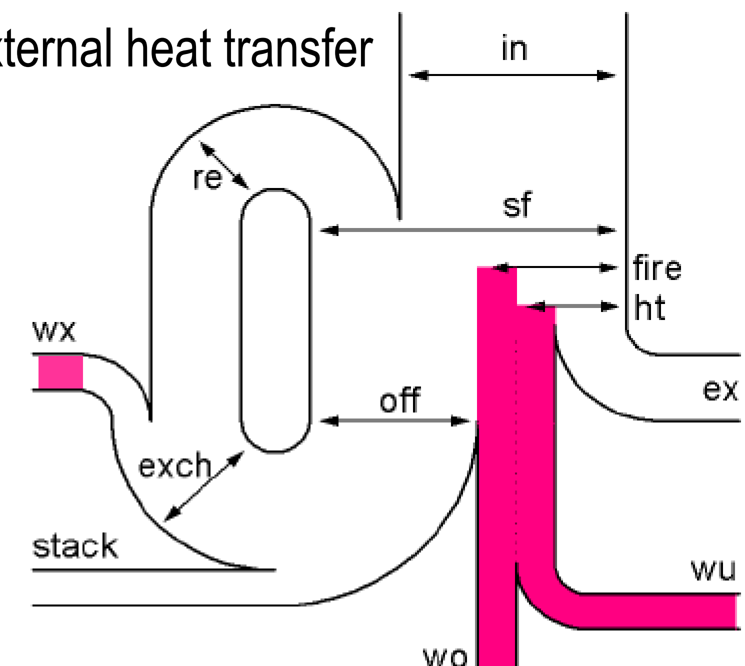
batch-to melt conv.



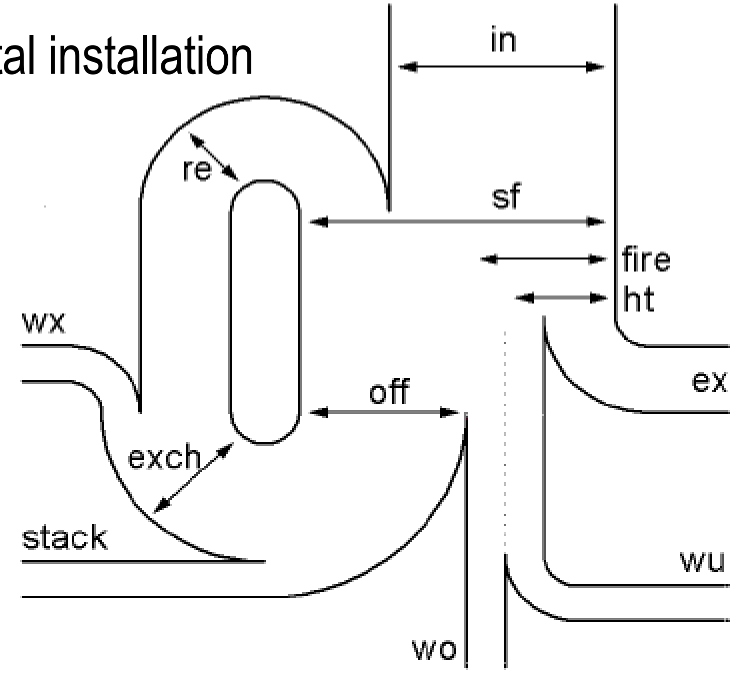
internal heat transfer



external heat transfer



total installation



the heat balance describes:

$$Q_{12} = \Delta H = H_2 - H_1$$

it does not describe the „values“ of the individual energy terms:

$$\frac{Q_{12}}{T} \leq \Delta S = S_2 - S_1$$

total installation: $Q_{in} = H_{ex} + Q_{wu} + Q_{wo} + Q_{stack} + Q_{wx}$

furnace: $Q_{sf} = Q_{in} + Q_{re} = H_{ex} + Q_{wu} + Q_{wo} + Q_{off}$

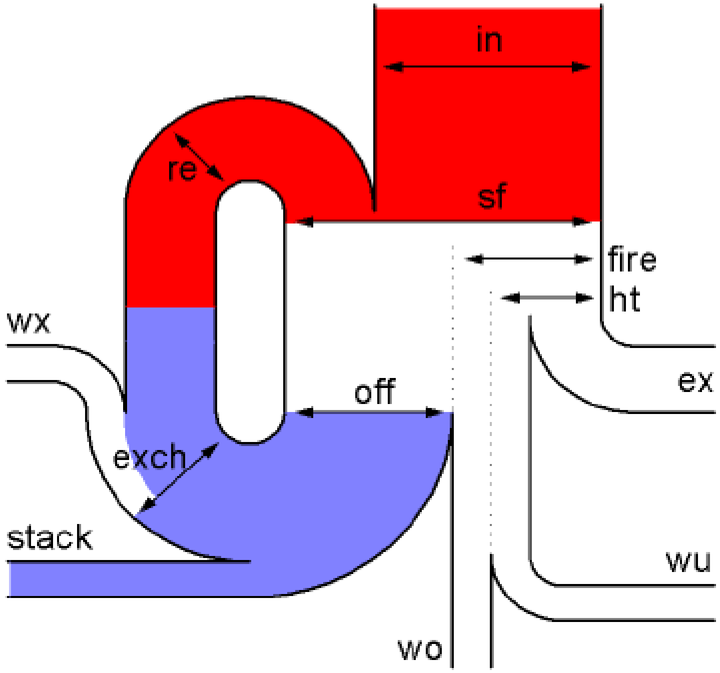
$Q_{in} = H_{ex} + Q_{wu} + Q_{wo} + Q_{off} \cdot (1 - h_{re})$

heat exchanger: $Q_{off} = Q_{re} + Q_{stack} + Q_{wx}$

combustion space: $Q_{sf} = Q_{in} + Q_{re} = Q_{ht} + Q_{wo} + Q_{off}$

$Q_{in} = Q_{ht} + Q_{wo} + Q_{off} \cdot (1 - h_{re})$

melting tank: $Q_{ht} = H_{ex} + Q_{wu}$



via combustion calculations

H_{NCV}, m_F, l,

T_{off}, T_{re}, T_{stack}, T_0

p

Q_{in}, Q_{off}, Q_{re}, Q_{stack}

total installation: $Q_{in} = H_{ex} + Q_{wu} + Q_{wo} + Q_{stack} + Q_{wx}$

furnace: $Q_{sf} = Q_{in} + Q_{re} = H_{ex} + Q_{wu} + Q_{wo} + Q_{off}$

$Q_{in} = H_{ex} + Q_{wu} + Q_{wo} + Q_{off} \cdot (1 - h_{re})$

heat exchanger: $Q_{off} = Q_{re} + Q_{stack} + Q_{wx}$

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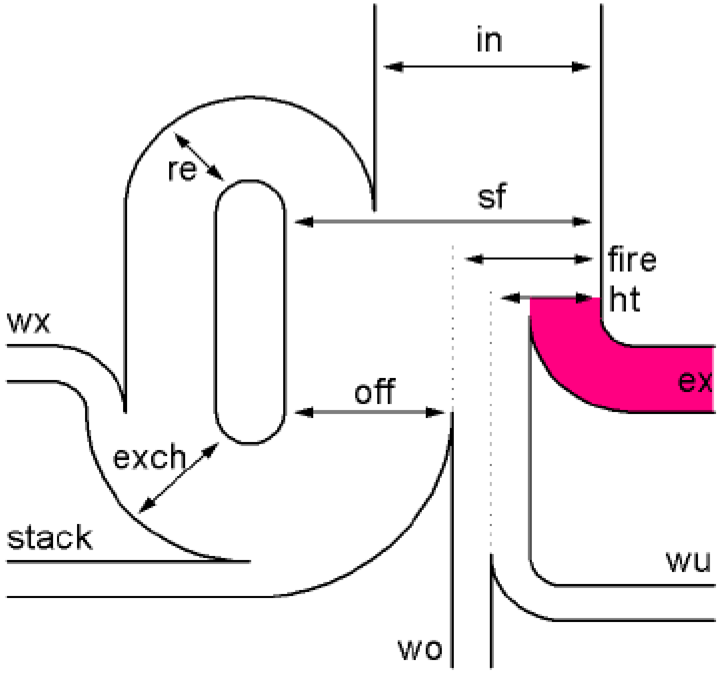

via combustion calculations
and batch-to-melt calculations

batch, glass, y_C, T_{ex}

p

$$H_{ex} = (1 - y_C) \cdot D H^\circ_{chem} + D H(T_{ex})$$

total installation: $Q_{in} = H_{ex} + Q_{wu} + Q_{wo} + Q_{stack} + Q_{wx}$

furnace: $Q_{sf} = Q_{in} + Q_{re} = H_{ex} + Q_{wu} + Q_{wo} + Q_{off}$

$Q_{in} = H_{ex} + Q_{wu} + Q_{wo} + Q_{off} \cdot (1 - h_{re})$

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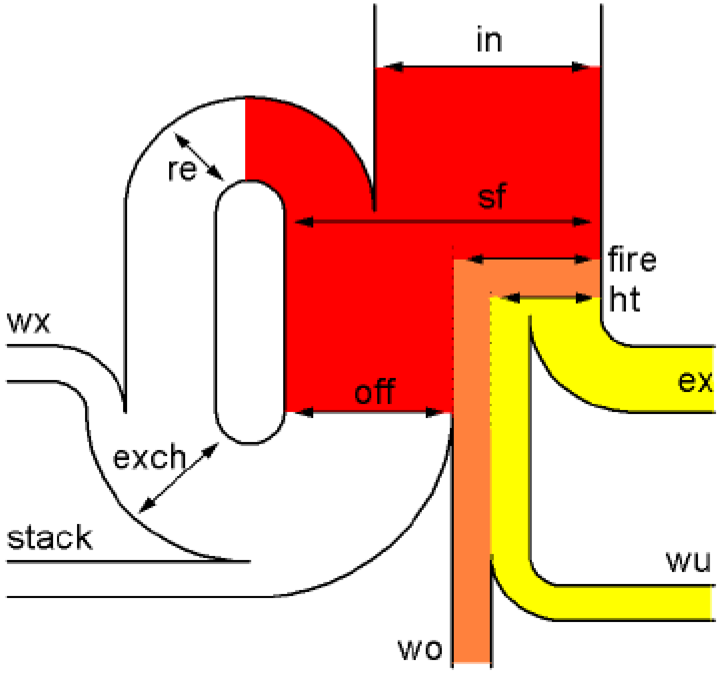


assessible by difference:

$$Q_{sf} = Q_{in} + Q_{re}$$

$$Q_{wx} = Q_{off} - Q_{re} - Q_{stack}$$

$$Q_{wu} + Q_{wo} = Q_{in} + Q_{re} - Q_{off} - H_{ex}$$

not directly assessible:

Q_{wu}, Q_{wo}, Q_{ht} — by heat transfer calcn. only

total installation: $Q_{in} = H_{ex} + Q_{wu} + Q_{wo} + Q_{stack} + Q_{wx}$

furnace: $Q_{sf} = Q_{in} + Q_{re} = H_{ex} + Q_{wu} + Q_{wo} + Q_{off}$

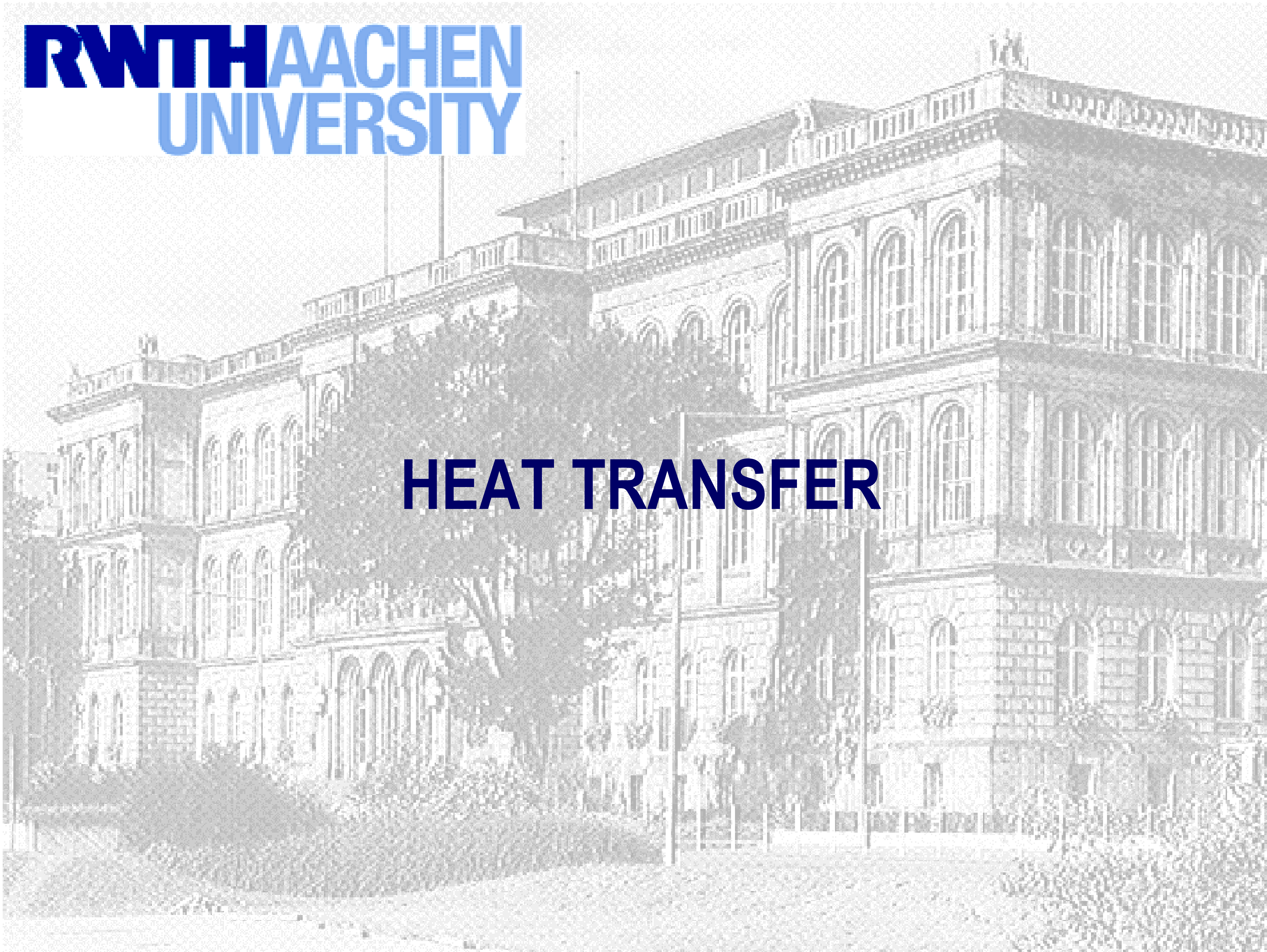
$$Q_{in} = H_{ex} + Q_{wu} + Q_{wo} + Q_{off} \cdot (1 - h_{re})$$

heat exchanger: $Q_{off} = Q_{re} + Q_{stack} + Q_{wx}$

combustion space: $Q_{sf} = Q_{in} + Q_{re} = Q_{ht} + Q_{wo} + Q_{off}$

$$Q_{in} = Q_{ht} + Q_{wo} + Q_{off} \cdot (1 - h_{re})$$

melting tank: $Q_{ht} = H_{ex} + Q_{wu}$



HEAT TRANSFER

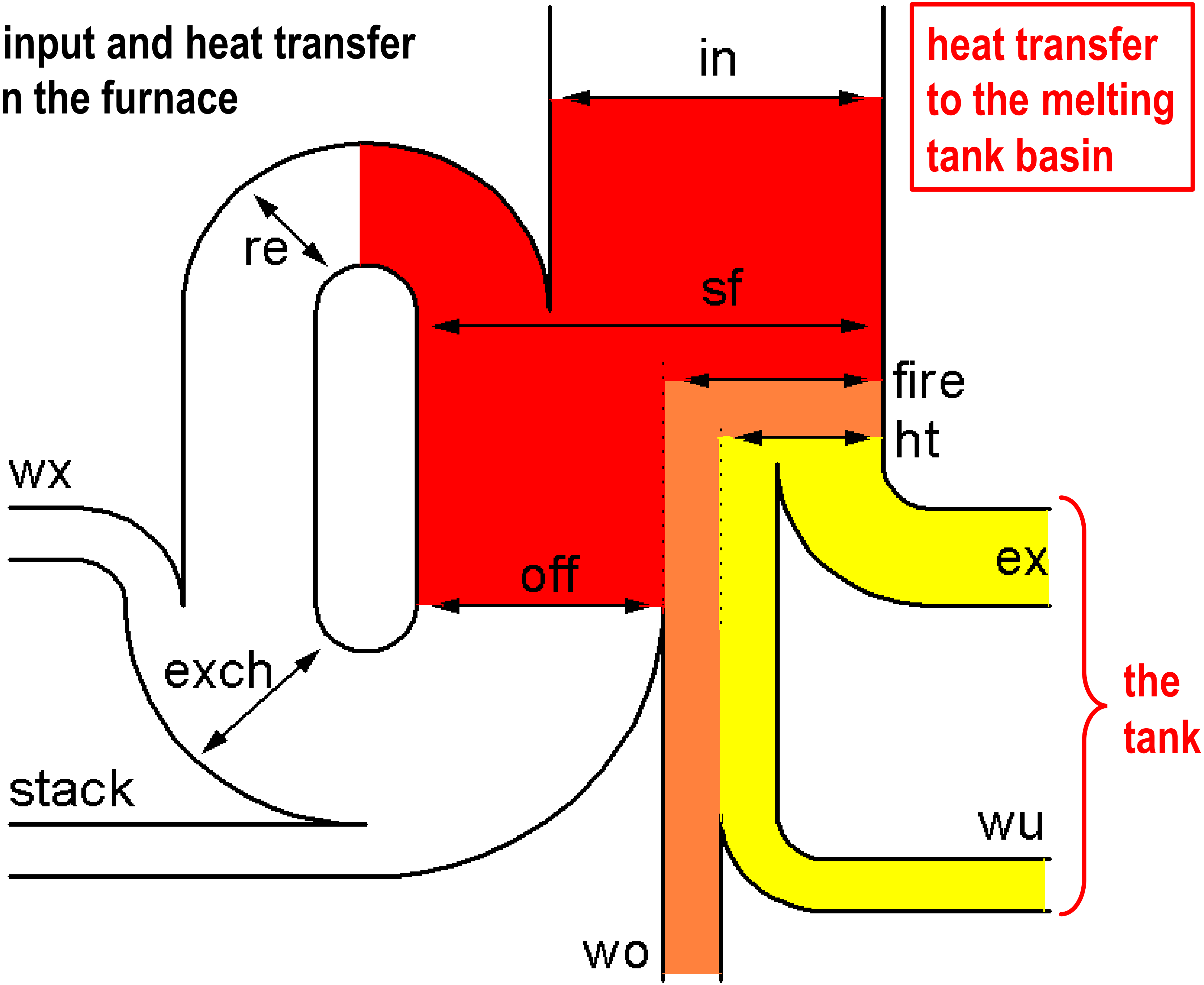
- *Heat can be transferred over any infinitesimally small temperature difference* T_H - $T_{L,}$.

- *The problem is the transfer rate achieved:*

$$\dot{Q} = A \cdot \boldsymbol{a}_{ht} \cdot (T_H - T_L),\ \dot{Q}\ in\ kW$$

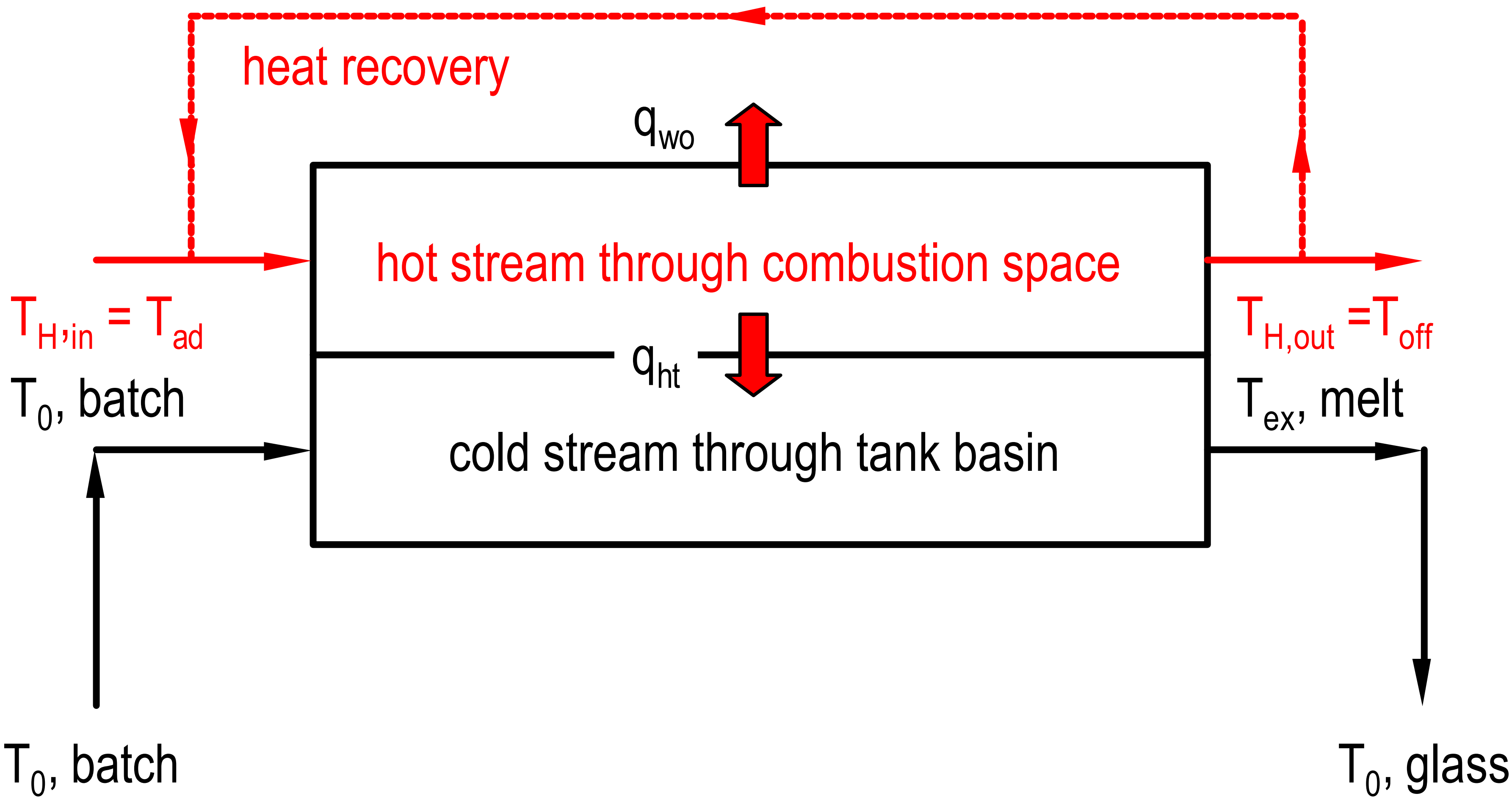
- *With a given transfer coeff.* $\boldsymbol{a}_{ht}$ *and transfer area A, a temperature difference* T_H-T_L *of a certain size is required to sustain the transfer rate* $\dot{Q}$.

heat input and heat transfer within the furnace



heat transfer problem:

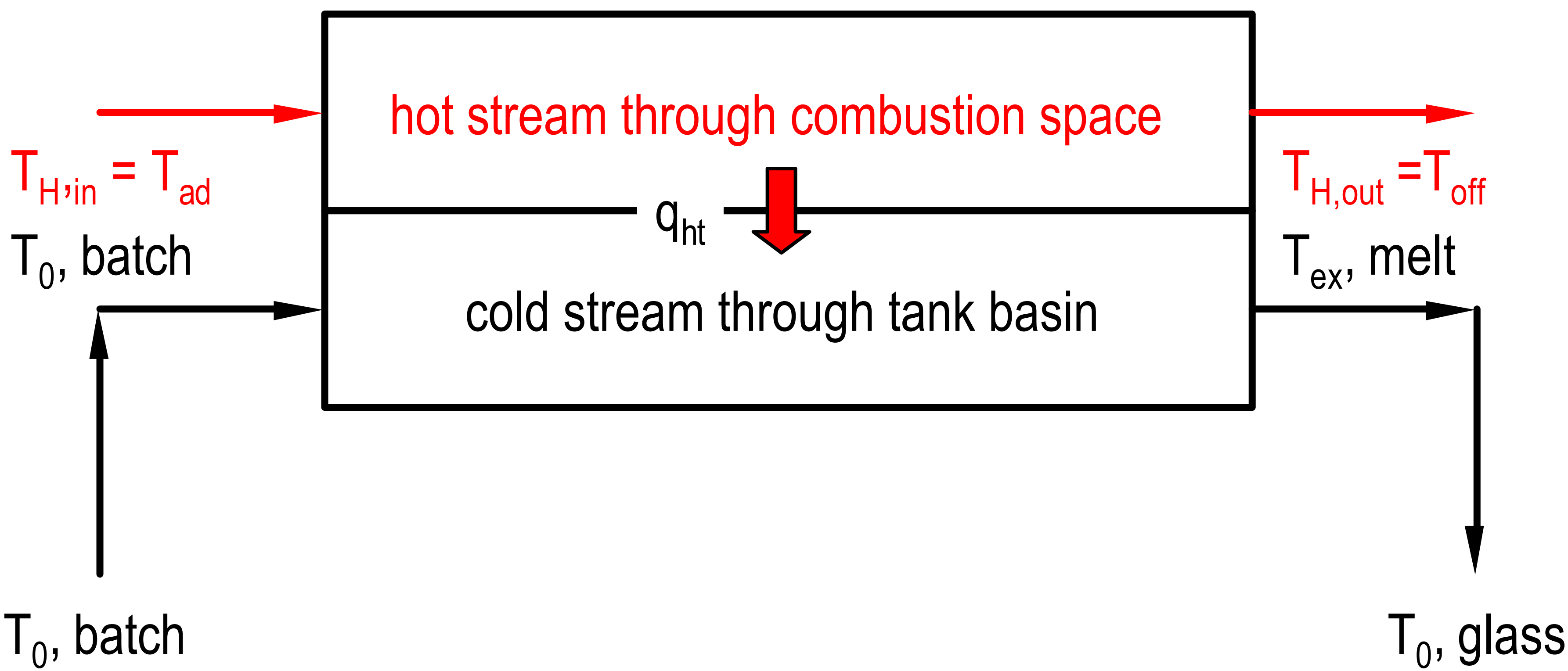
$$\frac{q_{ht}}{q_{in}} = \frac{\dot{m} \cdot c_P \cdot (T_{H,in} - T_{H,out})}{\dot{m} \cdot c_P \cdot (T_{H,in} - T_L)} = \frac{\text{heat extracted from hot stream}}{\text{heat made available by hot stream}}$$



heat transfer problem:

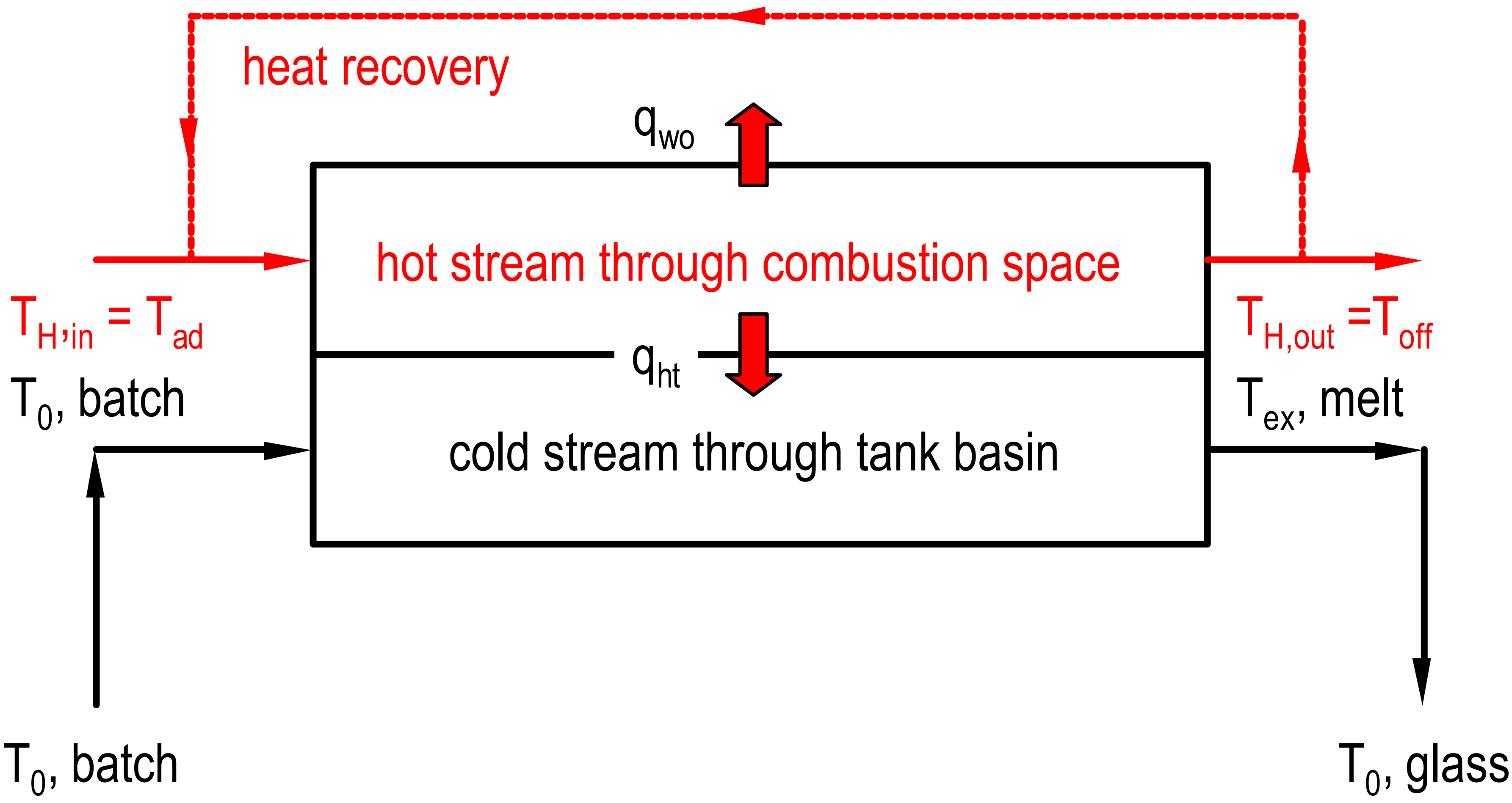
$$\frac{q_{ht}}{q_{in}} = \frac{\dot{m} \cdot c_P \cdot (T_{H,in} - T_{H,out})}{\dot{m} \cdot c_P \cdot (T_{H,in} - T_L)} = \frac{(T_{ad} - T_{off})}{(T_{ad} - T_0)} = 1 - \frac{\Delta T_{off}}{\Delta T_{ad}}$$

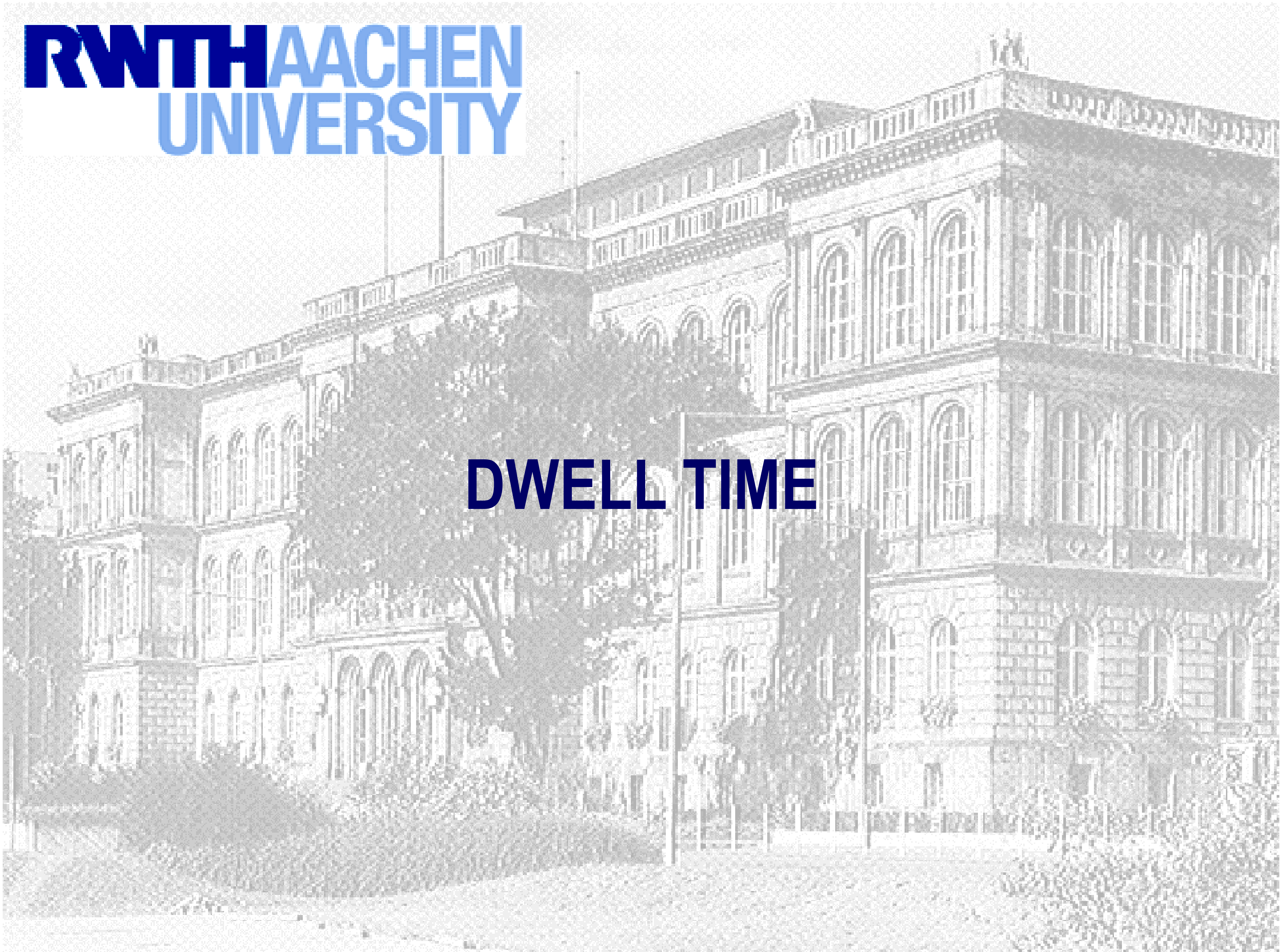
(no heat recovery, no wall losses q_{wo})



heat transfer problem:

$$\frac{q_{ht}}{q_{in}} = 1 - \left(1 - h_{re}\right) \cdot \frac{\Delta T_{off}}{\Delta T_{ad}^{0}} - \frac{a_{wo}}{\dot{m}_{off} \cdot c_{off}} \cdot \frac{\Delta T_{wo}}{\Delta T_{ad}^{0}}$$





DWELL TIME

$$q_{ht} = \left(H_{ex} \cdot r + q_{wu} \cdot i\right) \Rightarrow q_{in} = \left(H_{ex} \cdot r + q_0 \cdot i\right) \approx a + b \cdot r$$

utilization of reactor space:

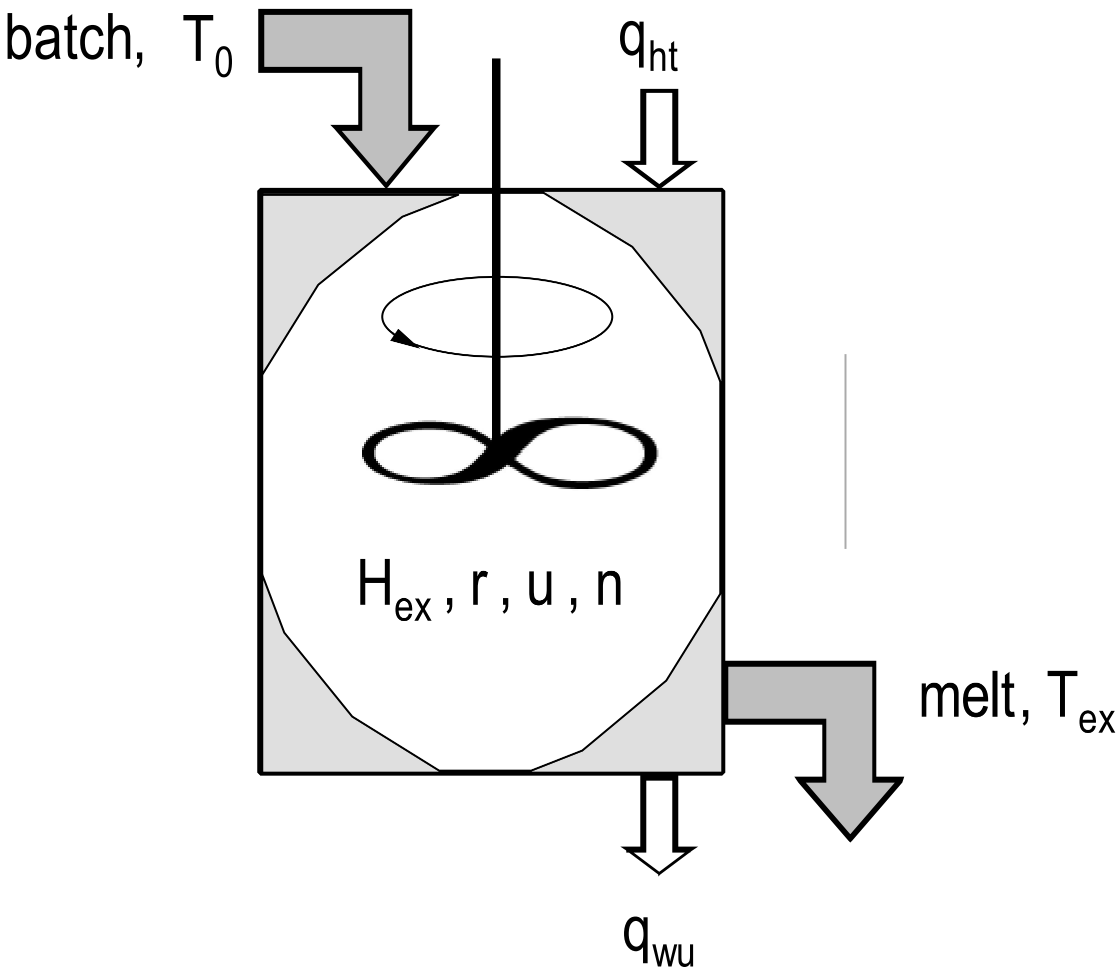
$$\frac{V_{eff}}{V_{geo}} = u \in \{0,\ 1\}$$

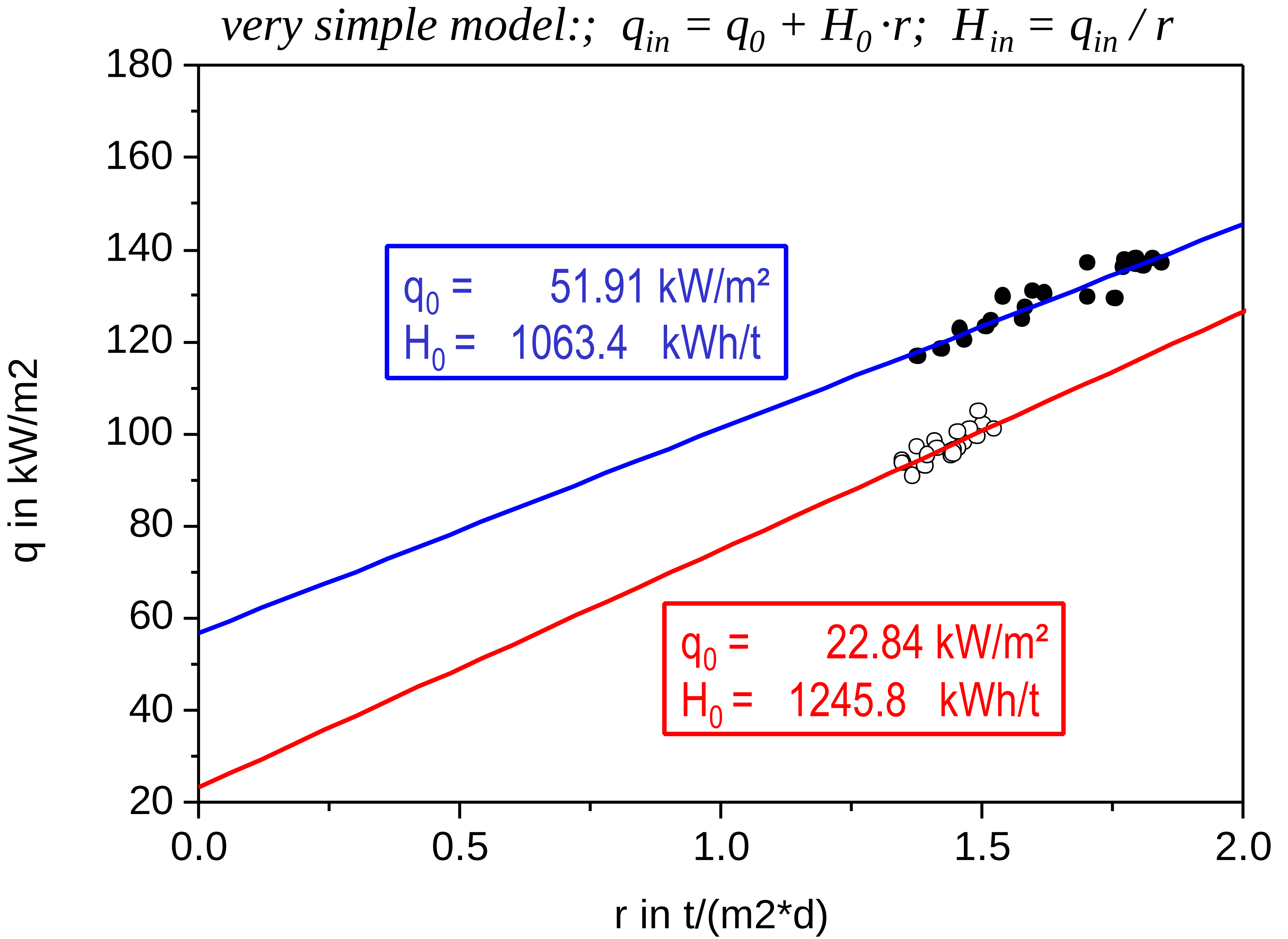
relative dwell time:

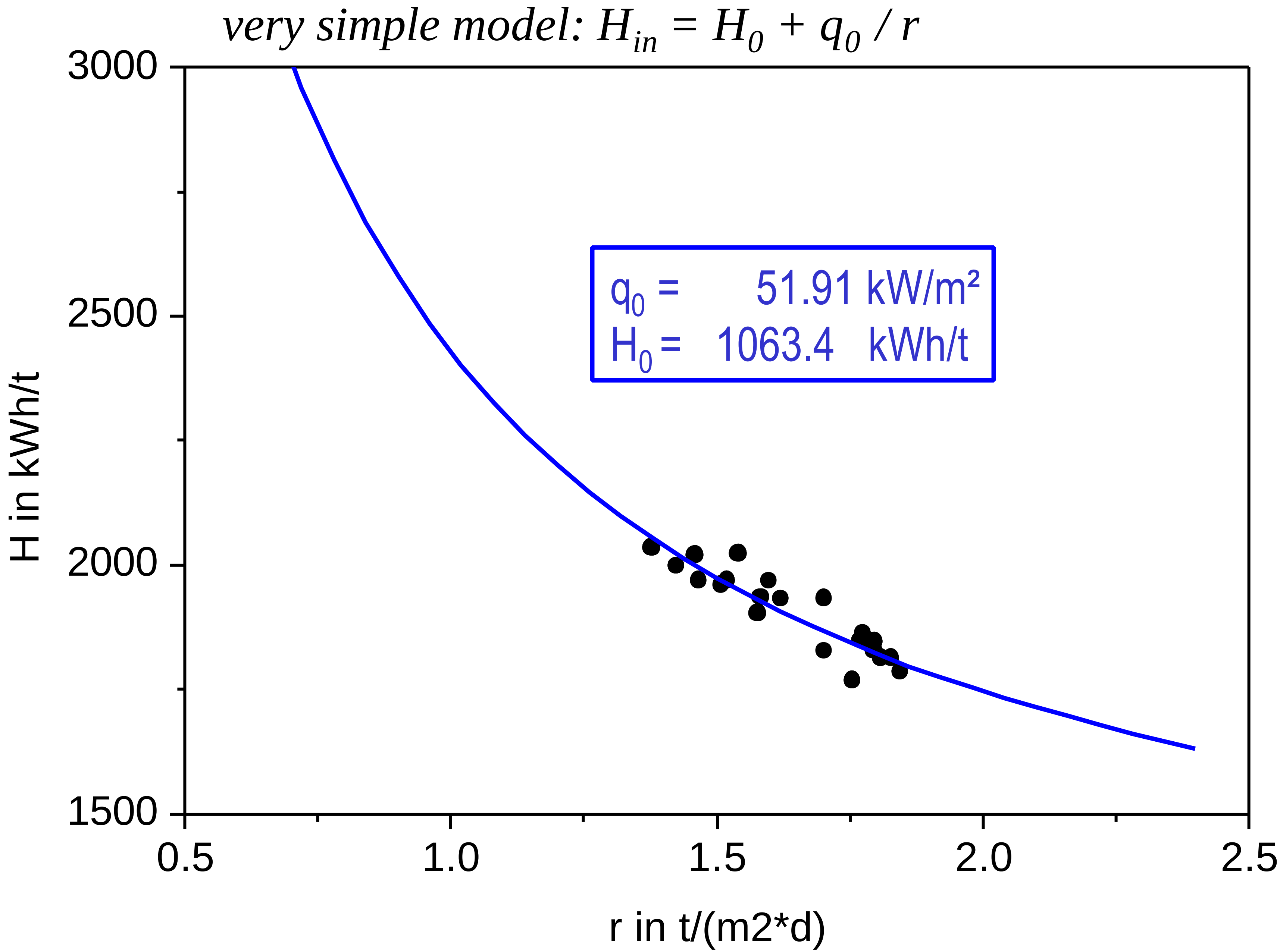
$$\frac{t}{t_{ref}} = n \in \{0,\ \infty\}$$

process intensity:

$$i = n / u$$



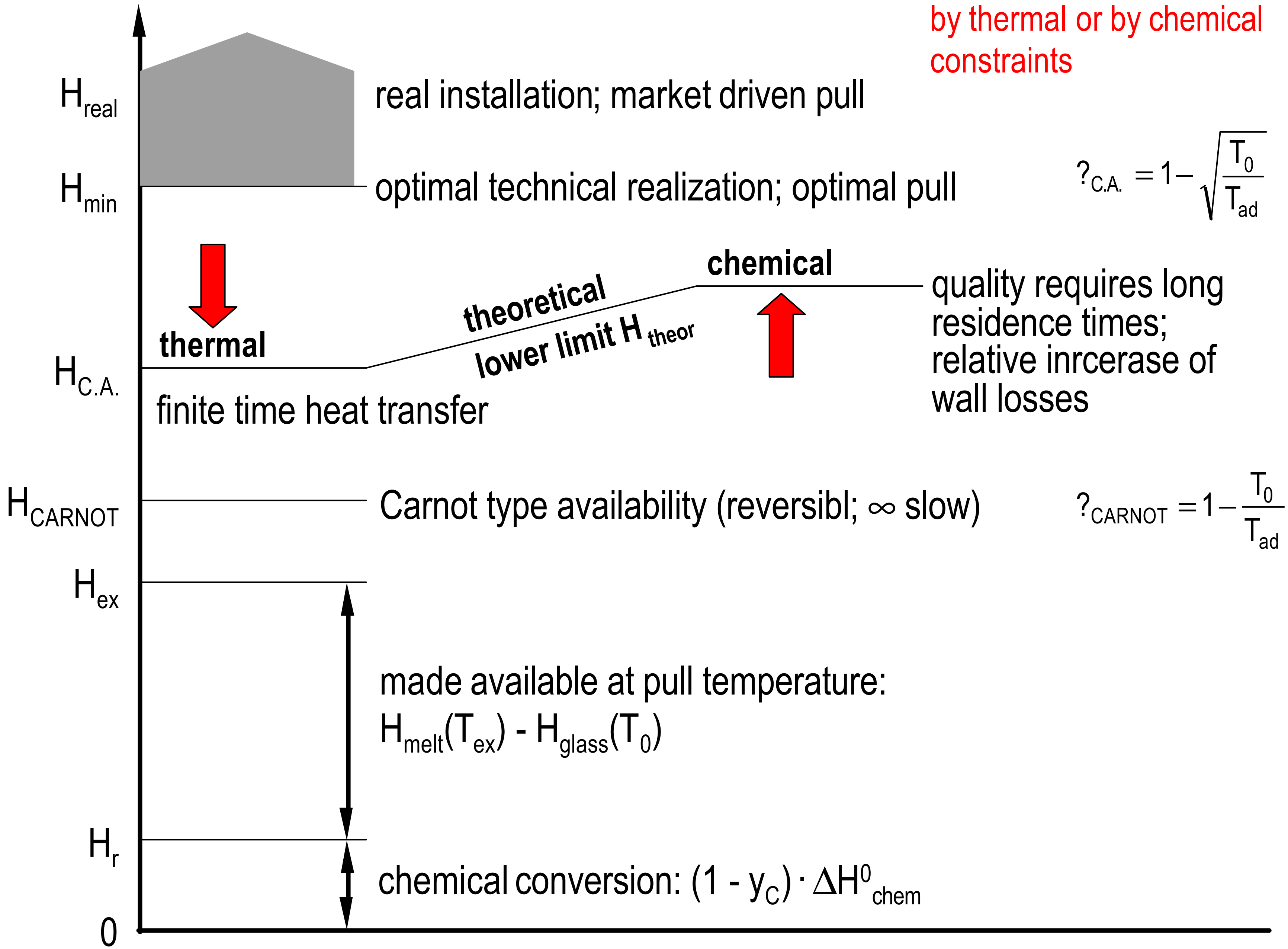

very simple model:; $q_{in} = q_0 + H_0 \cdot r$; $H_{in} = q_{in} / r$
q_0 = 51.91 kW/m²
H_0 = 1063.4 kWh/t
q_0 = 22.84 kW/m²
H_0 = 1245.8 kWh/t
q in kW/m2
r in t/(m2*d)
180
160
140
120
100
80
60
40
20
0.0
0.5
1.0
1.5
2.0

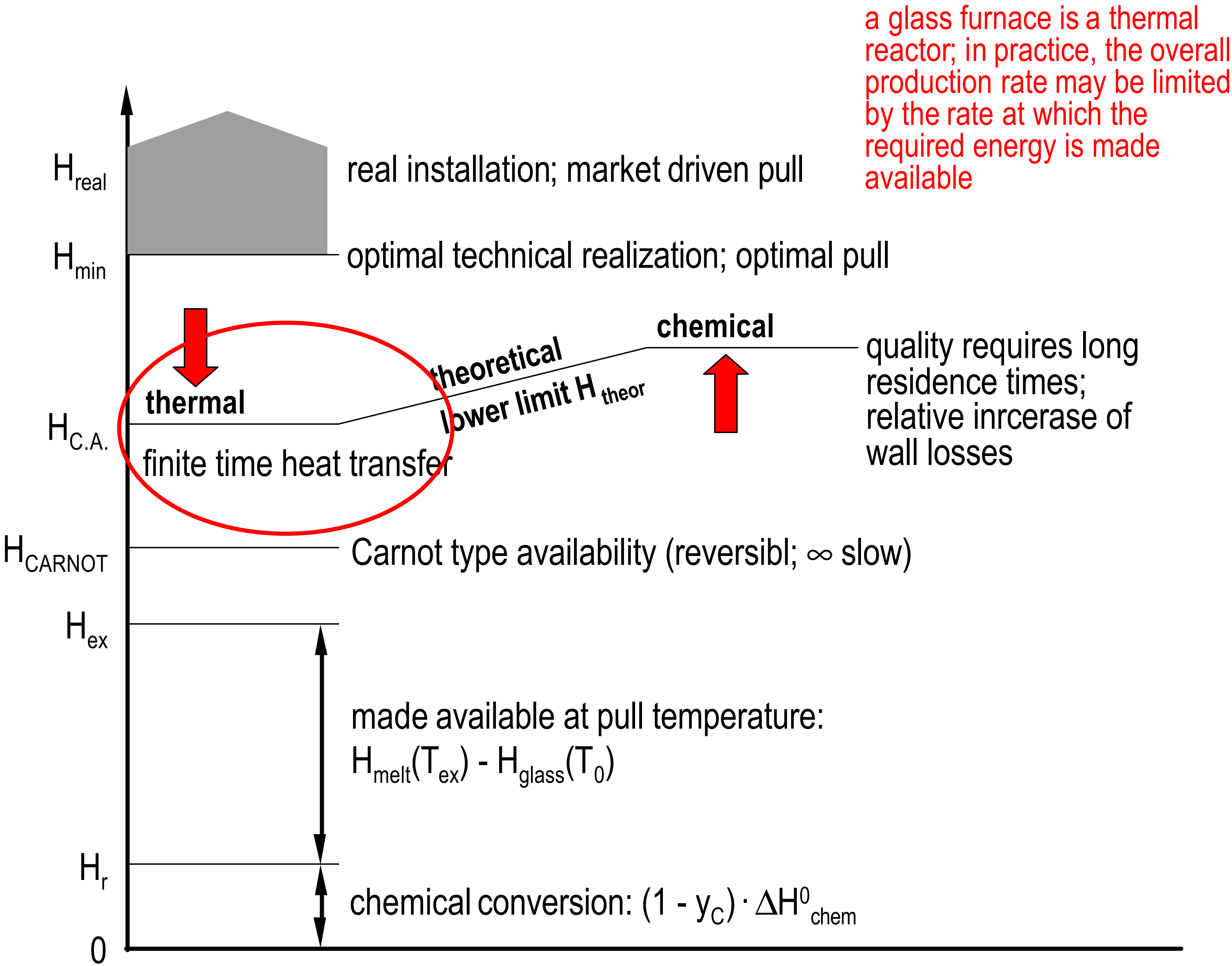

very simple model: H_in = H_0 + q_0 / r
3000
2500
2000
1500
H in kWh/t
q0 = 51.91 kW/m²
H0 = 1063.4 kWh/t
0.5
1.0
1.5
2.0
2.5
r in t/(m2*d)

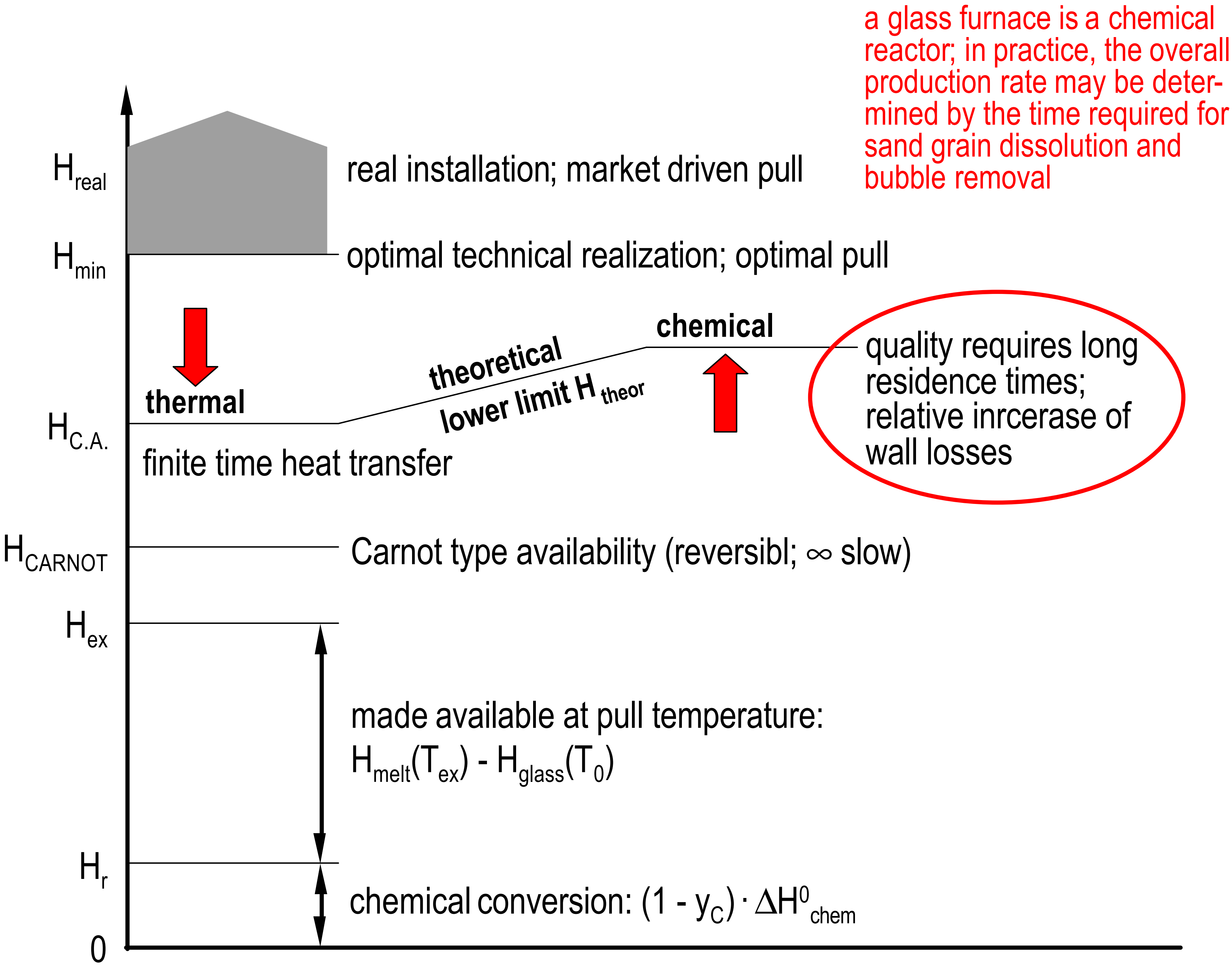
SUMMARY:

FURNACE BEHAVIOR

the energy demand of a glass furnace is determined either by thermal or by chemical constraints




a glass furnace is a thermal reactor; in practice, the overall production rate may be limited by the rate at which the required energy is made available
H_{real}
real installation; market driven pull
H_{min}
optimal technical realization; optimal pull
chemical
theoretical lower limit H_{theor}
quality requires long residence times; relative inrcerase of wall losses
thermal
$H_{C.A.}$
finite time heat transfer
H_{CARNOT}
Carnot type availability (reversibl; ∞ slow)
H_{ex}
made available at pull temperature:
$H_{melt}(T_{ex}) - H_{glass}(T_0)$
H_r
chemical conversion: $(1 - y_C) \cdot \Delta H^0_{chem}$
0


a glass furnace is a chemical reactor; in practice, the overall production rate may be determined by the time required for sand grain dissolution and bubble removal
H real
real installation; market driven pull
H min
optimal technical realization; optimal pull
thermal
theoretical
lower limit H theor
chemical
quality requires long residence times; relative inrcerase of wall losses
H C.A.
finite time heat transfer
H CARNOT
Carnot type availability (reversibl; ∞ slow)
H ex
made available at pull temperature:
H melt(T ex) - H glass(T 0)
H r
chemical conversion: (1 - y C) · ΔH0 chem
0

Today, most furnaces have reached and optimum state as thermal reactors.

There is a large potential to optimize glass melting by optimizing the intrinsic process, i.e., the batch-to-melt conversion.

Optimization may focus on

- the intrinsic heat demand,
- the turnover temperature,
- favorable reaction paths,
- the turnover rate.

experimental methods
to investigate the
batch-to-melt concersion

melting behavior

=

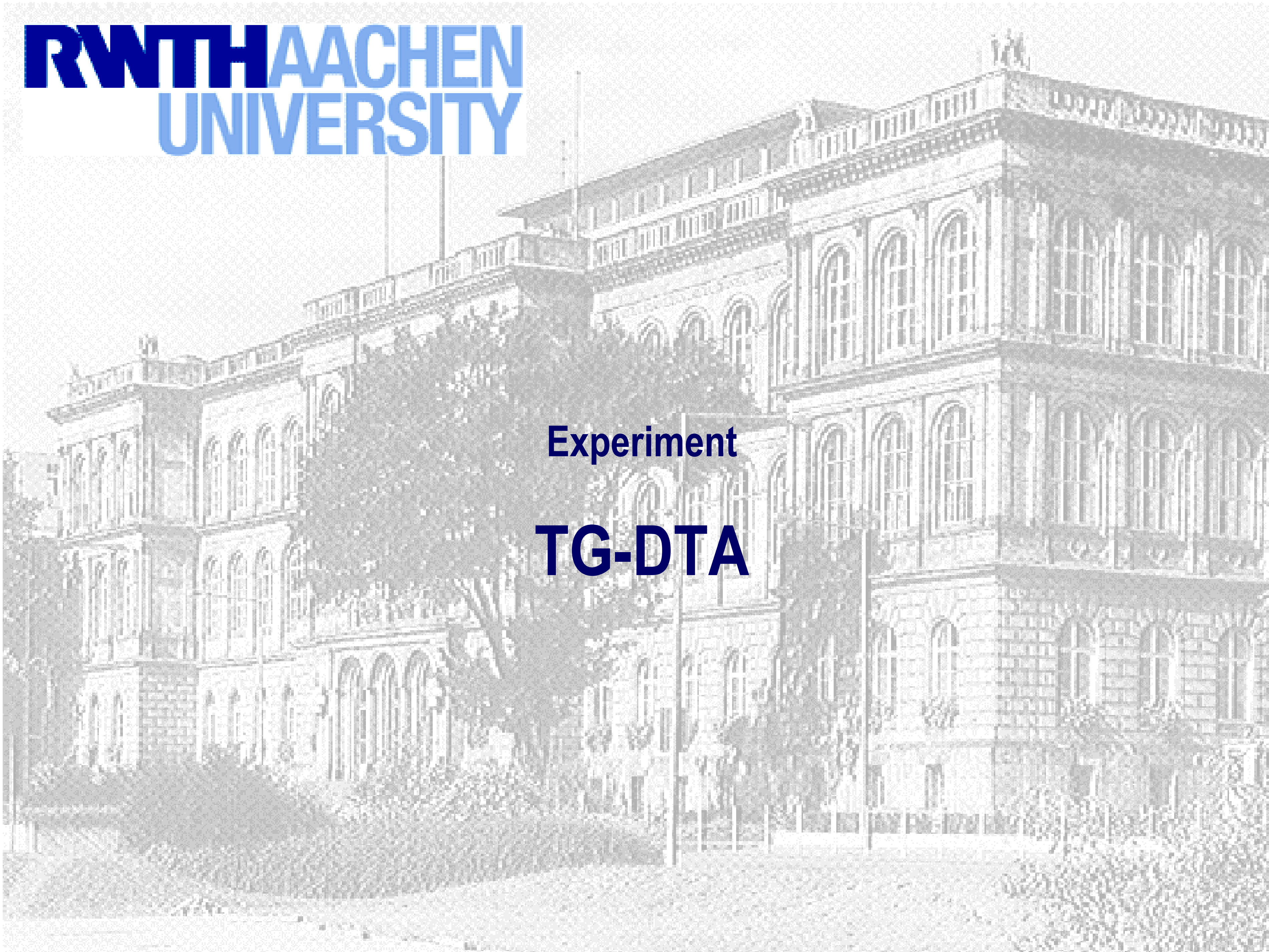
heat demand

⊕

quartz dissolution rate

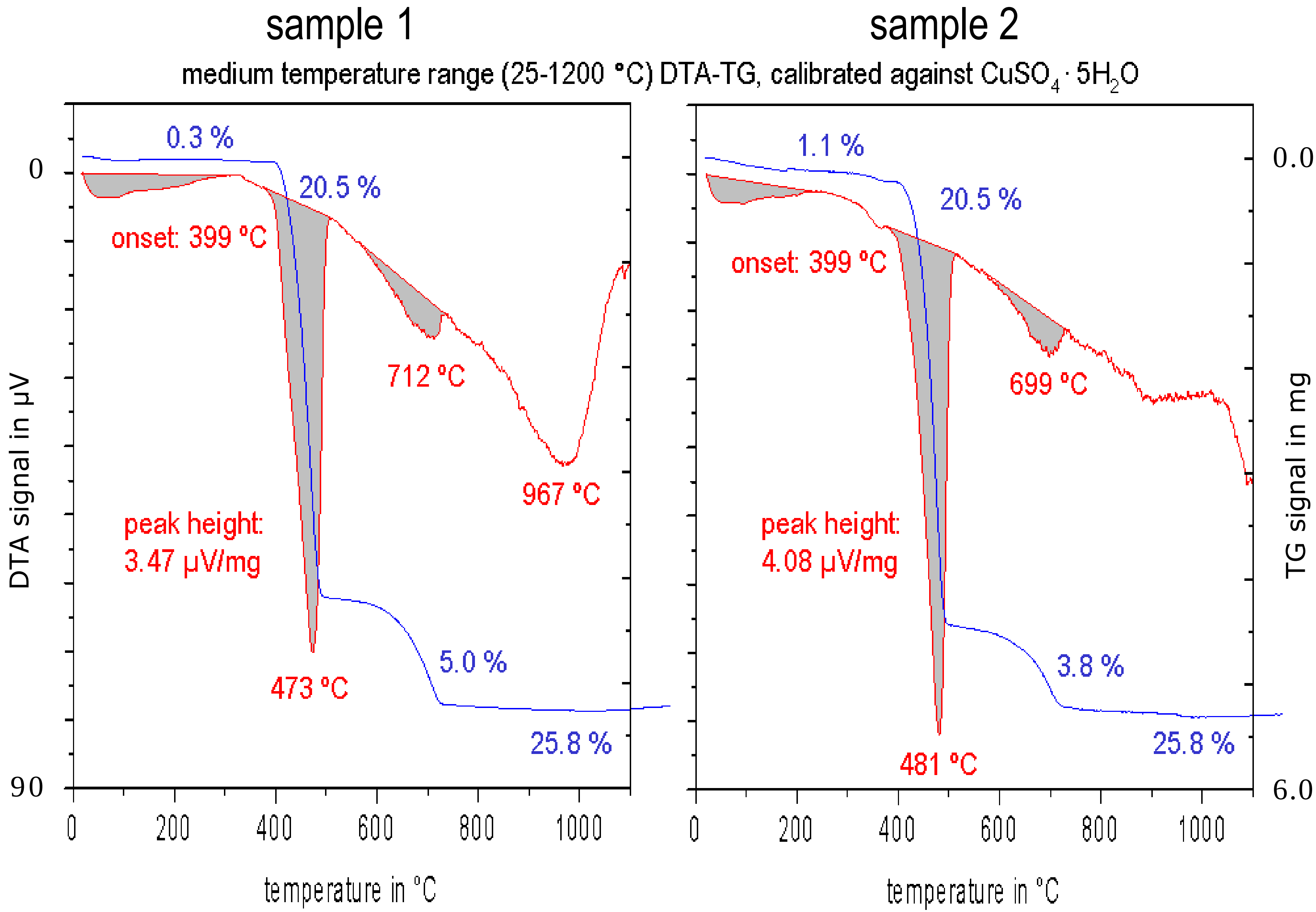
⊕

gas release rate

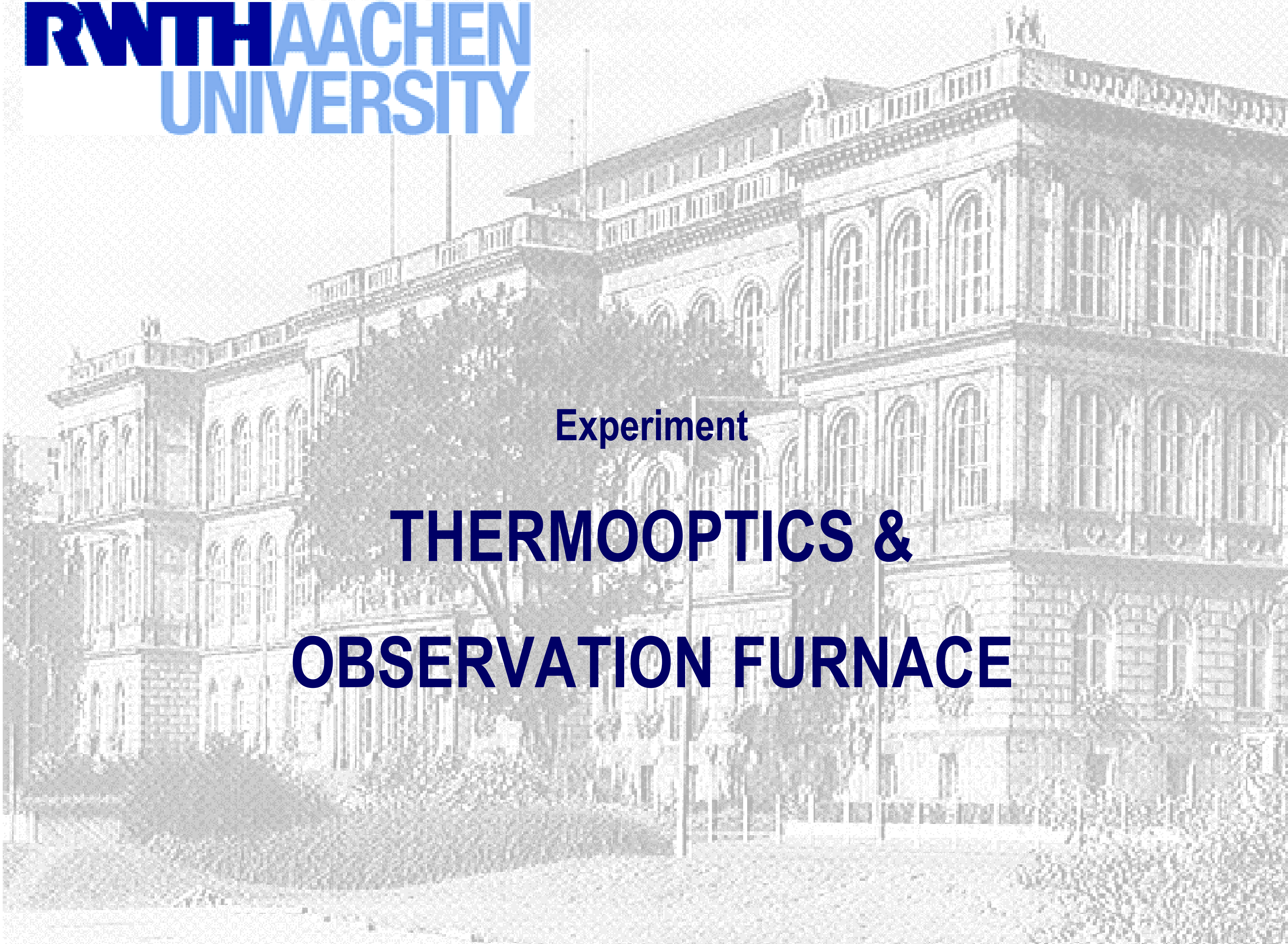


Experiment

TG-DTA



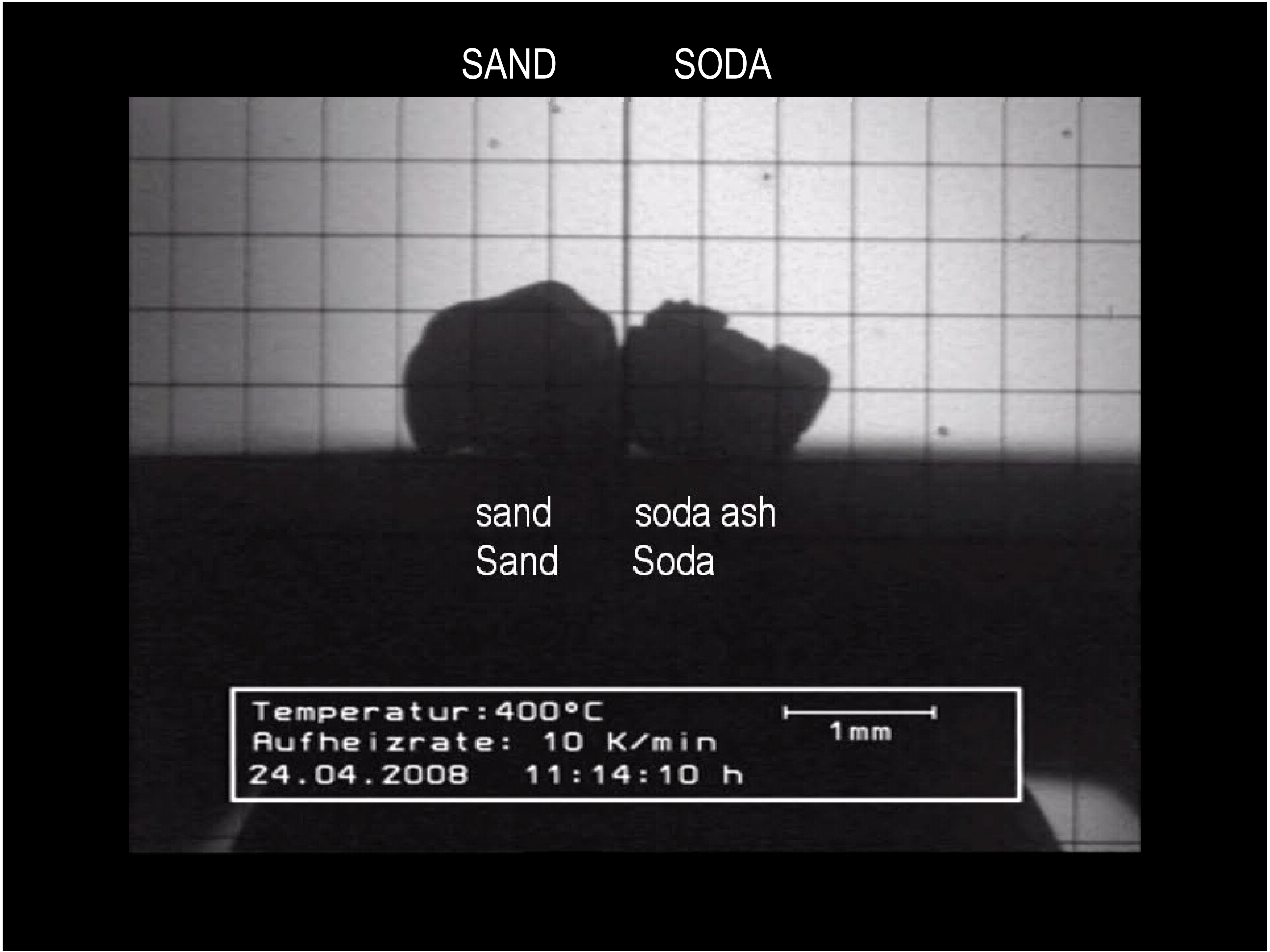
sample 1
sample 2
medium temperature range (25-1200 °C) DTA-TG, calibrated against $CuSO_4 \cdot 5H_2O$
0.3 %
20.5 %
onset: 399 °C
712 °C
967 °C
peak height:
3.47 µV/mg
473 °C
5.0 %
25.8 %
1.1 %
20.5 %
onset: 399 °C
699 °C
peak height:
4.08 µV/mg
481 °C
3.8 %
25.8 %
DTA signal in µV
0
90
TG signal in mg
0.0
6.0
0
200
400
600
800
1000
temperature in °C
temperature in °C



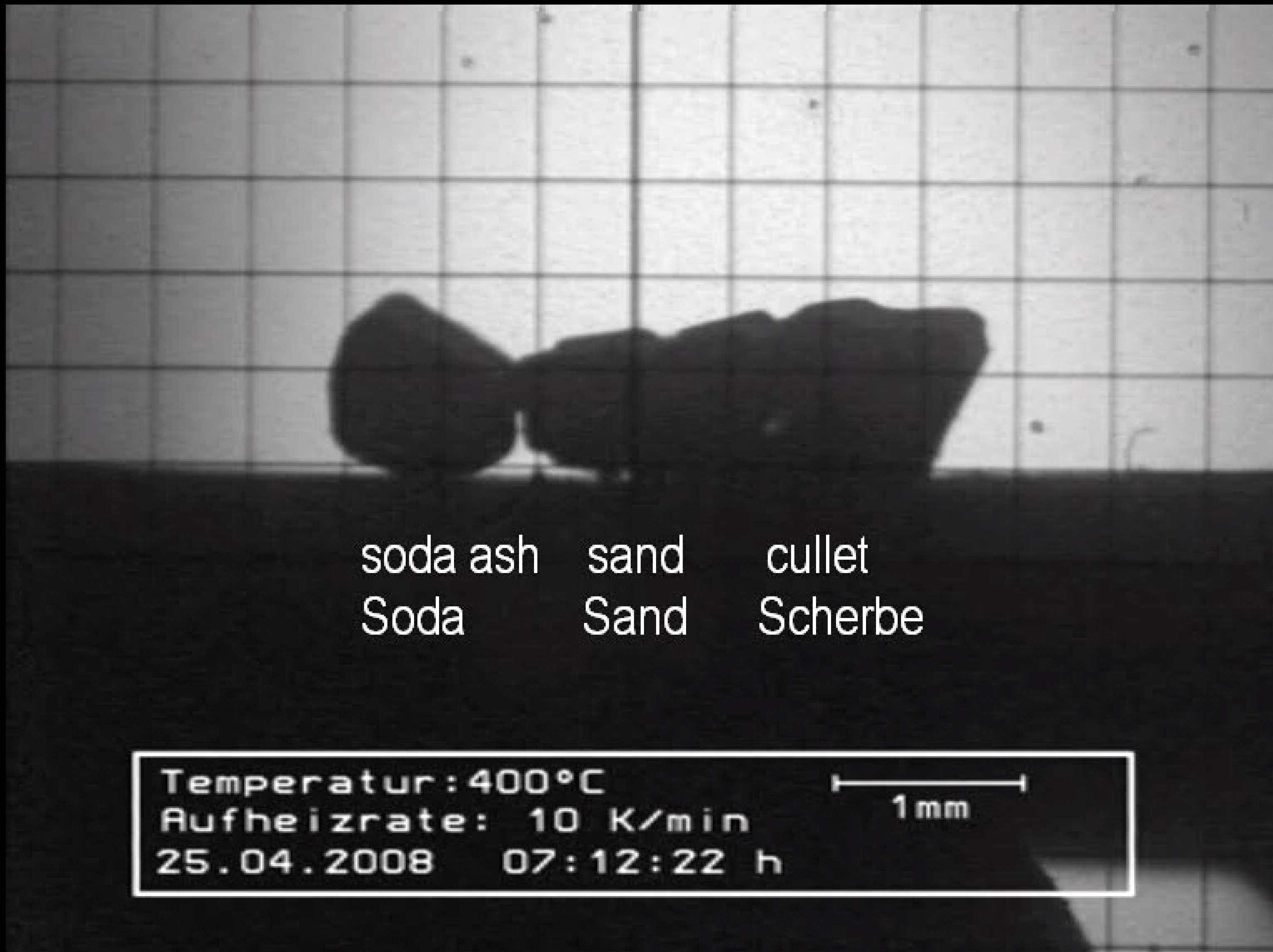
Experiment

THERMOOPTICS &

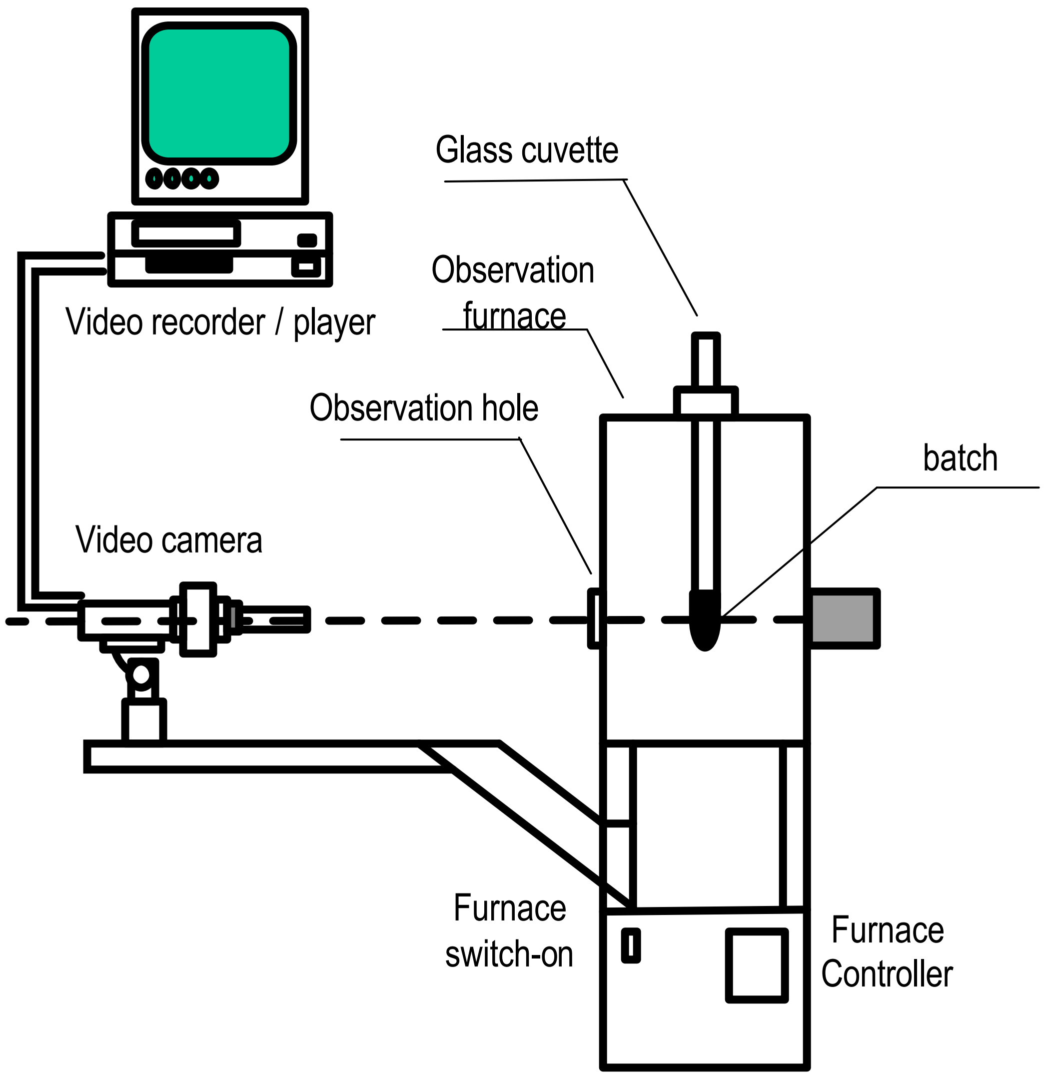
OBSERVATION FURNACE


SAND
SODA
sand
soda ash
Sand
Soda
Temperatur:400°C
Aufheizrate: 10 K/min
24.04.2008 11:14:10 h
1mm

SODA SAND SCHERBE

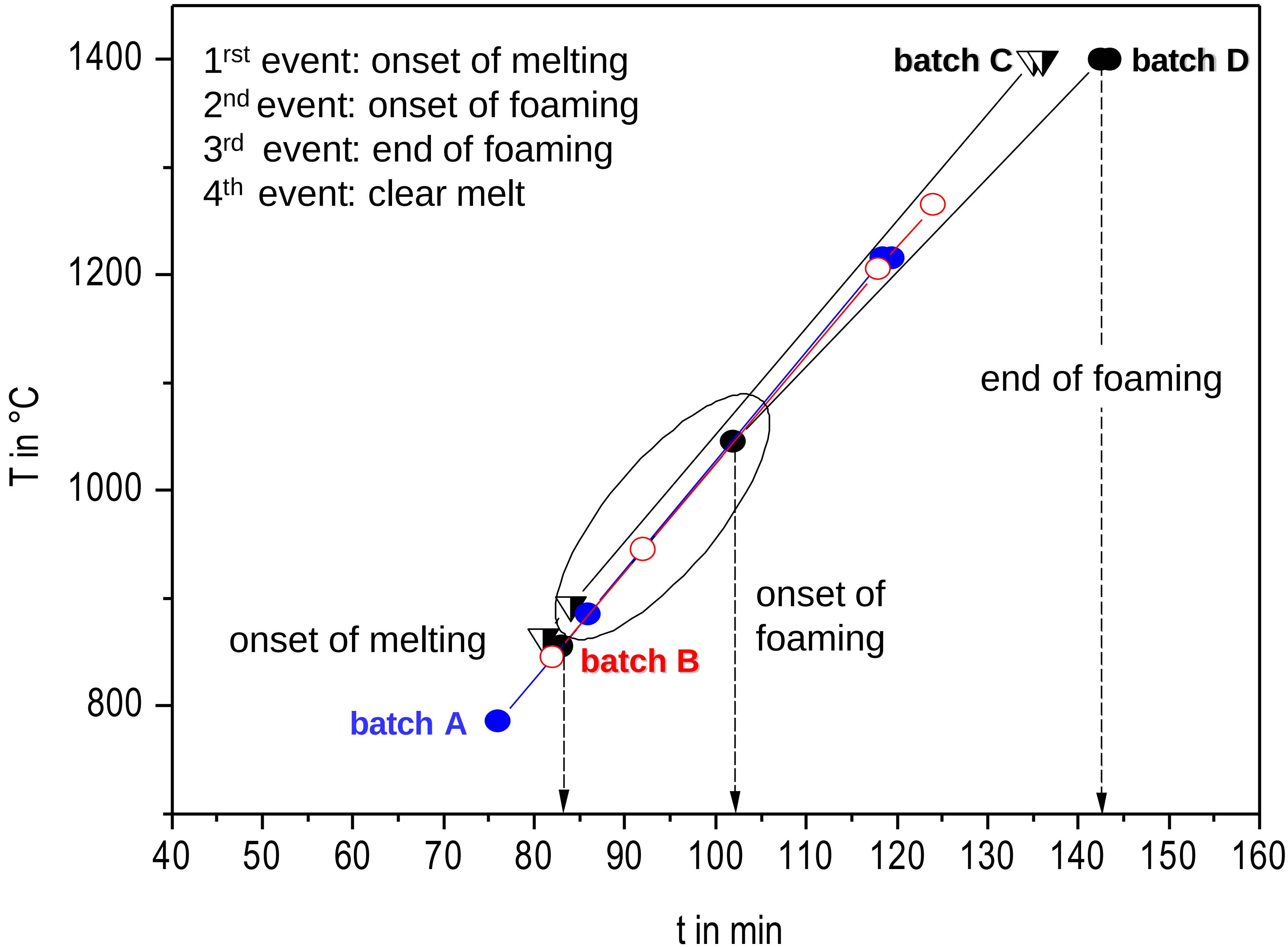


Observation Furnace



Experimental parameter:

- Target temperature : **1400 °C**
- Sample : **30 gr**
- Heating rate : **10 K/min.**
- Dwell time : **4 hour**

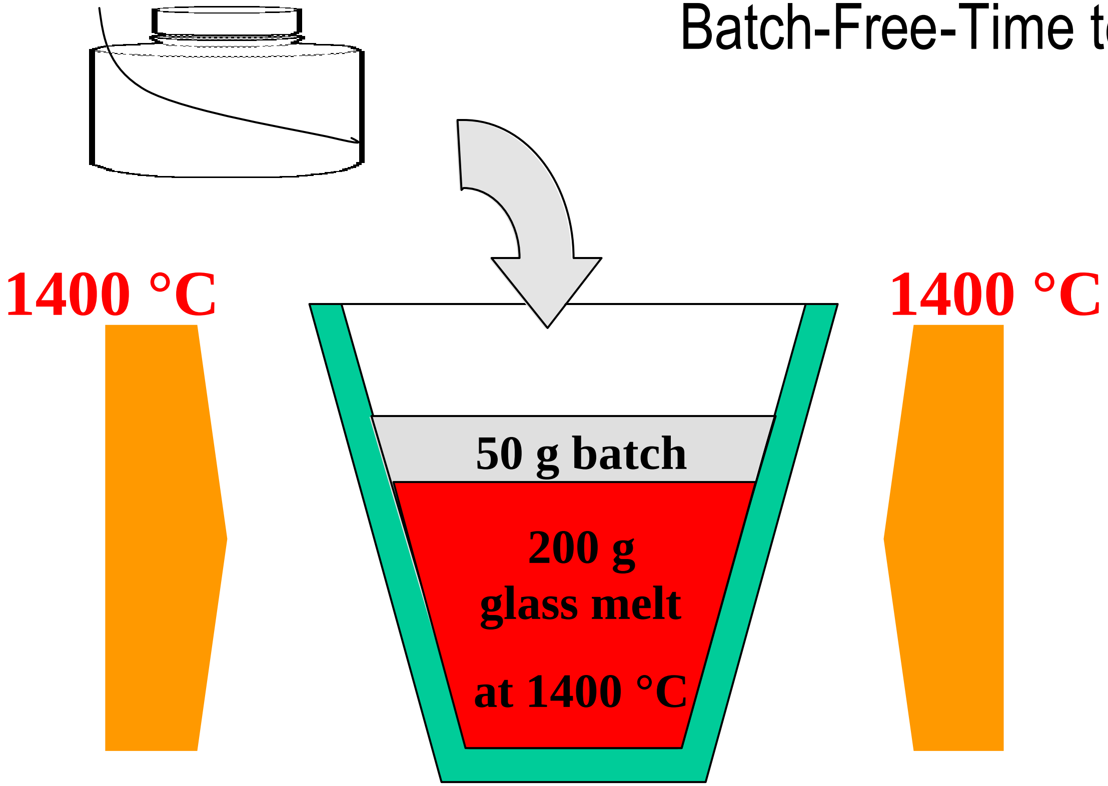


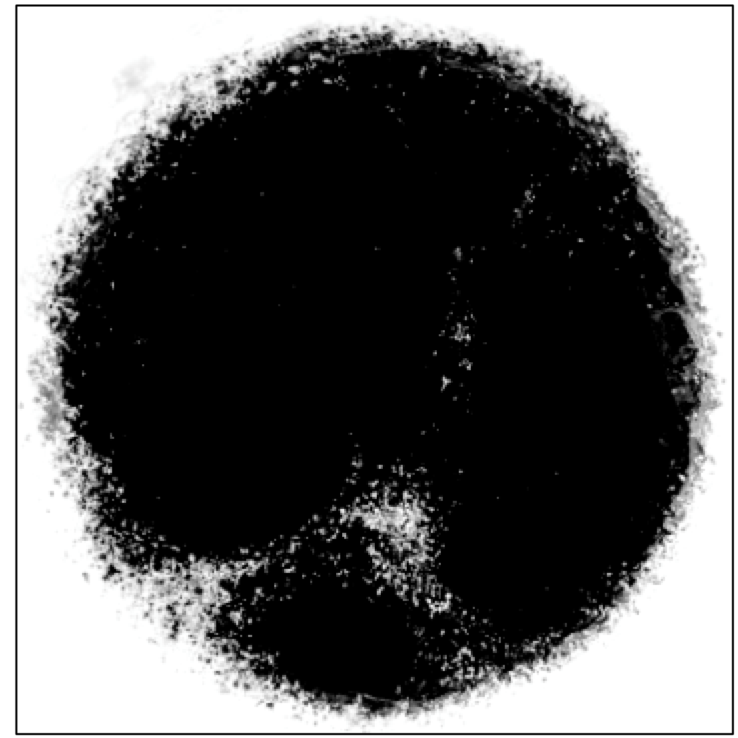
1rst event: onset of melting
2nd event: onset of foaming
3rd event: end of foaming
4th event: clear melt
batch C
batch D
batch A
batch B
onset of melting
onset of foaming
end of foaming
T in °C
t in min
1400
1200
1000
800
40
50
60
70
80
90
100
110
120
130
140
150
160

Experiment

BATCH-FREE-TIME

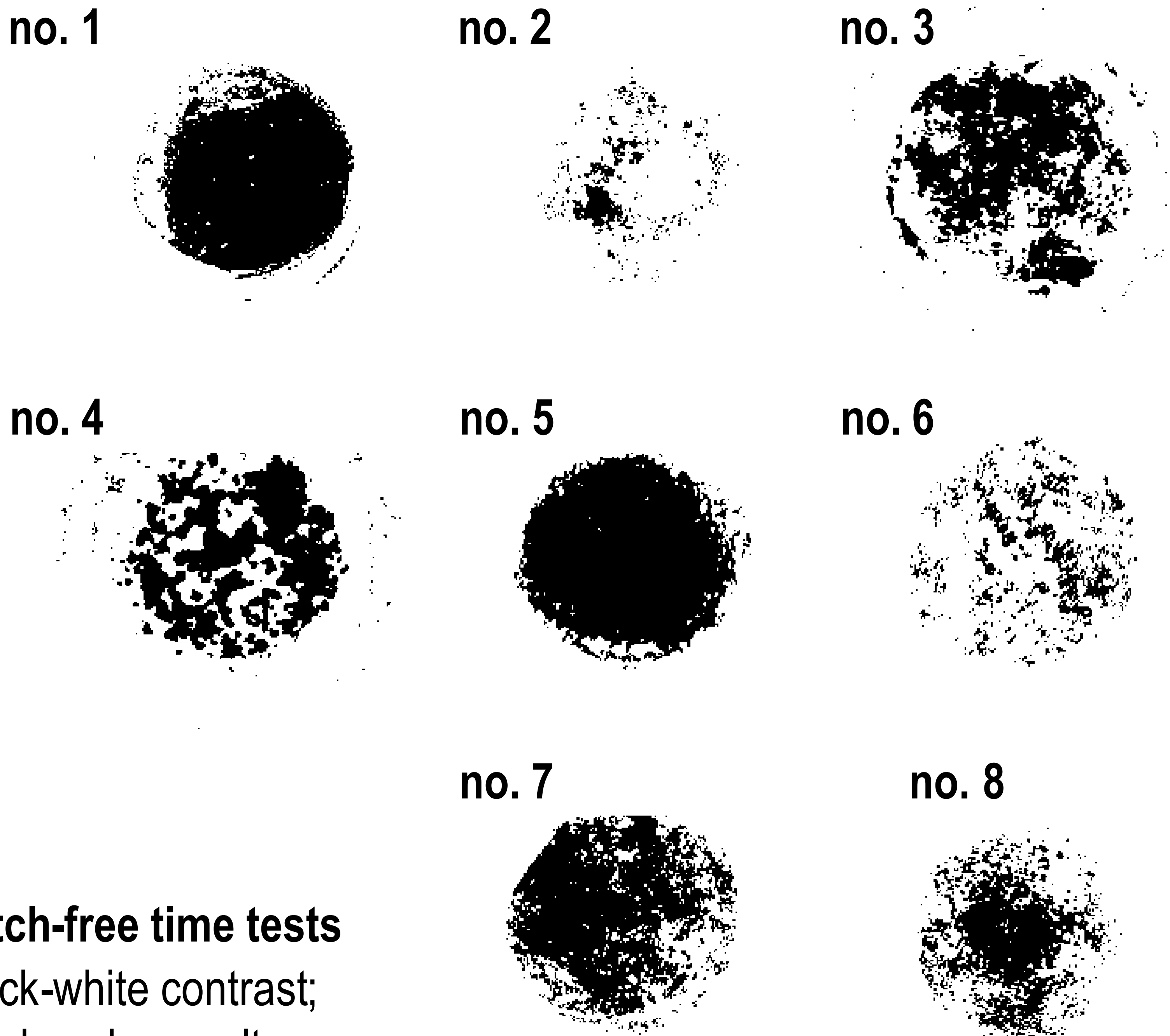
modified
Batch-Free-Time test





experimental parameters:

T_{melt} = 1400 °C
t_{hold} = 10 und 15 min
T_{anneal} = 550 °C
q_{cool} = -2 K/min



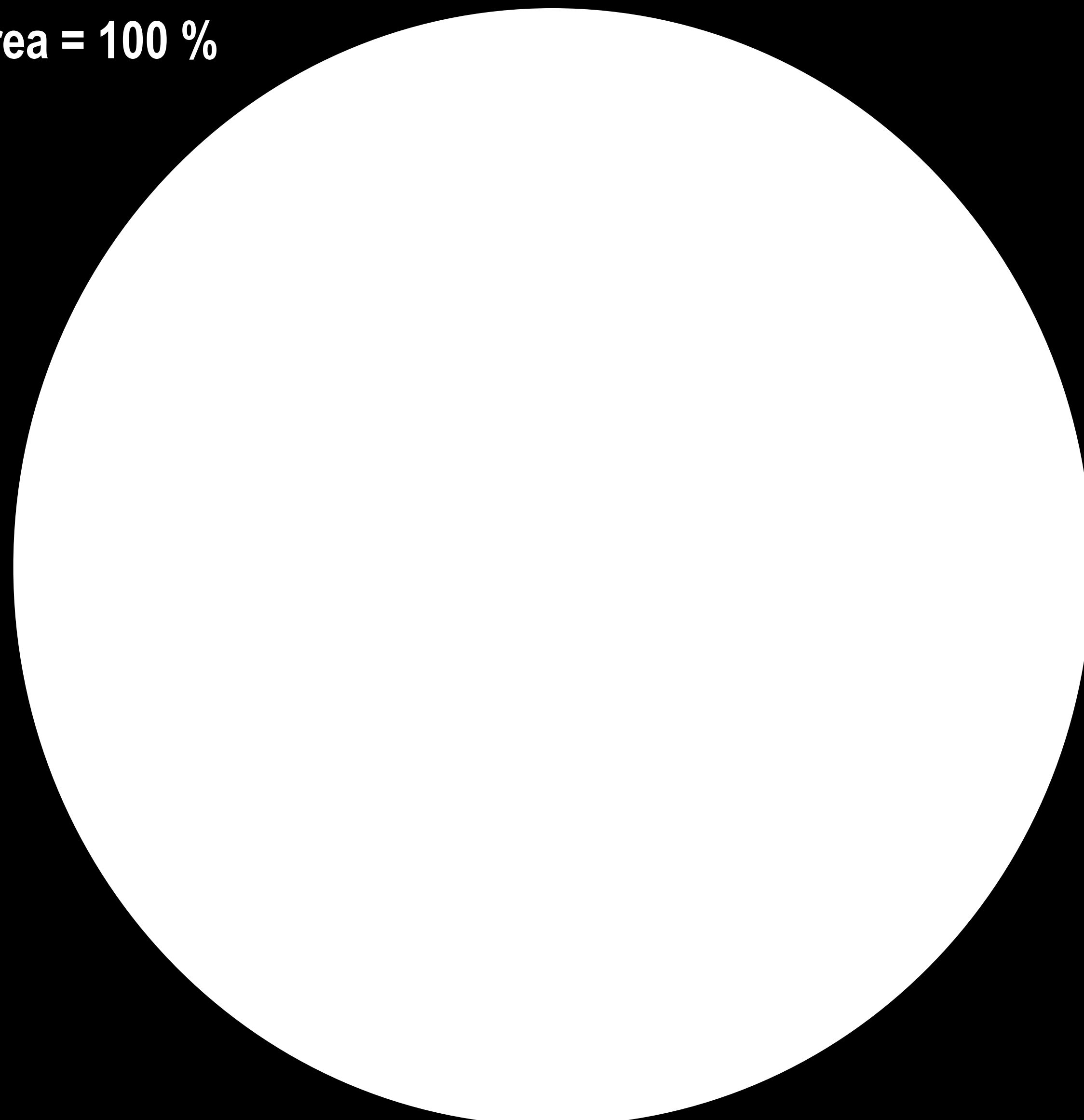
batch-free time tests

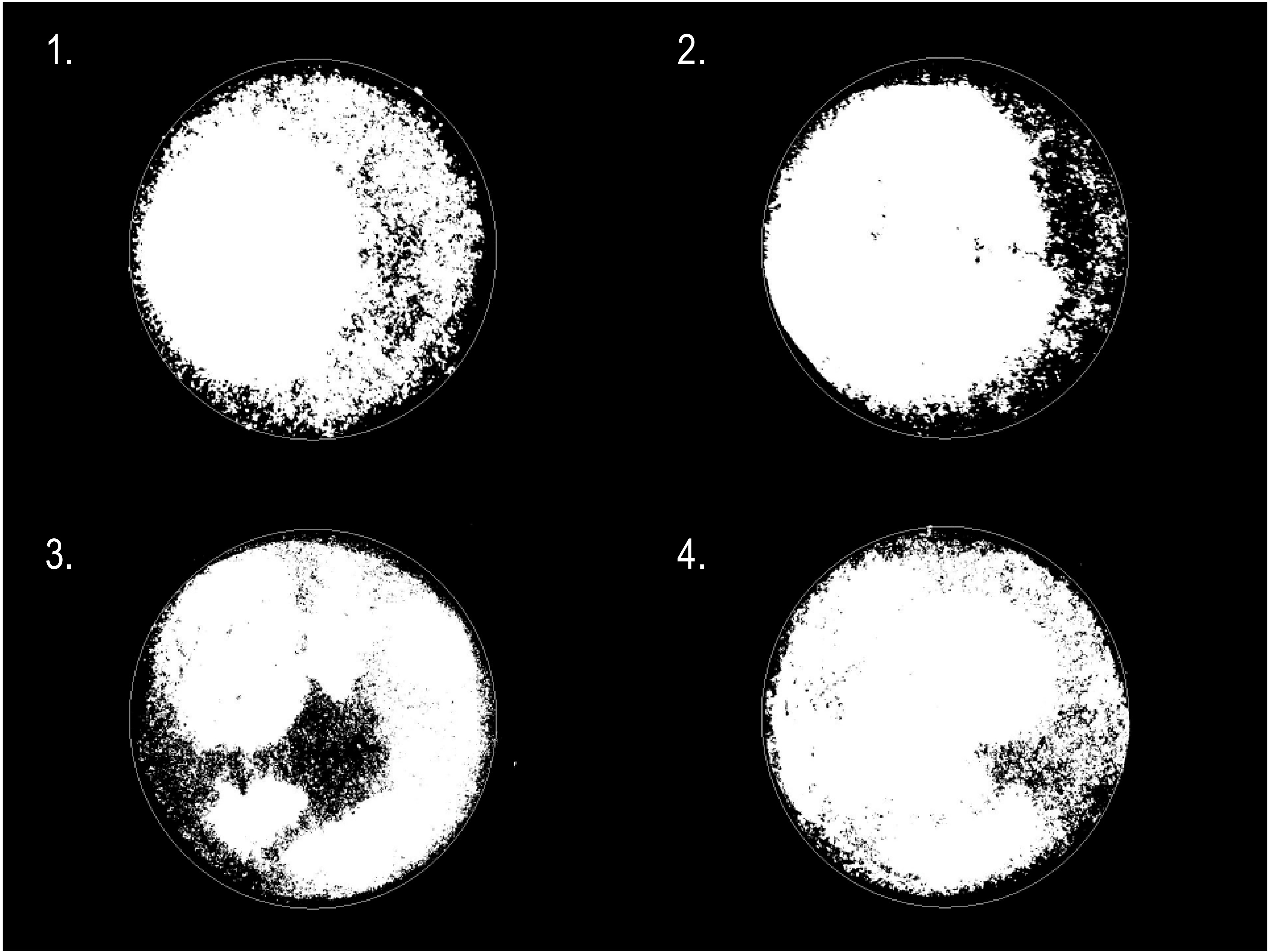
black-white contrast;

black = clear melt

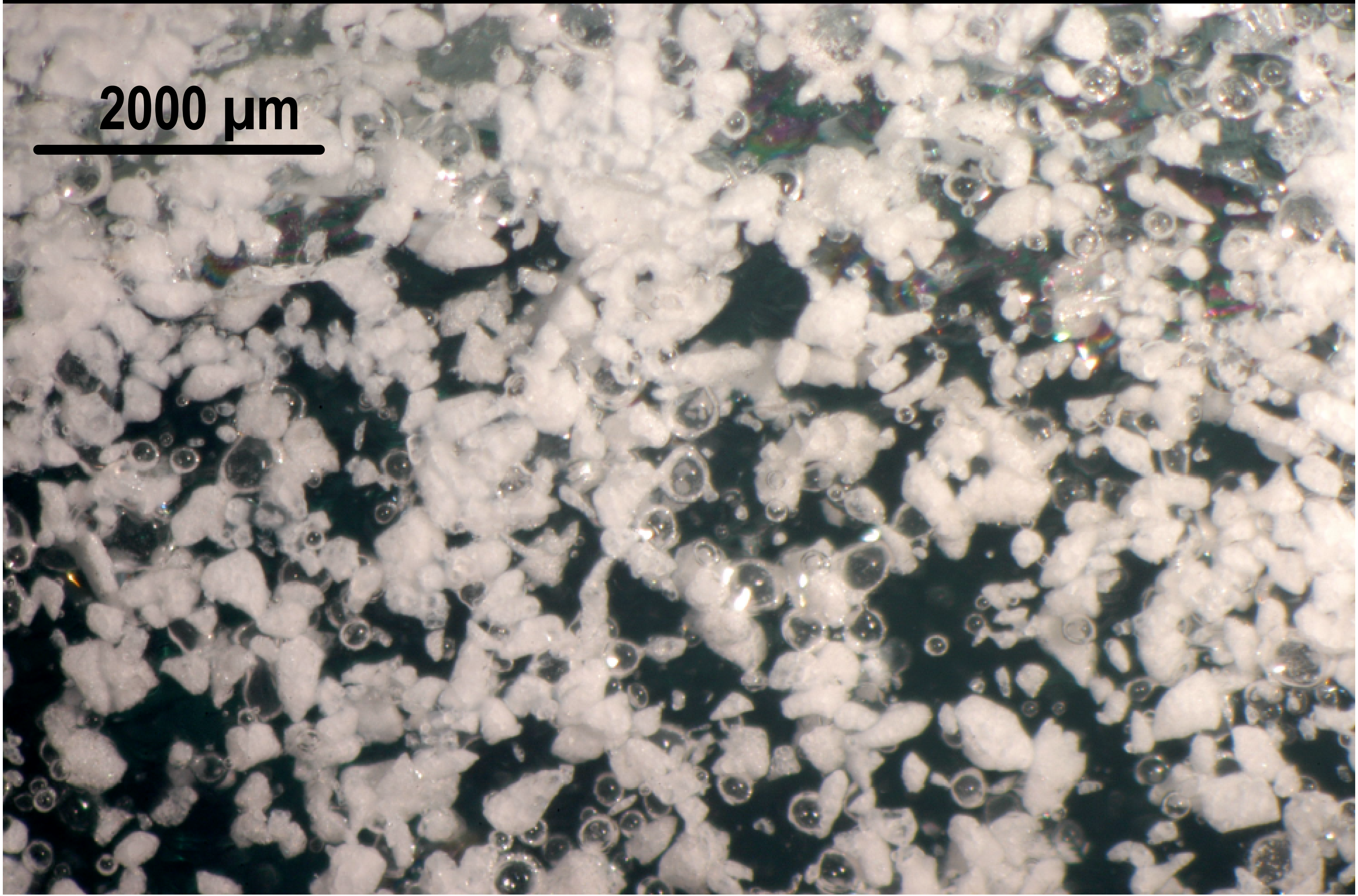
re-evaluation of free surface by black-white contrast image analysis;

calibration area = 100 %

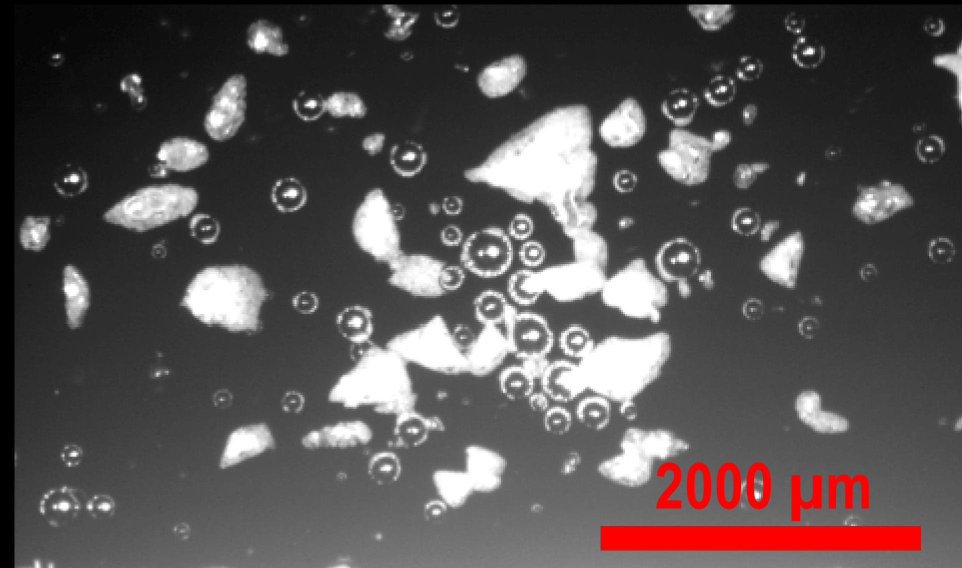


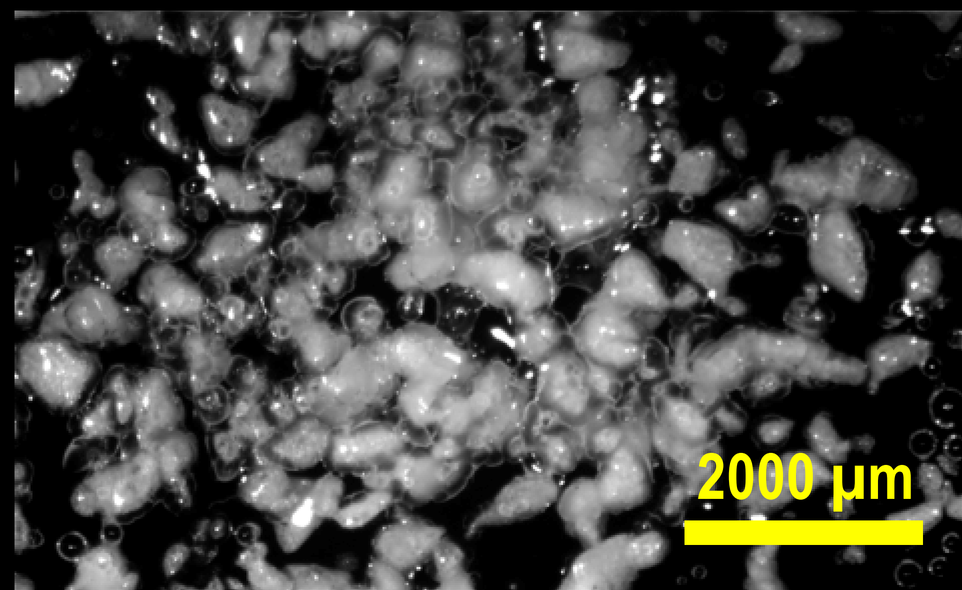

1.
2.
3.
4.

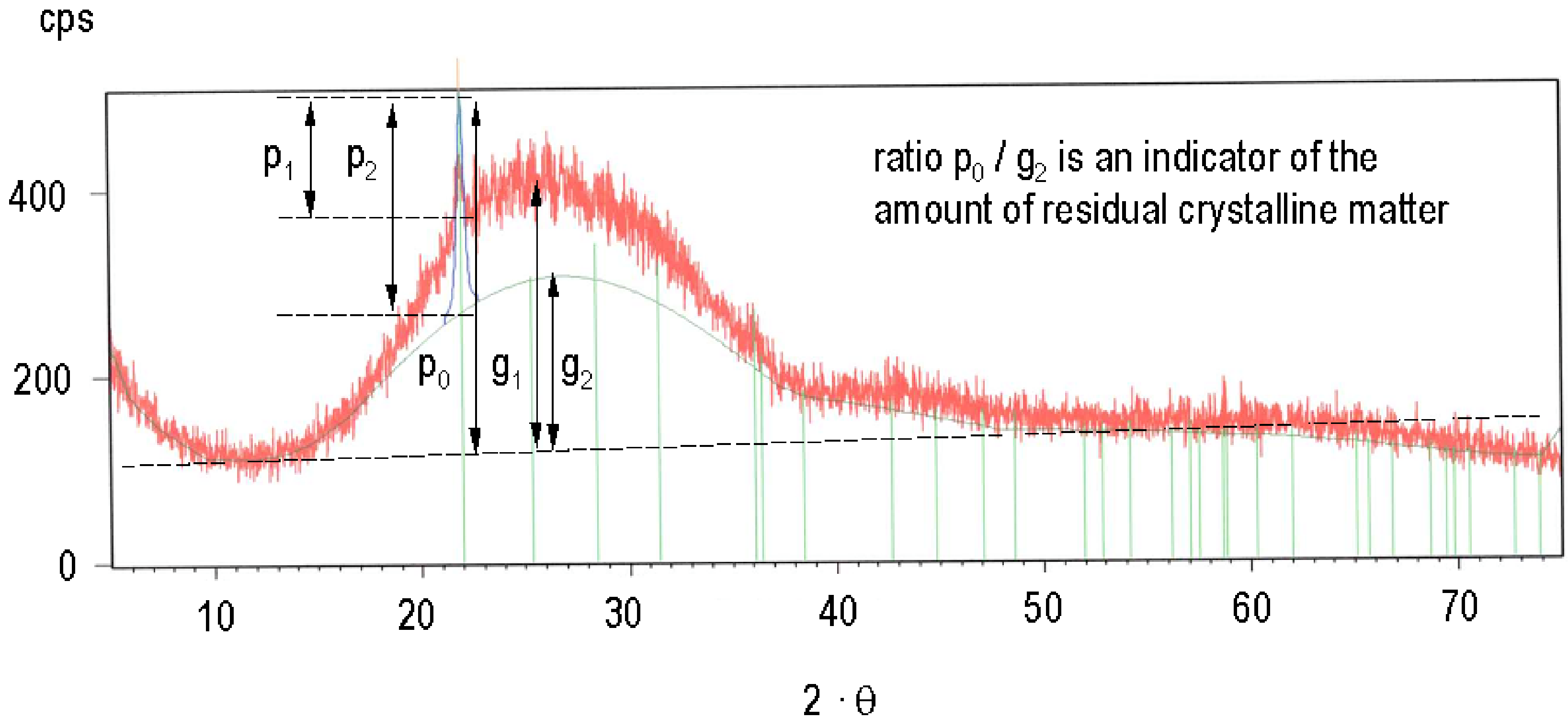
stereo microscopy

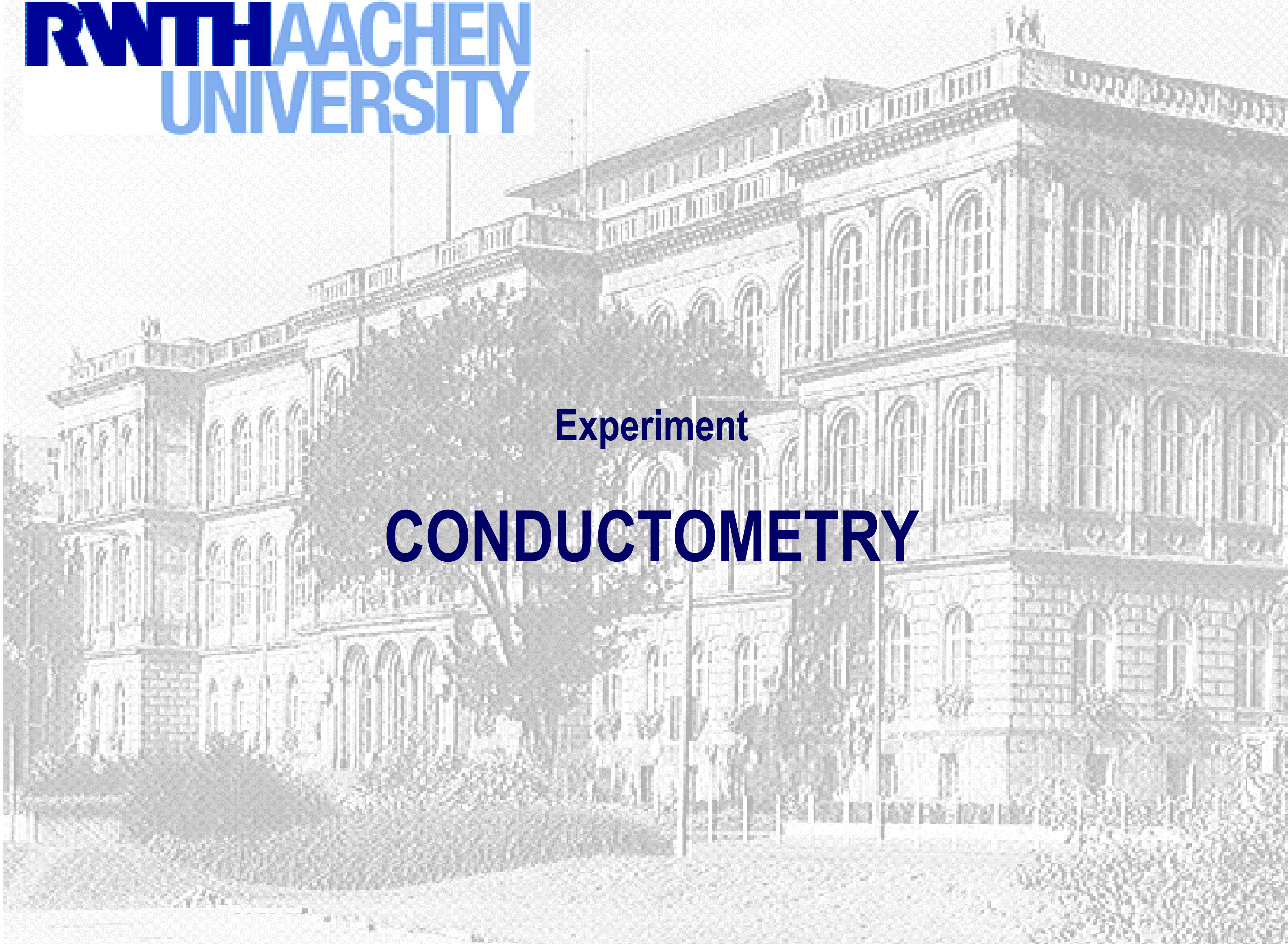


stereograph microscopy






cps
400
200
0
10
20
30
40
50
60
70
2 · θ
p1
p2
p0
g1
g2
ratio p0 / g2 is an indicator of the amount of residual crystalline matter



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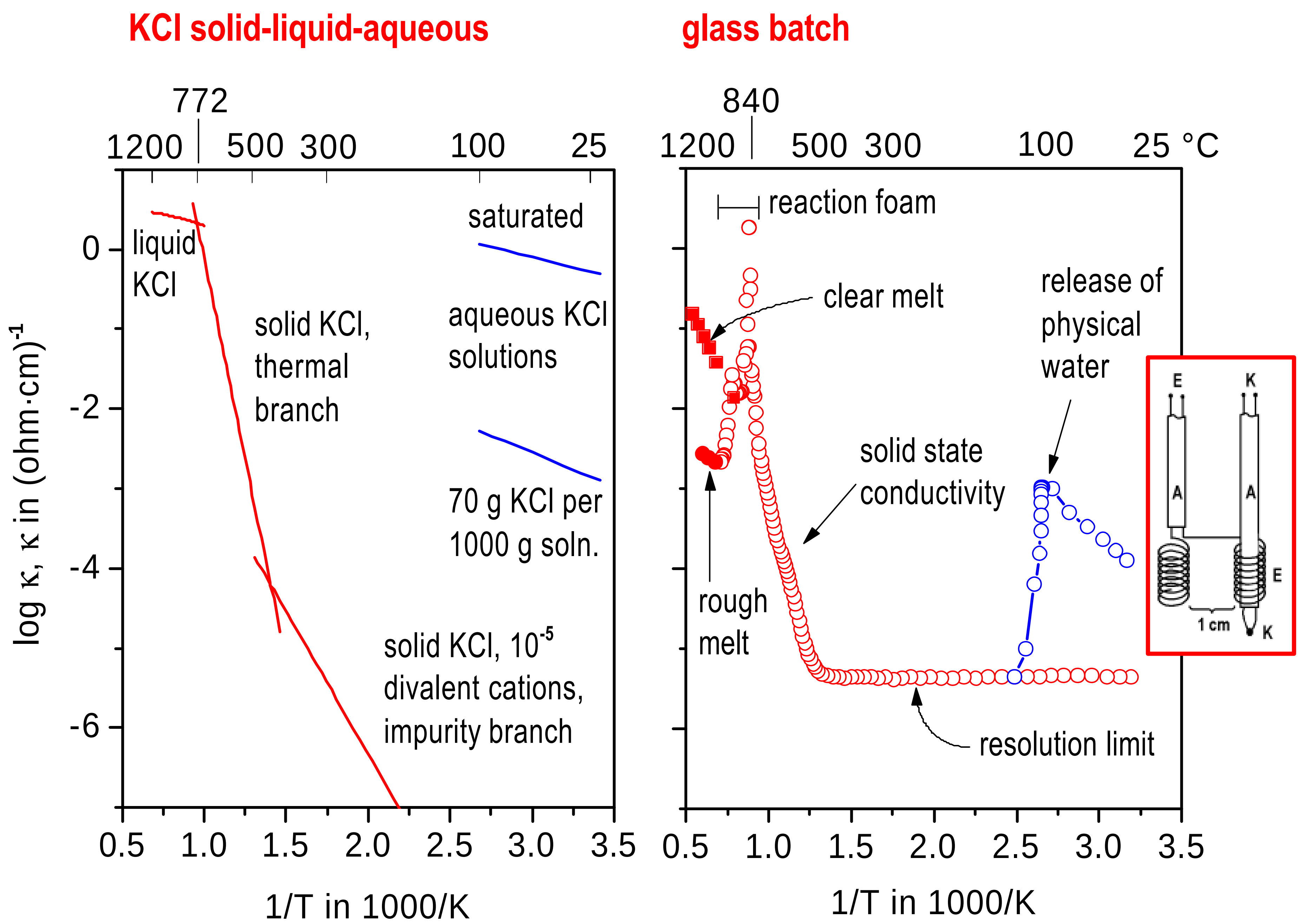
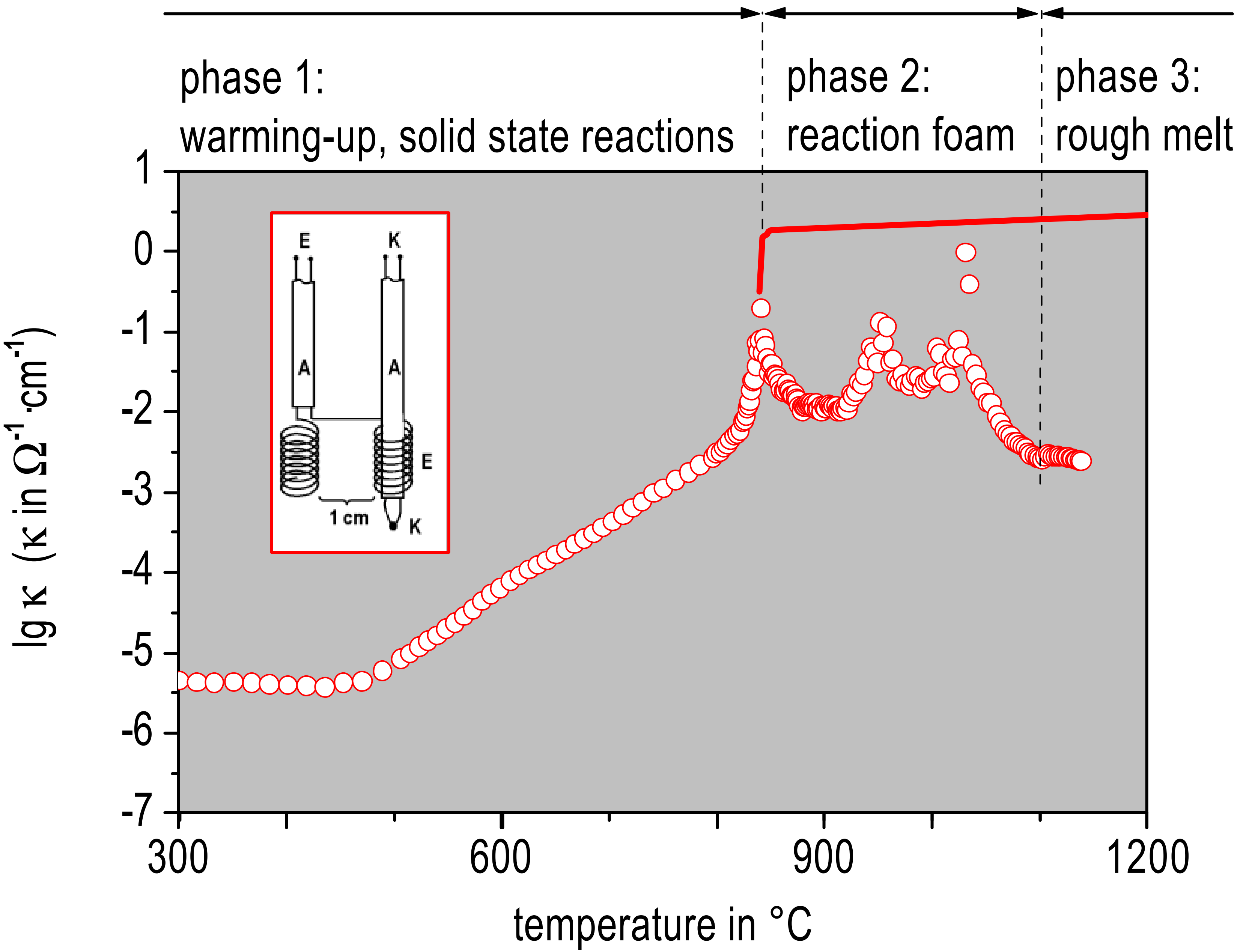
Experiment

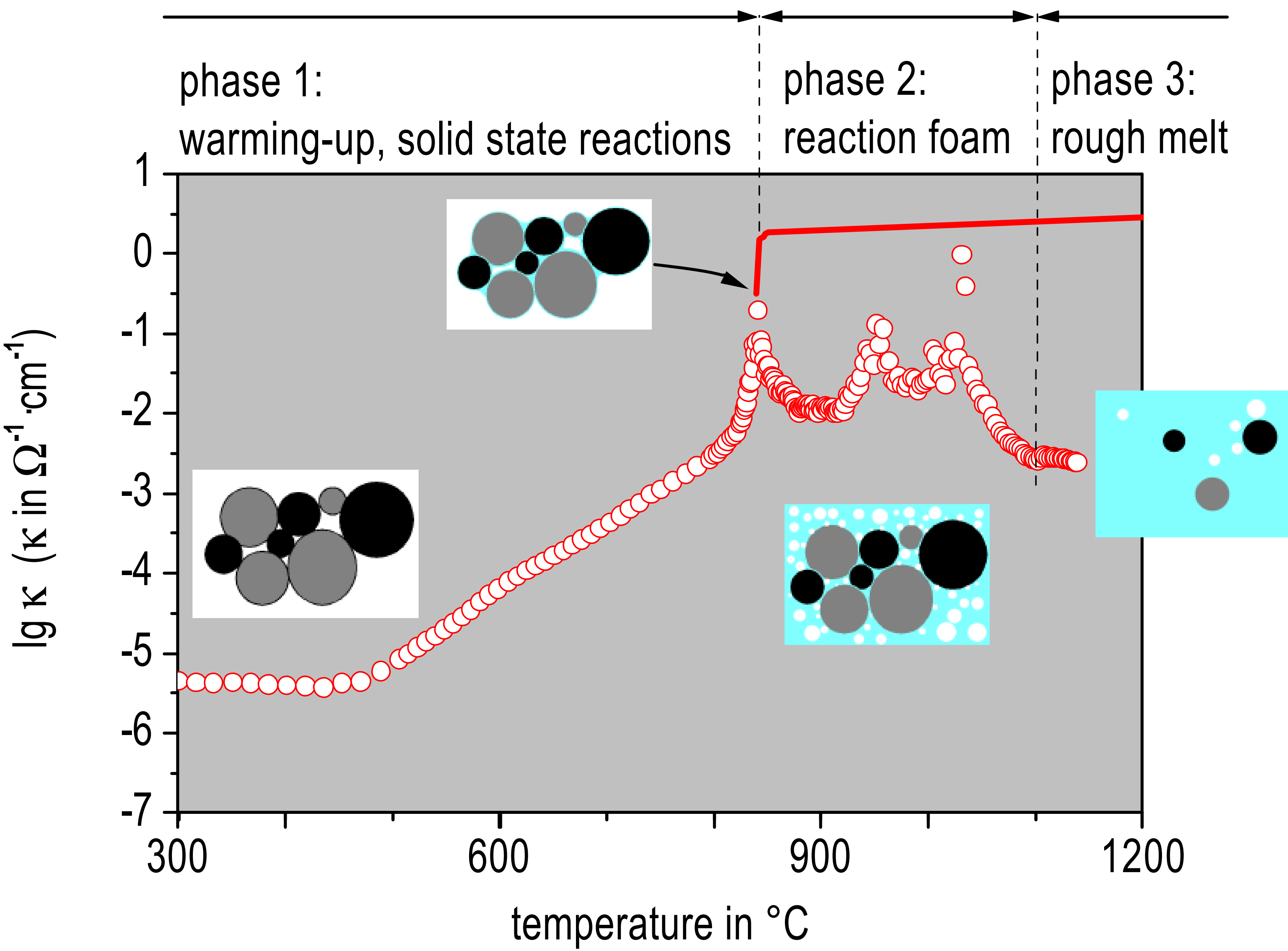
CONDUCTOMETRY



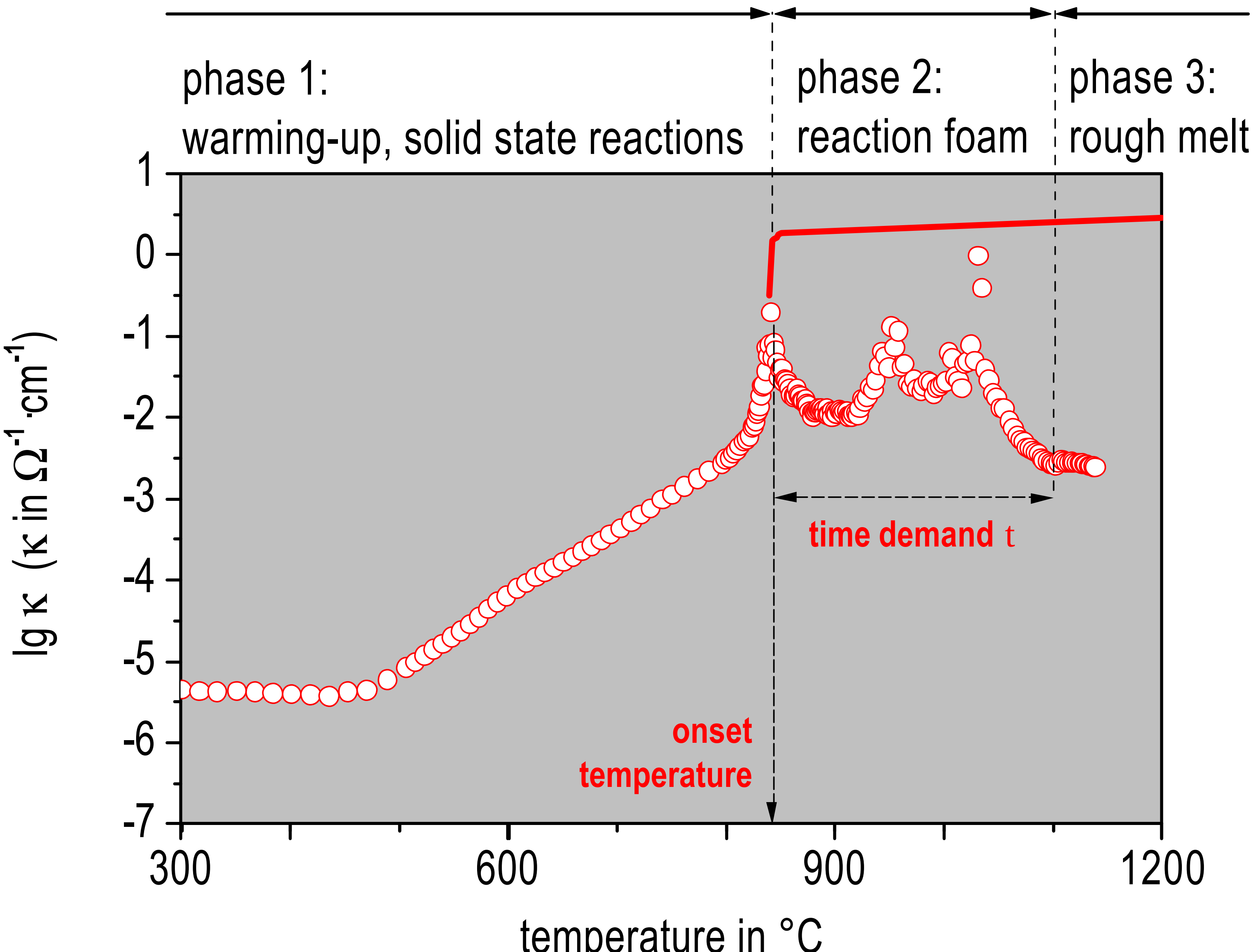
KCl solid-liquid-aqueous
glass batch
772
1200
500
300
100
25
840
25 °C
liquid
KCl
solid KCl,
thermal
branch
saturated
aqueous KCl
solutions
70 g KCl per
1000 g soln.
solid KCl, 10-5
divalent cations,
impurity branch
reaction foam
clear melt
release of
physical
water
solid state
conductivity
rough
melt
resolution limit
E
K
A
1 cm
0
-2
-4
-6
log κ, κ in (ohm·cm)-1
0.5
1.0
1.5
2.0
2.5
3.0
3.5
1/T in 1000/K



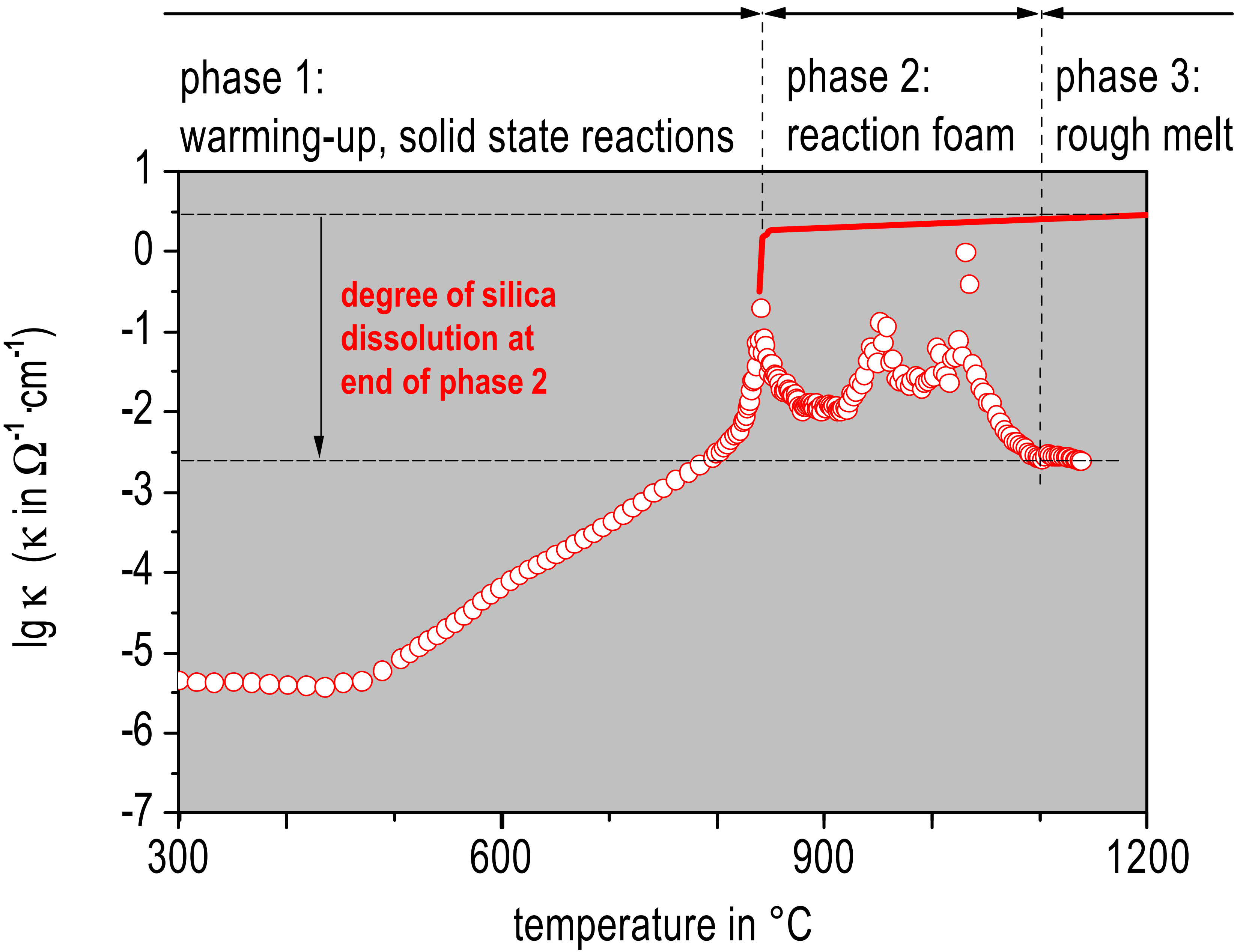
mit: O. Dubois, N. Samkham 2004



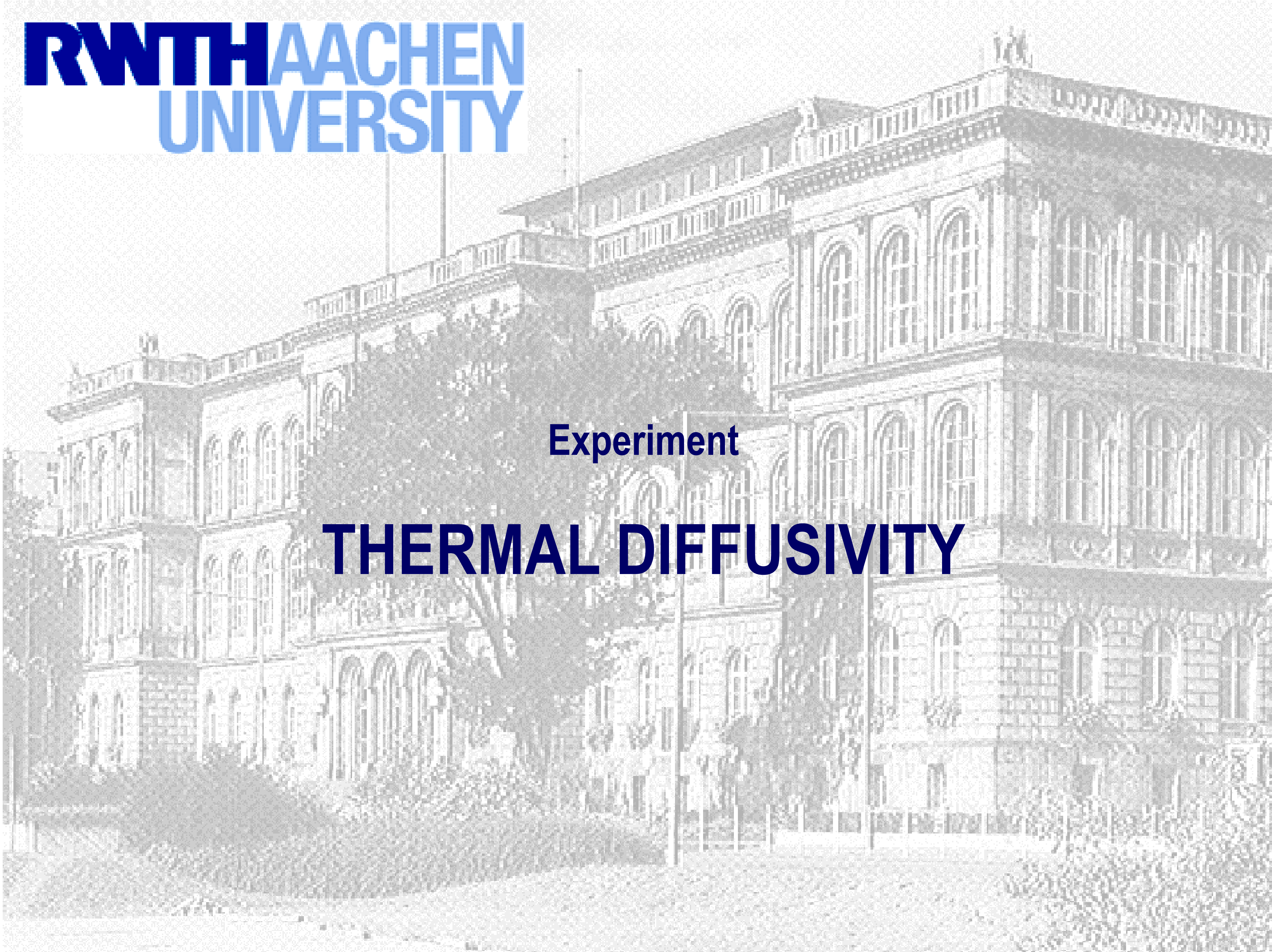
mit: O. Dubois, N. Samkham 2004



mit: O. Dubois, N. Samkham 2004



mit: O. Dubois, N. Samkham 2004



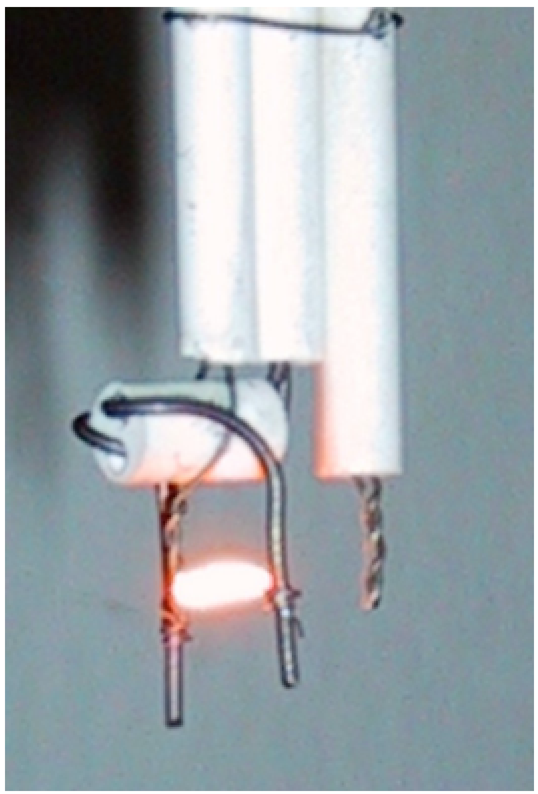
Experiment

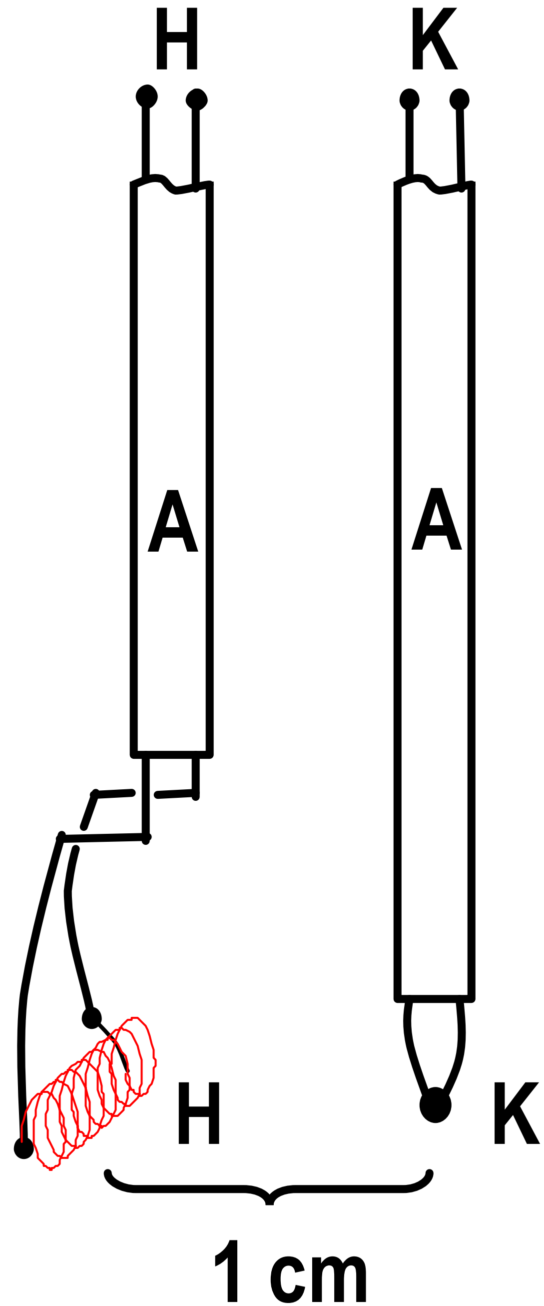
THERMAL DIFFUSIVITY

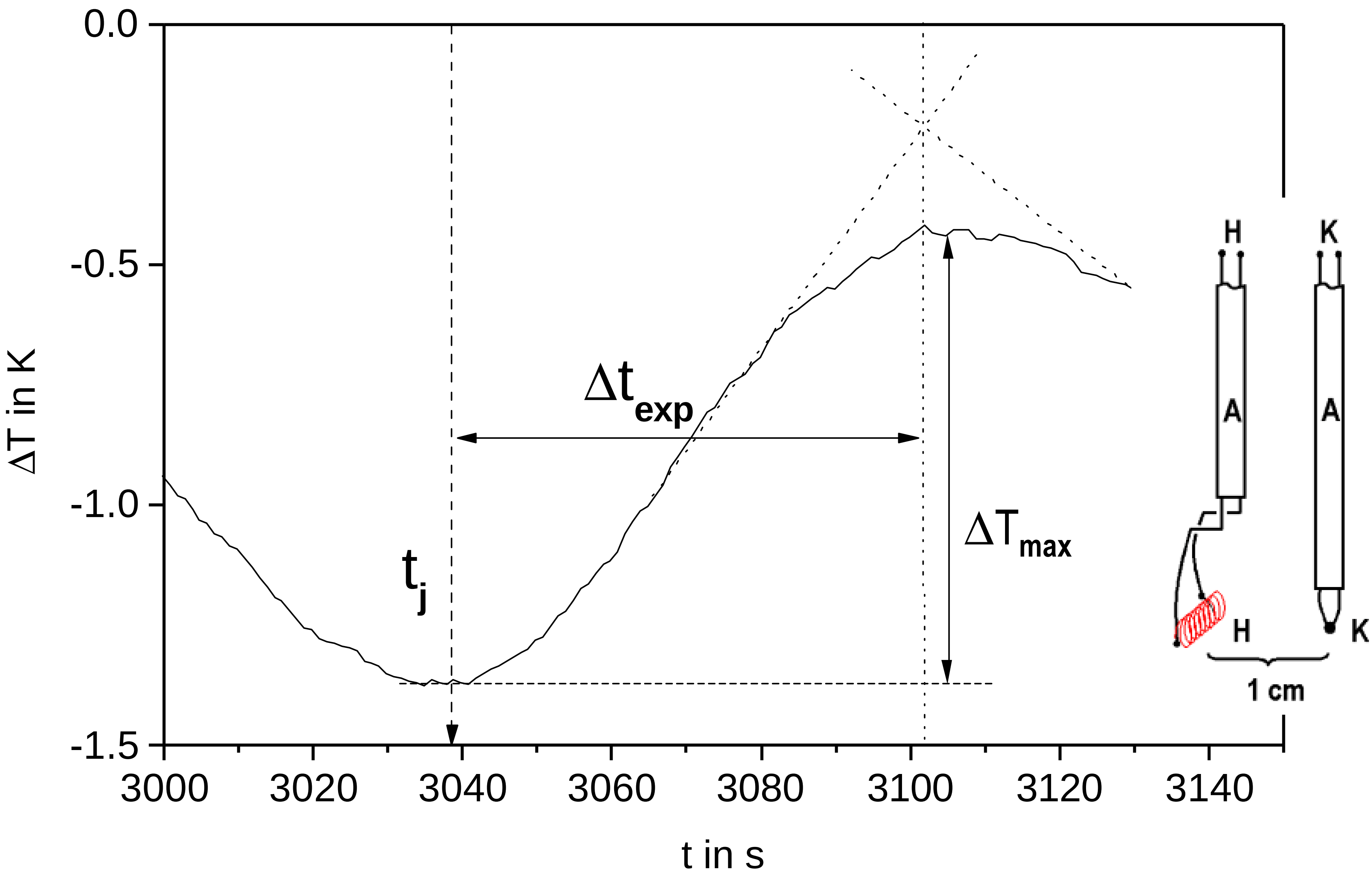
heat pulse:

- runtime $\Delta t_{exp} \Rightarrow$ thermal diffusivity a
- peak height $\Delta T_{max} \propto \Delta Q = U \cdot I \cdot \Delta t_{PULSE}$

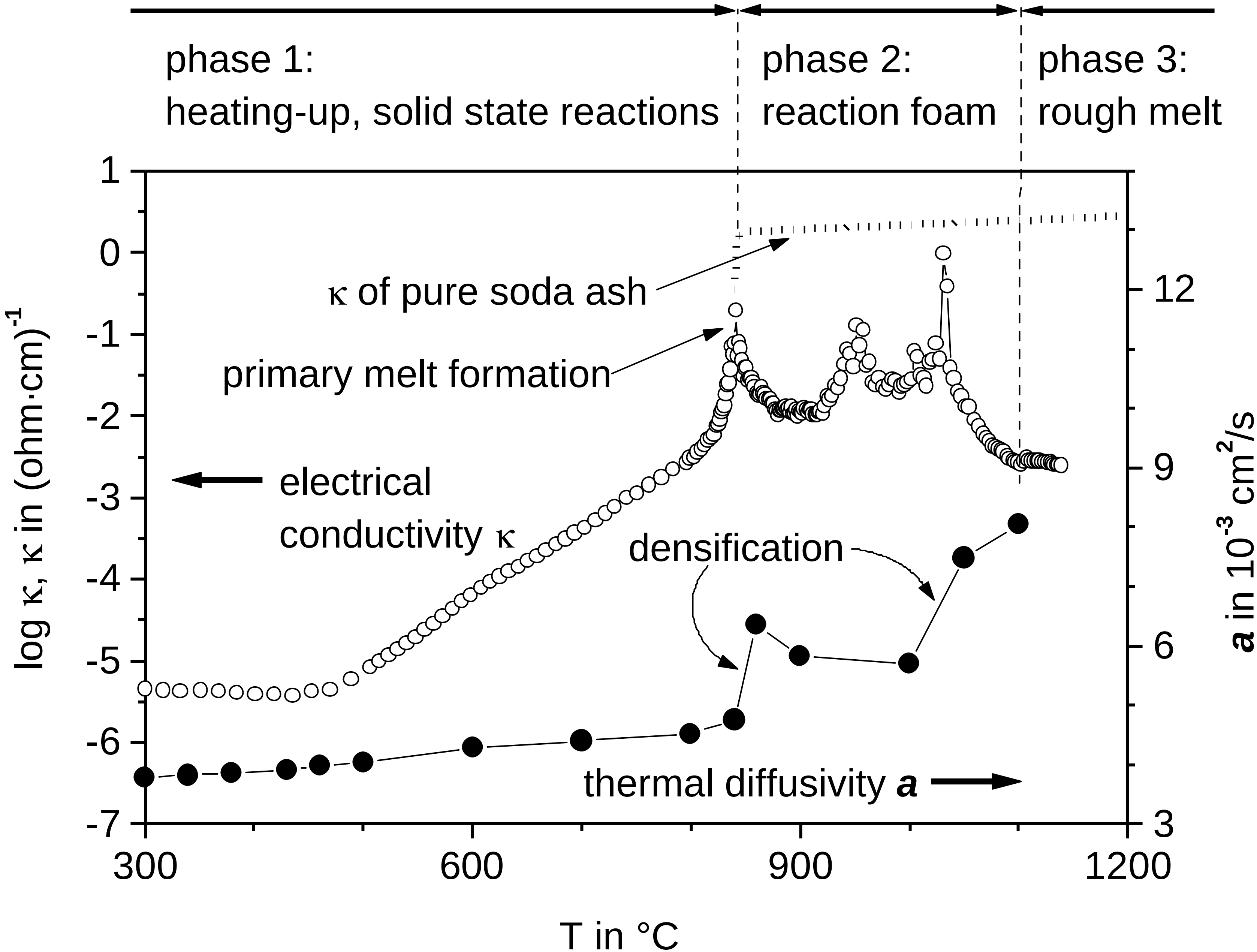
  $\Rightarrow$ heat conductivity λ







0.0
-0.5
-1.0
-1.5
ΔT in K
3000
3020
3040
3060
3080
3100
3120
3140
t in s
Δt exp
ΔT max
t j
H
K
A
A
H
K
1 cm



phase 1:
heating-up, solid state reactions
phase 2:
reaction foam
phase 3:
rough melt
κ of pure soda ash
primary melt formation
electrical
conductivity κ
densification
thermal diffusivity a
log κ, κ in (ohm·cm)-1
a in 10-3 cm2/s
T in °C
1
0
-1
-2
-3
-4
-5
-6
-7
12
9
6
3
300
600
900
1200

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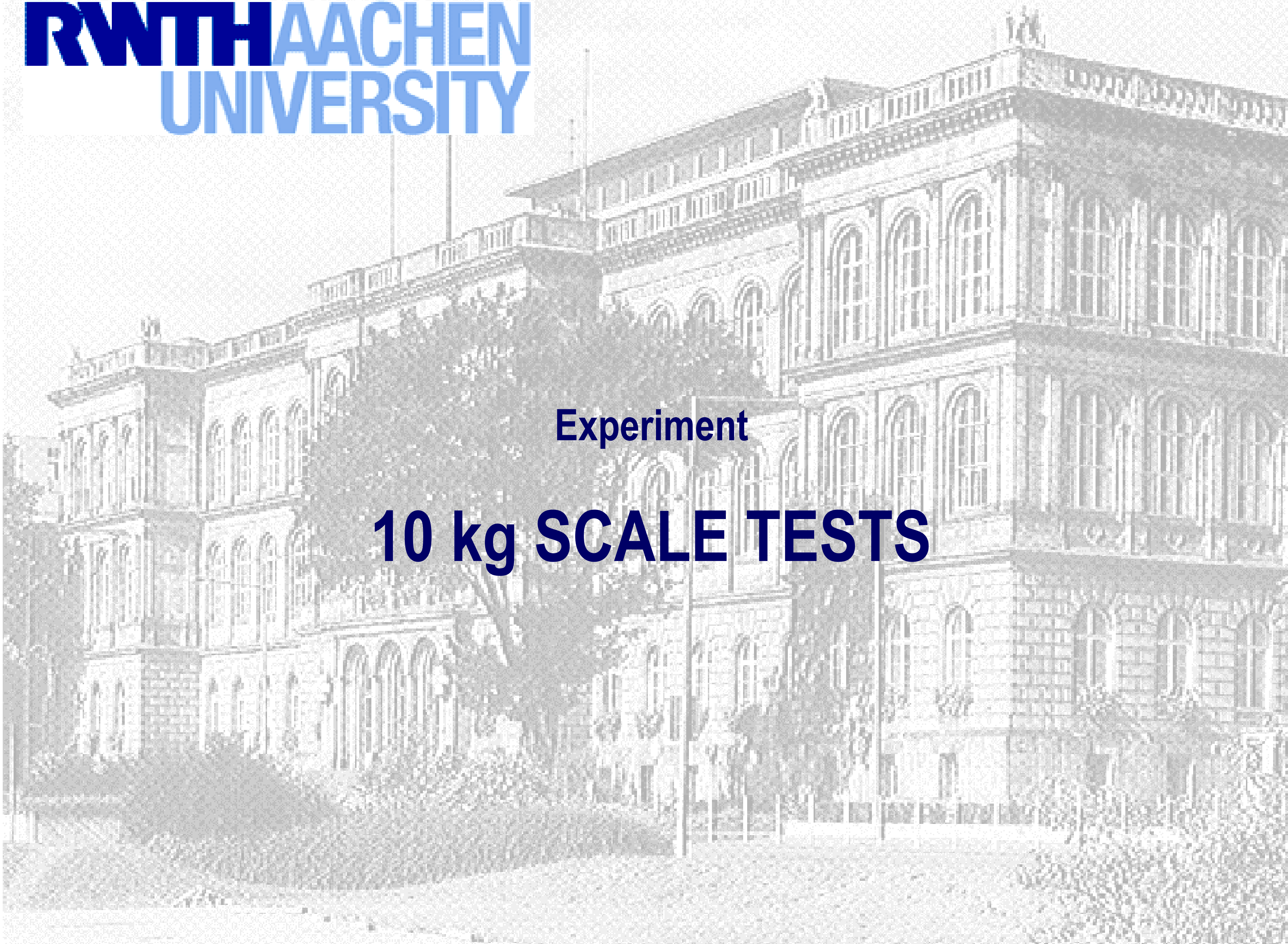
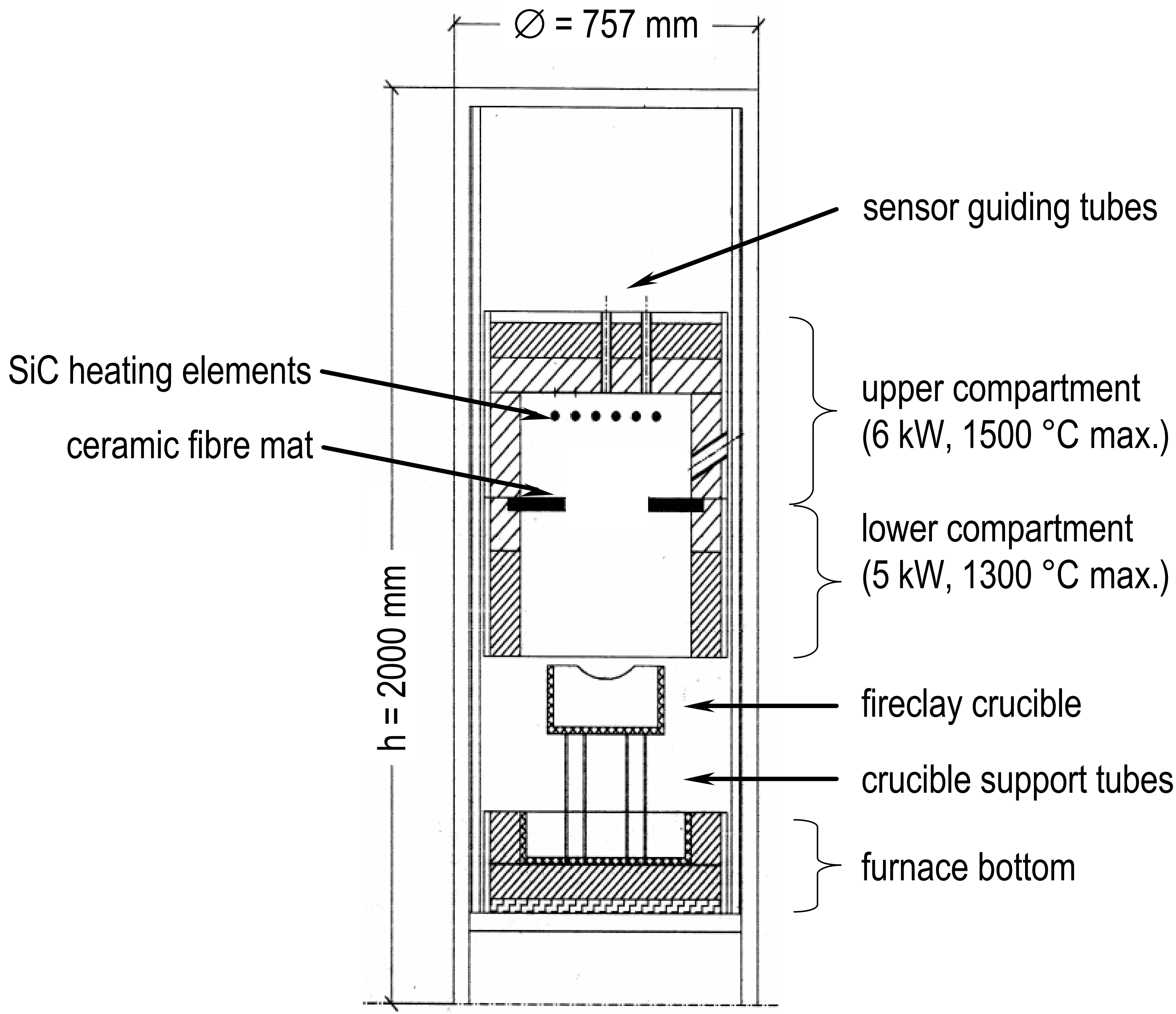
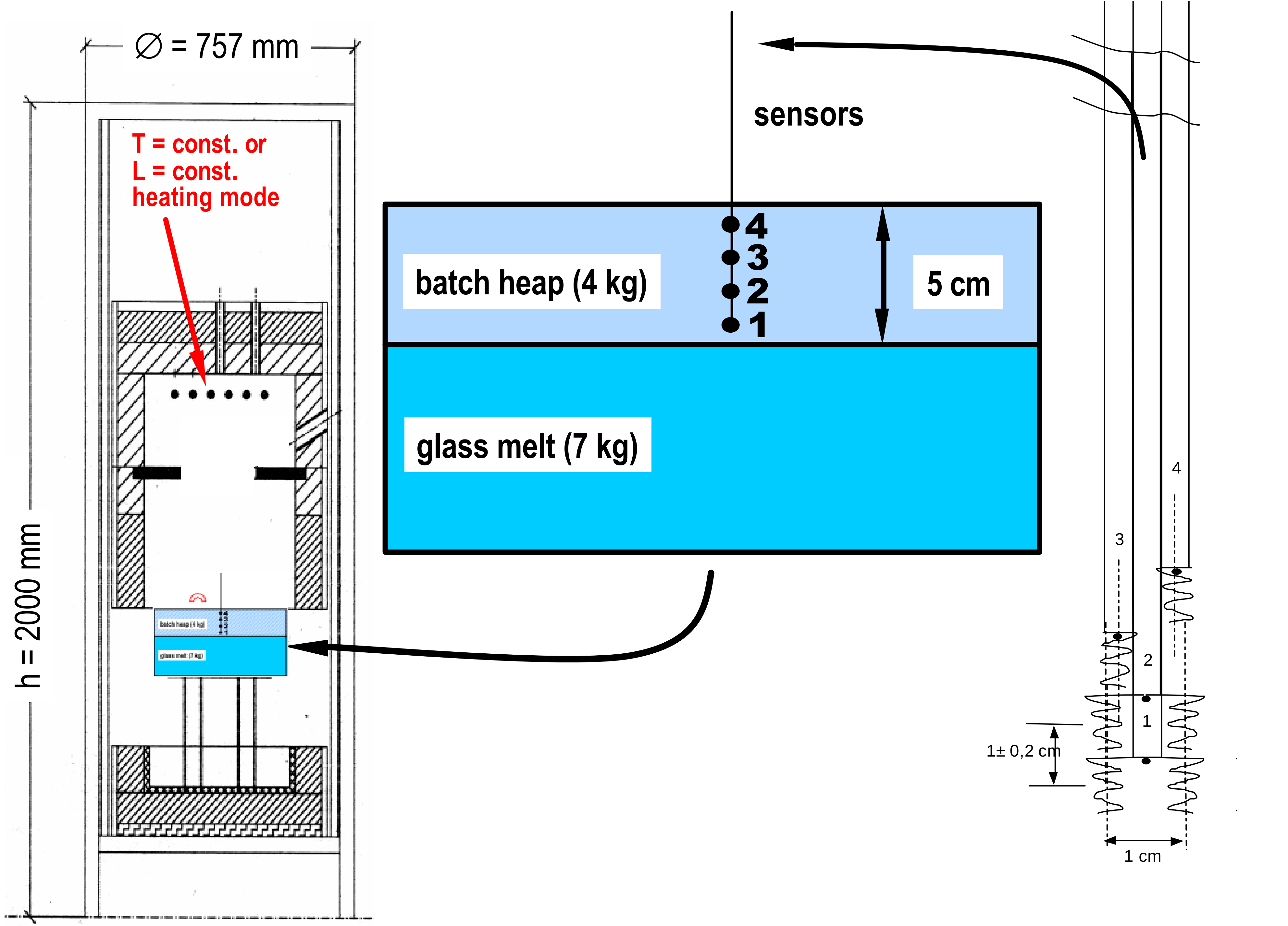


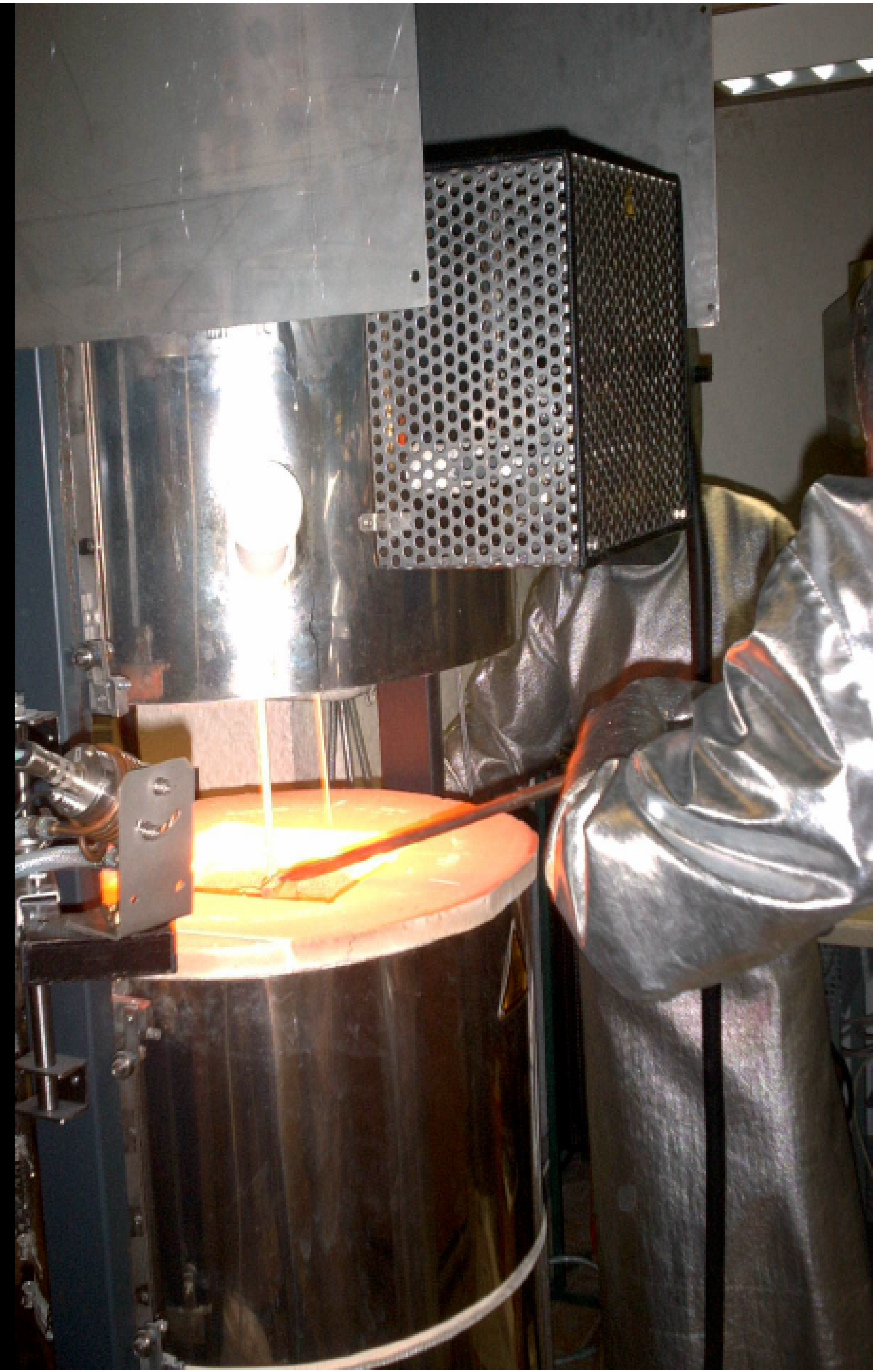
Experiment

10 kg SCALE TESTS


∅ = 757 mm
sensor guiding tubes
SiC heating elements
ceramic fibre mat
upper compartment
(6 kW, 1500 °C max.)
lower compartment
(5 kW, 1300 °C max.)
h = 2000 mm
fireclay crucible
crucible support tubes
furnace bottom



∅ = 757 mm
h = 2000 mm
T = const. or
L = const.
heating mode
sensors
batch heap (4 kg)
glass melt (7 kg)
5 cm
4
3
2
1
1± 0,2 cm
1 cm

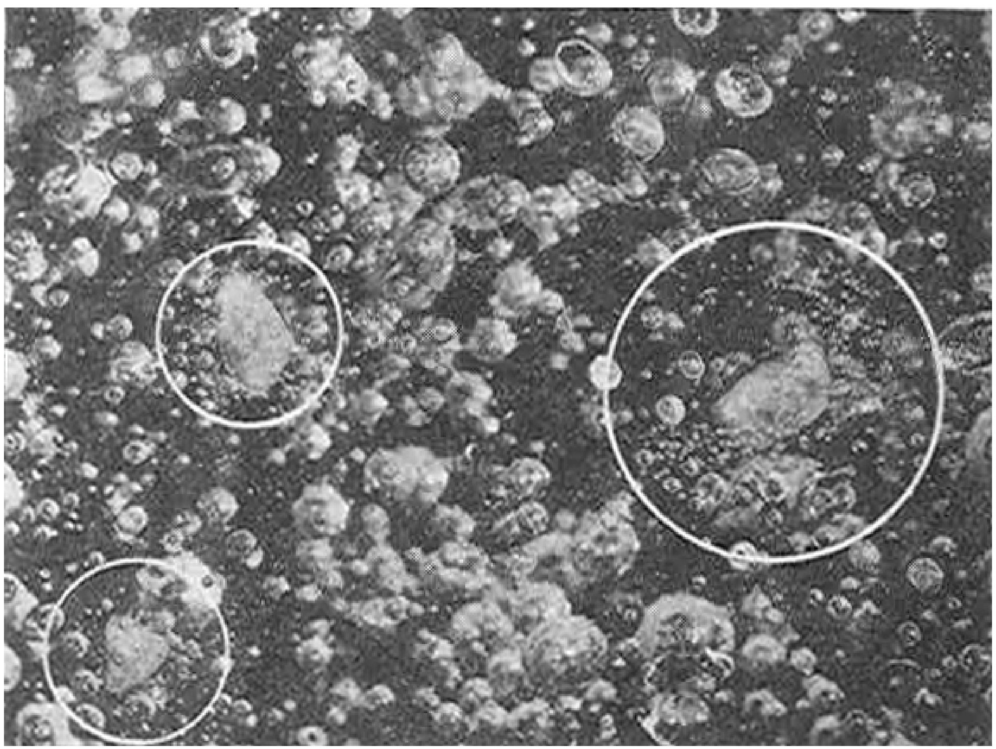
optimization of the batch-to-melt conversion

optimal reaction paths

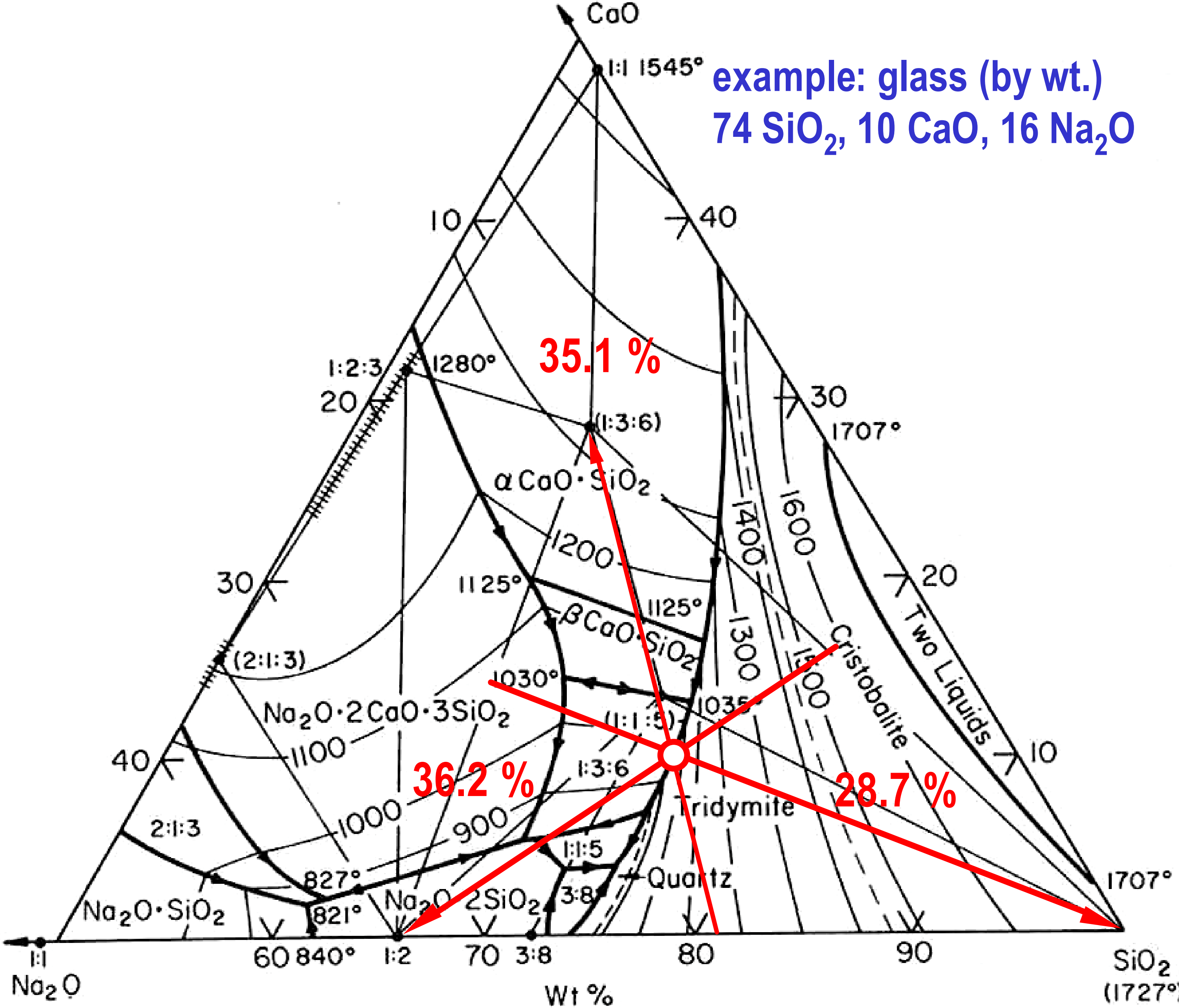
DH_{chem} does not tell the whole story!

quartz:	H°	= 910.9 kJ/mol
silica glass:	H°	= 901.4 kJ/mol
	DH_{chem}	= 9.5 kJ/mol
		= 43.9 kWh/t

As DH_{chem} for a conventional batch is approx. 140 kWh/t, is adding quartz sand a good way to save energy? OF COURSE NOT! Slow quartz dissolution is a main reason for late fining, long dwell times, high energy consumption.



DESIGN LOW RESIDUAL SILICA GLASS FORMULAE!



example: glass (by wt.)
74 SiO2, 10 CaO, 16 Na2O
CaO
1:1 1545°
10
40
1:2:3
1280°
20
30
(1:3:6)
1707°
α CaO·SiO2
1200
1400
1600
20
30
1125°
1125°
β CaO·SiO2
1300
1500
Cristobalite
Two Liquids
(2:1:3)
1030°
1035°
Na2O·2CaO·3SiO2
(1:1:5)
40
1100
10
1:3:6
Tridymite
1000
900
2:1:3
1:1:5
Quartz
827°
1707°
3:8
821°
Na2O·SiO2
Na2O·2SiO2
1:1
Na2O
60
840°
1:2
70
3:8
80
90
SiO2
(1727°)
Wt %
35.1 %
36.2 %
28.7 %

raw material i	kg/t		oxide j	kg/t		phase k	kg/t
sand	666.96		SiO_2	720.00		SiO_2	227.05
feldspar	77.15		Al_2O_3	15.00		$Na_2O{\cdot}Al_2O_3{\cdot}6SiO_2$	77.15
dolomite	182.98		MgO	40.00		$MgO{\cdot}SiO_2$	99.62
limestone	34.54		CaO	75.00		$Na_2O{\cdot}3CaO{\cdot}6SiO_2$	263.34
soda ash	240.91		Na_2O	150.00		$Na_2O{\cdot}2SiO_2$	332.84
			CO_2	202.54			
sum	1202.54			1202.54			1000.00

H°(batch) = 4589.5 kWh

H°(gl) = 3942.3 kWh

H°(gas) = 503.0 kWh;

DH°_{chem} = 144.2 kWh

DH_T(gl) = 404.1 kWh, T = 25 to 1200 °C

DH_T(gas) = 90.2 kWh, T = 25 to 1400 °C

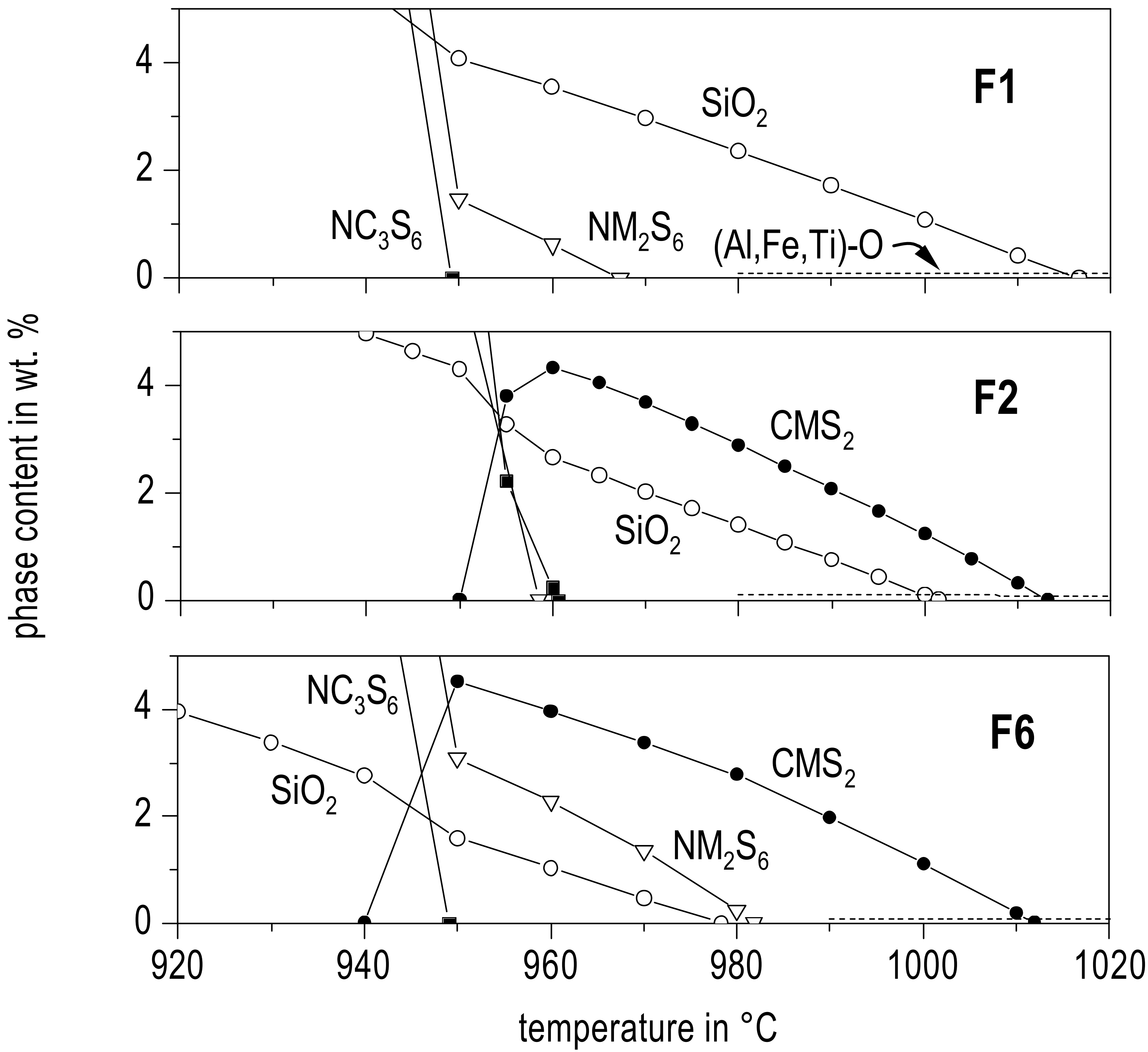
raw material i	kg/t	oxide j	kg/t	phase k	kg/t
sand	666.96	SiO_2	720.00	SiO_2	227.05
feldspar	77.15	Al_2O_3	15.00	$Na_2O{\cdot}Al_2O_3{\cdot}6SiO_2$	77.15
dolomite	182.98	MgO	40.00	$MgO{\cdot}SiO_2$	99.62
limestone	34.54	CaO	75.00	$Na_2O{\cdot}3CaO{\cdot}6SiO_2$	263.34
soda ash	240.91	Na_2O	150.00	$Na_2O{\cdot}2SiO_2$	332.84
		CO_2	202.54		
sum	1202.54		1202.54		1000.00

$H^\circ(batch)$ = 4589.5 kWh
$H^\circ(gl)$ = 3942.3 kWh
$H^\circ(gas)$ = 503.0 kWh;
ΔH°_{chem} = 144.2 kWh
$\Delta H_T(gl)$ = 404.1 kWh, T = 25 to 1200 °C
$\Delta H_T(gas)$ = 90.2 kWh, T = 25 to 1400 °C

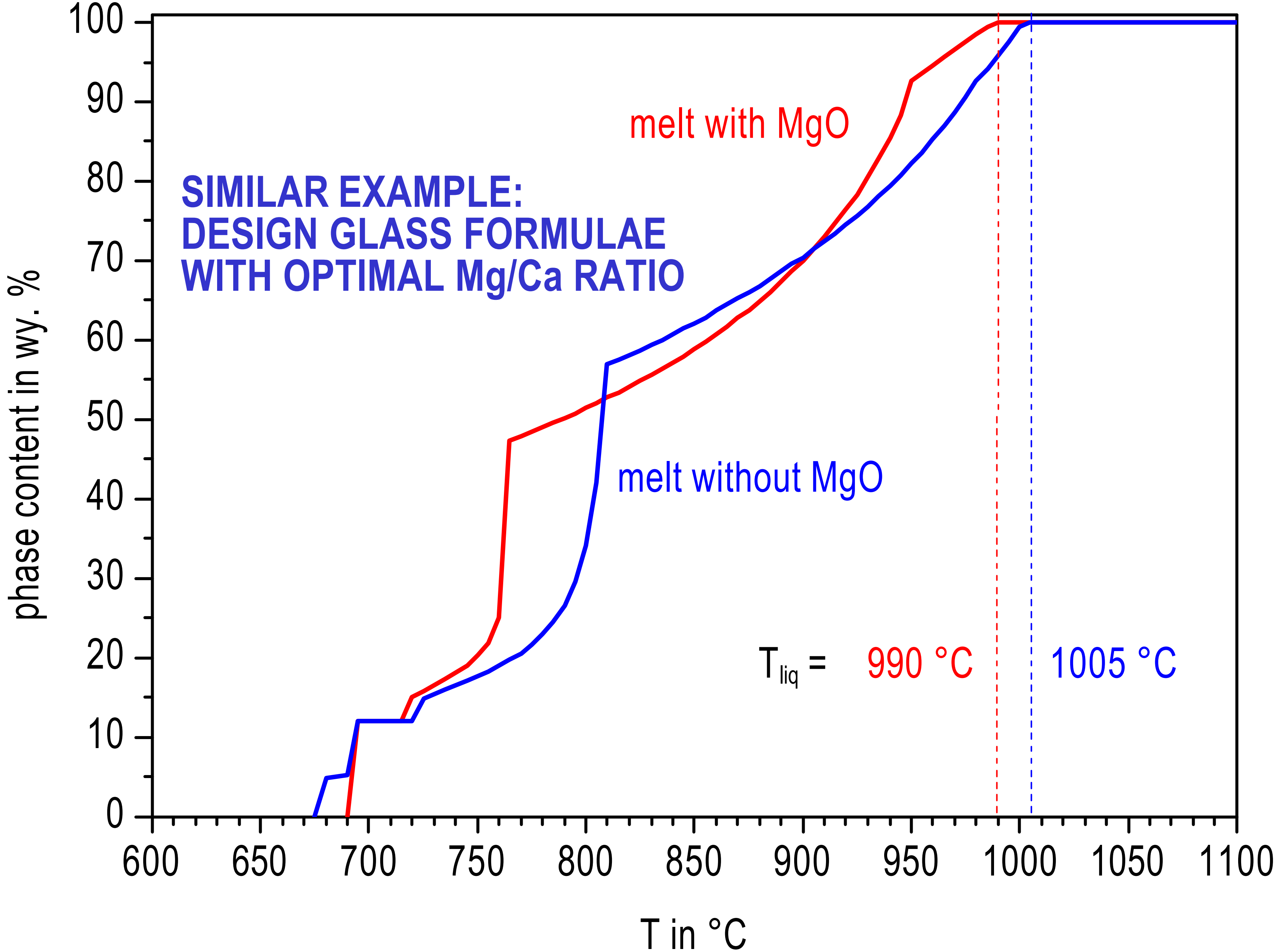
residual amount of crystalline SiO_2: >23 %, dissolved by diffusion, not by chem. reaction laboratory melts for round robin liquidus experiments

composition wt. %	F1	F2	F6
SiO2	72.6	72.6	72.0
TiO2	0.2	0.0	0.0
MgO	4.4	4.1	4.0
Na2O	13.5	14.0	13.5
CaO	8.4	8.8	8.5
K2O	0.2	0.0	0.7
Fe2O3	0.1	0.1	0.1
Al2O3	0.5	0.1	1.1
SO3	0.2	0.2	0.2

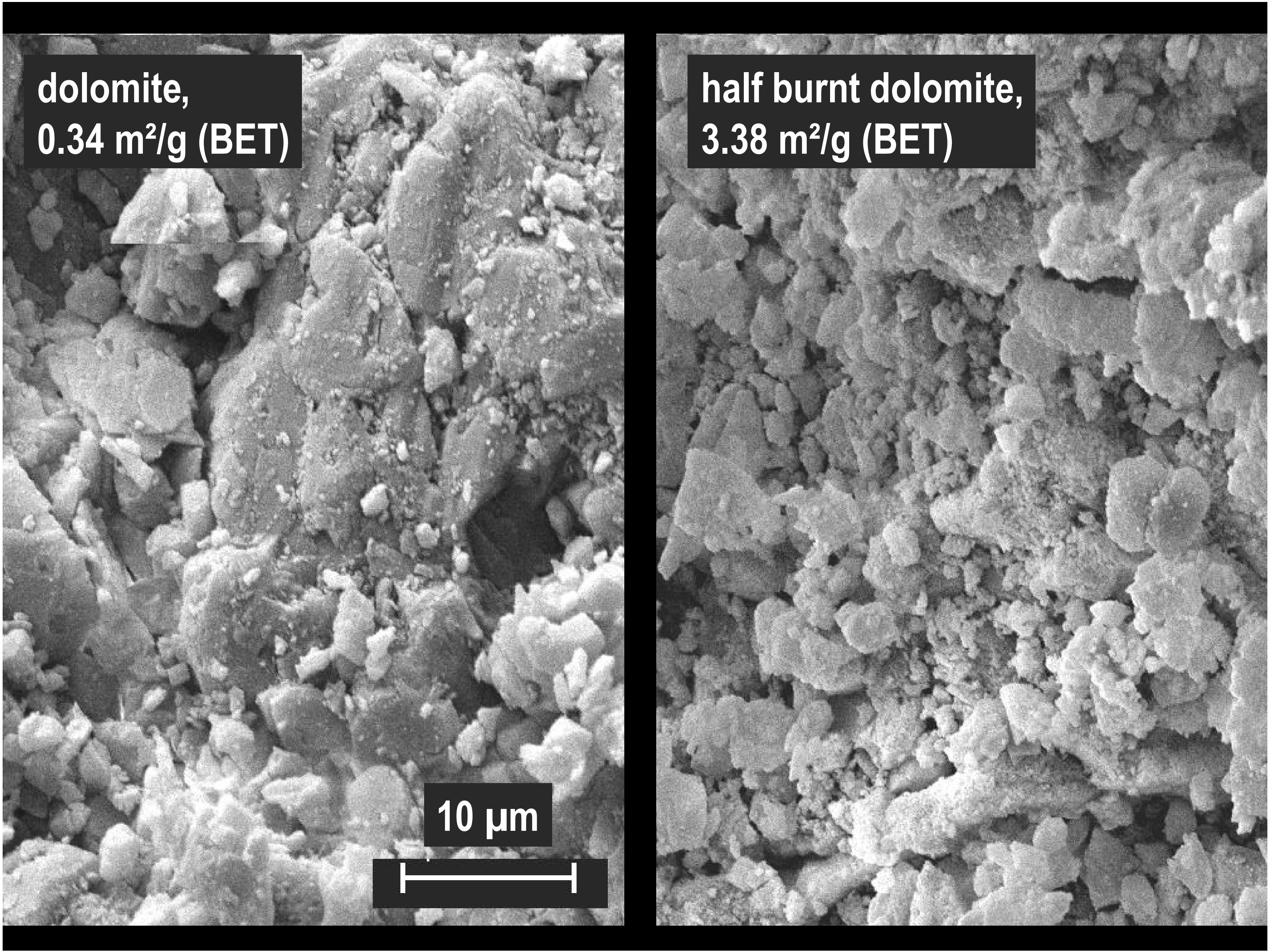
compound	F1	F2	F6
	wt. %	wt. %	wt. %
$CaO \cdot TiO_2$	0.34	-	-
SiO_2	26.65	26.61	24.25
$FeO \cdot Fe_2O_3$	0.09	0.09	0.09
$MgO \cdot SiO_2$	10.97	10.24	9.97
$Na_2O \cdot 3CaO \cdot 6SiO_2$	29.03	30.99	29.88
$K_2O \cdot Al_2O_3 \cdot 6SiO_2$	1.18	-	4.14
$FeO \cdot SiO_2$	0.02	0.02	0.02
$Na_2O \cdot Al_2O_3 \cdot 6SiO_2$	1.46	0.52	1.76
$Na_2O \cdot 2SiO_2$	30.26	31.53	29.89
sum	100.00	100.00	100.00



F1
SiO$_2$
NC$_3$S$_6$
NM$_2$S$_6$
(Al,Fe,Ti)-O
F2
CMS$_2$
SiO$_2$
F6
NC$_3$S$_6$
SiO$_2$
CMS$_2$
NM$_2$S$_6$
phase content in wt. %
temperature in °C


SIMILAR EXAMPLE:
DESIGN GLASS FORMULAE
WITH OPTIMAL Mg/Ca RATIO
melt with MgO
melt without MgO
T liq = 990 °C 1005 °C
phase content in wy. %
T in °C
0
10
20
30
40
50
60
70
80
90
100
600
650
700
750
800
850
900
950
1000
1050
1100

low enthalpy batches

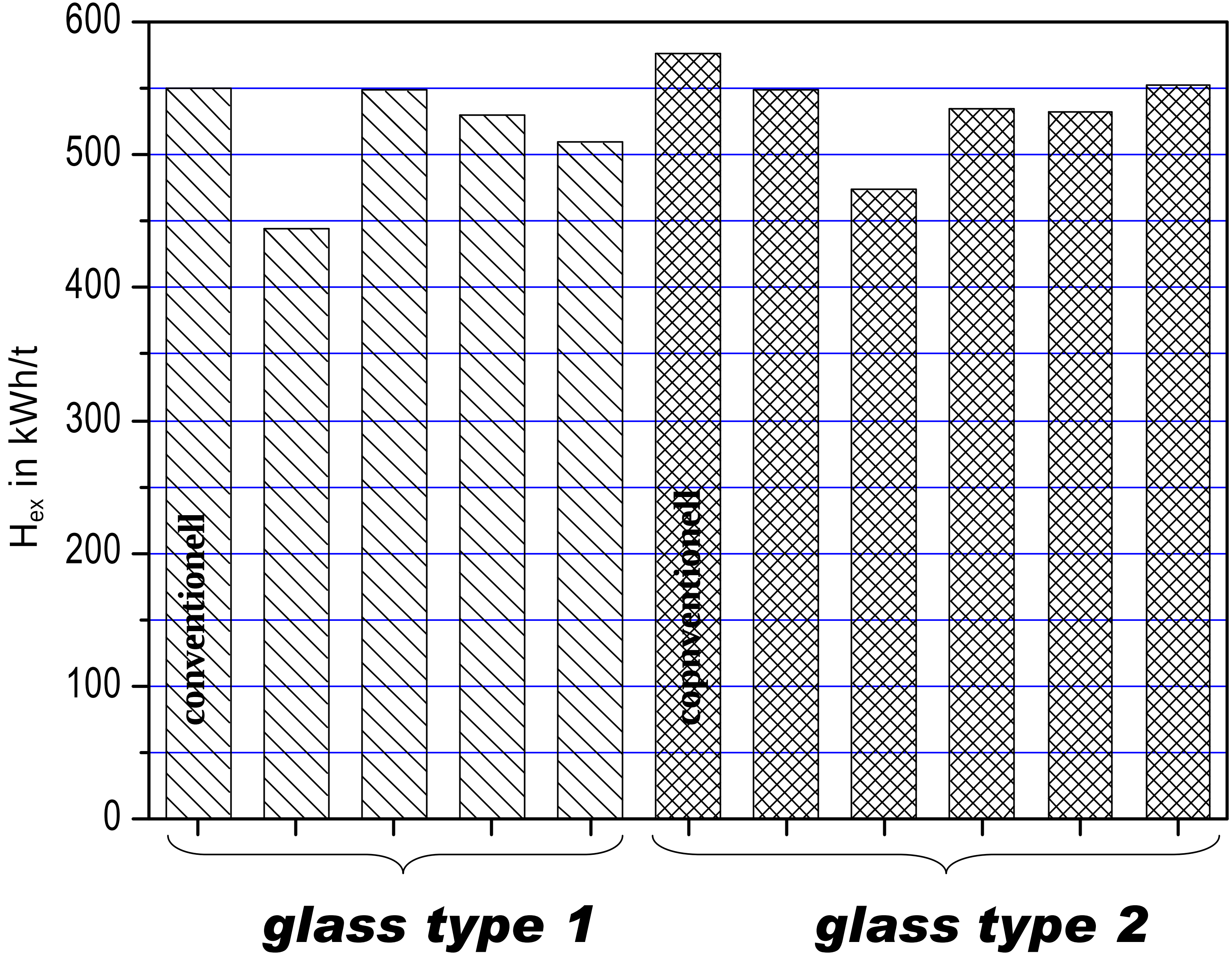

dolomite,
0.34 m²/g (BET)
10 µm
half burnt dolomite,
3.38 m²/g (BET)

	H°	$\Delta_r H^\circ$	$\Delta_r H^\circ$ per [MgO]		4 % MgO
	kJ/mol	kJ/mol	MJ/kg	kWh/kg	kWh/t glass
dolomite	2314.2	290.7	7.21	2.00	80
half-burnt	1808.5	178.5	4.43	1.23	49
difference		112.2	2.78	0.77	31

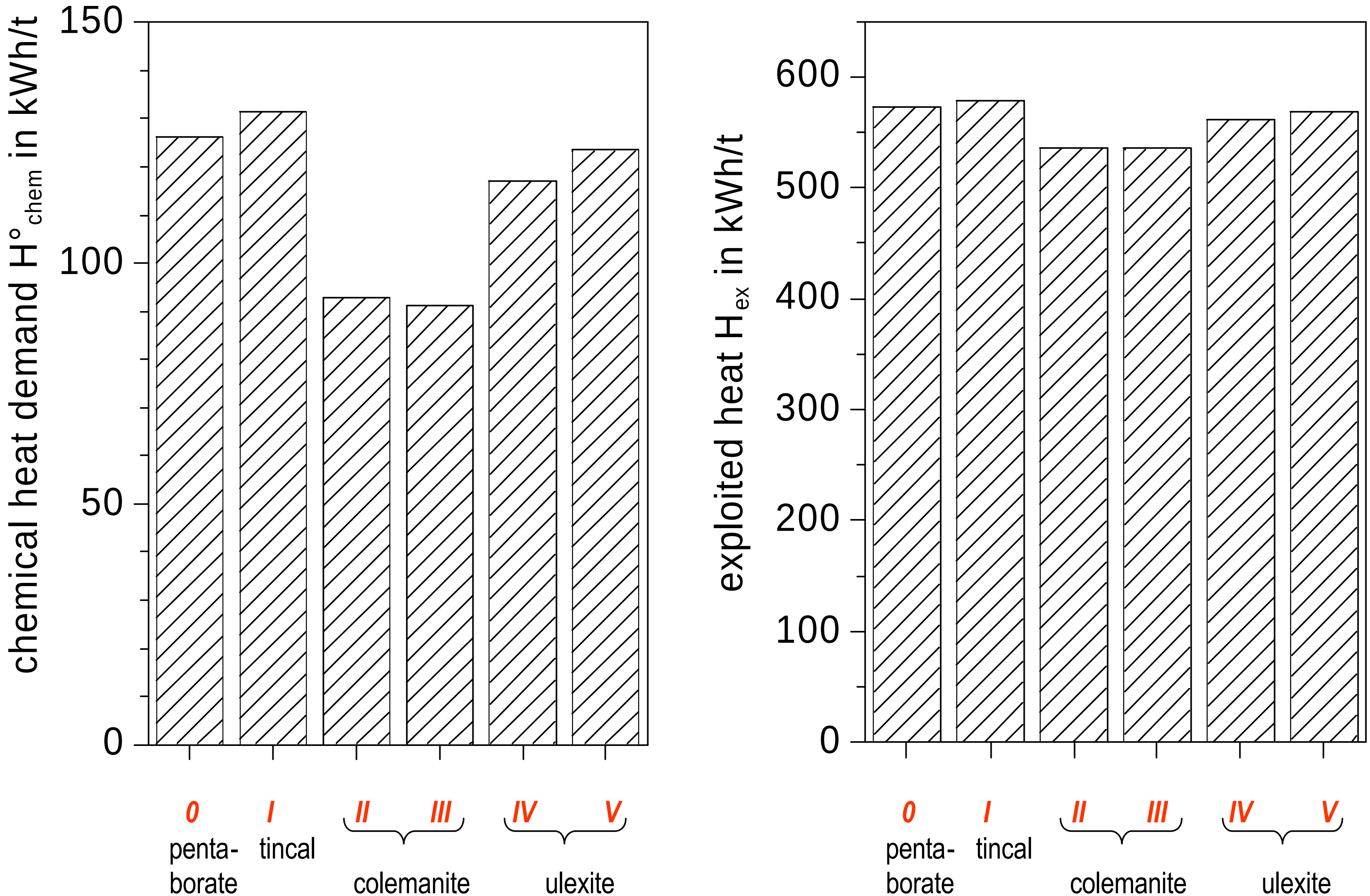
depending on η_{ex} (30 – 55 %) $\Rightarrow$ 60 – 105 kWh (0 % cullet)
43 – 80 kWh (25 %)

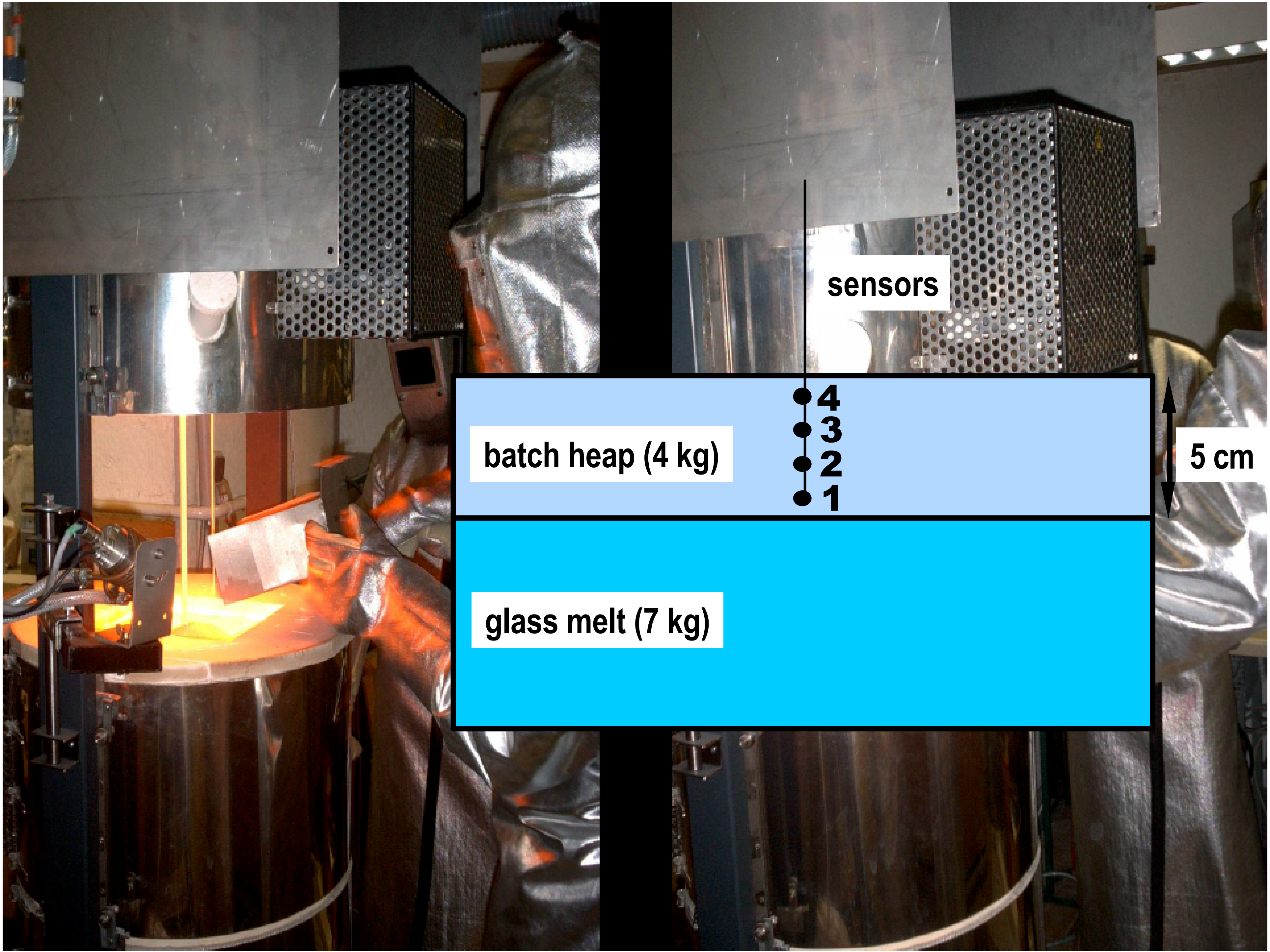
different lime and dolomite based raw materials

H_{ex} at T_{ex} = 1300 °C (no cullet)

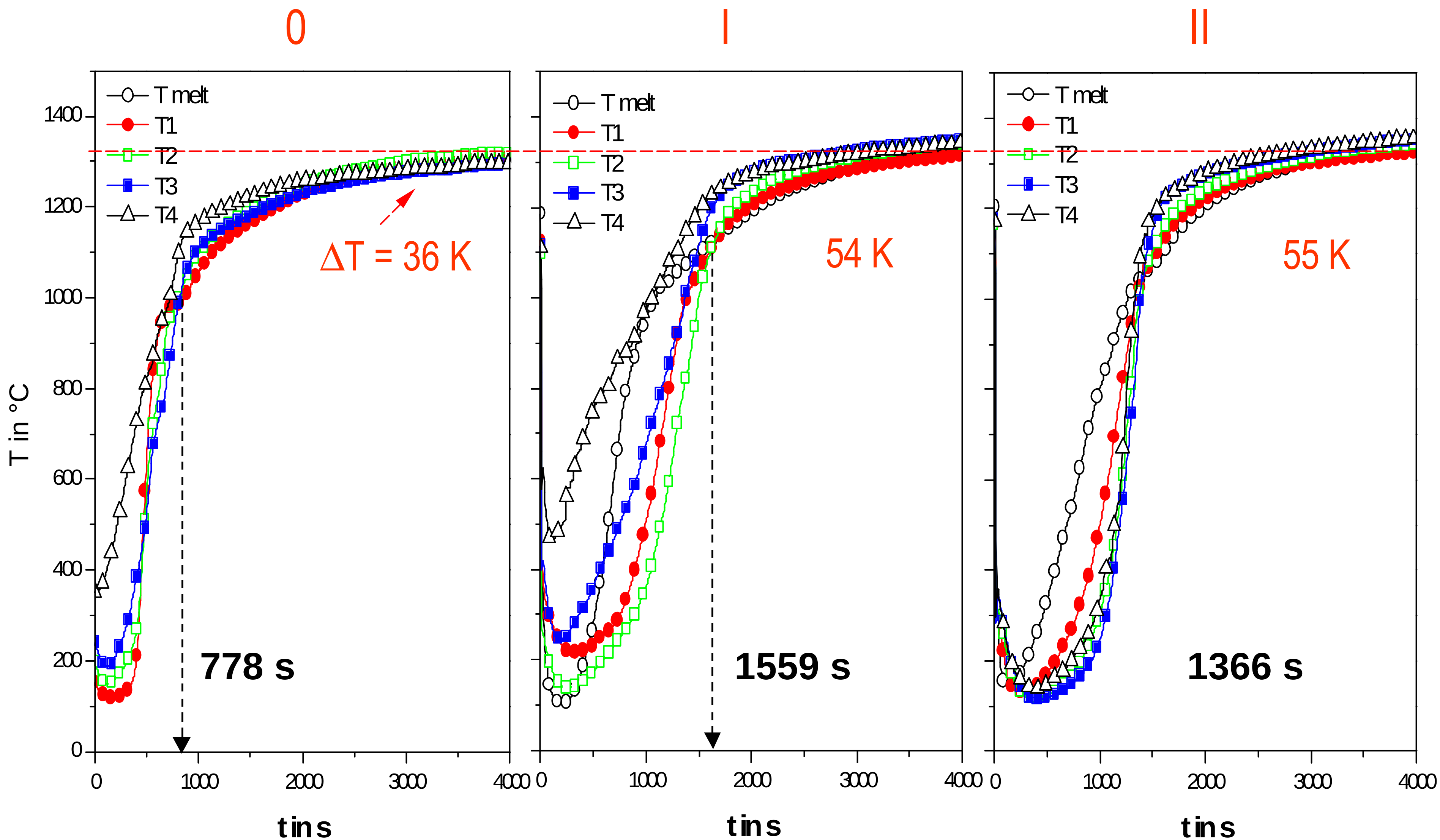


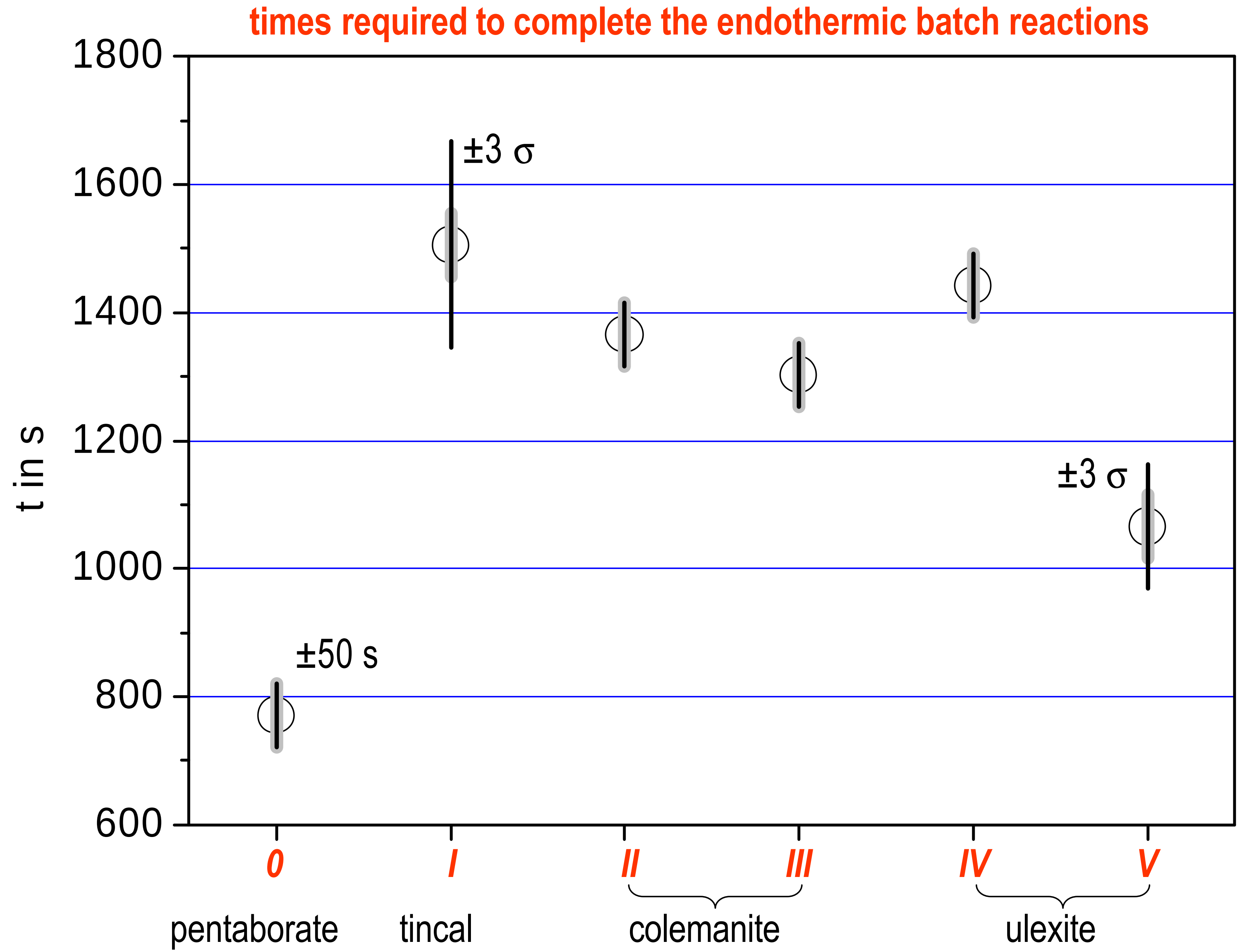
energy demand, calculated for batches with different boron oxide carriers (yielding identical glass composition)




sensors
4
3
2
1
batch heap (4 kg)
5 cm
glass melt (7 kg)

times required to complete the endothermic batch reactions
and temperature homogeneity after 1 h of melting




times required to complete the endothermic batch reactions
1800
1600
1400
1200
1000
800
600
t in s
±3 σ
±3 σ
±50 s
0
I
II
III
IV
V
pentaborate
tincal
colemanite
ulexite

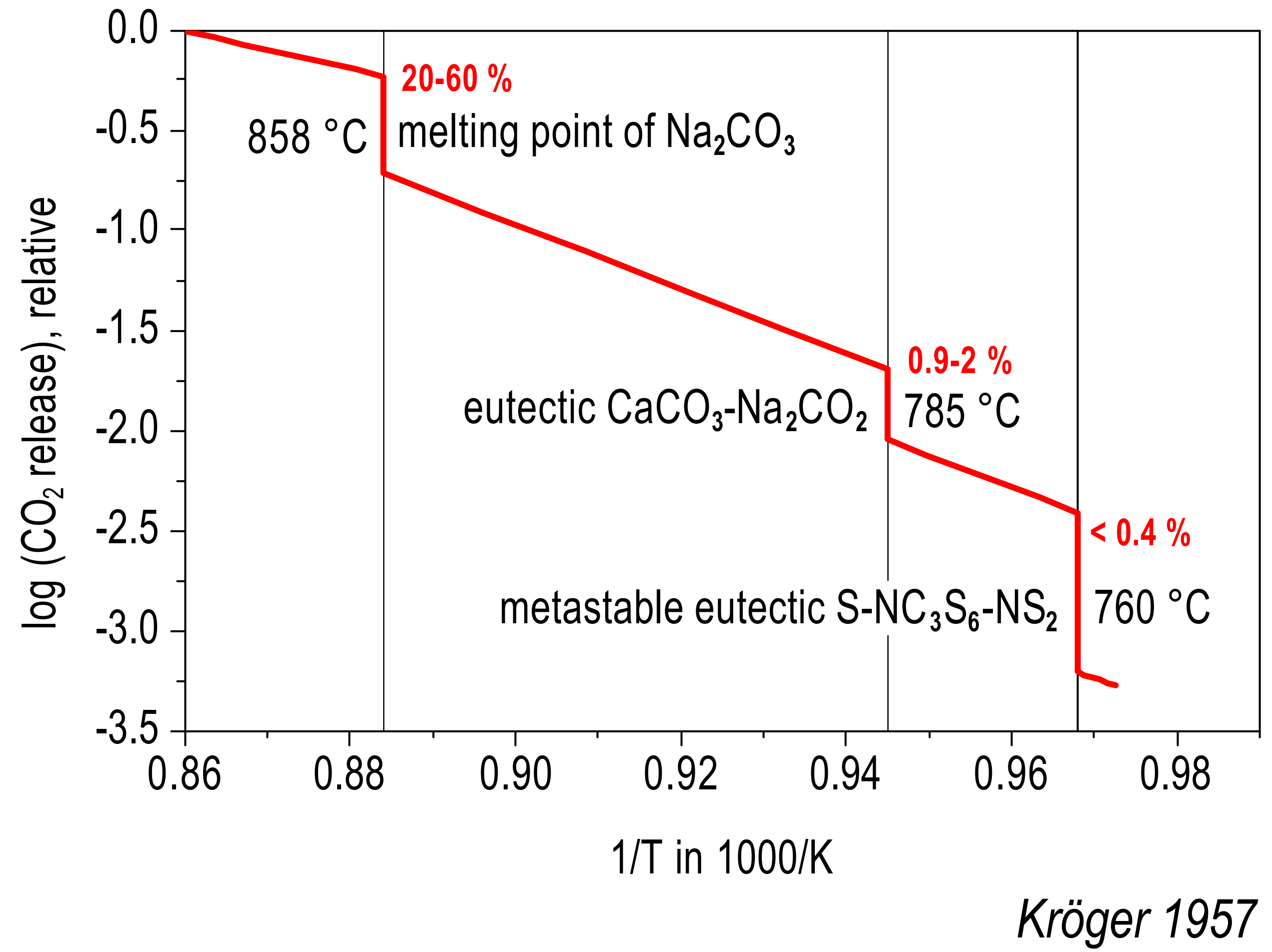
fast conversion rate batches

silicate formation reactions

		T in °C	T in K	-H°(T)	S°(T)	-G°(T)
		256		kJ/mol	J/(mol·K)	kJ/mol
SiO_2	quartz		529	898.5	72.0	936.5
Na_2CO_3	soda ash		529	1100.3	207.1	1209.8
$CaCO_3$	limestone		529	1184.5	147.8	1262.6
$CO_2(g)$			529	383.7	237.8	509.5
$Na_2O \cdot SiO_2$			529	1533.1	187.4	1632.3
$Na_2O \cdot 2SiO_2$			529	2430.5	270.1	2573.4
$2Na_2O \cdot CaO \cdot 3SiO_2$			529	4680.3	513.5	4952.0

reaction			**dG**	**Teq in °C**
$Na_2CO_3 + SiO_2$	<===>	$Na_2O \cdot SiO_2 + CO_2$	**0.0**	**287**
$Na_2CO_3 + 2SiO_2$	<===>	$Na_2O \cdot 2SiO_2 + CO_2$	**0.0**	**256**
$2Na_2CO_3 + CaCO_3 + 3SiO_2$	<===>	$2Na_2O \cdot CaO \cdot 3SiO_2 + 3CO_2$	**0.0**	**281**

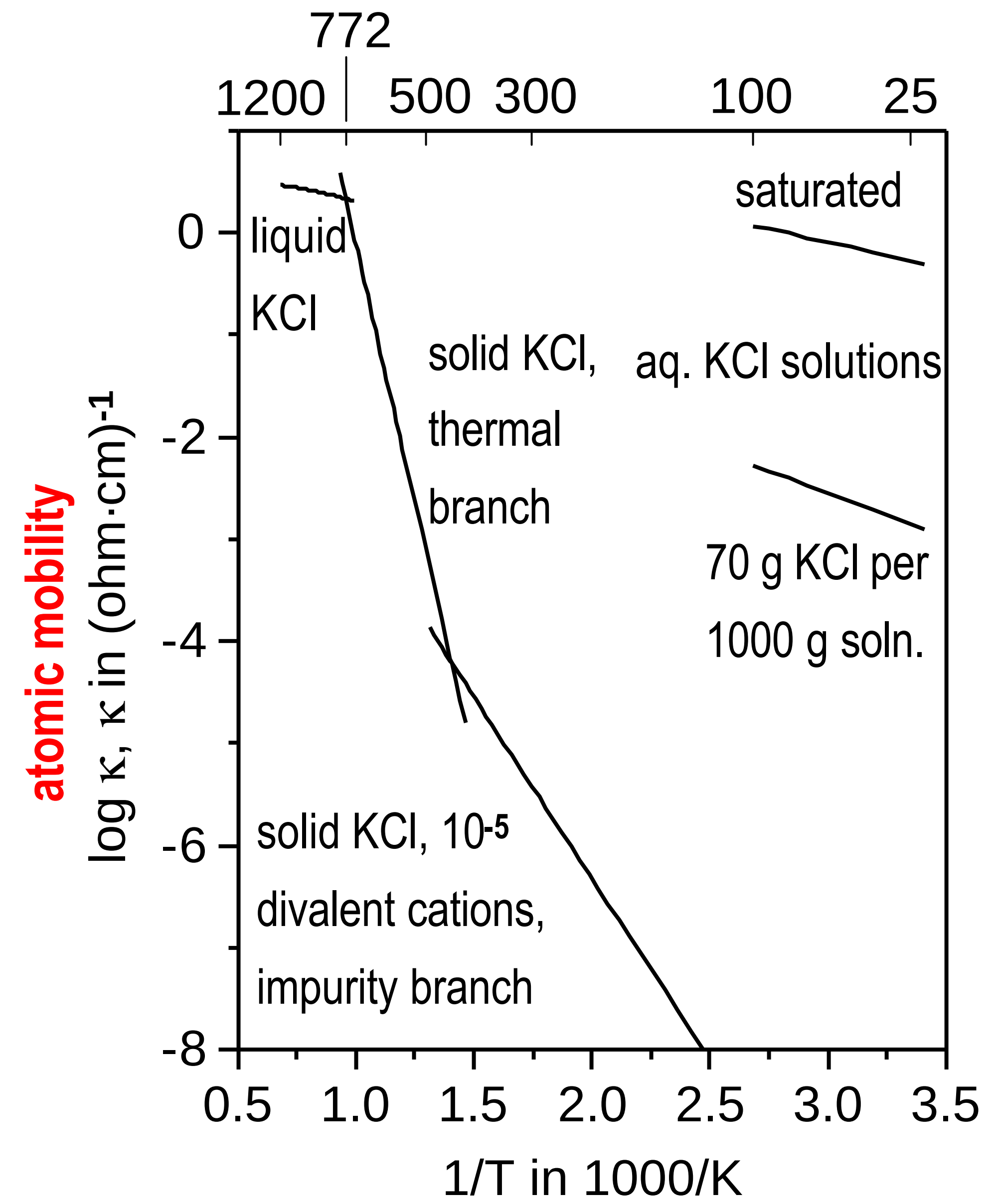
innovation potential



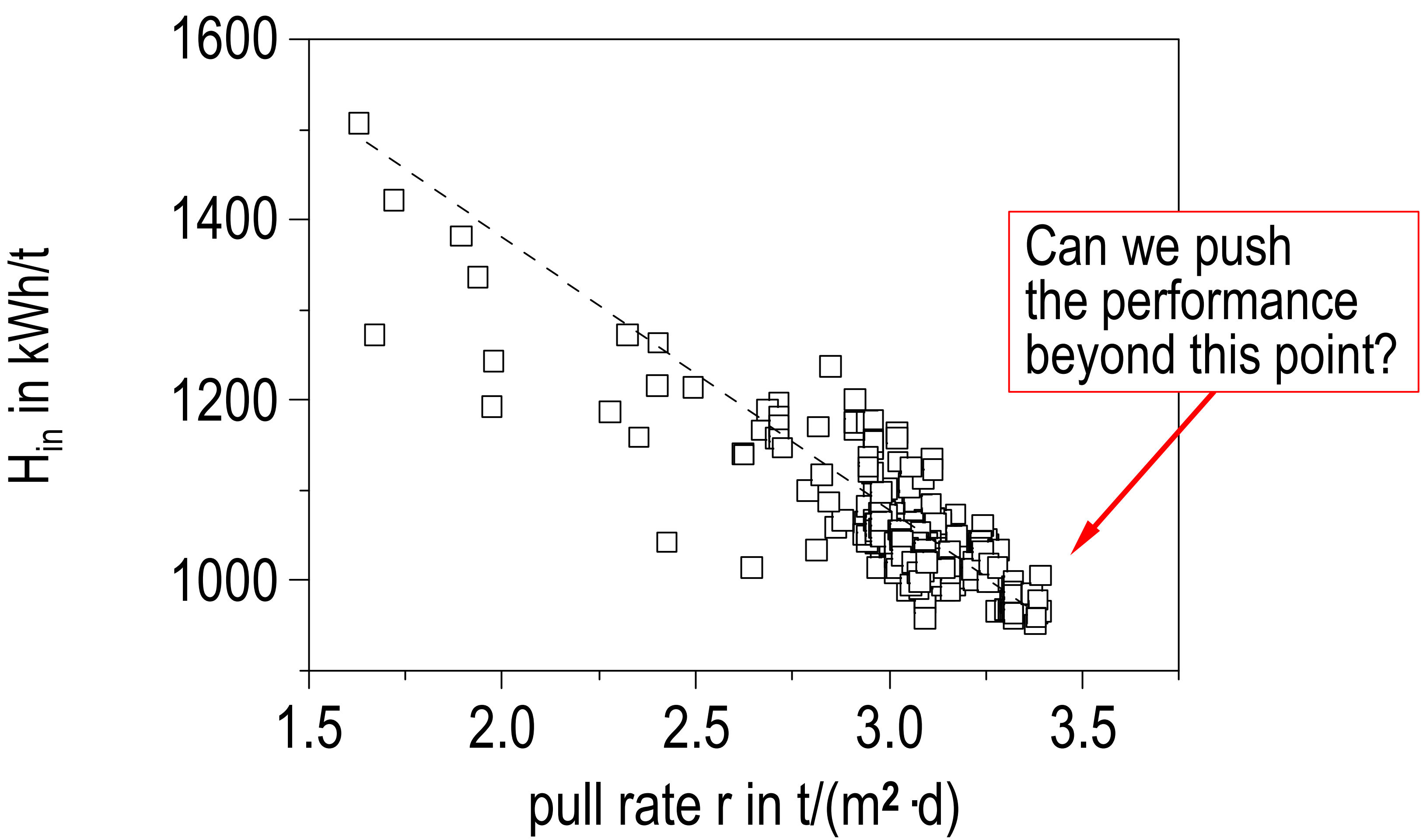
reactions gain turnover as soon as a liquid phase occurs

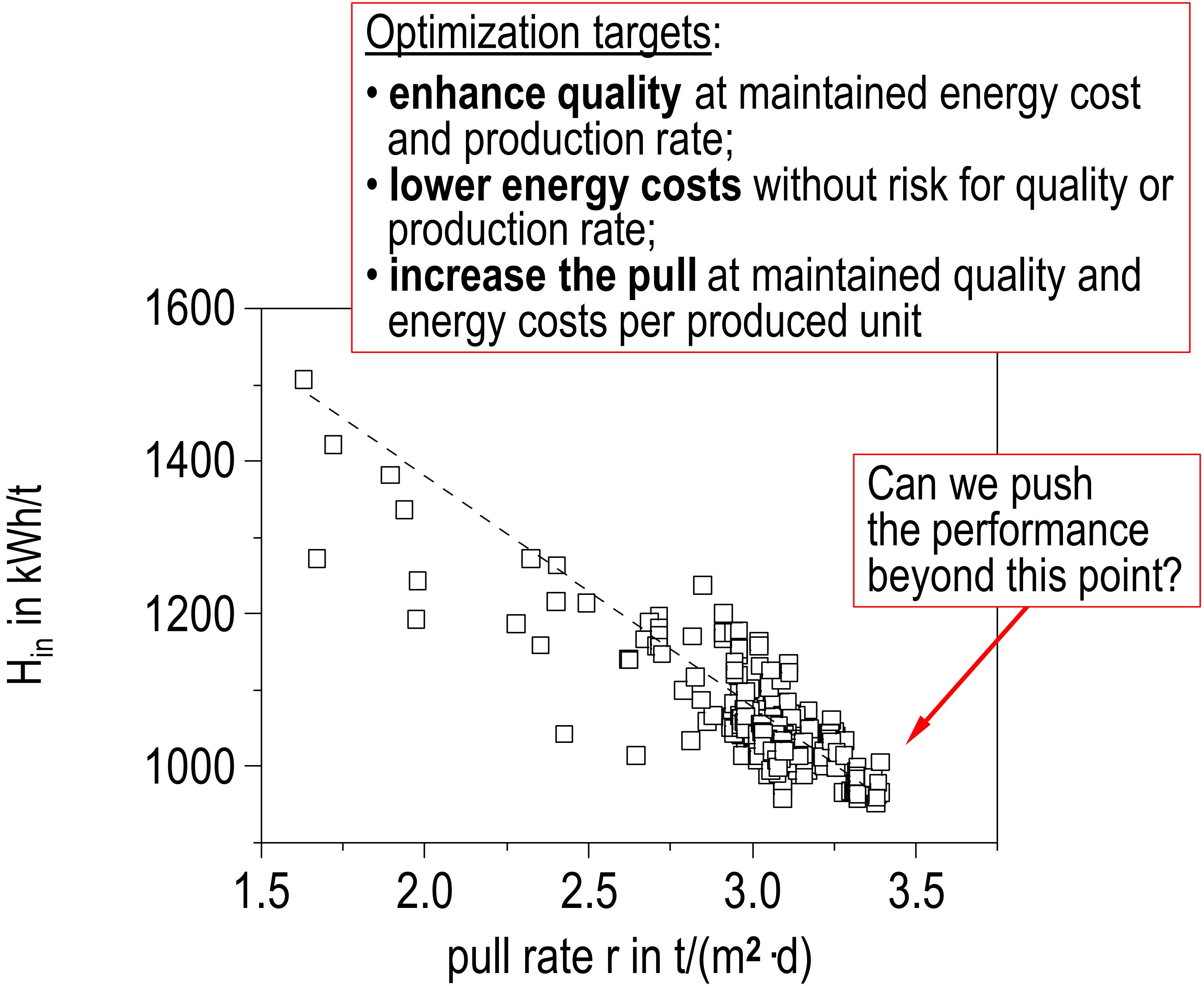
$$reaction\ turnover = \frac{contactf \times mobility}{distance}$$

- *grain size,*
- *grain-to-grain contact,*
- *humidity,*
- *temperature*



- transfer to the industrial scale
- analysis of furnace behavior
- verification by melt campaigns


1600
1400
1200
1000
H_in in kWh/t
1.5
2.0
2.5
3.0
3.5
pull rate r in t/(m² ·d)
Can we push
the performance
beyond this point?


Optimization targets:
• enhance quality at maintained energy cost and production rate;
• lower energy costs without risk for quality or production rate;
• increase the pull at maintained quality and energy costs per produced unit
Can we push the performance beyond this point?
1600
1400
1200
1000
H_in in kWh/t
1.5
2.0
2.5
3.0
3.5
pull rate r in t/(m² ·d)

melting behavior

=

heat demand

⊕

quartz dissolution rate

⊕

gas release rate

⇒

furnace performance

=

heat transfer

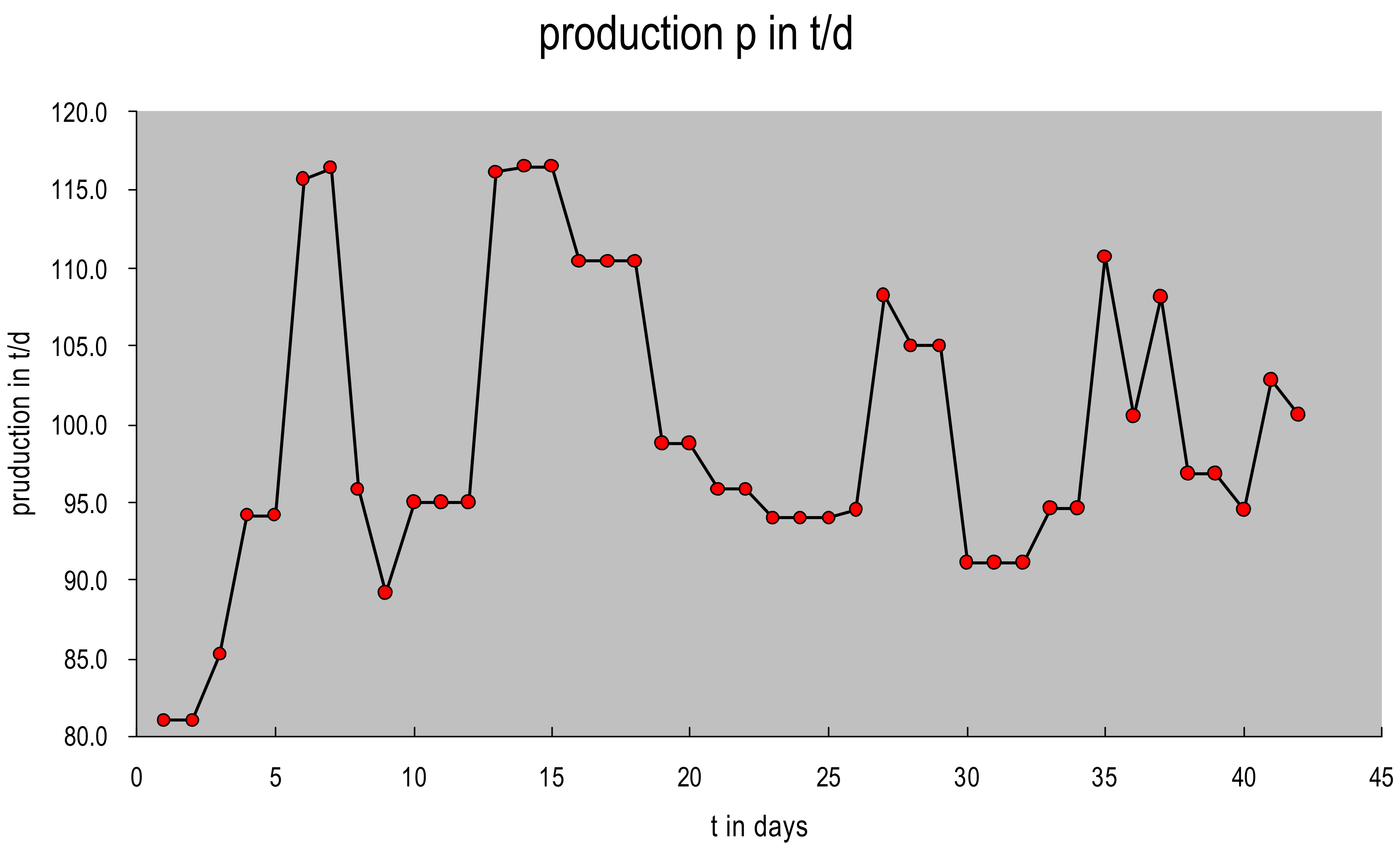
⊕

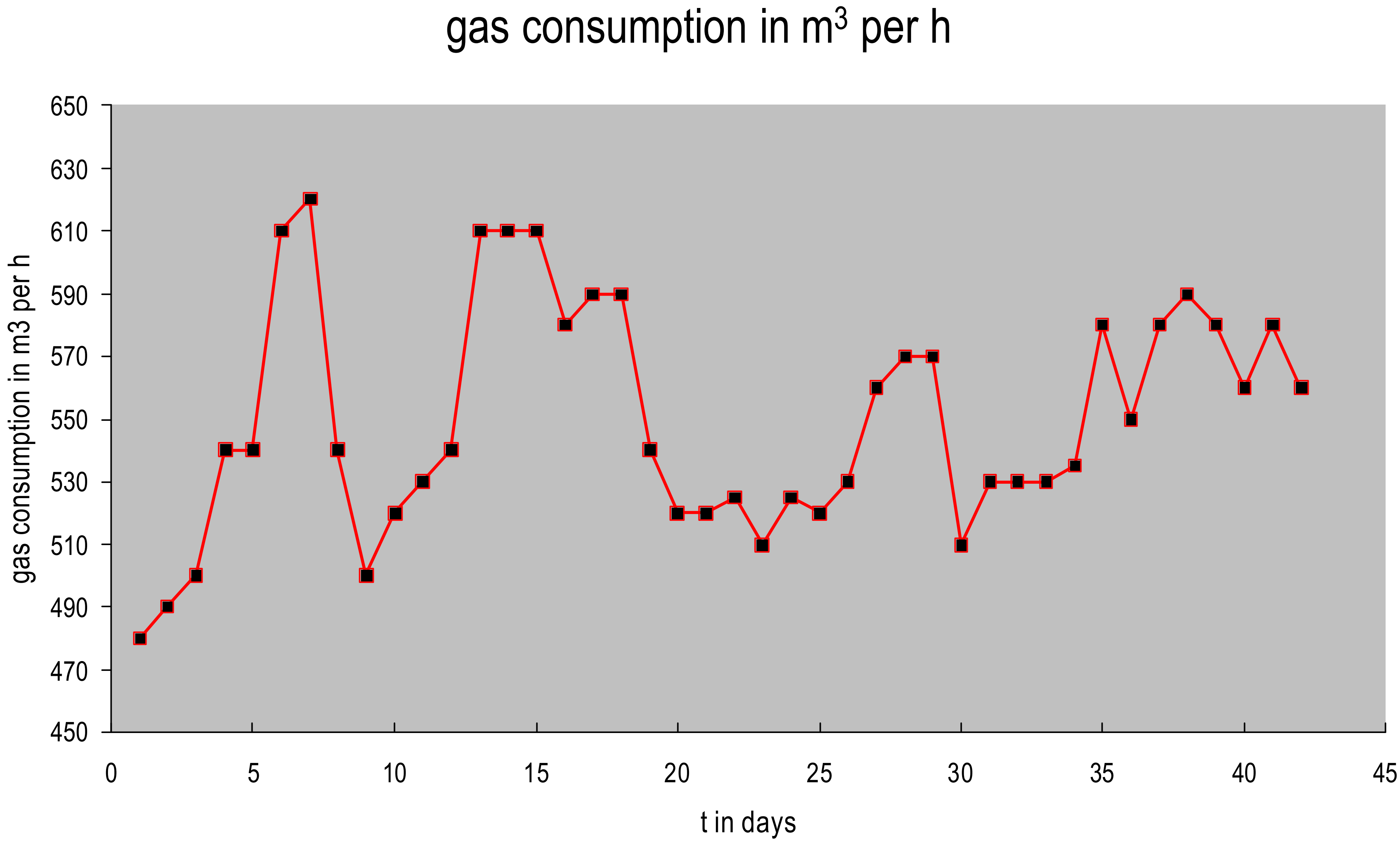
dwell time characteristics

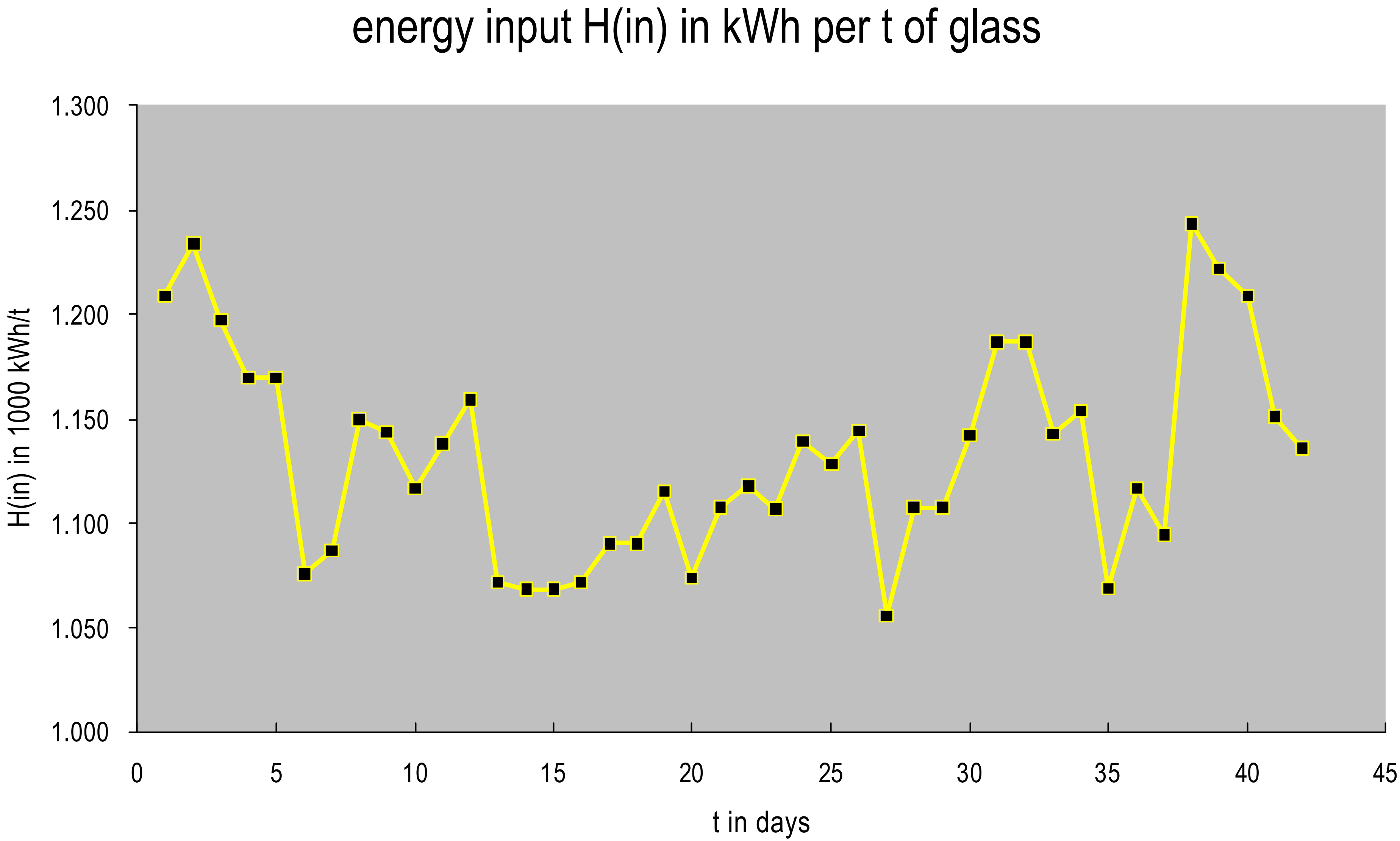
time	p	T01	T03	T05	B1	B2	B3
d	kg/h	°C	°C	°C	Nm3/h	Nm3/h	Nm3/h
0.00	5855.2	1444	1586	1629	261.6	65.2	225.0
0.25	5510.8	1445	1586	1624	260.8	65.2	224.4
0.50	5855.2	1441	1581	1619	260.3	65.3	223.8
0.75	6199.7	1442	1580	1619	260.5	65.2	224.1
1.00	5855.2	1443	1580	1619	261.7	65.1	225.0
1.25	6199.7	1448	1590	1625	261.6	64.9	225.0
1.50	5510.8	1447	1585	1624	261.2	65.3	224.7
1.75	5855.2	1442	1584	1621	260.2	65.1	223.8
2.00	6199.7	1441	1578	1619	260.2	65.1	223.8
2.25	6199.7	1443	1581	1618	260.7	65.2	224.3
2.50	5855.2	1443	1581	1618	261.7	65.5	225.1
2.75	6199.7	1442	1578	1618	261.8	65.4	225.2
3.00	5855.2	1446	1586	1622	265.5	66.3	228.2
3.25	5855.2	1450	1596	1629	266.5	66.6	229.2
3.50	5855.2	1455	1598	1632	263.9	66.1	227.0
3.75	5855.2	1450	1589	1624	259.7	65.0	223.3
4.00	5855.2	1446	1585	1621	258.1	64.5	222.0
4.25	5855.2	1445	1587	1621	256.6	64.1	220.6
4.50	6199.7	1442	1584	1618	255.4	63.9	219.6
4.75	5510.8	1442	1581	1617	255.3	63.9	219.6

Furnace data, collected over 6 weeks; melting area = 40 m²

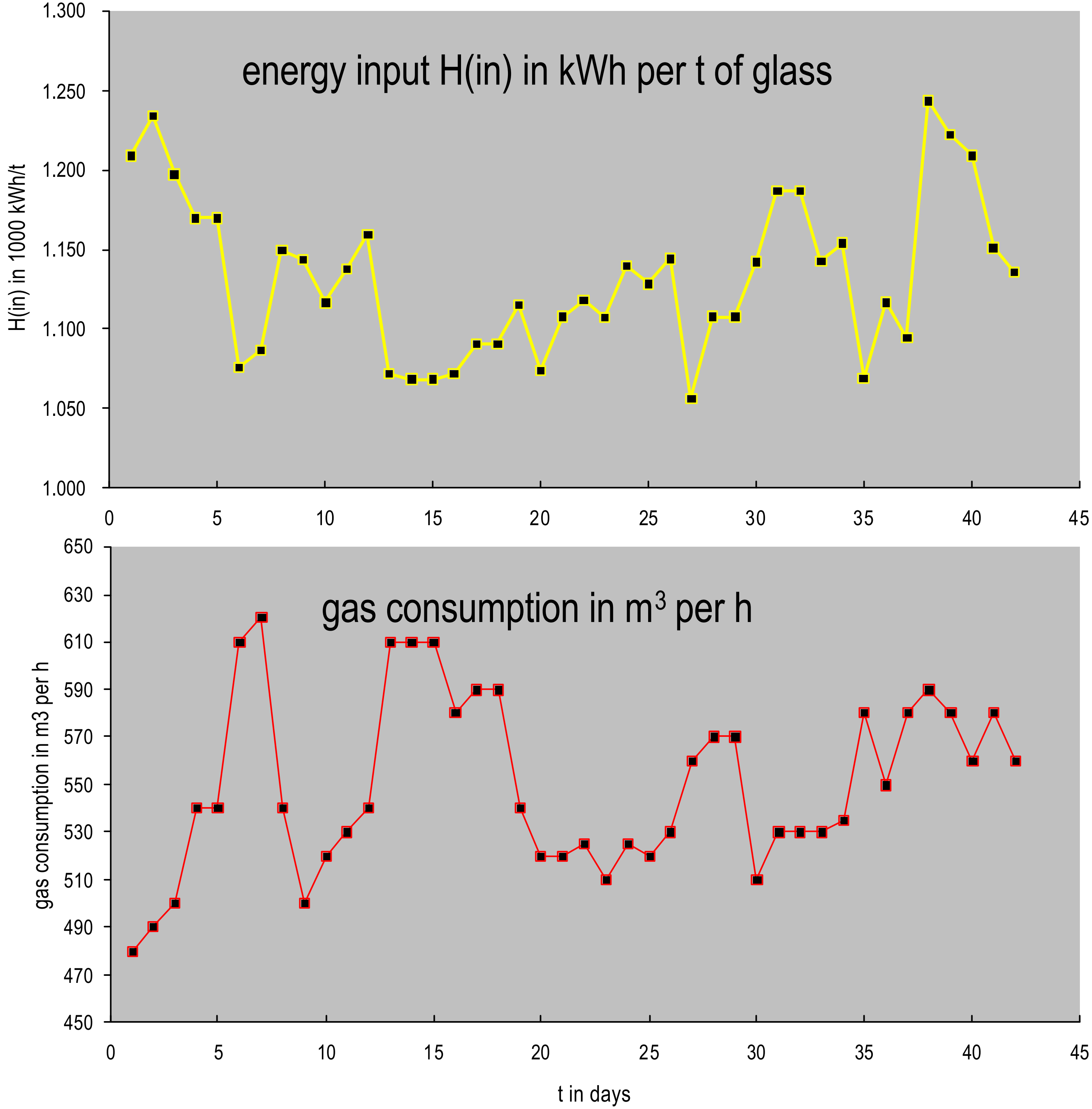
no.	date	p t/d	r t/m²·d	r t/m²·h	gas Nm3/h	gas Nm3/d	Hin kwh/kg	1/r m²·h/t	qin kW/m2	Tex	Toff	Tre	Tstack
1	1	81.0	2.03	0.0844	480	11520	1.209	11.85	0.102				
2	2	81.0	2.03	0.0844	490	11760	1.234	11.85	0.104				
3	3	85.2	2.13	0.0888	500	12000	1.197	11.27	0.106				
4	4	94.2	2.36	0.0981	540	12960	1.169	10.19	0.115				
5	5	94.2	2.36	0.0981	540	12960	1.169	10.19	0.115				
6	6	115.7	2.89	0.1205	610	14640	1.076	8.30	0.130				
7	7	116.4	2.91	0.1213	620	14880	1.087	8.25	0.132				
8	8	95.8	2.40	0.0998	540	12960	1.150	10.02	0.115				
9	9	89.2	2.23	0.0929	500	12000	1.143	10.76	0.106				
10	10	95.0	2.38	0.0990	520	12480	1.117	10.11	0.111				
11	11	95.0	2.38	0.0990	530	12720	1.138	10.11	0.113				
12	12	95.0	2.38	0.0990	540	12960	1.160	10.11	0.115				
13	13	116.1	2.90	0.1209	610	14640	1.072	8.27	0.130				
14	14	116.5	2.91	0.1214	610	14640	1.068	8.24	0.130				
15	15	116.5	2.91	0.1214	610	14640	1.068	8.24	0.130				
16	16	110.4	2.76	0.1150	580	13920	1.072	8.70	0.123				
17	17	110.4	2.76	0.1150	590	14160	1.090	8.70	0.125				
18	18	110.4	2.76	0.1150	590	14160	1.090	8.70	0.125				
19	19	98.8	2.47	0.1029	540	12960	1.115	9.72	0.115				
20	20	98.8	2.47	0.1029	520	12480	1.074	9.72	0.111				
21	21	95.8	2.40	0.0998	520	12480	1.107	10.02	0.111				
22	22	95.8	2.40	0.0998	525	12600	1.118	10.02	0.112				
23	23	94.0	2.35	0.0979	510	12240	1.107	10.21	0.108				
24	24	94.0	2.35	0.0979	525	12600	1.139	10.21	0.112				
25	25	94.0	2.35	0.0979	520	12480	1.129	10.21	0.111				

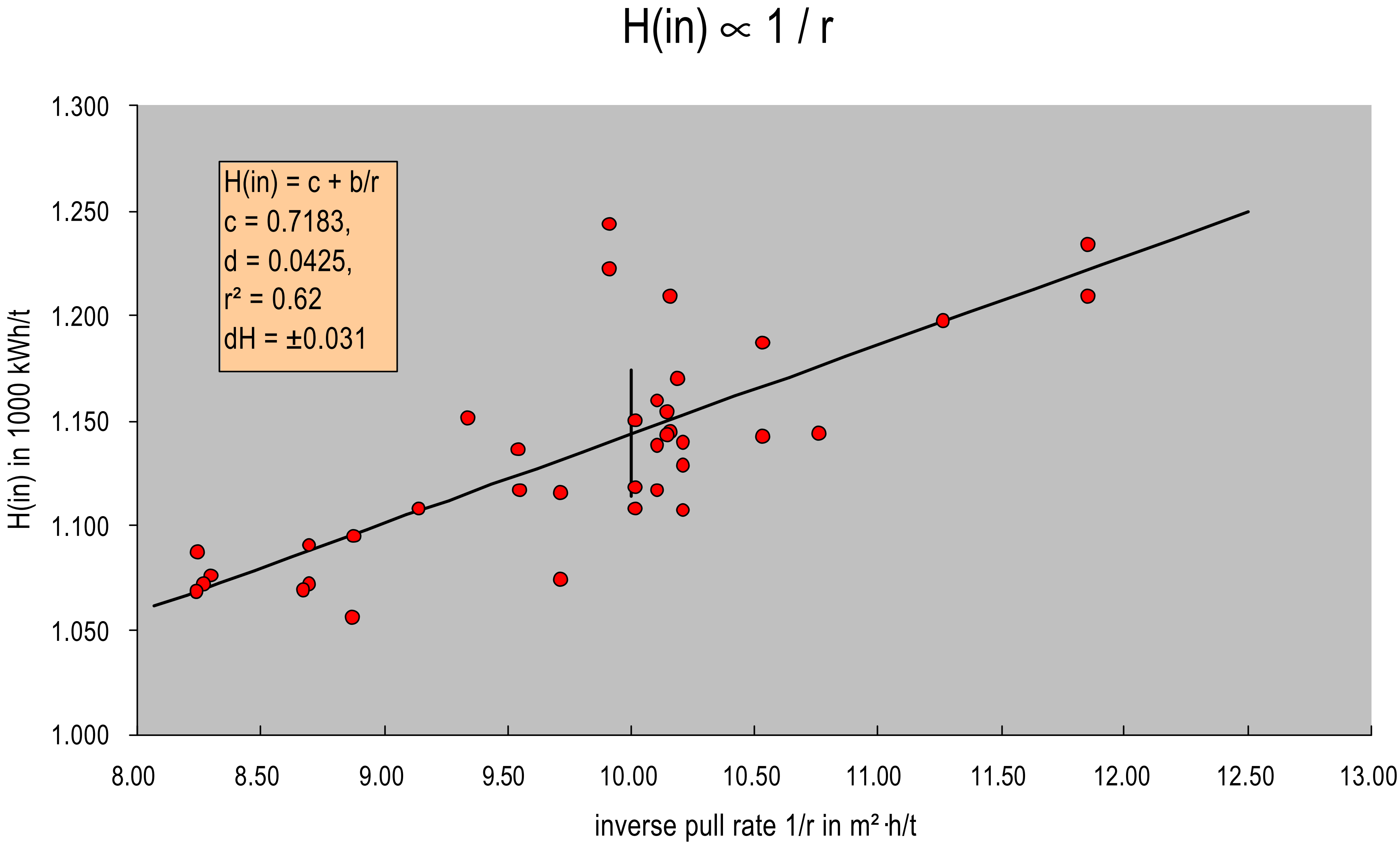

production p in t/d
pruduction in t/d
t in days
120.0
115.0
110.0
105.0
100.0
95.0
90.0
85.0
80.0
0
5
10
15
20
25
30
35
40
45


gas consumption in m3 per h
gas consumption in m3 per h
650
630
610
590
570
550
530
510
490
470
450
0
5
10
15
20
25
30
35
40
45
t in days

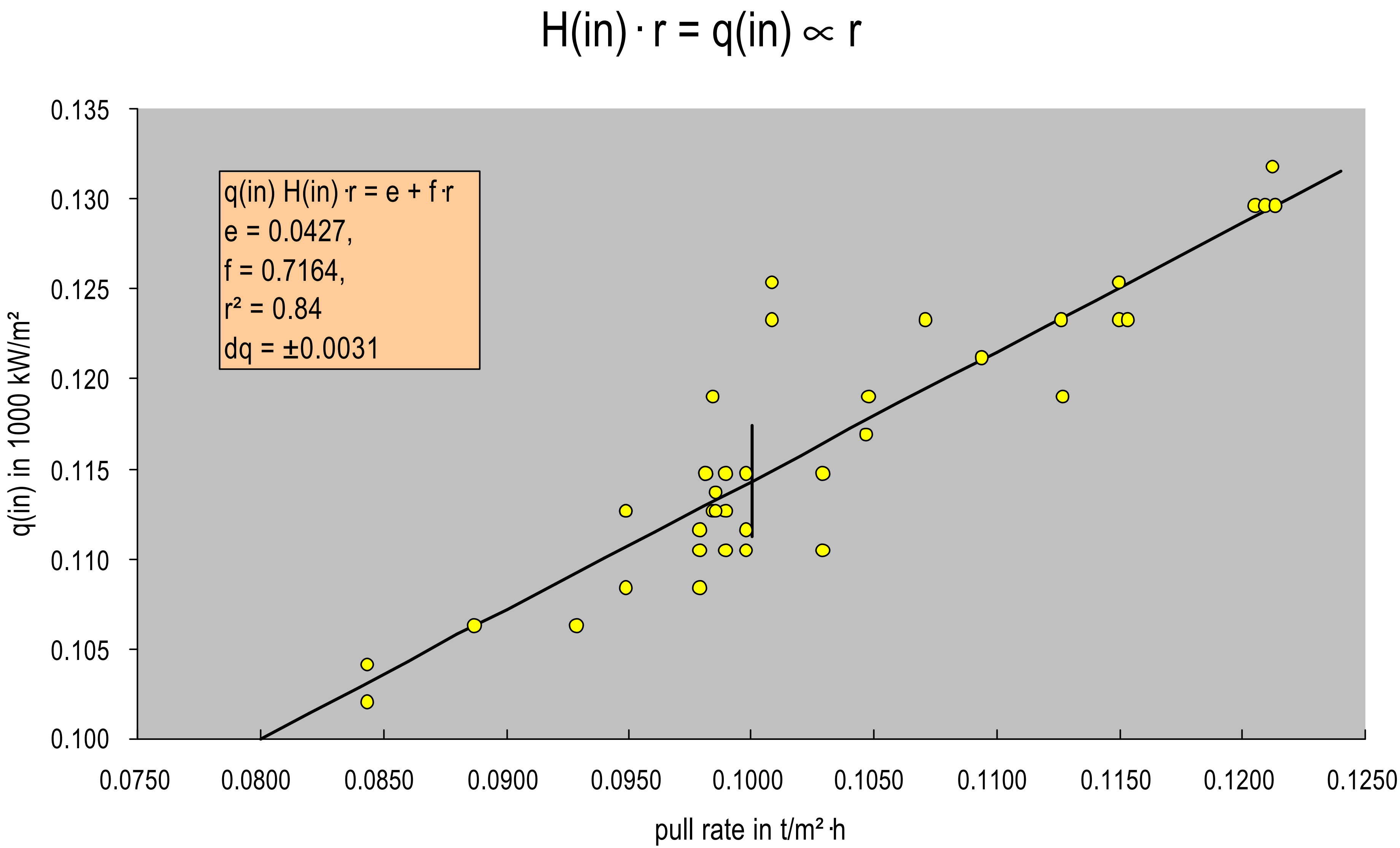


energy input H(in) in kWh per t of glass
H(in) in 1000 kWh/t
1.300
1.250
1.200
1.150
1.100
1.050
1.000
0
5
10
15
20
25
30
35
40
45
t in days


energy input H(in) in kWh per t of glass
H(in) in 1000 kWh/t
1.300
1.250
1.200
1.150
1.100
1.050
1.000
0
5
10
15
20
25
30
35
40
45
gas consumption in m3 per h
gas consumption in m3 per h
650
630
610
590
570
550
530
510
490
470
450
0
5
10
15
20
25
30
35
40
45
t in days

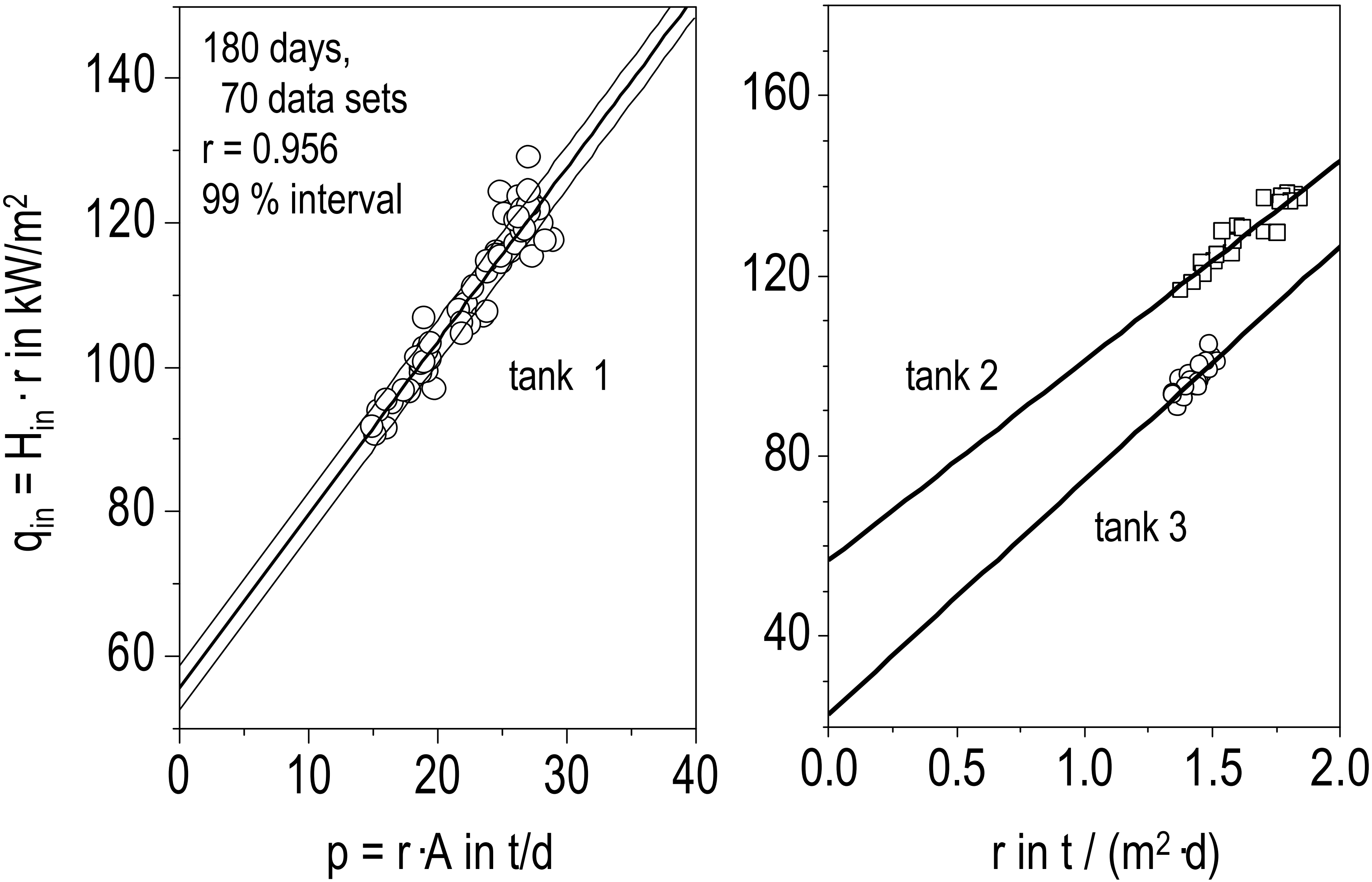


H(in) ∝ 1 / r
H(in) = c + b/r
c = 0.7183,
d = 0.0425,
r² = 0.62
dH = ±0.031
1.300
1.250
1.200
1.150
1.100
1.050
1.000
H(in) in 1000 kWh/t
8.00
8.50
9.00
9.50
10.00
10.50
11.00
11.50
12.00
12.50
13.00
inverse pull rate 1/r in m²·h/t



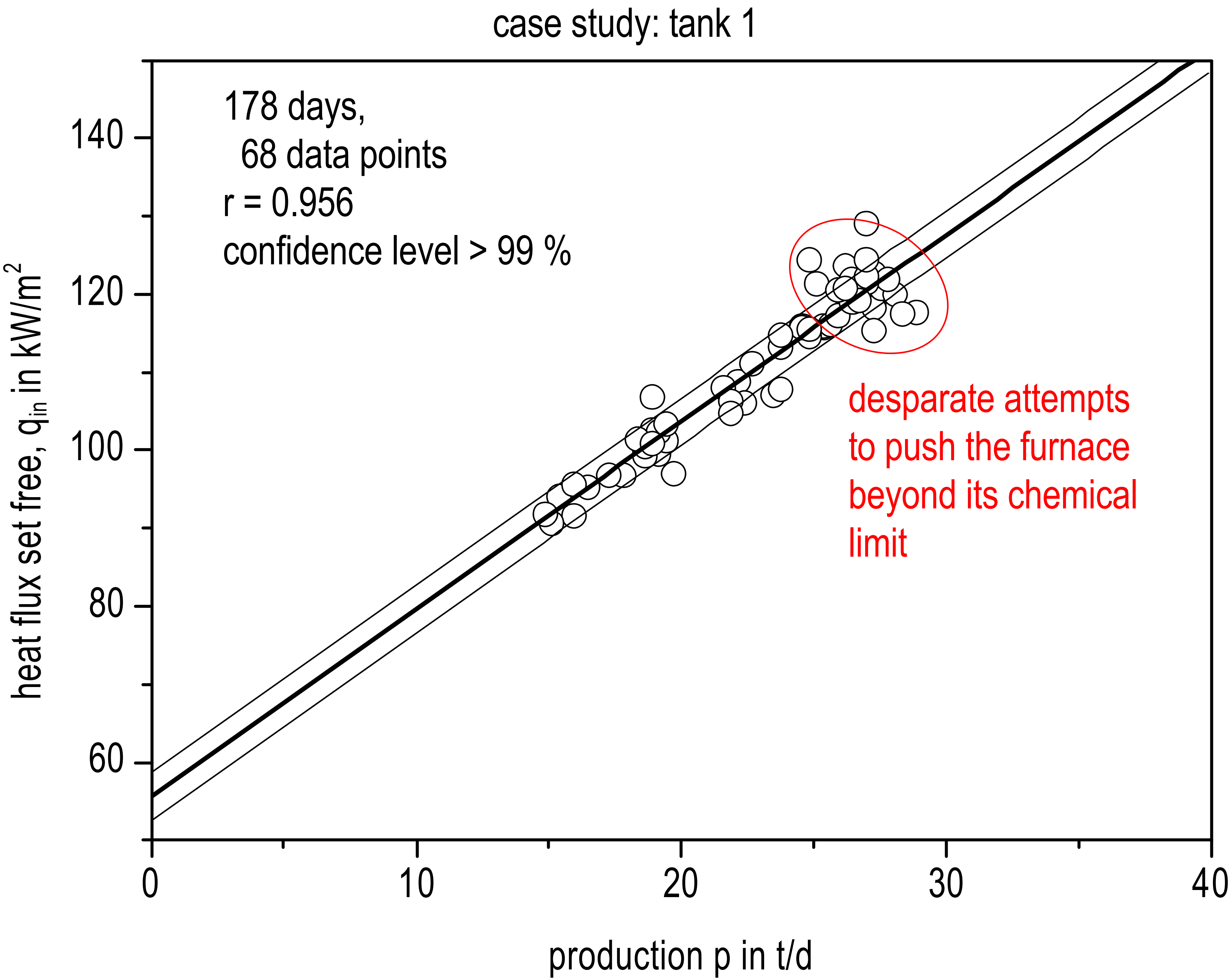
H(in) · r = q(in) ∝ r
q(in) H(in) ·r = e + f ·r
e = 0.0427,
f = 0.7164,
r² = 0.84
dq = ±0.0031
0.135
0.130
0.125
0.120
0.115
0.110
0.105
0.100
q(in) in 1000 kW/m²
0.0750
0.0800
0.0850
0.0900
0.0950
0.1000
0.1050
0.1100
0.1150
0.1200
0.1250
pull rate in t/m² ·h

industrial case studies

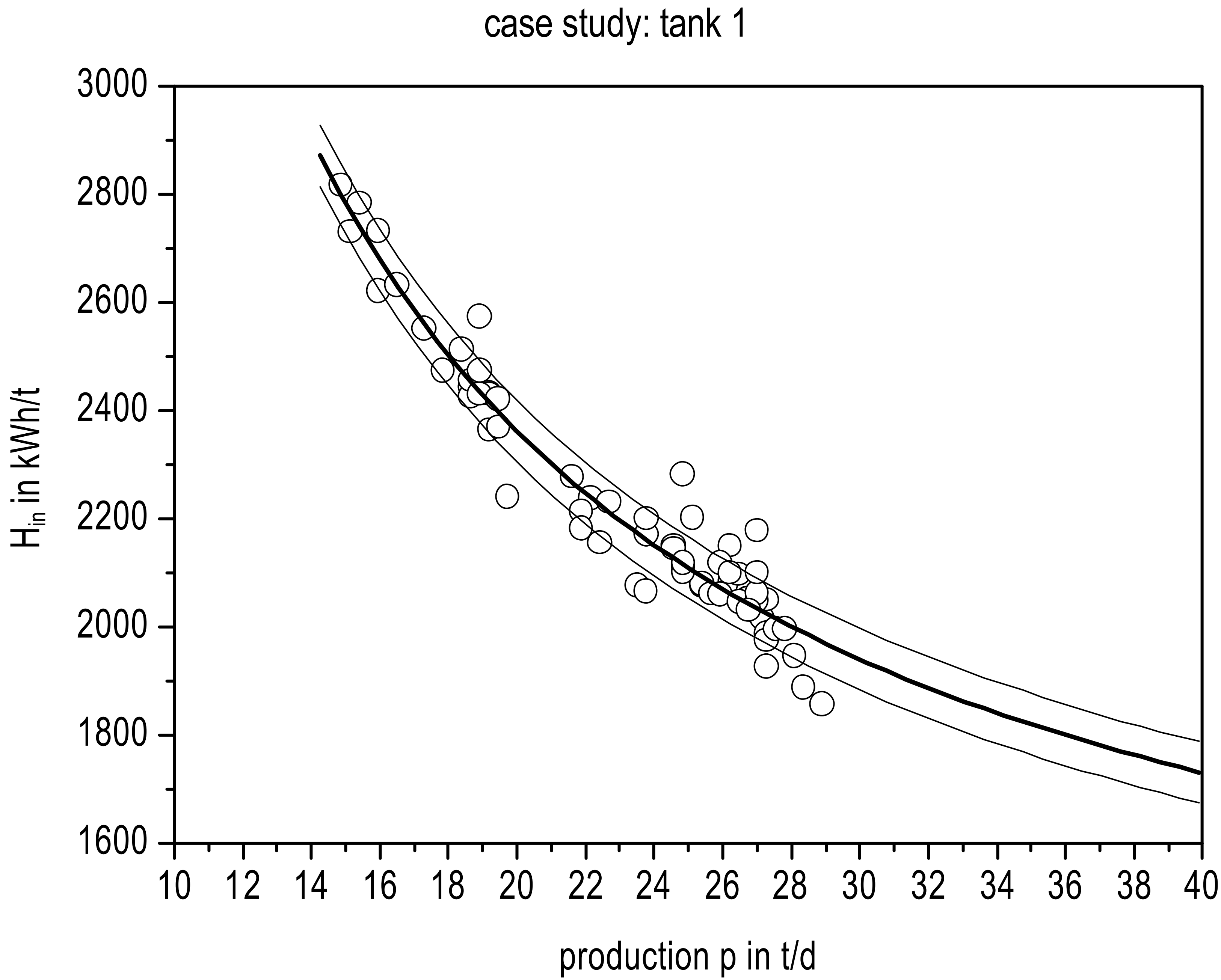


CASE 1:

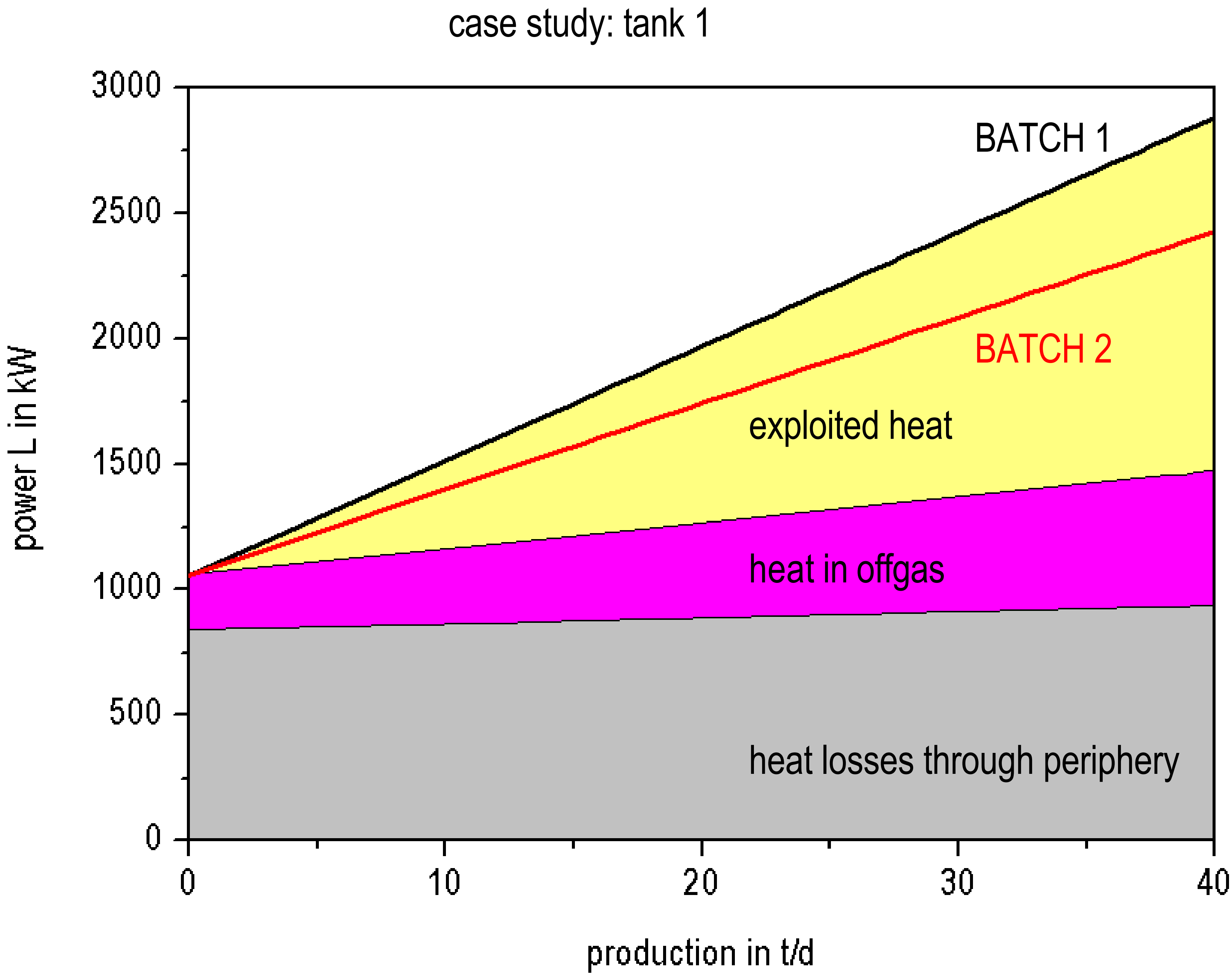
Can the pull be increased by using a low-H batch?

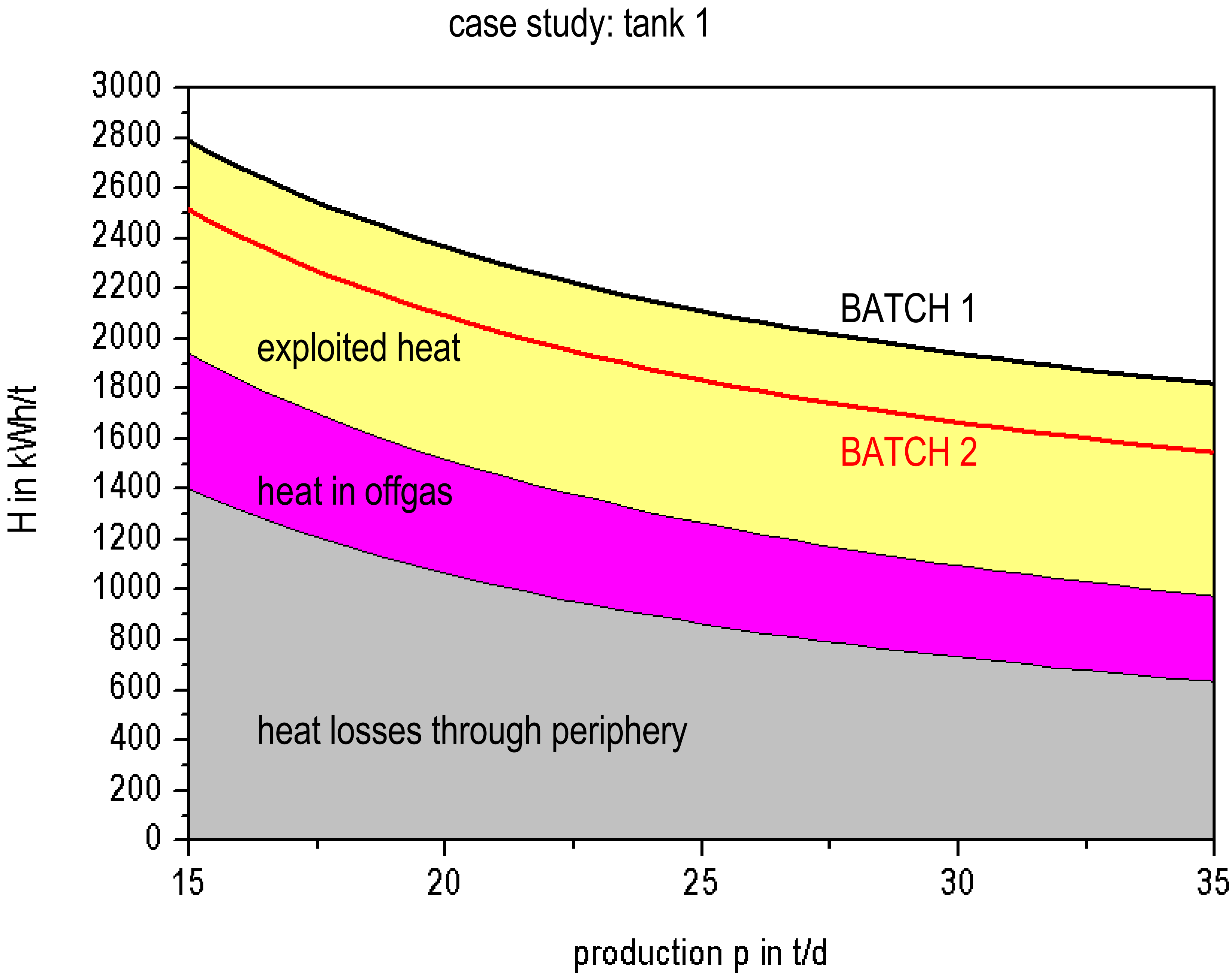


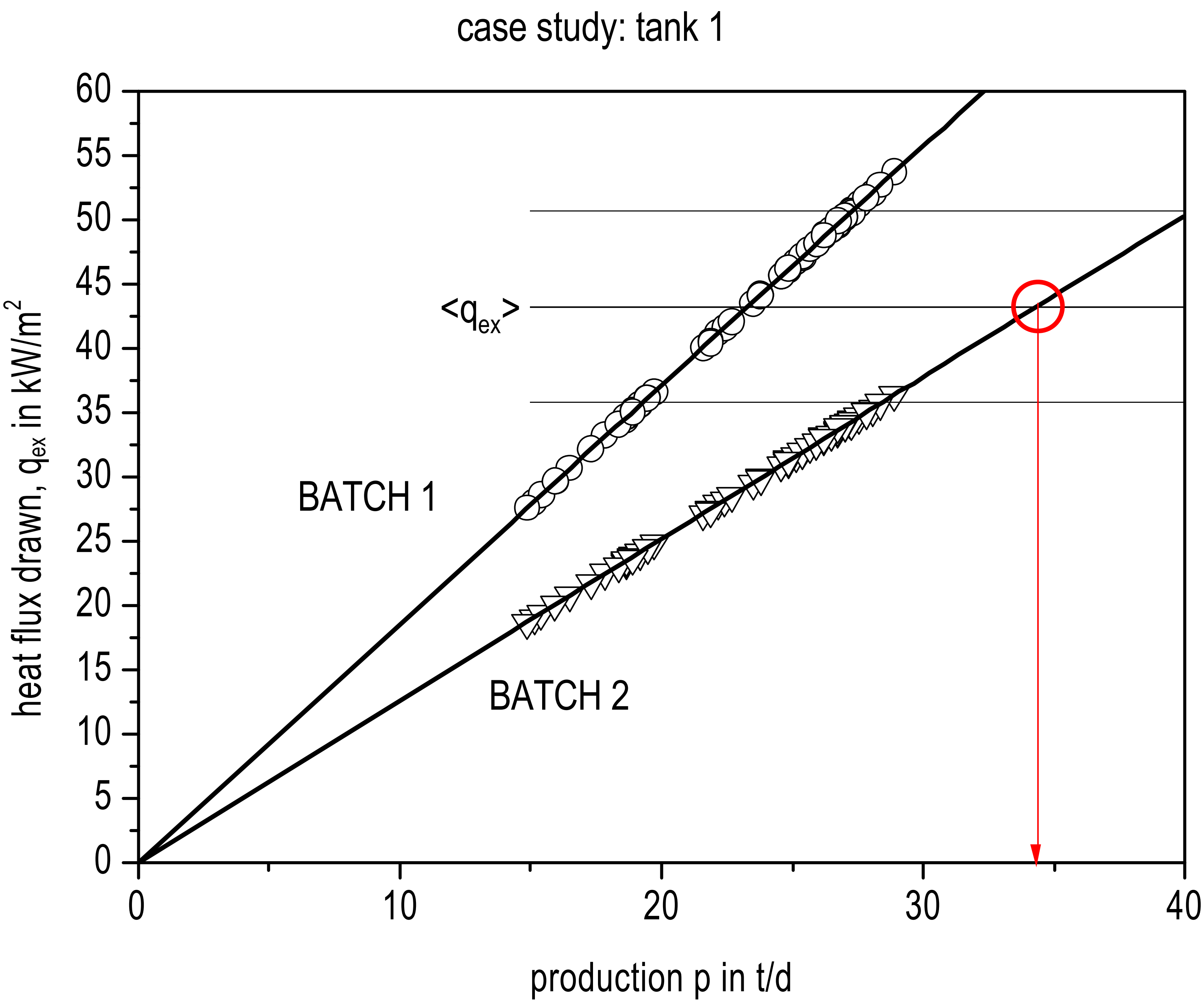
case study: tank 1
178 days,
68 data points
r = 0.956
confidence level > 99 %
desparate attempts
to push the furnace
beyond its chemical
limit
heat flux set free, q_{in} in kW/m^2
production p in t/d
140
120
100
80
60
0
10
20
30
40



case study: tank 1
3000
2800
2600
2400
2200
2000
1800
1600
H_{in} in kWh/t
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
production p in t/d


case study: tank 1
power L in kW
3000
2500
2000
1500
1000
500
0
BATCH 1
BATCH 2
exploited heat
heat in offgas
heat losses through periphery
0
10
20
30
40
production in t/d


case study: tank 1
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
H in kWh/t
BATCH 1
BATCH 2
exploited heat
heat in offgas
heat losses through periphery
15
20
25
30
35
production p in t/d

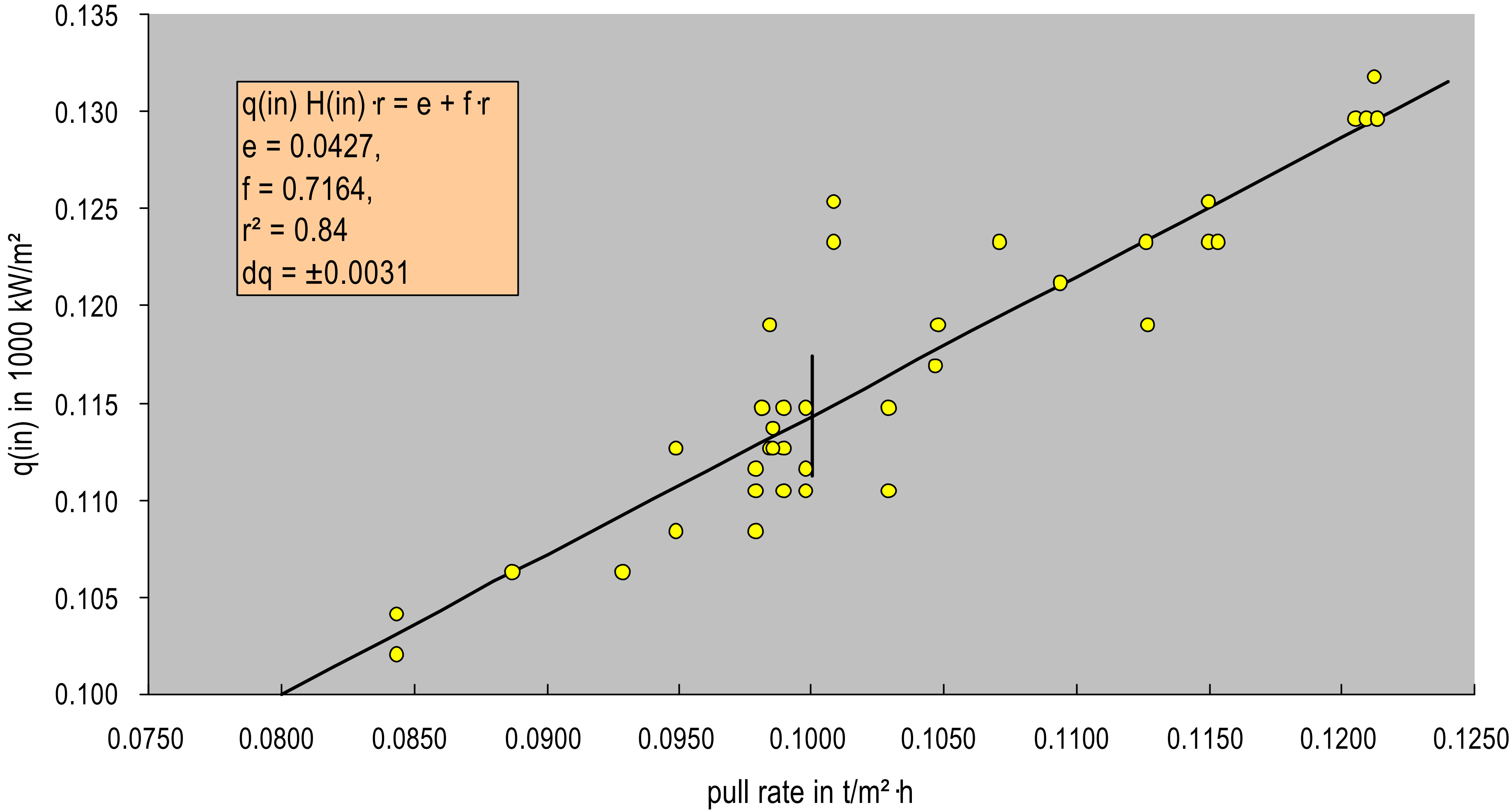

case study: tank 1
heat flux drawn, q_{ex} in kW/m^2
production p in t/d
BATCH 1
BATCH 2
$\langle q_{ex} \rangle$
0
5
10
15
20
25
30
35
40
45
50
55
60
0
10
20
30
40

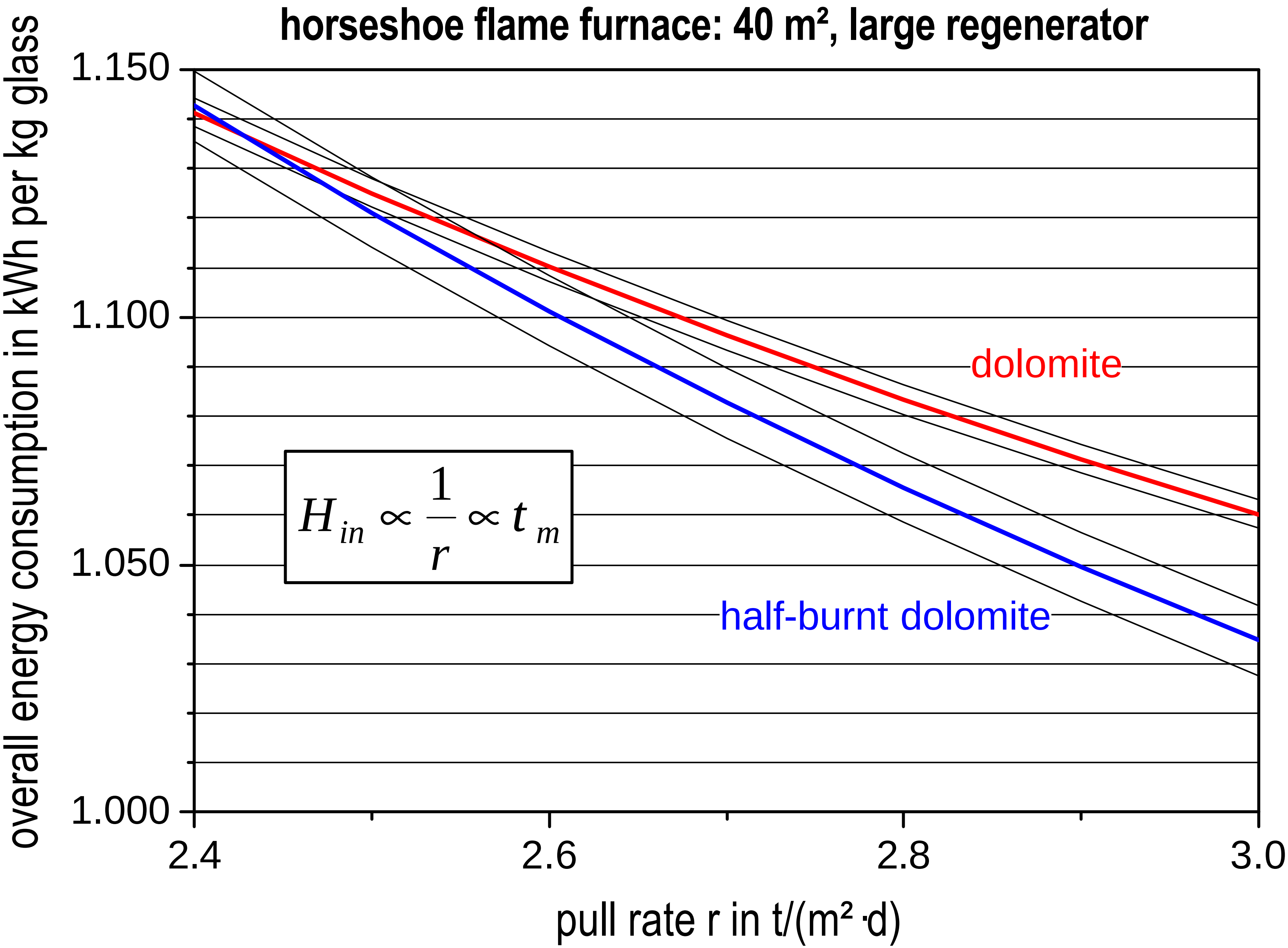
CASE 2:
Can energy be saved by using half-burnt lime?

	$H°$	$\Delta_r H°$	$\Delta_r H°$ per [MgO]		4 % MgO
	kJ/mol	kJ/mol	MJ/kg	kWh/kg	kWh/t glass
dolomite	2314.2	290.7	7.21	2.00	80
half-burnt	1808.5	178.5	4.43	1.23	49
difference		112.2	2.78	0.77	31

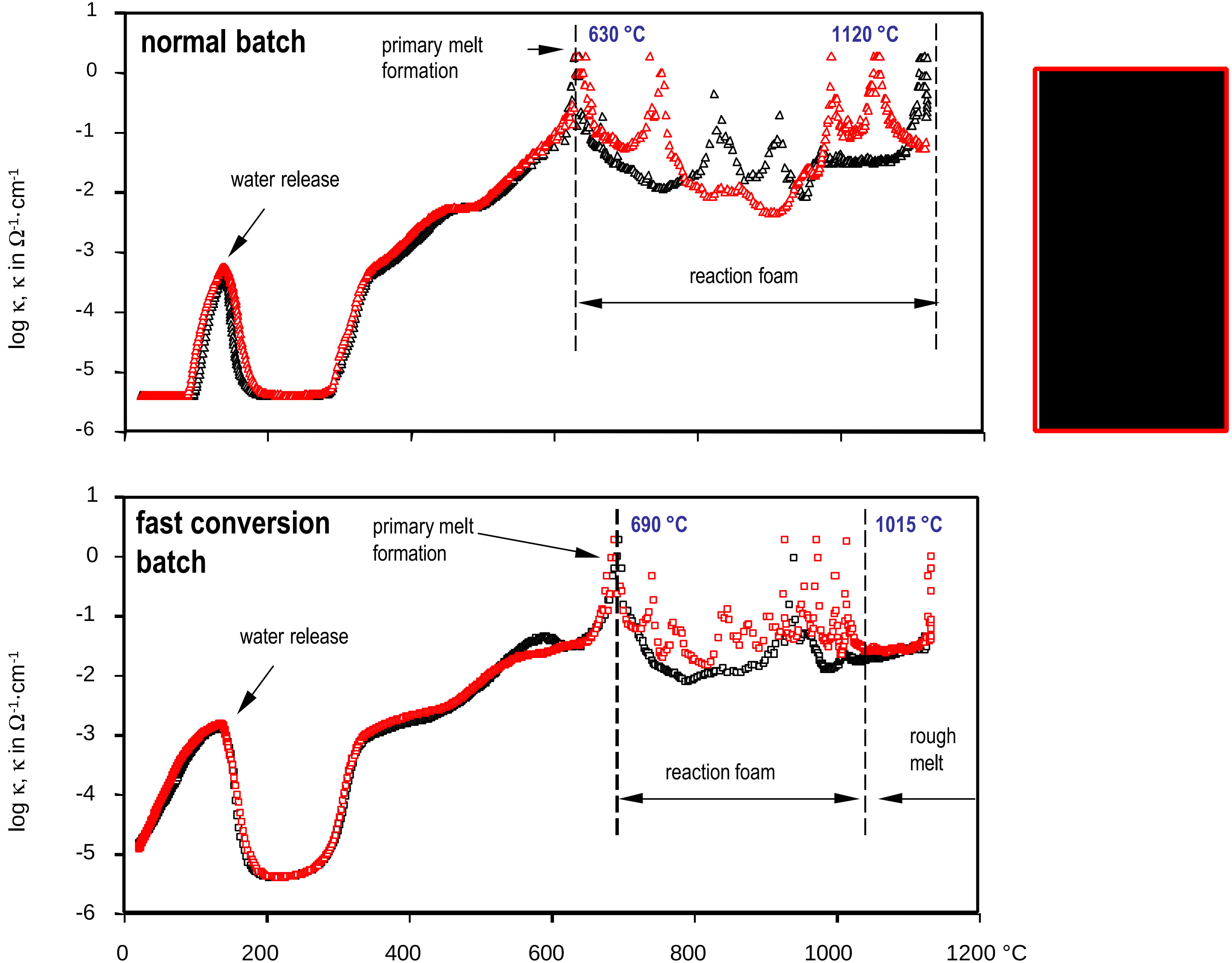
depending on η_{ex} (30 – 55 %) $\Rightarrow$ 60 – 105 kWh (0 % cullet)
43 – 80 kWh (25 %)

$H(in) \cdot r = q(in) \propto r$

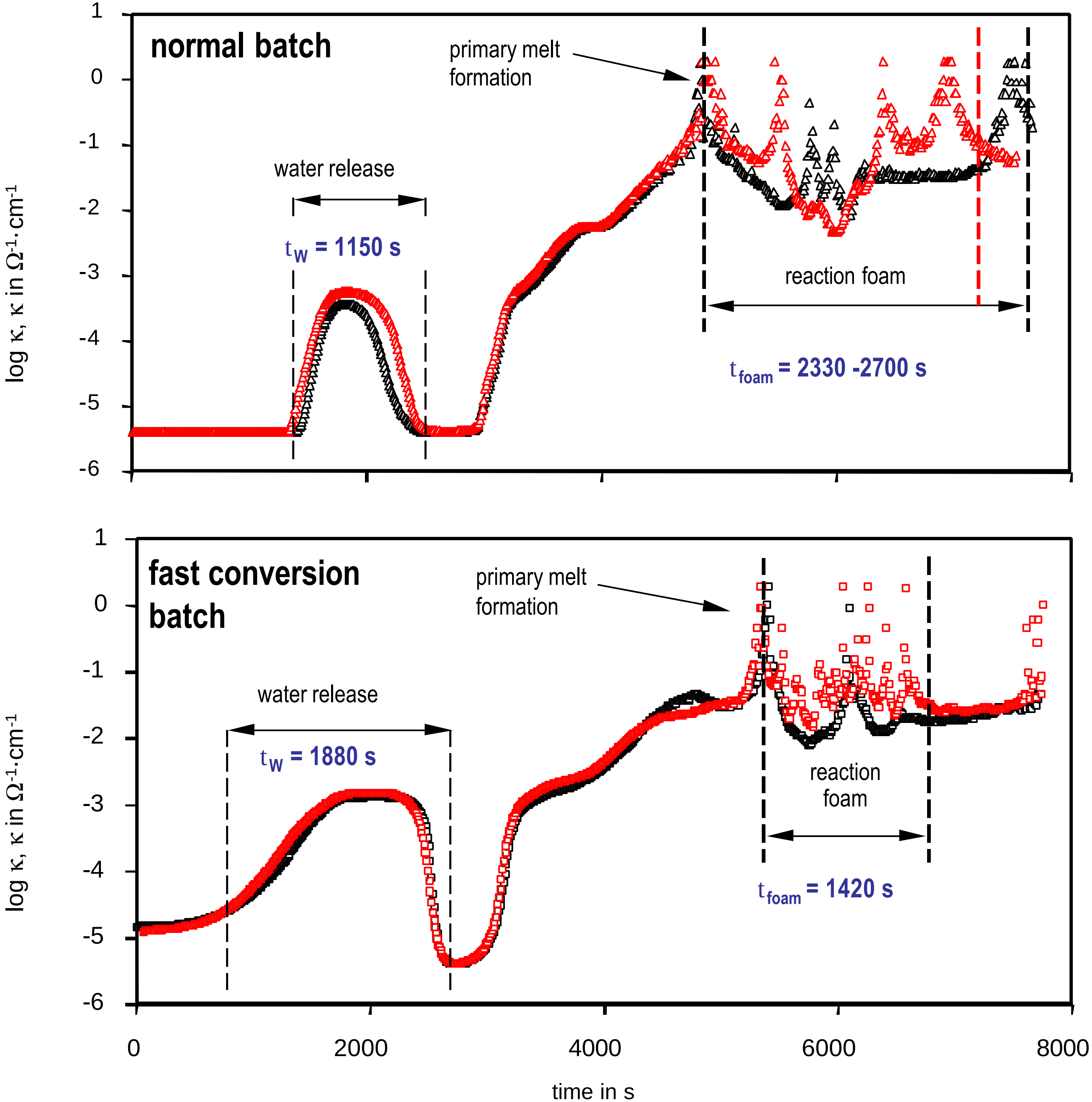



horseshoe flame furnace: 40 m², large regenerator
overall energy consumption in kWh per kg glass
1.150
1.100
1.050
1.000
2.4
2.6
2.8
3.0
pull rate r in t/(m²·d)
dolomite
half-burnt dolomite
$H_{in} \propto \frac{1}{r} \propto t_m$

CASE 3:
Can energy be saved by an intelligently designed fast conversion batch („instant coffee batch")?

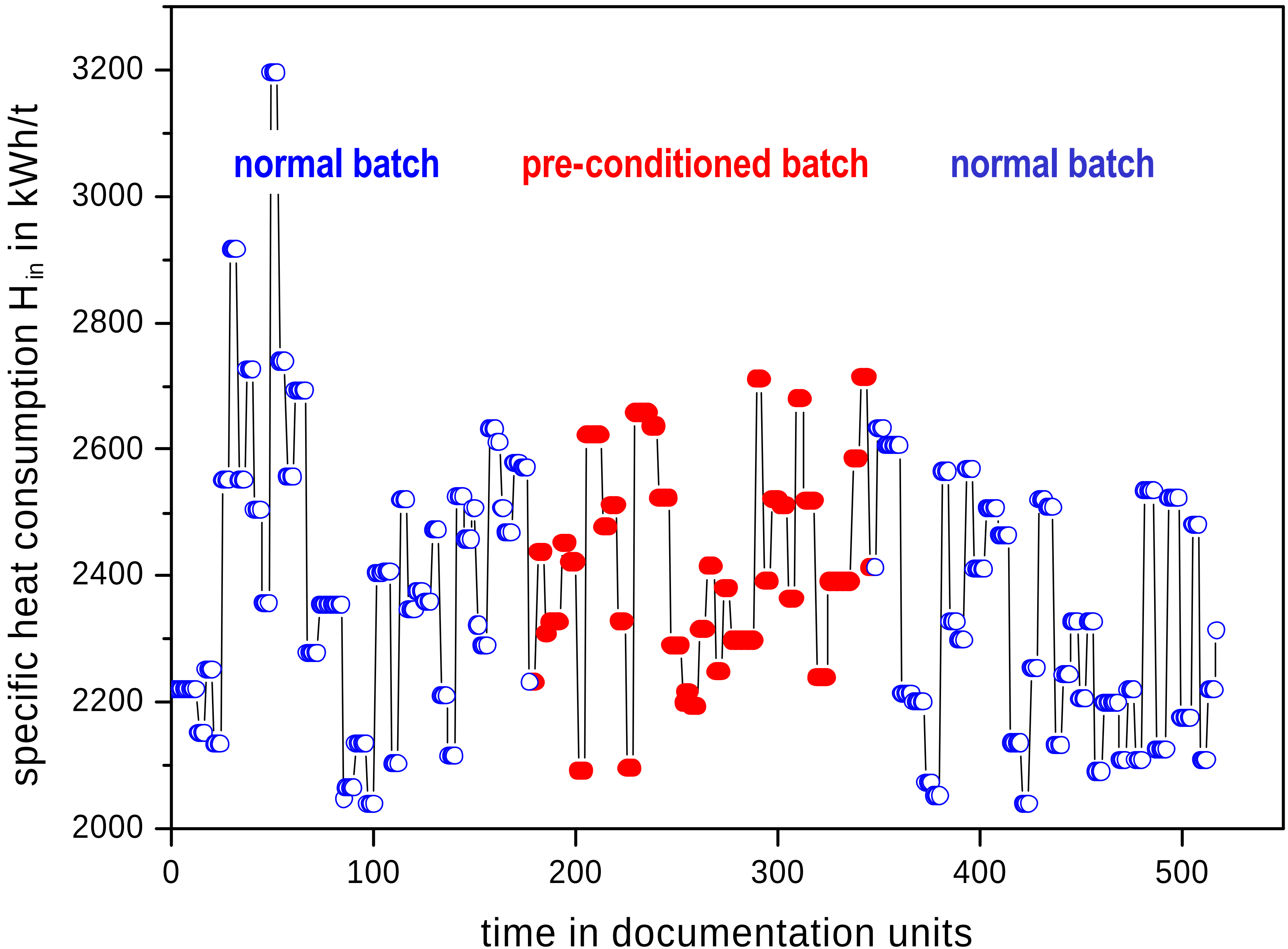


normal batch
primary melt formation
630 °C
1120 °C
water release
reaction foam
log κ, κ in Ω-1·cm-1
1
0
-1
-2
-3
-4
-5
-6
fast conversion batch
primary melt formation
690 °C
1015 °C
water release
reaction foam
rough melt
log κ, κ in Ω-1·cm-1
1
0
-1
-2
-3
-4
-5
-6
0
200
400
600
800
1000
1200 °C

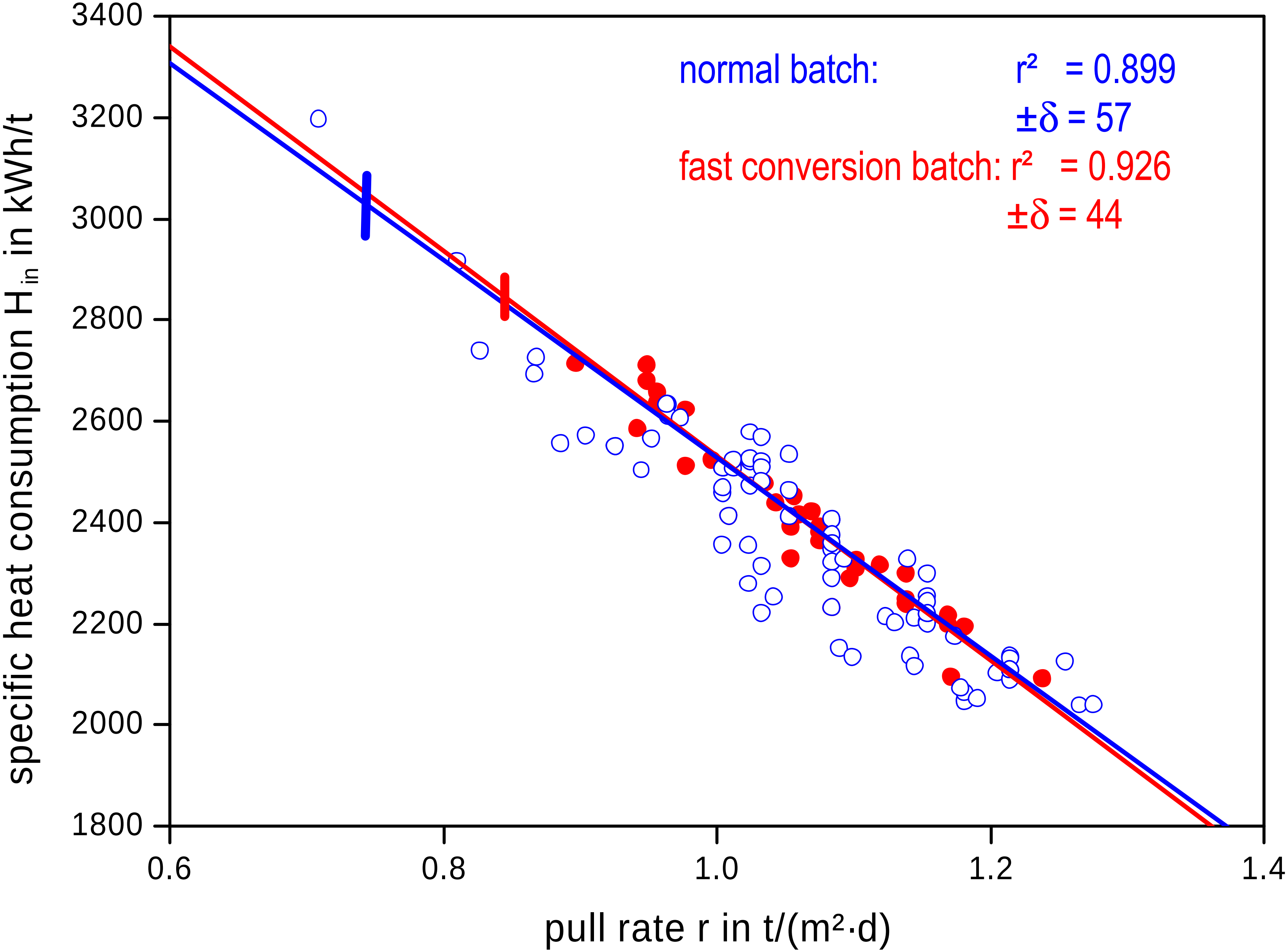

normal batch
primary melt formation
water release
tw = 1150 s
reaction foam
tfoam = 2330 -2700 s
fast conversion batch
primary melt formation
water release
tw = 1880 s
reaction foam
tfoam = 1420 s
log κ, κ in Ω-1·cm-1
log κ, κ in Ω-1·cm-1
time in s
1
0
-1
-2
-3
-4
-5
-6
0
2000
4000
6000
8000

[redacted]

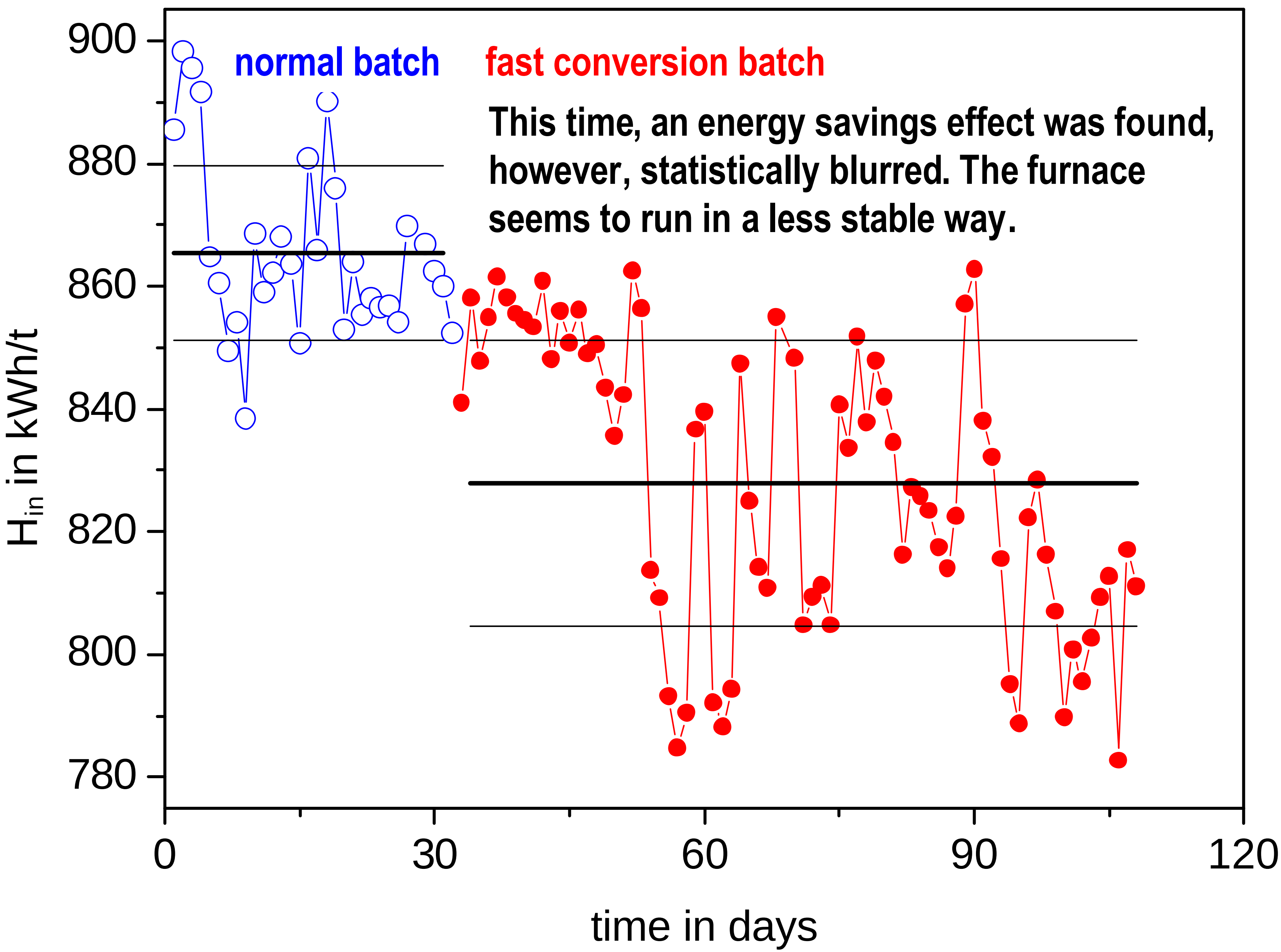
Due to the manager's impatience, no significant difference was found ...



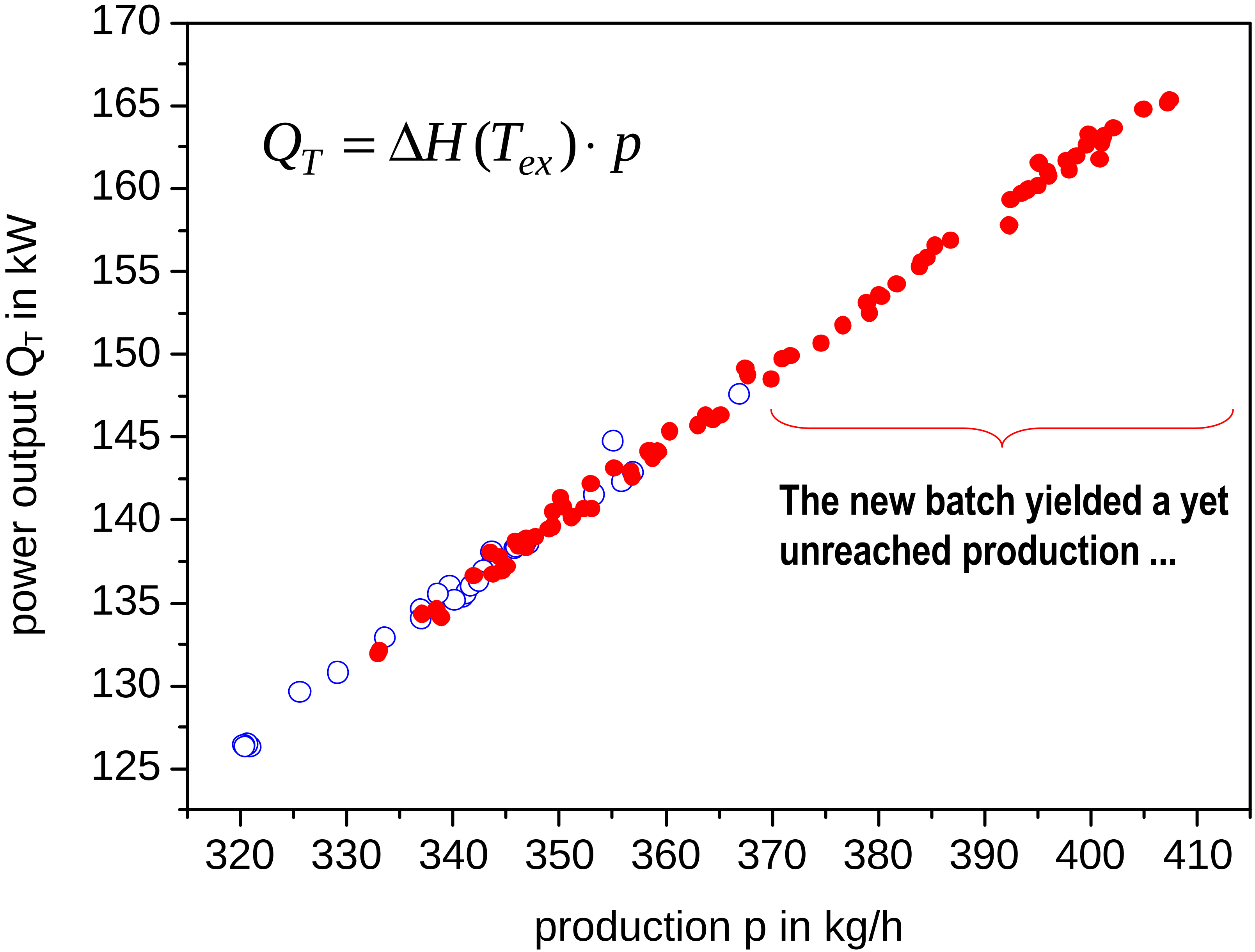
... although the new batch quickly makes the furnace more stable.

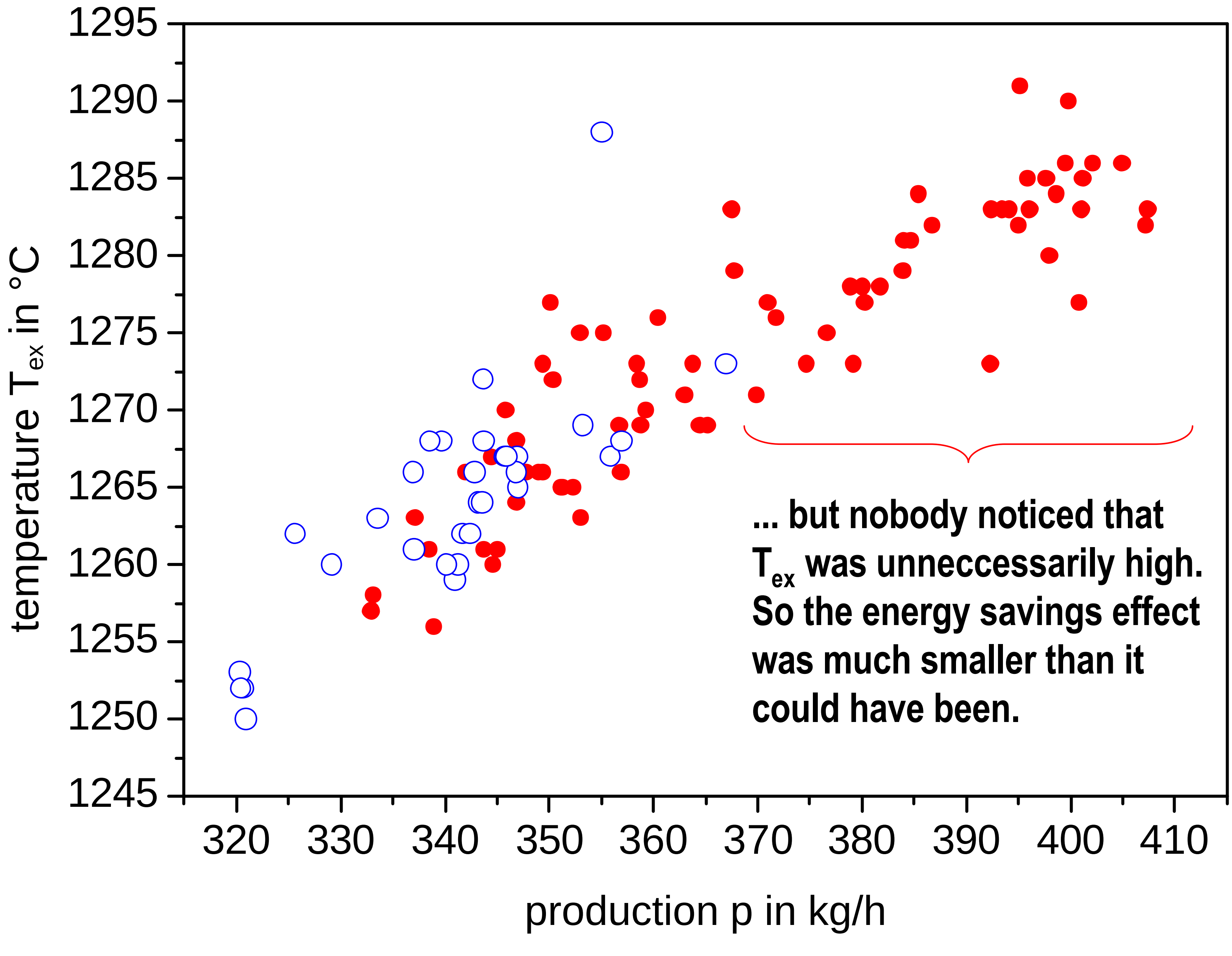


Same type of batches in a different factory.



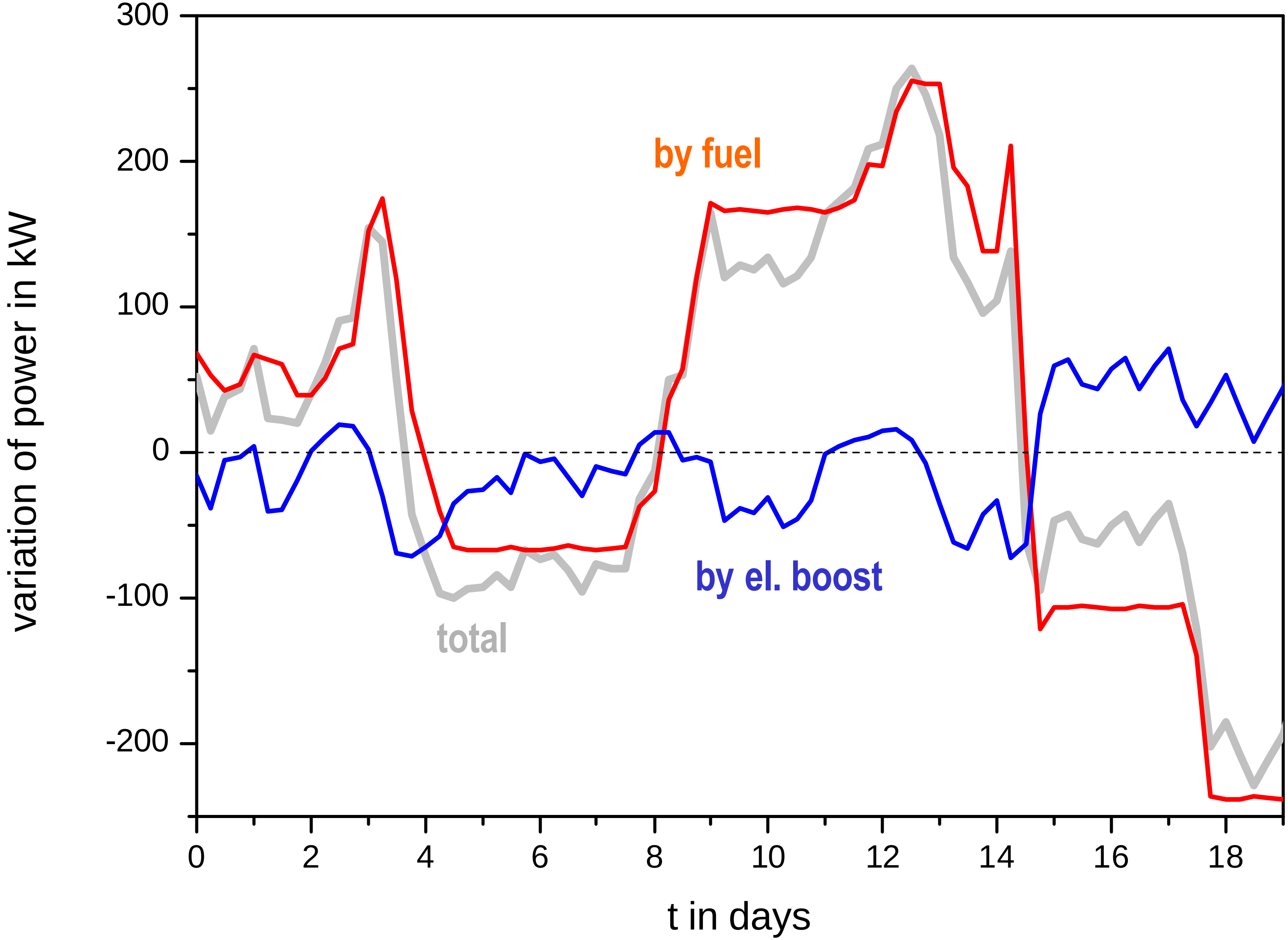
Evaluating the mass and power pulled from the furnace speaks a different language!



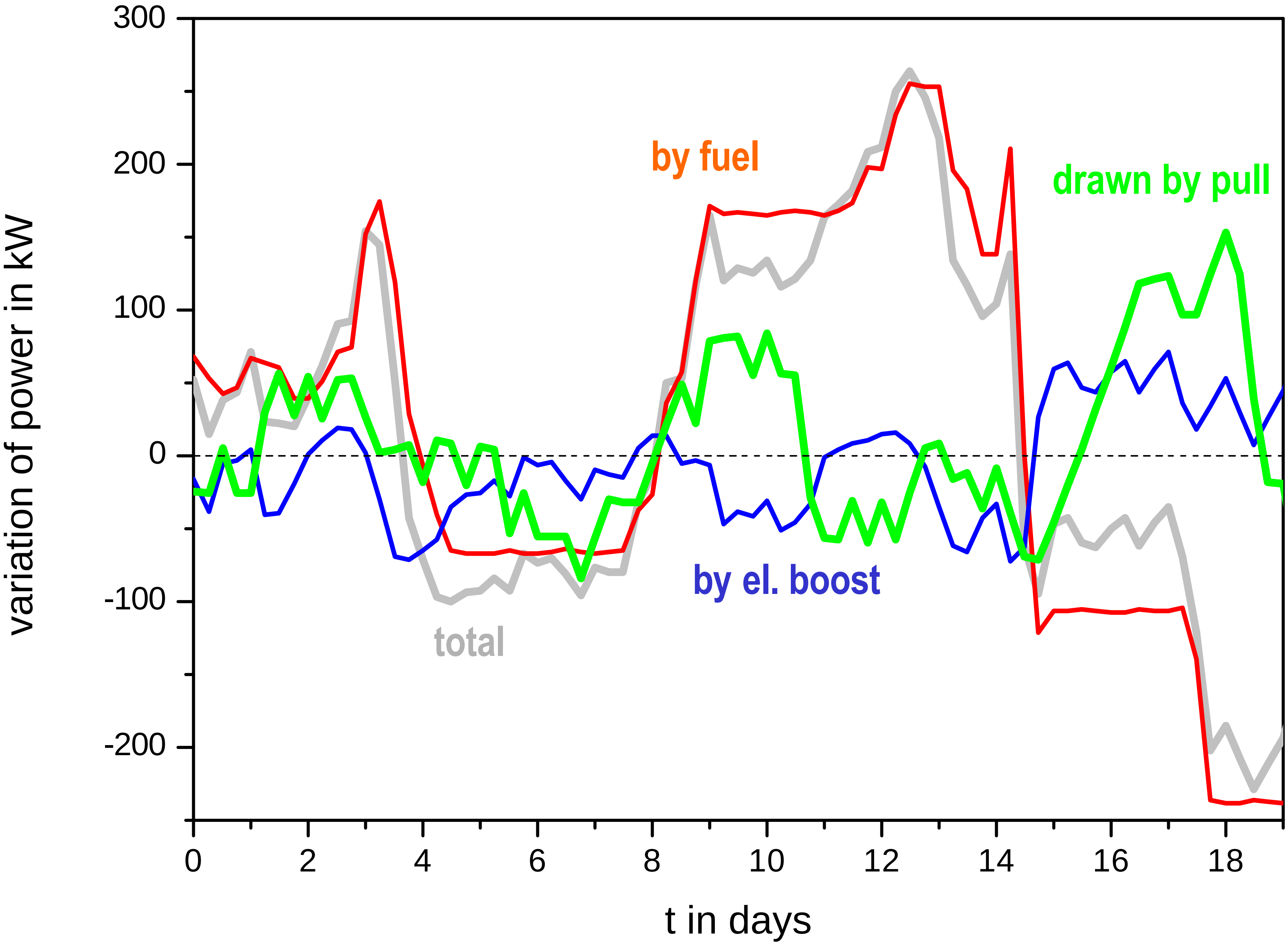


1295
1290
1285
1280
1275
1270
1265
1260
1255
1250
1245
320
330
340
350
360
370
380
390
400
410
temperature T_{ex} in °C
production p in kg/h
... but nobody noticed that
T_{ex} was unneccessarily high.
So the energy savings effect
was much smaller than it
could have been.

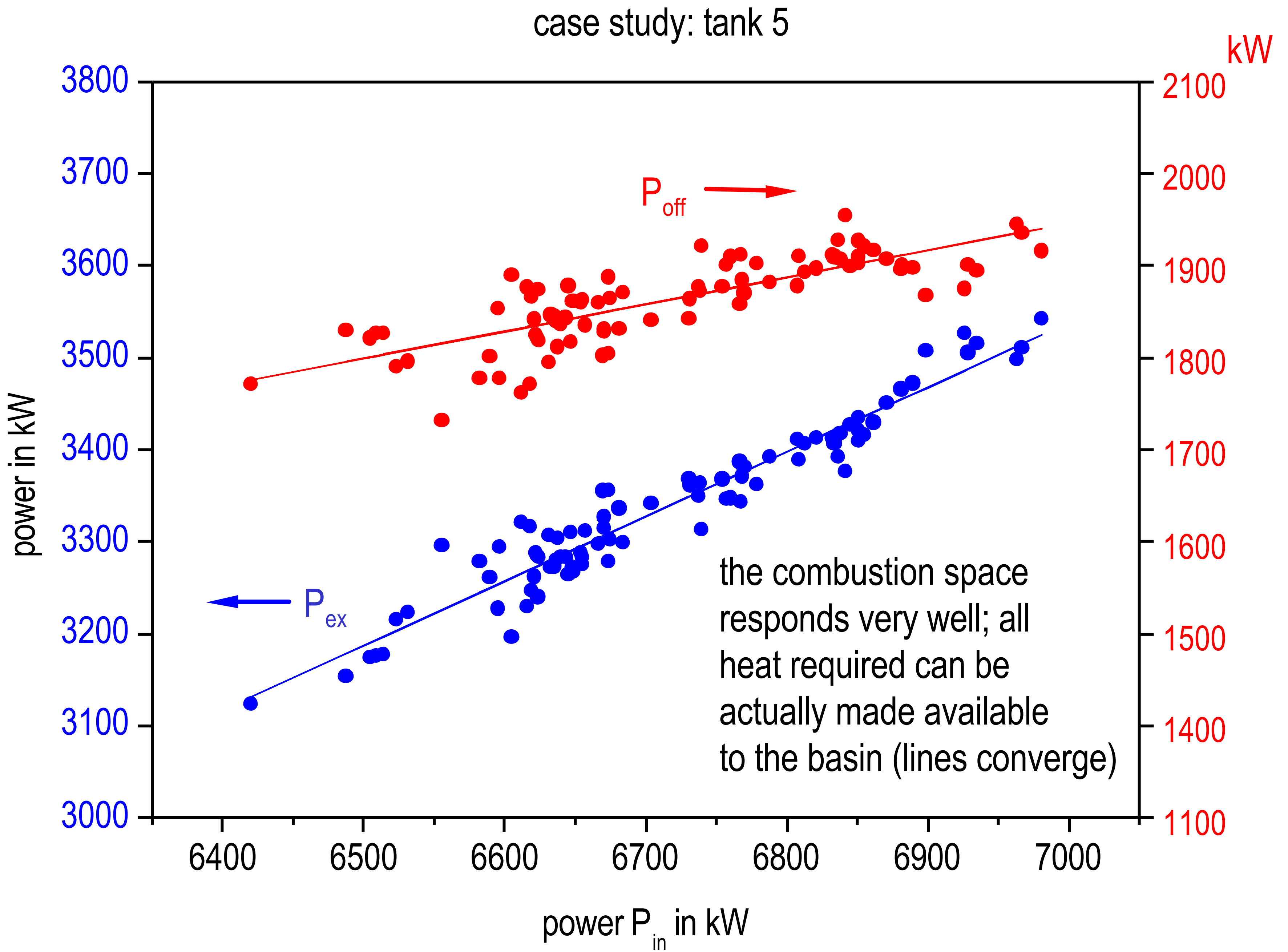
CASE 5:
When furnace control and furnace characteristics counteract the effects of an optimized melting process.

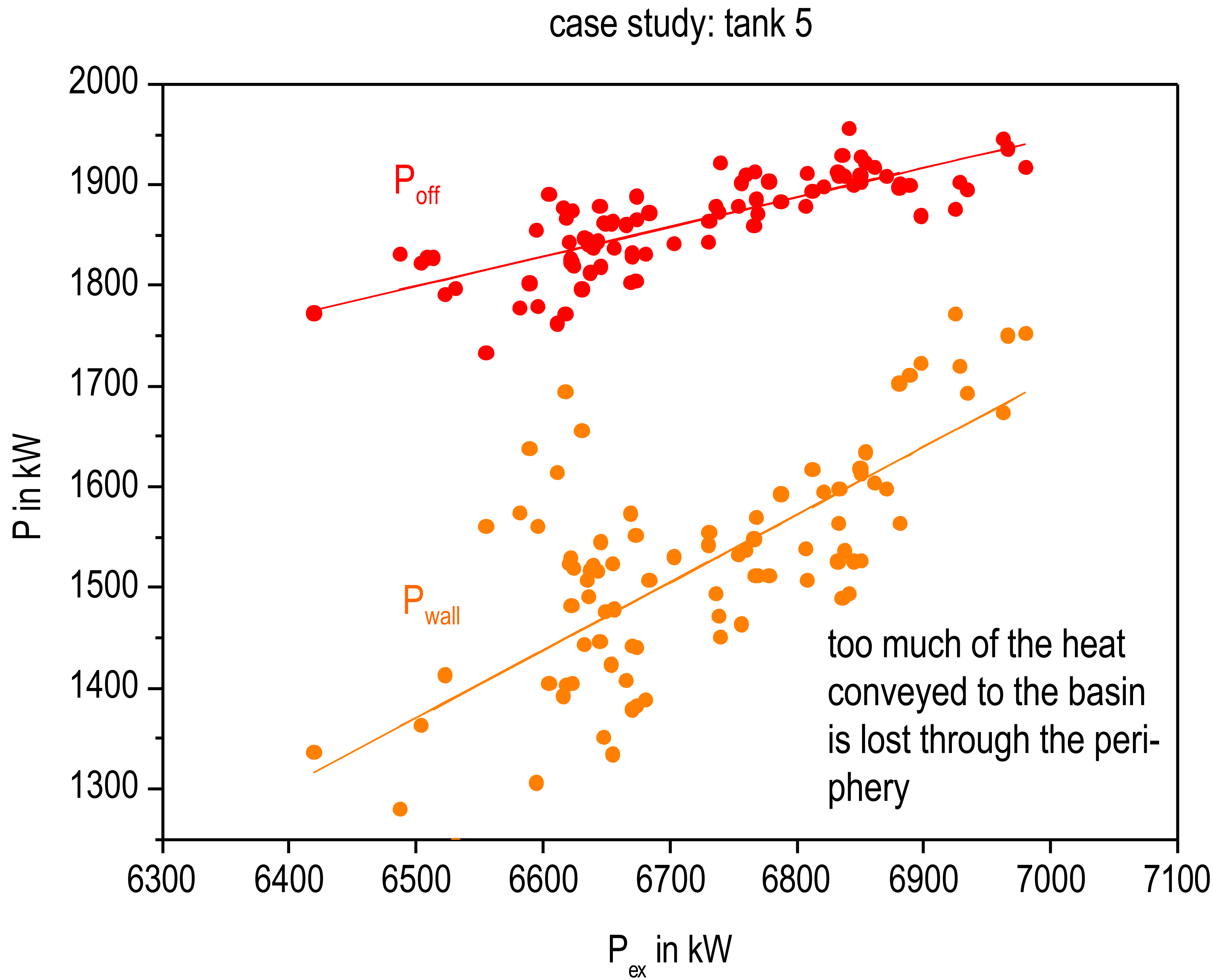


300
200
100
0
-100
-200
variation of power in kW
by fuel
by el. boost
total
0
2
4
6
8
10
12
14
16
18
t in days



300
200
100
0
-100
-200
variation of power in kW
0
2
4
6
8
10
12
14
16
18
t in days
by fuel
drawn by pull
by el. boost
total


case study: tank 5
kW
3800
3700
3600
3500
3400
3300
3200
3100
3000
2100
2000
1900
1800
1700
1600
1500
1400
1100
P off
P ex
power in kW
the combustion space
responds very well; all
heat required can be
actually made available
to the basin (lines converge)
6400
6500
6600
6700
6800
6900
7000
power P in in kW



case study: tank 5
2000
1900
1800
1700
1600
1500
1400
1300
P in kW
6300
6400
6500
6600
6700
6800
6900
7000
7100
P ex in kW
P off
P wall
too much of the heat conveyed to the basin is lost through the periphery

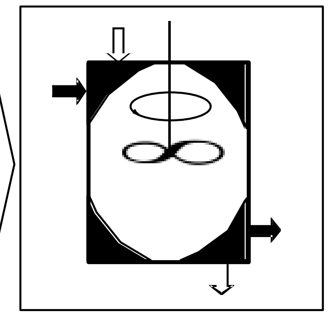
a novel service
to the
glass industry

step 1: retrospective analysis: heat & power balance; casting into a model

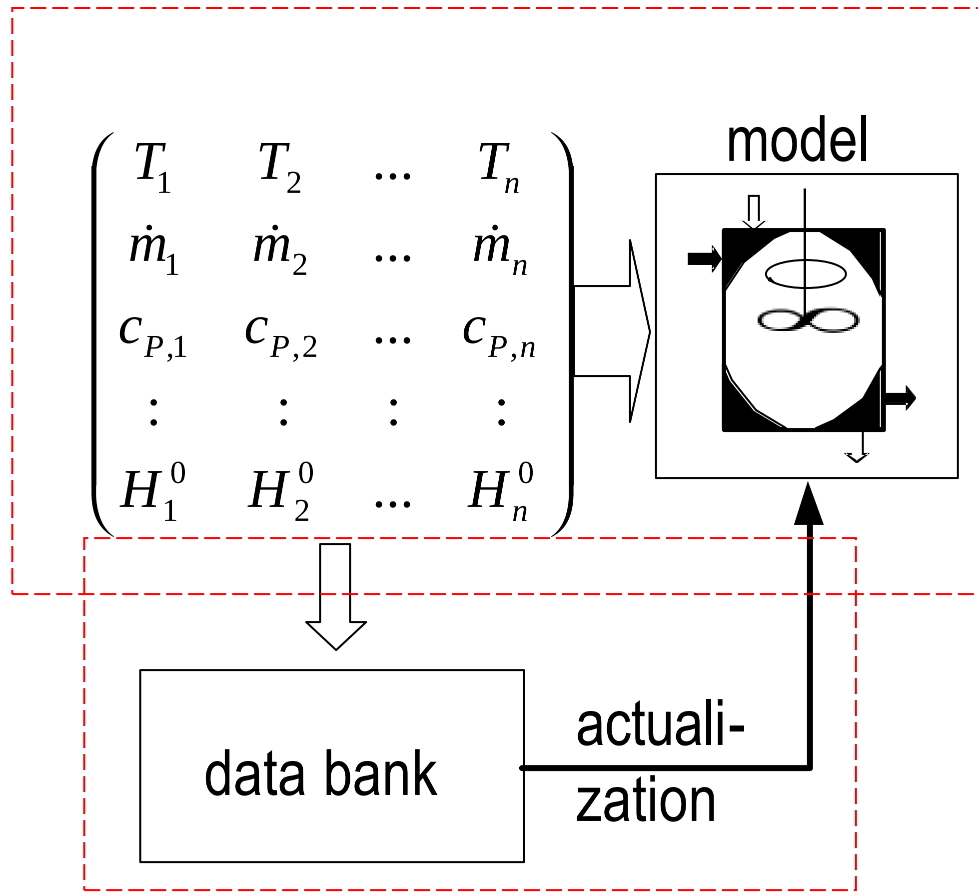
data acquisition

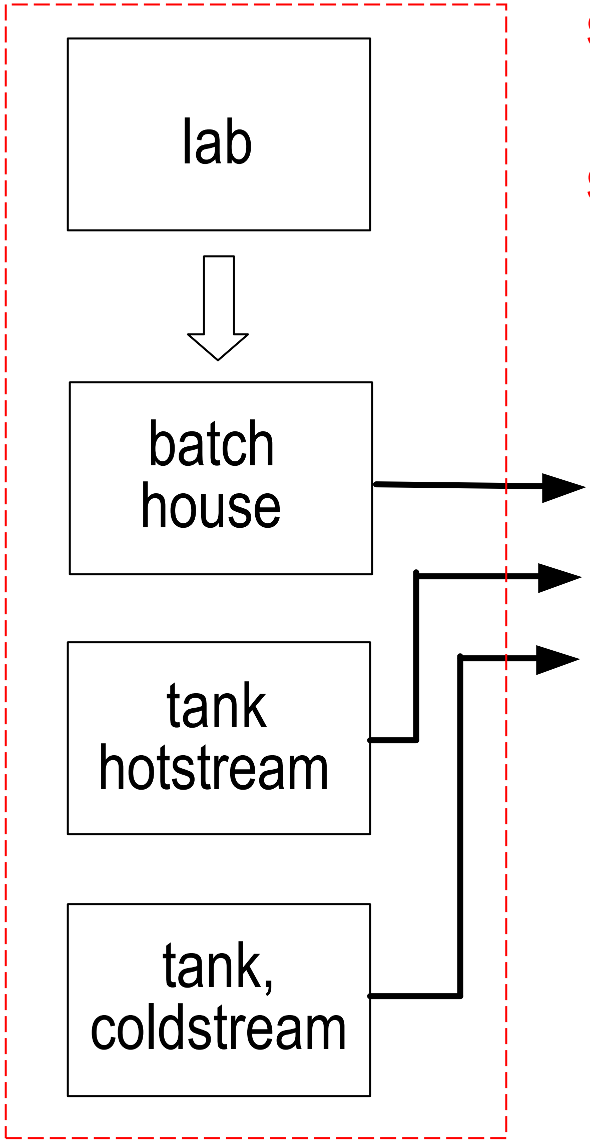
$$\begin{pmatrix} T_1 & T_2 & \dots & T_n \\ \dot{m}_1 & \dot{m}_2 & \dots & \dot{m}_n \\ c_{P,1} & c_{P,2} & \dots & c_{P,n} \\ \vdots & \vdots & \vdots & \vdots \\ H_1^0 & H_2^0 & \dots & H_n^0 \end{pmatrix}$$

model



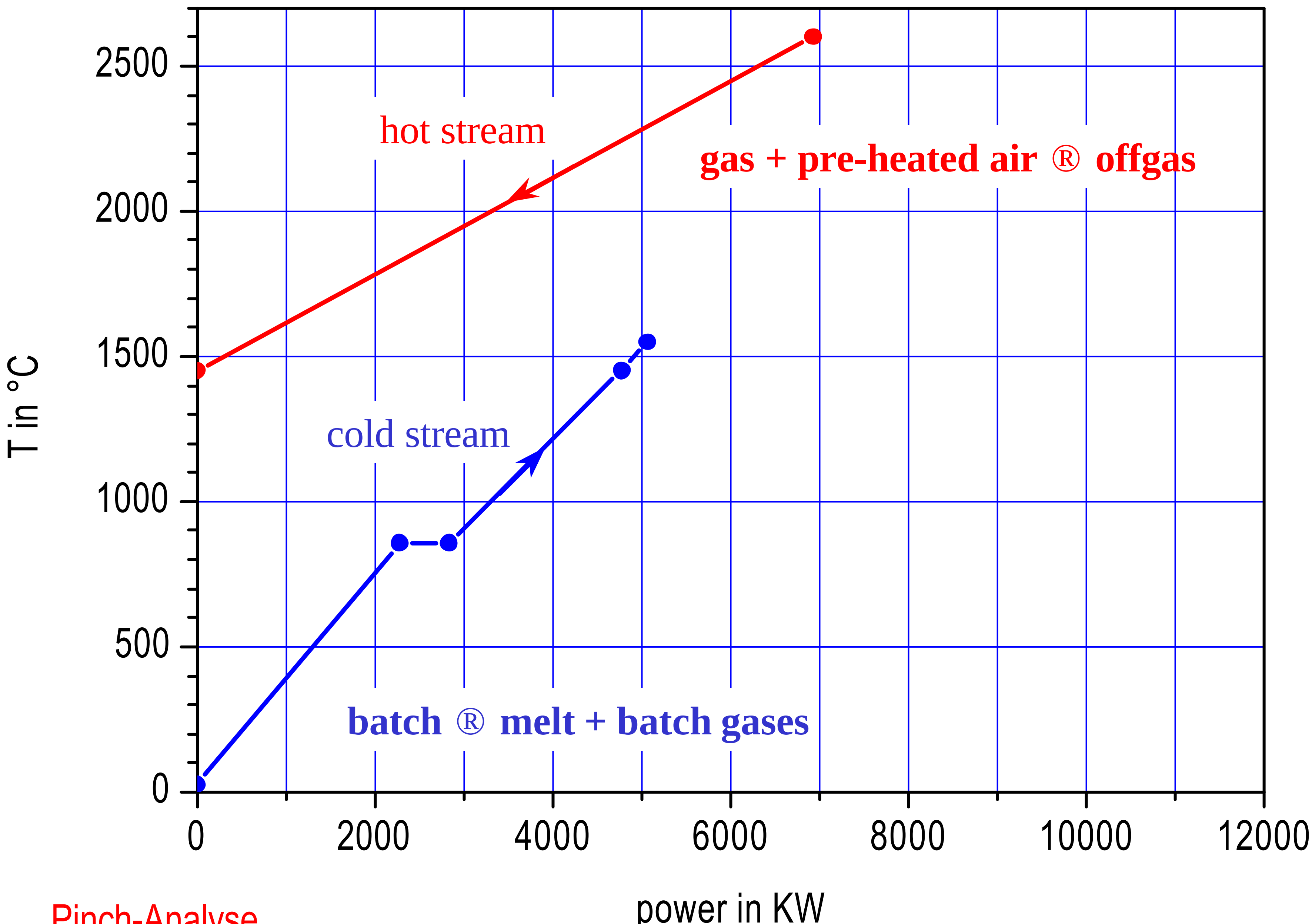
step 2: retrospective analysis: reactor (dwell time) behavior; on-line actualization of model



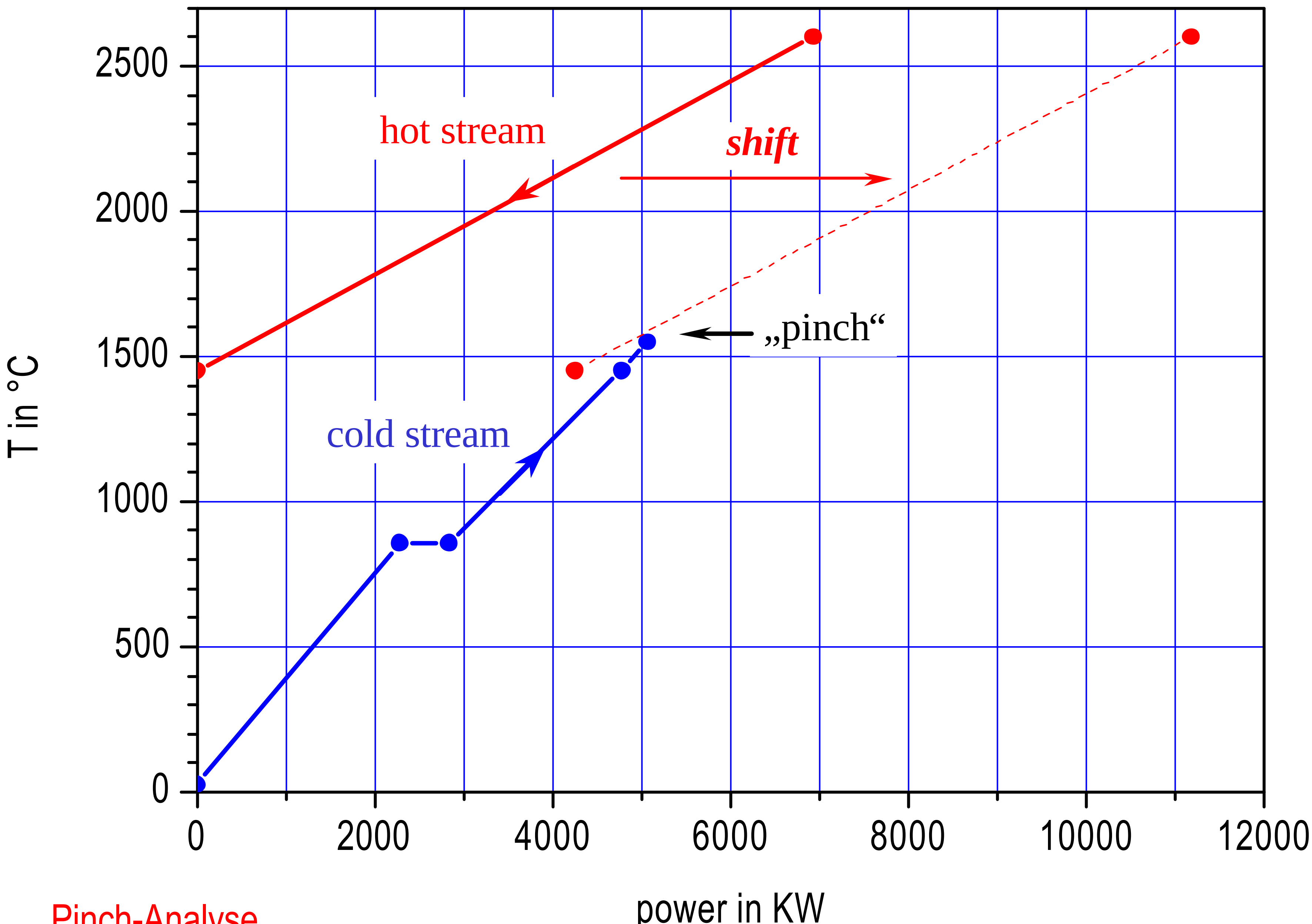


step 3: in-factory analysis of heat and mass flows;
data acquisition and formatting;

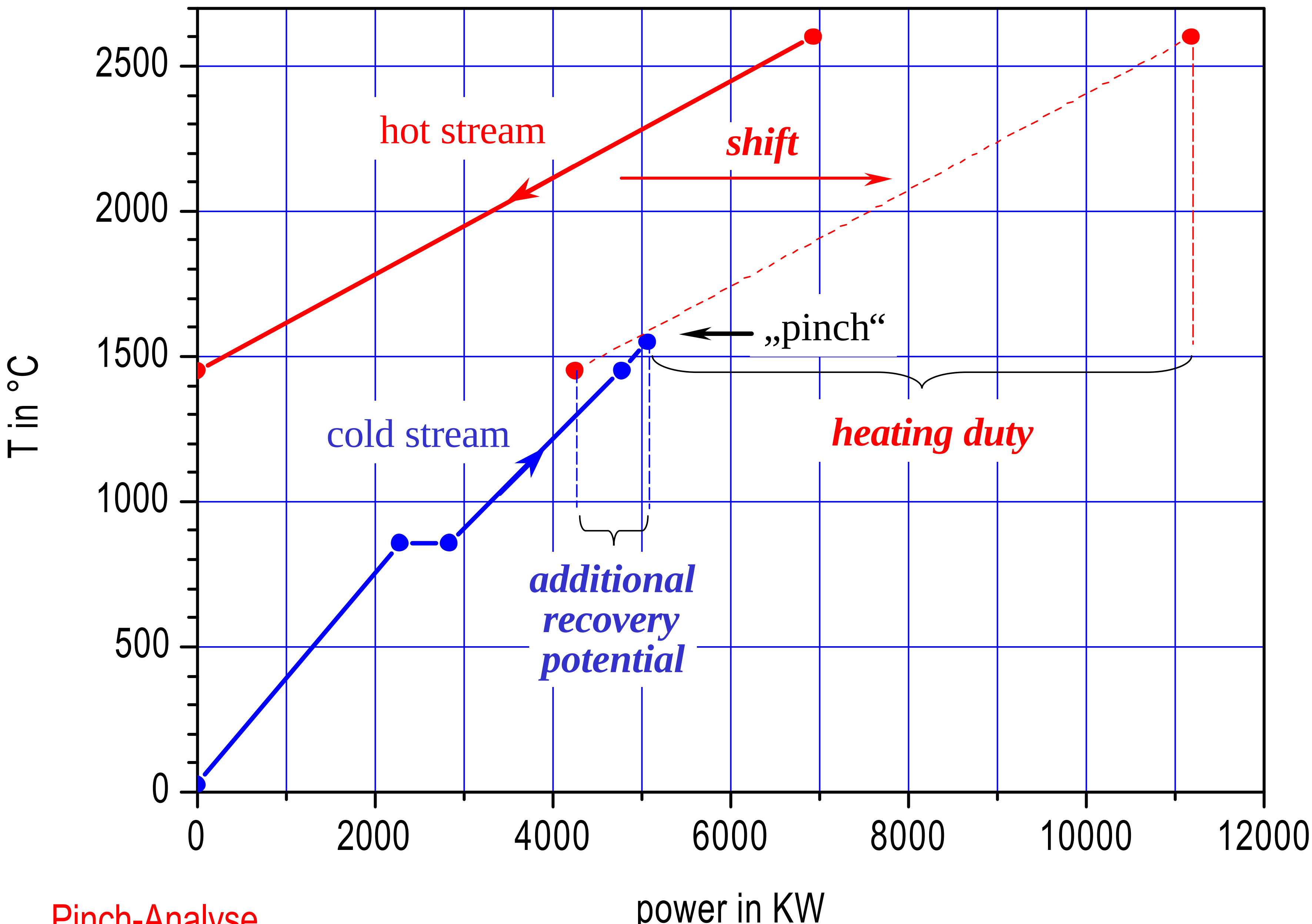
step 4: pinch analysis (esp. in float production)



Pinch-Analyse

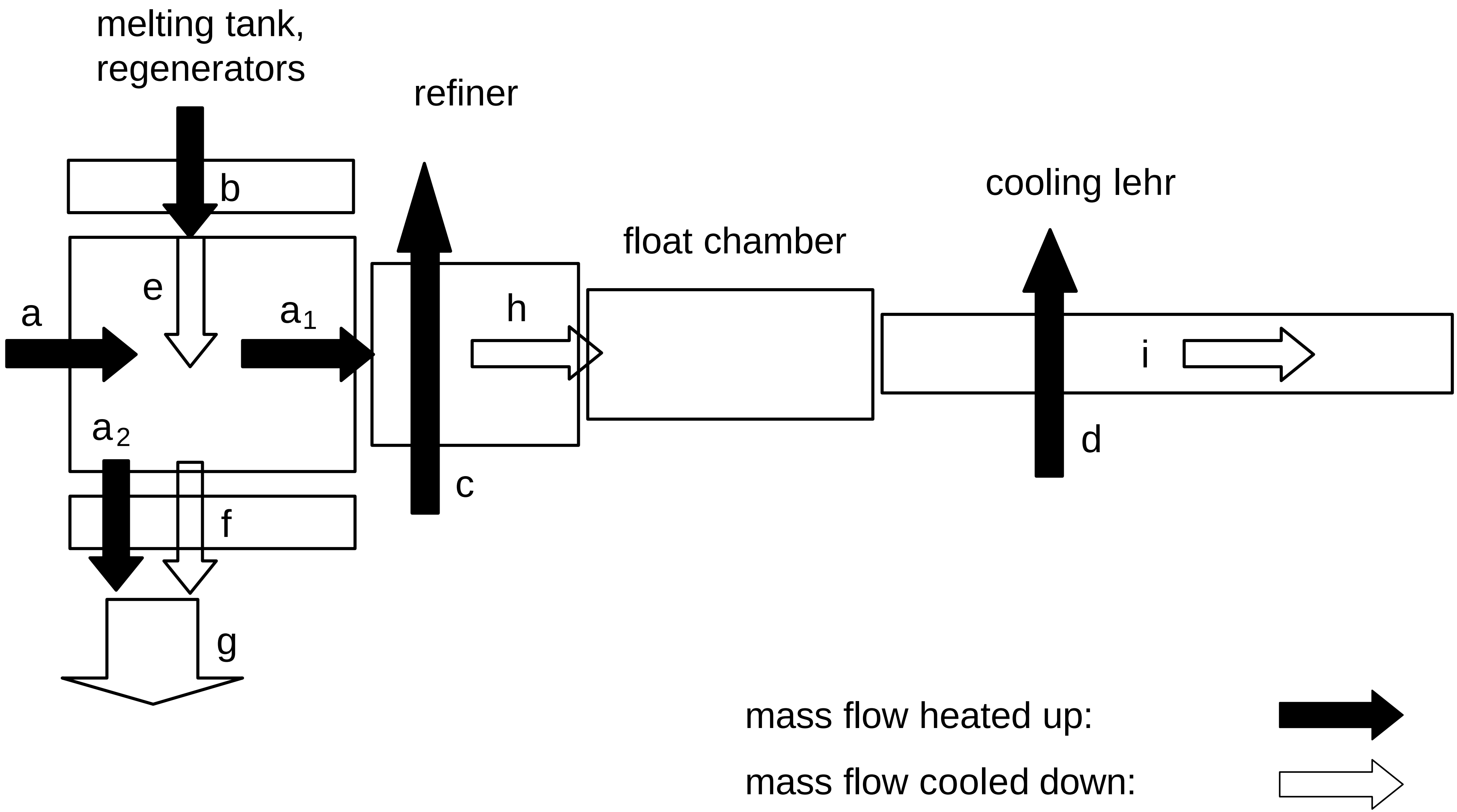


Pinch-Analyse

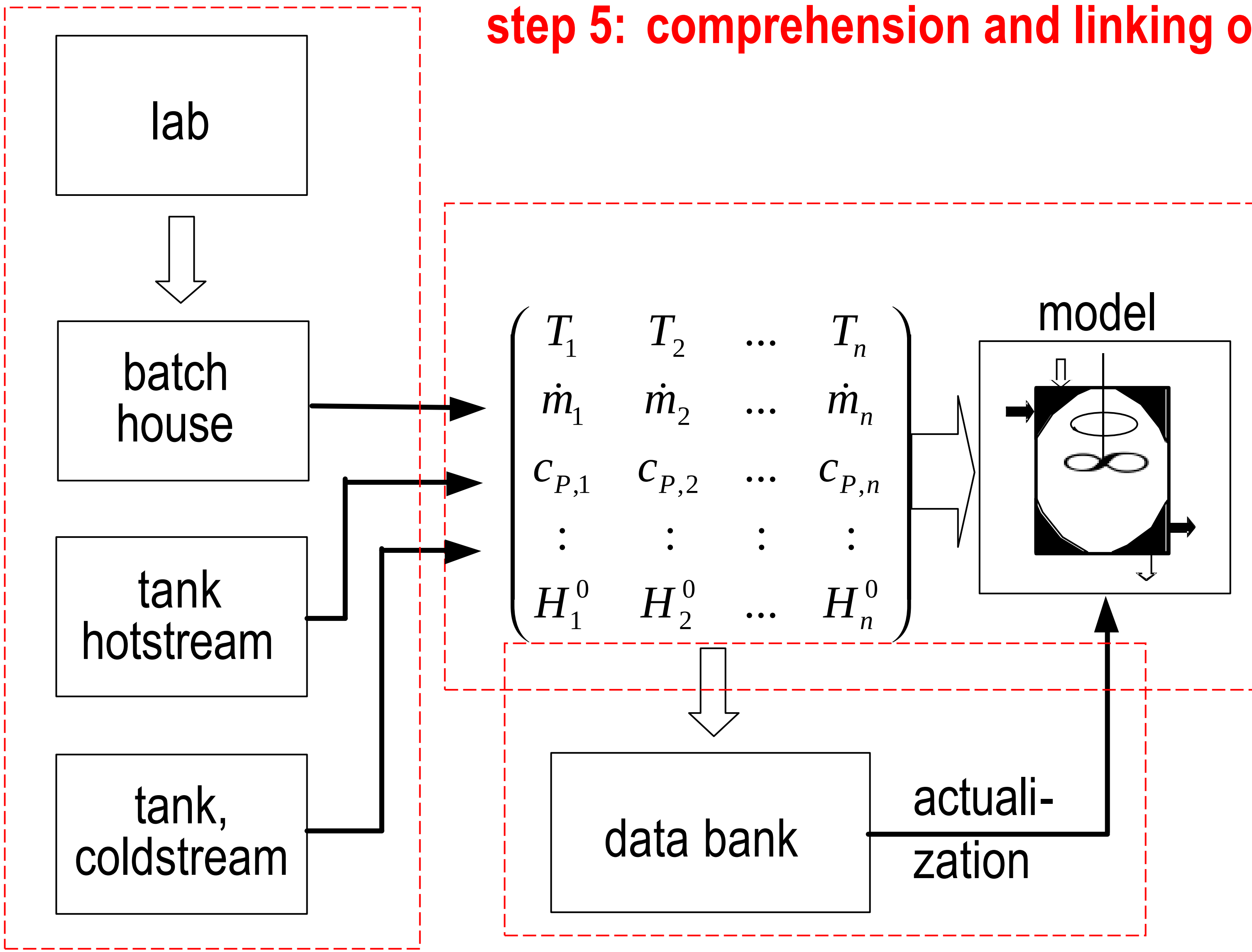


Pinch-Analyse

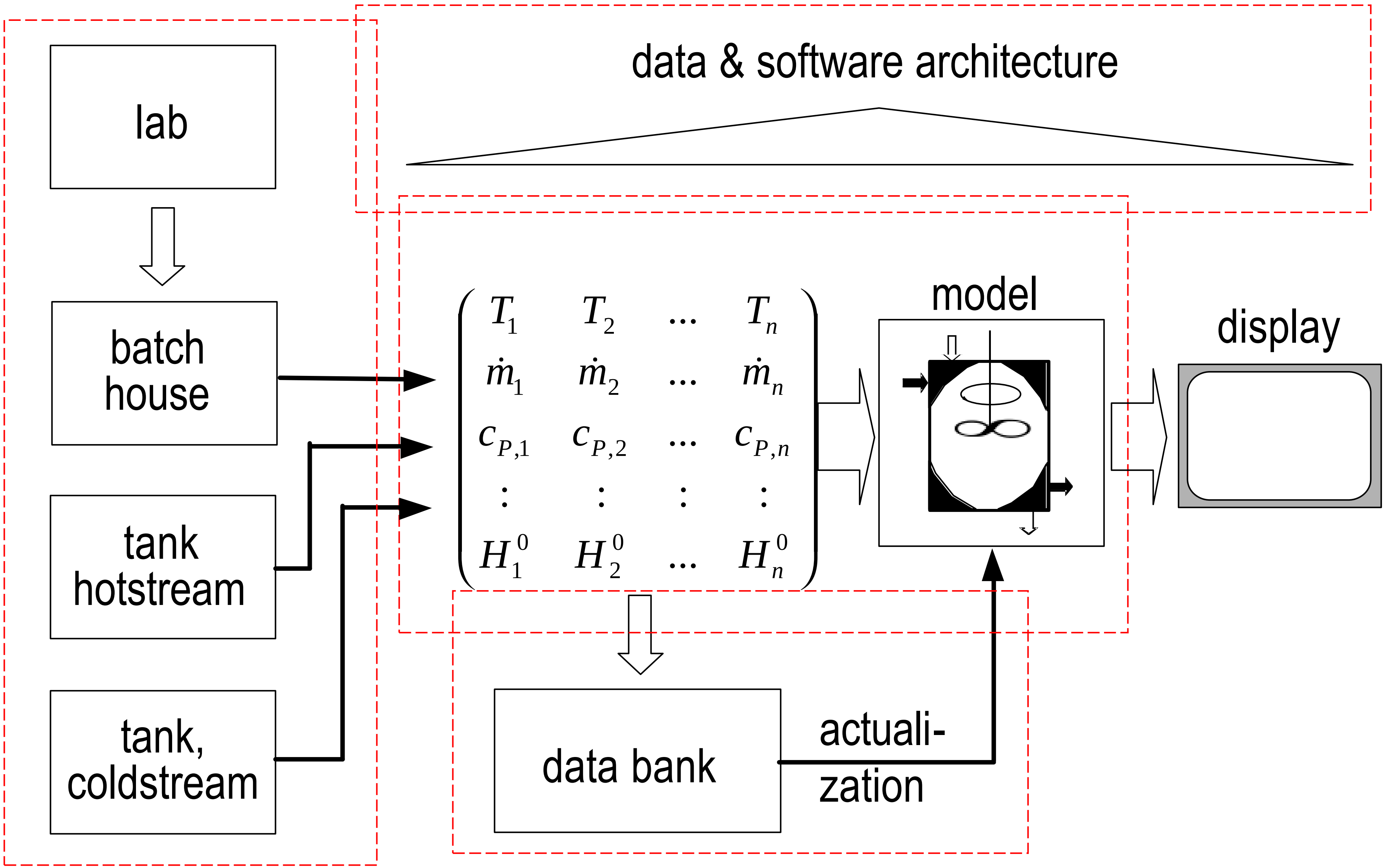
sketch of a float glass production



step 5: comprehension and linking of data



step 6: realization: structuring of the processes



step 7: factory test and evaluation

Thank you

for your kind attention!