TECHNICAL REPORT

No. 7/83

Thermal Losses of the Sodium Storage Vessels of the Central Receiver System

by

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IEA SMALL SOLAR POWER SYSTEMS PROJECT

Technical Report No. 7/83

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International Test and Evaluation Team

Prepared for

IEA - Operating Agent DFVLR

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ABSTRACT

In solar thermal power stations, the knowledge about the plant efficiency has a very high priority. The thermal losses of the heat transfer system are needed as one input value for calculating this efficiency and for developing the loss stair step diagram.

The thermal losses of both sodium tanks of the SSPS Central Receiver System (CRS) in Tabernas (Spain) are determinated using two different methods. The values are calculated using the well known laws of heat transfer. The results are verified by observing the cooling down behaviour under different conditions such as sodium level in the tanks and status of the electrical trace heating.

The result of the calculations are summarized into characteristic heat transfer values, which are independent of the temperatures and the sodium level in the tanks.

To make these values more transparent, the losses are expressed in kW for different conditions. Other figures show the temperature inside the tank during nighttime. Investigation of the sodium system by looking at the consumption of electrical energy of the trace heating is to be accomplished in the near future.

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1. Introduction

The knowledge about the losses in the sodium tanks is important in the evaluation of the operational behaviour of the Central Receiver System (CRS).

The losses thus determined are input values for:

- calculation of the total plant efficiency,
- optimization of plant operation,
- calculation of the energy content in the tanks, and
- design of other sodium tanks considering the losses.

Data, which are available on site fitting a selection criteria, are used. It is possible to have more information about the tanks by reading the operational data tapes. All formulas needed for the calculation of losses are defined in this report. The losses of the cold tank can be determined with this data.

The calculations in this report were performed using a PDP-11/03 computer which is available on site. All the program is written in BASIC computer language. The program is attached.

2. Summary

The losses of both tanks are determined in two different ways:

- theoretical calculations, and
- measurement during cool-down.

The theoretical calculated losses are the following:

- losses through the insulation
- losses through the supports, and
- losses through the connected tubes.

The results of measuring the temperature drop are:

- the half value time (HVT),
- the k-value.

With these numbers it is possible to make a prediction about the temperature drop during the night and the time required to heat up the tanks using electrical trace heating.

The approach is to measure the temperatures of the sodium and the wall of the tank during cool-down, thus giving a measure of the quality of insulation surrounding the tank.

The requirements for the measurements were:

- CRS plant not in operation for more than one day,
- DAS working for more than 3 hours per day during the measurements, and
- the status of the electrical trace heating does not change during the test period.

3. Calculation of tne constant values and the ambient temperature

In determining the losses, it is necessary to have the following values:

- volume of the tank
- mass of the tank (steel)
- trace heating power
- ambient temperature
- constants for steel and sodium

The constants used are presented in table 1. The specific values for sodium and steel are calculated in references 4,5, and 8.

TABLE 1

Table of symbols and constant values used

A_{cap}	m^2	surface of the reapir-caps at the cold storage: $4 m^2$
A_{out}	m^2	outside surface of the tanks (hot: 138 m^2; cold: 129 m^2)
A_p	m^2	cut edge of one tube
A_{supp}	m^2	cut edge of the supports: 0,174 m^2
A_t	m^2	tank surface inside the insulation: 100 m^2
$a_o \ldots a_3$		constants
c_pNa	J/g/K	specific heat at constant pressure of sodium
c_{pst}	J/g/K	specific heat at constant pressure of steel(ref.4)
Gr	1	Grashof - number
g	m/s^2	gravitation constant: 9,81 m/s^2
h	m^2	outside diameter of the tank with insulation hot: 4,1 m cold: 3,9 m
HVT	h	half value time

TABLE 1 (continued)

k	$W/m^2/K$	characteristic heat transfer number (k-number)
k_p	$W/m^2/K$	k-number of the pipe
k_r	$W/m^2/K$	k-number of the cold storage with repair-caps
L	m	Sodium level measured by DAS
l	m	Characteristic length of the tank hot: 6,44m cold: 6,13m
l_t	m	Length of the tubes
m_{Na}	kg	mass of the sodium in the tank
m_{st}	kg	mass of the tank
Pr	1	Prandtl-number for air: 0,7
Q	W	summ of the thermal losses
Q_1	W	losses of the insulation
Q_2	W	losses of the supports
Q_3	W	losses of the connected tubes
Q_4	W	losses of the repair-caps
Q_t	W	losses of one pipe
Q_{th}	W	energy of the traceheating
S_i	m	thickness of the insulation hot: 0,4 m cold: 0,3 m
T_{Na}	ºC	sodium temperature measured by DAS
T_{amb}	ºC	ambient temperature in the sodium hall
T_{peri}	ºC	periphery temperature of the tank
T_{supp}	ºC	support temperature
T_{out}	ºC	outside temperature
ΔT	K	temperature drop
ΔT_m	K	logarithmic temperature difference
t	h	time
Δt	h	time of the measurement
U	m	length of the periphery
V	m^3	volume of the tank
α_{in}	$W/m^2/K$	α-value inside the Na-tank
α_{out}	$W/m^2/K$	α-value insulation-air
	K^{-1}	coefficient of the thermal expansion (air): 0,0033 K^{-1}(ref.3d)
ν	m^2/s	cinematic viscosity: 16.10^{-6} m^2/s(ref.3d)
λ_{air}	W/m/K	conductivity of air: 0,027 W/m/K (ref.3d)
λ_i	W/m/K	conductivity of the insulation: 0,1 W/m.K (ref.3e)
λ_{st}	W/m/K	conductivity of steel: 45 W/m/K (ref.5)

3.1 Relationship between the ambient temperature in the sodium hall and the outside temperature

Knowledge of the temperature in the sodium hall and in the steam generator house is necessary for the evaluation of the thermal losses in each component of the plant.
The inside temperatures are measured by a min-max thermometer during May, June and July 1982. Additional point measurements are taken at the begining of October.
The outside temperatures are taken by the DAS and written in the daily meteo report.

The first observation is that the temperature in the steam generator house is close to the temperatures in the sodium hall. The difference is less than 3 K.

The next evaluation compared the inside to the outside temperature using the program "POLFIT" which is described inref. 1. The result is:

$$T_{amb} = 12{,}74\,°C + 0{,}84 \cdot T_{out} , \qquad (1)$$

with the following statistic values:

TABLE 2

- Number of data points		=	74	
- Linear correlation coefficient		=	0,904	
- Min. outside temperature	t_{out}	=	11,2	ºC
- Max. outside temperature	t_{out}	=	39,5	ºC
- Min. ambient temperature	t_{amb}	=	23	ºC
- Max. ambient temperature	t_{amb}	=	46	ºC
- Accuracy of formula (1)		=	± 3	K

In the winter the CRS-plant was switched off. During this period of time (December 82 to February 83), the empirical relation between outside and ambient temperatures becomes:

$$T_{amb} = 5{,}74\,°C + 0{,}84 \cdot T_{out} . \qquad (2)$$

3.2 Calculation of the volume of the sodium tanks

The content of energy in storage is a function of the Na-volume inside the tank, the mass of the wall and the temperature.

The sodium volume can be calculated by the level, which is measured by the DAS, and the geometry of the tank. A proposal to calculate the volume is in reference 6.

Starting from these values and considering the level measurements by the DAS (LK01 CL01 and LK02 CL01) which begins at 0,122 m (that means the real level is the measured level plus 0,122 m) a regression-calculation was made by "POLFIT" (reference 7).

The result is:

$$V = a_0 + a_1 L + a_2 L^2 + a_3 L^3 , \qquad (3)$$

with the numbers:

TABLE 3

L	= 0,516 m	0,516 m
a_0	0,8344	0,9181
a_1	9,2685	11,1062
a_2	18,2613	11,7256
a_3	-7,7387	-2,5850
Variance	0,99998	0,99997

To have a good accuracy, the numbers $a_0 \ldots a_3$ are subdivided in two groups; one for a level less than 0,516 m and one for higher one. Therefore, the difference between the initial values of reference 6 and the calculated values is less than 0,8%.

In addition, the volume was calculated by a computer program using geometrical laws. The difference between these numbers and those calculated by equation (3) is at most 0,2 m^3. Therefore the proposed calculation is sufficient.

3.3 Calculation of the mass and the surface of both sodium storage vessels

To calculate the stored energy the mass of the tank-wall is also needed. Therefore the tank is subdivided into several pieces (see fig. 1). The values are in reference 1. The caps are calculated as an ellipsoid.

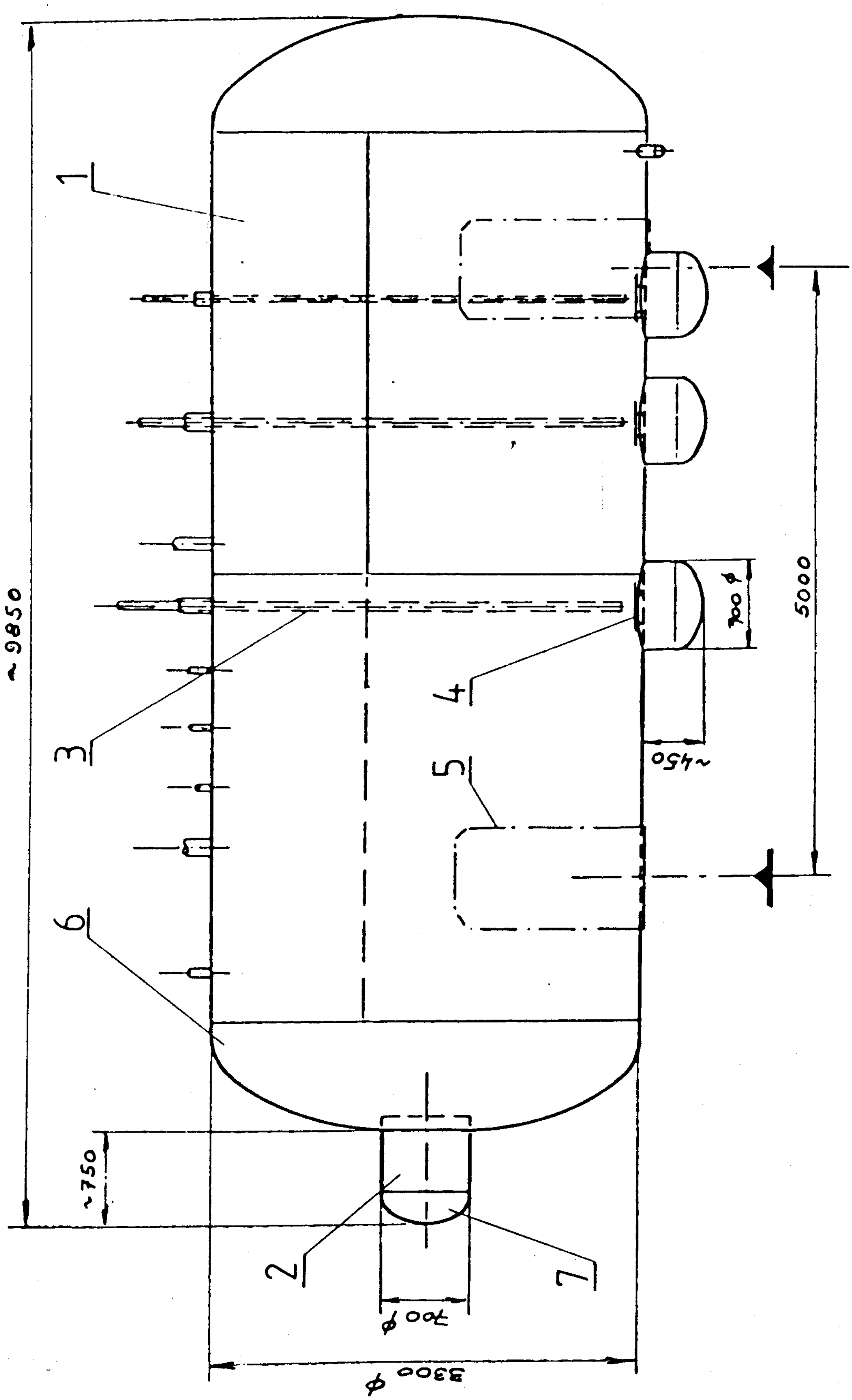
The numbers are:
- diameter x length x thickness(for tubes)
- length x length x thickness (for plates)
- diameter x thickness (for caps)

TABLE 4

ITEM		HOT STORAGE (mm)			MASS (kg)	SURFACE (m^2)
1	1 tube	3300 x	7260 x	22	13168	75
2	1 tube	700 x	700 x	20	236	2
3	2 tube	88,9 x	82,5 x	3248,5	44	--
4	2 paffle plate	400 x	400 x	20	51	--
5	2 chord plate	20 x	800 x	4694	1172	--
6	2 cap	3300 x	22		4059	20
7	1 cap	700 x	20		94	--
					18824 kg	97 m^2

TABLE 5

ITEM		COLD STORAGE (mm)			MASS (kg)	AREA (m^2)
1	1 tube	3300 x	7260	x 16	9407	75
2	1 tube	700 x	700	x 16	189	2
3	1 tube	60,3 x	54,5	x 3238,5	13	--
3	2 tube	88,9 x	82,5	x 3253,5	45	--
4	3 paffle plate	400 x	400	x 17	64	--
5	2 chord plate	14 x	800	x 4685	824	--
6	2 cap	3300 x	17		3128	20
7	1 cap	700 x	14		66	--
					13736 kg	
		plus repair nozzles			+ 635	
					14371 kg	97 m^2



Cold Sodium Storage Vessel fig 1

3.4 Determination of the trace heating electrical power

The energy needed by the trace heater was measured by two different methods:

- by a clamp-on ampere-meter
- by switching off and observing the decrease of the total energy of the plant (switch-test).

The number which is normally used for calculations is an average between the designed and the measured power.

Between July and October 1982 the trace heating circuit no.13 took only 5,9 kW. It seems that some fuse disconnections are responsible for this low number.

TABLE 6

Storage	Trace heating No.	clamp-on kW	switch test kW	designed kW	used for calculat.
Hot	41	9,2	9,1	9,2	9,2
	42	10,4	10,3	10,5	10,4
Cold	13	5,9	--	9,2	5,9
W. caps	14	9,6	10,3	10,5	10,3
Cold	13	9,6	8,3	9,2	9,0
	14	9,9	10,8	10,5	10,4

The status (on-off) of the traceheating, which is used for the calculations, was picked up of the CRS log book.

4. Theoretical calculation of the thermal losses

To aid in this calculation, the thermal losses are divided into several groups:

Q_1 - Losses through the insulation, "insulation losses" etc
Q_2 - Losses through the supports
Q_3 - Losses through the inlet and outlet tubes
Q_4 - Losses through the insulation of the repair-caps (only with the cold storage).

The following temperatures, which are needed for the calculations, were measured between the 5th and the 11th of October '82:

- Ambient temperature
- Temperature at the surface of the insulation (2 measurement points for each tank)
- Temperatures at the supports (3 measurement points for each tank)

The calculations are performed using the average of the temperatures. The result is a k-value, which is the total of the losses, divided by the area of the tank and the temperature difference (see formula 15).

The results are collected in tables 8 and 9.

4.1 Losses through the insulation

These are calculated using:

$$Q_i = A_t \cdot k \cdot (T_{Na} - T_{amb}) \quad \text{, and} \qquad (4)$$

$$\frac{1}{A_t \cdot k} = \frac{1}{\alpha_{in} \cdot A_t} + \frac{s_i \cdot \ln(A_{out}/A_t)}{\lambda_i \cdot (A_{out} - A_t)} + \frac{1}{\alpha_{out} \cdot A_{out}} \quad , \qquad (5)$$

ref. 3c

where α_{in} is the heat transfer coefficient between sodium and steel.

For sodium, α_{in} is very high. For this reason the first part of formula (5) becomes nearly zero.

The α out was calculated by formulas (6) and (7) (ref. 3a and 3g).

$$\alpha_{out} = \frac{1}{l} \cdot 0{,}1 \cdot (Gr \cdot Pr)^{1/3} \cdot \lambda_{air} \quad \text{, and} \qquad (6)$$

$$Gr = \frac{g \cdot h \cdot l^2 \cdot \beta \cdot (T_{peri} - T_{amb})}{\nu^2} \quad . \qquad (7)$$

4.2 Losses through the supports

These are calculated from:

$$Q_2 = \frac{1}{s_i} \cdot \lambda_{St} \cdot A_{supp} \cdot (T_{Na} - T_{supp}) \quad . \qquad (8)$$

The area of the two supports are calculated using the drawing of the tanks in ref. 1.

4.3 Losses through the connected pipes

The thermal losses for the tubes with insulation is determined with formula (9) (ref 2):

$$Q_T = (T_{Na} - T_{amb}) \cdot (U \cdot k_P \cdot \lambda_{St} \cdot A_P)^{1/2} \cdot \tanh \frac{U \cdot k_P \cdot l_t}{\lambda_{St} \cdot A_P} \quad . \qquad (9)$$

For very long tubes the third factor is equal to one.

The second factor is calculated for each diameter with insulation and for DN 50 without insulation.

The conductivity k_p is determined from:

$$k_P = \left[\frac{1}{\alpha_{out}} + \frac{s_i}{\lambda_i} \right]^{-1} \quad , \qquad (10)$$

where

$$\alpha_{out} = 8 + 0{,}04 \cdot (T_{Na} - T_{amb}) \, , \qquad \text{ref. 3f} \qquad (11)$$

yielding the following results:

for the hot storage α_{out} = 24 $W/m^2/K$, and
for the cold storage α_{out} = 16 $W/m^2/K$.

Table 7 shows how the second factor of equation (9) is calculated. The final calculation is very easy.

TABLE 7

DN	Diameter mm	k W/m/K	Hot Storage number of pipes	Hot Storage $(U.kp.\lambda.A)^{0,5}$ W/K	Cold storage number of pipes	Cold storage $(U.kp.\lambda.A)^{0,5}$ W/K
25	33,7/28,5	0,1	3	0,2817	3	0,2789
50	60,3/54,5	0,1	4	0,5563	4	0,5519
50	60,3/54,5	19	1	0,3569	1	0,2911
80	88,9/82,5	0,1	3	0,5469	4	0,7246
Total			Hot	1,7418	Cold	1,8465

The results are the following formulas:

hot storage: $Q_3 = 1{,}742 \cdot (T_{Na} - T_{amb})$, and (12)

cold storage: $Q_3 = 1{,}847 \cdot (T_{Na} - T_{amb})$. (13)

4.4 Losses at the repair-caps of the cold storage vessel

Because of the thickness of the insulation of the repair caps, the losses in this part of the cold storage are relatively high.
These losses are calculated separately using formula (5).
For the insulation, the thickness Si is approximately 0,2 m, and the total area A_{cap} is approximately 4 m^2. These values are used in

$$Q_4 = \frac{T_{Na} - T_{amb}}{\frac{s_i}{\lambda_i \cdot A_{cap}} + \frac{1}{\alpha_{out} \cdot A_{cap}}} \quad . \qquad (14)$$

4.5 Result of the calculation

The desired result is the k-value, which is calculated by:

$$k = \frac{\sum Q_i}{A_t \cdot (T_{Na} - T_{amb})} \quad . \qquad (15)$$

The results are tabulated in the following tables.

TABLE 8

CALCULATED LOSSES OF THE HOT STORAGE

Date	Time	T_{amb} ºC	T_{peri} ºC	T ºC	T_{supp} ºC	Q_1 W	Q_2 W	Q_3 W	k $W/m^2/K$
5.10	8.40	30	52	380	112	9583	5705	609	0.454
5.10	13.20	30	56	365	116	9227	5304	584	0.451
5.10	16.40	32	54	410	127	10372	6039	659	0.451
6.10	9.35	23	47	362	111	9302	5350	591	0.450
6.10	14.05	27	47	460	110	11829	7467	754	0.463
6.10	17.20	28	48	468	137	12027	7048	766	0.451
7.10	10.00	27	53	460	118	11900	7283	754	0.460
7.10	17.00	31	62	500	132	12935	7837	817	0.460
8.10	8.50	24	52	430	124	11196	6515	708	0.453
8.10	20.50	27	45	305	103	7581	4313	484	0.445
9.10	9.50	26	38	300	98	7379	4313	477	0.445
10.10	13.40	28	40	285	95	6921	4050	447	0.445
11.10	8.45	25	33	278	90	6780	4018	442	0.443
Average:		27	48	385	113	9776	5788	623	0.453
Losses expressed in per cent:						60.4%	35.8%	3.8%	

TABLE 9

CALCULATED LOSSES OF THE COLD STORAGE

Date	Time	T_{amb} ºC	T_{peri} ºC	T ºC	T_{supp} ºC	Q_1 W	Q_2 W	Q_3 W	k $W/m^2/K$	Q_4 W	k_r $W/m^2/K$
5.10	8.40	30	38	230	76	6715	4367	369	0.573	322	0.589
5.10	13.20	30	41	240	81	7189	4509	388	0.574	347	0.591
5.10	16.40	32	42	250	86	7426	4651	403	0.571	358	0.588
6.10	9.35	23	32	212	76	6398	3865	349	0.561	308	0.578
6.10	14.05	27	37	262	75	7958	5315	434	0.583	383	0.600
6.10	17.20	28	36	278	87	8384	5428	461	0.571	401	0.587
7.10	10.00	27	37	248	81	7500	4746	408	0.573	361	0.589
7.10	17.00	31	42	272	85	8202	5305	444	0.579	396	0.596
8.10	8.50	24	33	240	78	7338	4614	399	0.570	353	0.587
8.10	20.50	27	35	225	75	6640	4263	365	0.569	318	0.585
9.10	9.50	26	33	200	66	5774	3818	320	0.571	275	0.587
10.10	13.40	28	33	153	57	4086	2738	230	0.566	193	0.582
11.10	8.45	25	28	130	50	3395	2264	195	0.555	159	0.570
Average:		27	36	226	75	6694	4299	367	0.572	321	0.588
Losses expressed in percent:						58.9%	37.8%	3.2%		--	
						57.3%	36.8%	3.1%		2.7%	

5 Tank losses as determined by measuring the temperature during cool-down

The calculation of the losses presupposes that the cooling down behaviour of the tanks follow the theoretical equation.

One characteristic number to be determined is the half-value -time, which is the time needed to cut the temperatures in half with normal cooling.

The half value-time is a function of the amount of sodium which is in the tank.

The properties of sodium are calculated in the same way as described in reference 8.

The other characteristic number is the k-value. This figure is constant and is only determinated by the quality of the insulation.

Both numbers are part of the exponent of the cooling down function.

The source and the energy balance equations are:

$$T_{Na} = T_{amb} + (T_{Na_0} - T_{amb}) \cdot e^{-\frac{A_t \cdot k}{\sum m_i \cdot c_{pi}} \cdot t} \quad \text{, and} \qquad (16)$$

$$\Delta T \cdot \sum m_i \cdot c_{pi} + Q_{th} \cdot t = A_t \cdot k \cdot t \cdot \Delta T_m \; , \qquad (17)$$

To calculate the characteristic numbers from the measured temperatures, these equations are needed:

$$HVT = \frac{t \cdot \ln 2}{\ln \frac{T_{Na1} - T_{amb}}{T_{Na2} - T_{amb}}} \; , \qquad (18)$$

$$HVT = \frac{t \cdot \ln 2}{\ln \frac{T_{Na1} - T_{amb}}{T_{Na2} - T_{amb}}} - \frac{Q_{th} \cdot t}{A_t \cdot k \cdot \Delta T} \quad \text{, and} \qquad (19)$$

$$k = \frac{\ln \frac{T_{Na1} - T_{amb}}{T_{Na2} - T_{amb}}}{A_t \cdot t} \cdot \left[\sum m_i \cdot c_{pi} + \frac{Q_{th} \cdot t}{\Delta T} \right] . \qquad (20)$$

An example of the undisturbed cooling down of the sodium in the hot tank is presented in Figure 2. The temperature scale of the y-axis is scaled lagarithmically to produce a graph which is linear.

Formula (19) allows to calculation of the cooling down behaviour by heating up the sodium with the trace heating.

All the calculations are executed with a computer program. The input data, which are taken up from the daily summaries, are written in a data-file, allowing for addition of new numbers in the future.

The characteristic values, which are needed for the calculation and are not described in this report, are taken from the references 3,4,5, and 8.

The print-outs are tables, which are subdivided in several groups within the same lavel. The average of each group is factored out due to the cooling down time.

One important result is that the sodium level inside the tank has no influence on the specific thermal losses, if steady state conditions are achieved (as expected).

Undisturbed Cooling Down

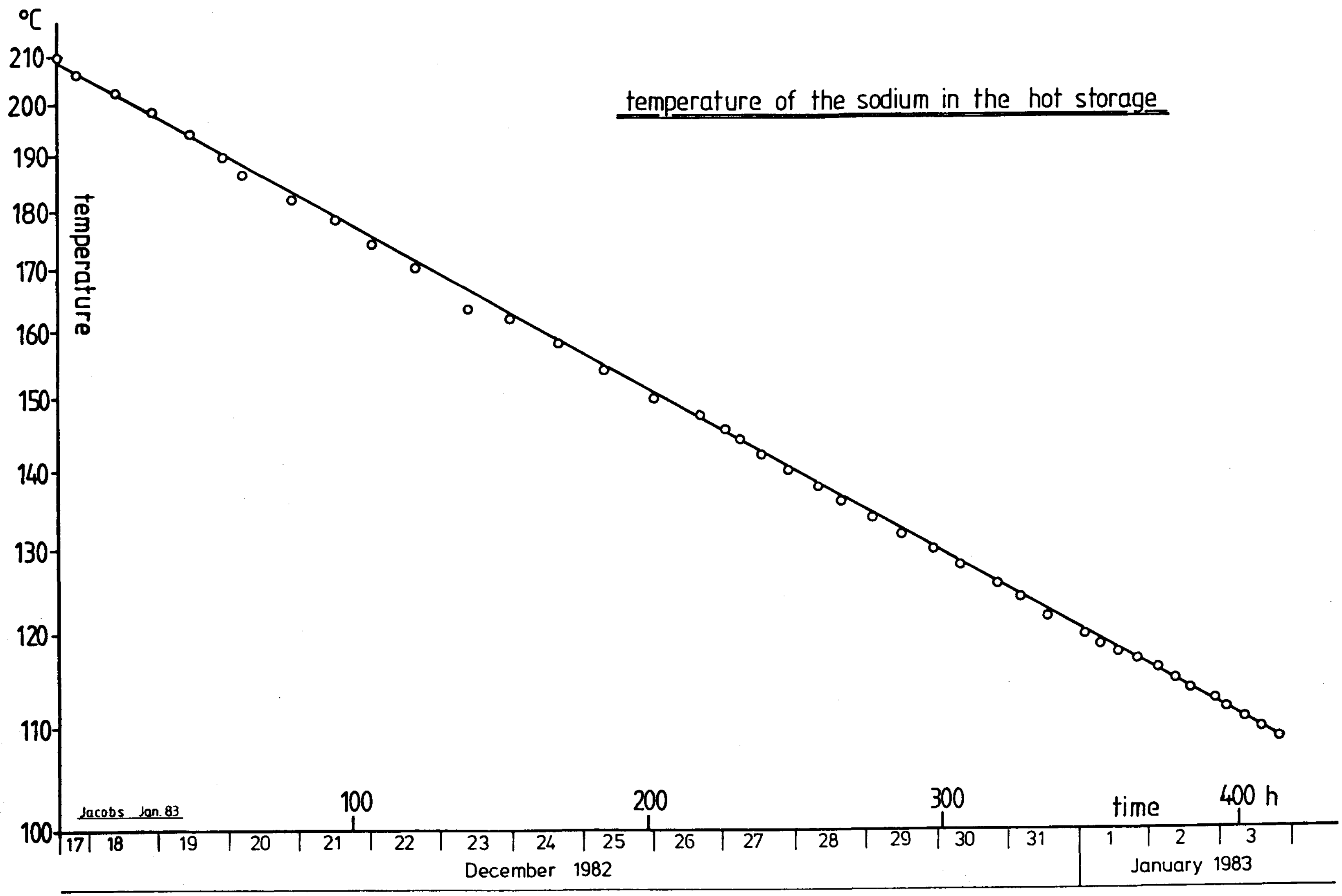


fig. 2

5.1 Results of the measurement at the hot storage

There were some periods of time in which the conditions were optimal for the calculations:

- during the repair of the sodium valve LK02 AA14
- during the provisional repair of the cold storage (Sept '82)
- after the new leakage at the cold storage (Oct '82)
- during and after the general repair of the cold storage in '82/'83.

TABLE 10

Measured losses of the hot storage without trace heating

CUHNT2 23-FEB-83

date	time	T amb	Na temp.	change	level	Q th	m Na	HVT	k
	h	deg	deg	deg	m	kW	kg	h	W/m^2/K
14.09	18	30.4	394.70	381.90	2.896	0.0	58960	348.9	0.482
15.09	7	29.9	379.10	374.30	2.886	0.0	59022	350.5	0.480
16.09	20	30.7	362.98	350.82	2.861	0.0	59044	371.8	0.453
17.09	7	29.9	347.43	343.18	2.851	0.0	59093	360.0	0.469
18.09	21	34.4	341.39	329.37	2.838	0.0	59084	364.4	0.463
19.09	21	32.1	327.62	316.14	2.824	0.0	59115	367.4	0.460
20.09	21	30.3	314.51	303.01	2.816	0.0	59214	352.4	0.481
1. average :				343.20	2.848	0.0	59084	360.5	0.468
9.10	20	26.0	295.25	286.15	2.825	0.0	59627	403.2	0.424
10.10	19	26.4	283.76	275.15	2.812	0.0	59630	387.0	0.442
11.10	19	26.7	272.82	264.60	2.800	0.0	59639	387.6	0.442
12.10	19	27.5	262.40	254.71	2.790	0.0	59658	395.7	0.434
13.10	21	32.7	253.39	245.33	2.780	0.0	59649	391.2	0.439
14.10	21	28.5	244.17	236.27	2.768	0.0	59620	390.0	0.441
15.10	21	23.4	235.10	227.43	2.758	0.0	59615	394.5	0.436
2. average :				259.14	2.790	0.0	59634	392.8	0.437

TABLE 1C (Continued)

COHHTZ 23-FEB-83

date	time h	T amb deg	Hs temp. deg	change deg	level m	Q th kW	m Hs kg	HVT h	k W/m^2/K
18.12	24	10.0	204.50	197.00	3.070	0.0	63901	423.0	0.435
19.12	24	11.8	197.00	190.00	3.070	0.0	64021	431.7	0.427
20.12	24	10.2	190.00	181.30	3.070	0.0	64152	335.4	0.552
21.12	24	9.9	181.30	174.20	3.070	0.0	64283	393.3	0.472
22.12	24	6.9	174.20	167.90	3.070	0.0	64394	433.3	0.429
23.12	24	8.2	167.90	161.50	3.070	0.0	64499	406.8	0.459
24.12	24	9.5	161.50	155.70	3.070	0.0	64600	427.5	0.438
25.12	24	10.6	155.70	150.00	3.070	0.0	64695	415.0	0.452
26.12	24	9.8	150.00	144.60	3.070	0.0	64787	423.6	0.444
27.12	24	8.7	144.60	139.30	3.070	0.0	64875	418.2	0.450
28.12	24	8.3	139.30	134.30	3.070	0.0	64960	427.6	0.442
29.12	24	7.8	134.30	129.50	3.070	0.0	65041	429.9	0.440
30.12	24	7.7	129.50	124.80	3.070	0.0	65120	422.8	0.448
31.12	24	7.3	124.80	120.10	3.070	0.0	65197	407.7	0.466
1.01	24	7.6	120.10	116.40	3.070	0.0	65266	497.5	0.383
2.01	24	8.0	116.40	112.00	3.070	0.0	65333	401.4	0.475
3.01	12	8.1	112.00	110.20	3.070	0.0	65384	475.7	0.401
3. average :				151.54	3.070	0.0	64716	420.1	0.449
6.01	24	9.0	116.80	113.00	3.070	0.0	65321	463.7	0.411
7.01	24	9.3	113.00	109.50	3.070	0.0	65382	484.4	0.394
4. average :				113.08	3.070	0.0	65352	474.1	0.403
10.01	12	11.4	117.50	115.70	3.070	0.0	65293	486.2	0.392
11.01	24	11.5	115.70	111.40	3.070	0.0	65644	394.8	0.483
5. average :				114.57	3.070	0.0	65327	425.2	0.453
19.01	24	12.7	118.00	113.80	3.070	0.0	65305	408.5	0.466
20.01	24	11.7	113.80	109.70	3.070	0.0	65373	405.8	0.470
21.01	7	10.7	109.70	108.50	3.070	0.0	65417	398.0	0.480
6. average :				113.22	3.070	0.0	65349	406.0	0.470
24.01	24	12.5	117.90	113.40	3.070	0.0	65309	381.6	0.500
25.01	24	13.4	113.40	109.50	3.070	0.0	65378	418.1	0.457
7. average :				113.55	3.070	0.0	65344	399.7	0.478
1.02	24	16.7	114.40	110.90	3.070	0.0	65359	455.9	0.419
2.02	14	14.9	110.90	108.40	3.070	0.0	65408	367.9	0.519
8. average :				111.55	3.070	0.0	65377	423.5	0.456
6.02	18	13.2	118.80	115.20	3.070	0.0	65287	359.7	0.529
7.02	24	13.1	115.20	111.50	3.070	0.0	65347	450.9	0.423
8.02	12	11.9	111.50	109.50	3.070	0.0	65394	409.9	0.466
9. average :				113.93	3.070	0.0	65337	411.4	0.468

TABLE 11

Measured losses of the hot storage with trace heating

COHTH2   23-FEB-83

date	time h	T amb deg	Na temp. deg	change deg	level m	Q th kW	m Na kg	HVT h	k W/m^2/K
19.07	3	34.8	203.60	204.90	0.300	10.4	4554	61.8	0.500
20.07	21	34.2	205.80	215.10	0.295	10.4	4471	64.3	0.479
1. average :				209.68	0.296	10.4	4481	64.0	0.481
23.07	7	35.7	212.50	215.90	0.296	10.4	4483	66.9	0.461
24.07	22	35.3	216.60	224.30	0.299	10.4	4522	65.1	0.477
25.07	16	34.1	225.20	229.70	0.297	10.4	4486	65.7	0.473
2. average :				221.97	0.298	10.4	4503	65.6	0.473
9.09	18	30.0	400.40	401.60	2.912	19.6	58941	346.3	0.485
10.09	21	30.0	401.60	402.70	2.913	19.6	58928	340.8	0.493
11.09	21	30.1	402.70	403.90	2.911	19.6	58892	343.7	0.488
12.09	19	29.9	404.00	405.20	2.912	19.6	58876	347.7	0.482
3. average :				402.78	2.912	19.6	58909	344.5	0.487
8.01	17	8.1	110.00	113.80	3.070	10.4	65371	466.7	0.409
9.01	24	7.0	113.80	118.80	3.070	10.4	65298	445.5	0.428
10.01	5	11.4	118.80	119.70	3.070	10.4	65250	375.9	0.506
4. average :				115.00	3.070	10.4	65320	445.8	0.429
17.01	24	13.3	111.10	116.30	3.070	10.4	65341	431.3	0.442
18.01	18	13.8	116.30	119.50	3.070	10.4	65272	359.3	0.530
5. average :				115.50	3.070	10.4	65312	400.4	0.480
26.01	12	14.4	110.20	112.80	3.070	10.4	65377	418.3	0.456
27.01	12	15.1	112.80	115.00	3.070	10.4	65338	351.9	0.542
6. average :				112.70	3.070	10.4	65358	385.1	0.499
4.02	18	12.4	110.40	114.00	3.070	10.4	65366	389.1	0.490
5.02	24	14.9	114.00	119.00	3.070	10.4	65295	413.9	0.460
7. average :				114.66	3.070	10.4	65325	403.3	0.473
12.02	24	6.7	118.30	123.50	3.050	10.4	65034	484.0	0.392
13.02	24	7.4	123.50	128.00	3.070	10.4	65143	426.2	0.445
14.02	13	7.1	128.00	130.00	3.070	10.4	65089	372.8	0.508
8. average :				124.53	3.062	10.4	65088	437.5	0.438

5.2 Results of the measurements at the cold storage

The results of the calculation for the cold storage with repair caps are given in the following table.

TABLE 12

Measured losses of the cold storage with trace heating and with repair caps.

COCTC4 21-MAR-83

date	time h	T amb deg	Na temp. deg	change deg	level m	Q th kW	m NA kg	HVT h	k W/m^2/K
14.07	21	34.4	269.00	260.20	2.456	5.9	54163	232.0	0.656
15.07	21	33.7	259.00	250.60	2.449	5.9	54167	229.3	0.665
16.07	6	35.3	249.50	247.30	2.444	5.9	54160	232.8	0.656
16.07	11	35.3	245.70	241.70	2.444	5.9	54238	228.9	0.668
17.07	21	34.8	240.70	233.70	2.441	5.9	54261	236.6	0.656
19.07	10	34.8	224.40	221.80	2.407	5.9	53789	247.0	0.617
1. average :				247.67	2.443	5.9	54154	233.1	0.655
23.07	12	35.7	215.40	217.40	2.403	16.2	53802	220.0	0.693
2. average :				216.40	2.403	16.2	53802	220.0	0.693
24.07	21	35.3	272.00	263.90	2.446	5.9	53929	246.0	0.616
25.07	21	34.1	262.60	254.40	2.440	5.9	53947	235.7	0.644
26.07	8	34.9	250.50	247.60	2.440	5.9	54072	235.3	0.648
3. average :				260.96	2.442	5.9	53959	240.0	0.633
8.09	21	30.1	254.00	208.60	0.000	5.9	315	28.9	0.535
9.09	18	30.0	197.60	168.10	0.000	5.9	319	24.1	0.619
10.09	21	30.0	163.60	128.50	0.000	5.9	322	17.8	0.816
4. average :				186.93	0.000	5.9	318	23.5	0.658
19.09	9	32.1	202.58	221.04	0.000	16.2	316	23.4	0.651
20.09	21	30.3	196.70	242.61	0.000	16.2	316	25.4	0.604
21.09	21	31.1	253.15	264.61	0.000	16.2	312	23.9	0.657
5. average :				234.42	0.000	16.2	314	24.4	0.634
8.10	10	25.6	245.33	222.10	0.000	5.9	314	29.0	0.533
9.10	20	26.0	213.36	175.69	0.000	5.9	318	25.3	0.595
10.10	19	26.4	167.73	141.70	0.000	5.9	321	21.2	0.687
6. average :				187.09	0.000	5.9	318	24.5	0.618

After the general repair of the cold storage vessel it was possible to observe some usable data while heating up the empty tank (first average in table 13).

For the full tank the calculation become complicated. Because there is natural convection of the sodium through the steam generator.

The calculation is performed in this way, that the energy of the trace heating is equal to the energy of the trace heating of the tubes and the steam generator minus the expected losses in tubes and steam generator.

For these calculations (2. and 3. average) the trace heating energy is 4 kW more than in chapter 3.4 calculated.

TABLE 13

Measured losses of the cold storage after the general repair

COLTH3 22-MAR-93

date	time h	T amb deg	Na temp. deg	change deg	level m	Q th kW	m NA kg	HVT h	k W/m^2/K
28.02	3	23.2	181.21	182.25	0.000	10.4	0	21.9	0.614
1.03	13	24.4	182.75	187.68	0.000	10.4	0	22.5	0.601
1. average :				184.96	0.000	10.4	0	22.4	0.603
3.03	20	21.2	172.58	183.66	2.871	23.4	62031	289.6	0.603
4.03	20	20.4	185.78	196.01	2.878	23.4	61932	279.8	0.621
5.03	10	20.1	197.50	202.48	2.802	23.4	61838	284.1	0.609
2. average :				187.60	2.876	23.4	61960	284.6	0.611
6.03	10	20.1	202.44	199.62	2.784	4.0	60474	281.6	0.602
7.03	6	18.4	196.17	194.34	2.775	4.0	60433	261.7	0.649
3. average :				198.86	2.781	4.0	60458	274.1	0.620

5.3 Summary and discussion of the results

The relation between calculated and measured numbers can be described as written under the following points:

- The calculated figures, and the figures measured are very close.

- Due to the trace heating the losses at the hot storage increase. It seems that the temperature difference between the sodium and the ambient becomes higher (17 ºC for design conditions).

- The temperature increases due to the trace heating for the cold storage with repair caps is much higher. Therefore, it seems reasonable that the repair caps are responsible for additional losses in the range of 0,7 kW (see calculation in Table 14). It could be that there was not enough space to replace the insulation properly.

- The accuracy is a function of the standard deviation (S.D.) of the measured or calculated figures. (Accuracy = S.D. divided by the average).

All the numbers are in the following tables for the cold storage. Some numbers are still missing. The second and third averages of table 13 are not used for the overall average.

TABLE 14

Averages of the calculated and measured figures

Storage		Calculated (1)	Measured with t.h. (2)	Measured without t.h. (3)	Increasing due to t.h. k-value (2)-(1)	Increasing due to t.h. temp. dif.
Hot	av	0.452	0.468	0.452	+3.5%	+17.5ºC
	acc	1.35%	7.76%	7.34%		
Cold with caps	av	0.587	0.644		+9.7%	+21.1ºC
	acc	1.23%	9.63%			
Cold	av	0.570	0.603		+5.8%	+17.4ºC
	acc	1.20%	--			

av = average of the losses ($W/m^2/K$)
acc = accuracy (%)
t.h. = trace heating
caps = repair caps at the cold storage

Calculation of the additional losses due to the caps =
$= 0.587\ W/m^2/K \times 100\ m^2\ (29.1-17.4)\ K = 700\ W$

The results of the calculations (losses, half value-time, temperature decrease during the night) are plotted in the following figures.

Figure 3 shows the half value-time of the hot storage versus the mass of sodium in the tank. The "+" are the averages of the calculations. The graph is calculated using formulas (19) and (20).

Figure 4 shows the losses of both tanks as a function of the sodium temperature. Because of several reasons, the effect of the level of the sodium inside the tanks on the losses is not as important. The shell (conductivity) and the cover gas in the tank (convection) transport the heat to the upper parts, if the level is low. Besides the supports, which are situated at the bottom of the tanks, account for 36% of the losses (see table 8)

Under design conditions, the losses are:

at the hot storage: 23 kW
at the cold storage: 17 kW

The temperature drops during 12 hours depend on the starting temperature. Figures 5 and 6 show the drop due to the mass of sodium in the tanks at an ambient temperatures of 20 ºC.

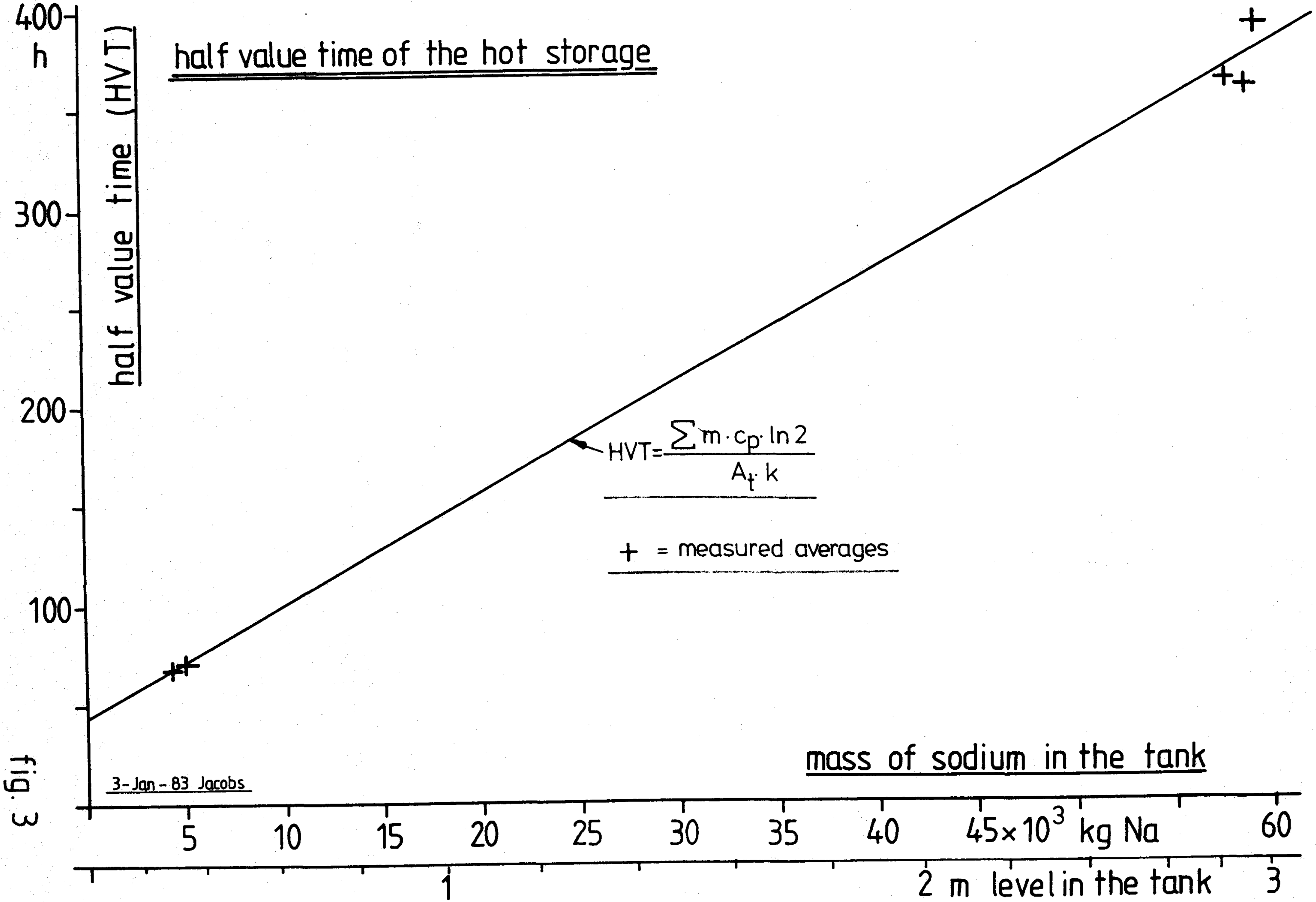

half value time of the hot storage
half value time (HVT)
400
h
300
200
100
$HVT = \frac{\sum m \cdot c_p \cdot \ln 2}{A_t \cdot k}$
+ = measured averages
mass of sodium in the tank
3-Jan-83 Jacobs
5
10
15
20
25
30
35
40
45×10³ kg Na
60
1
2 m level in the tank
3

fig. 3

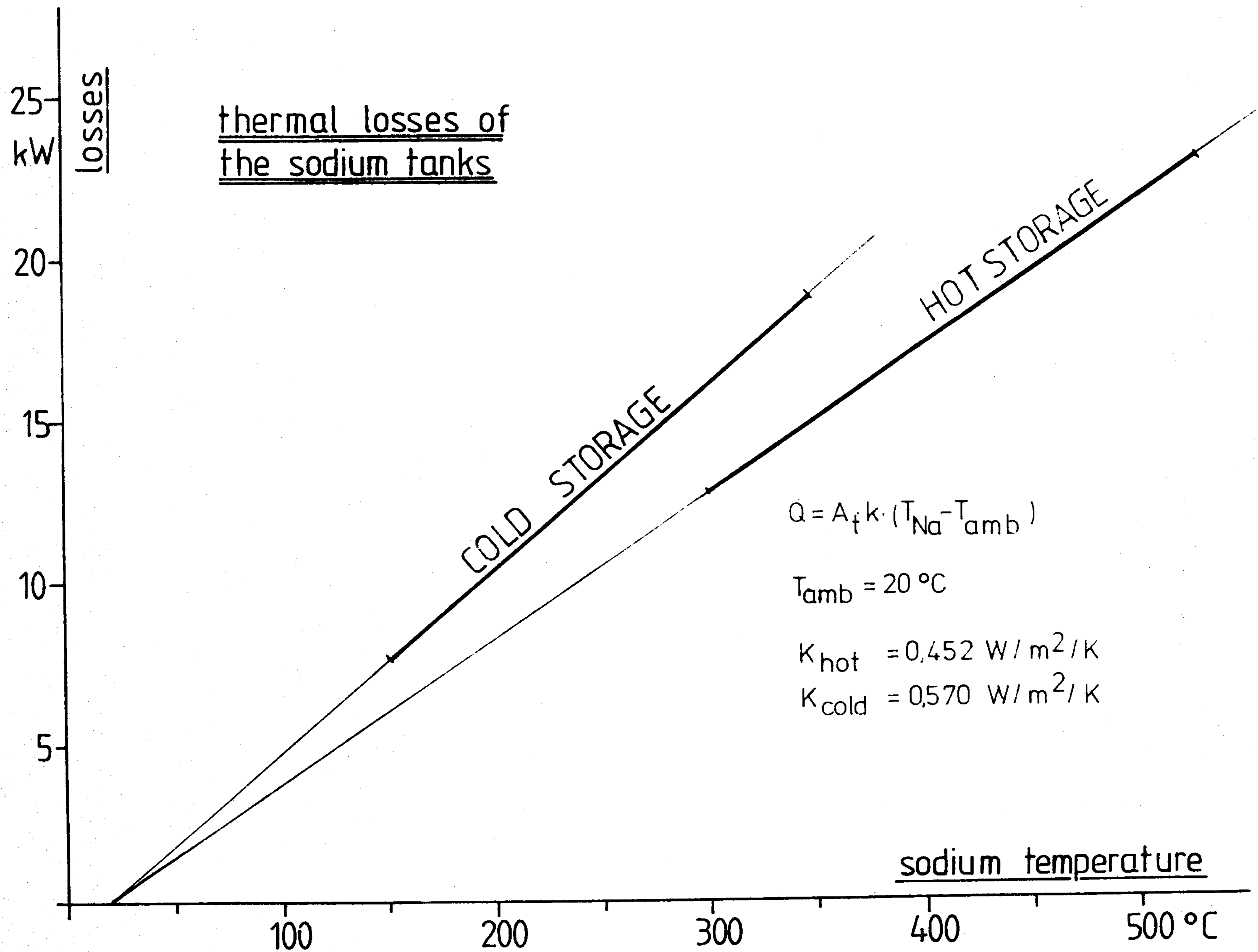
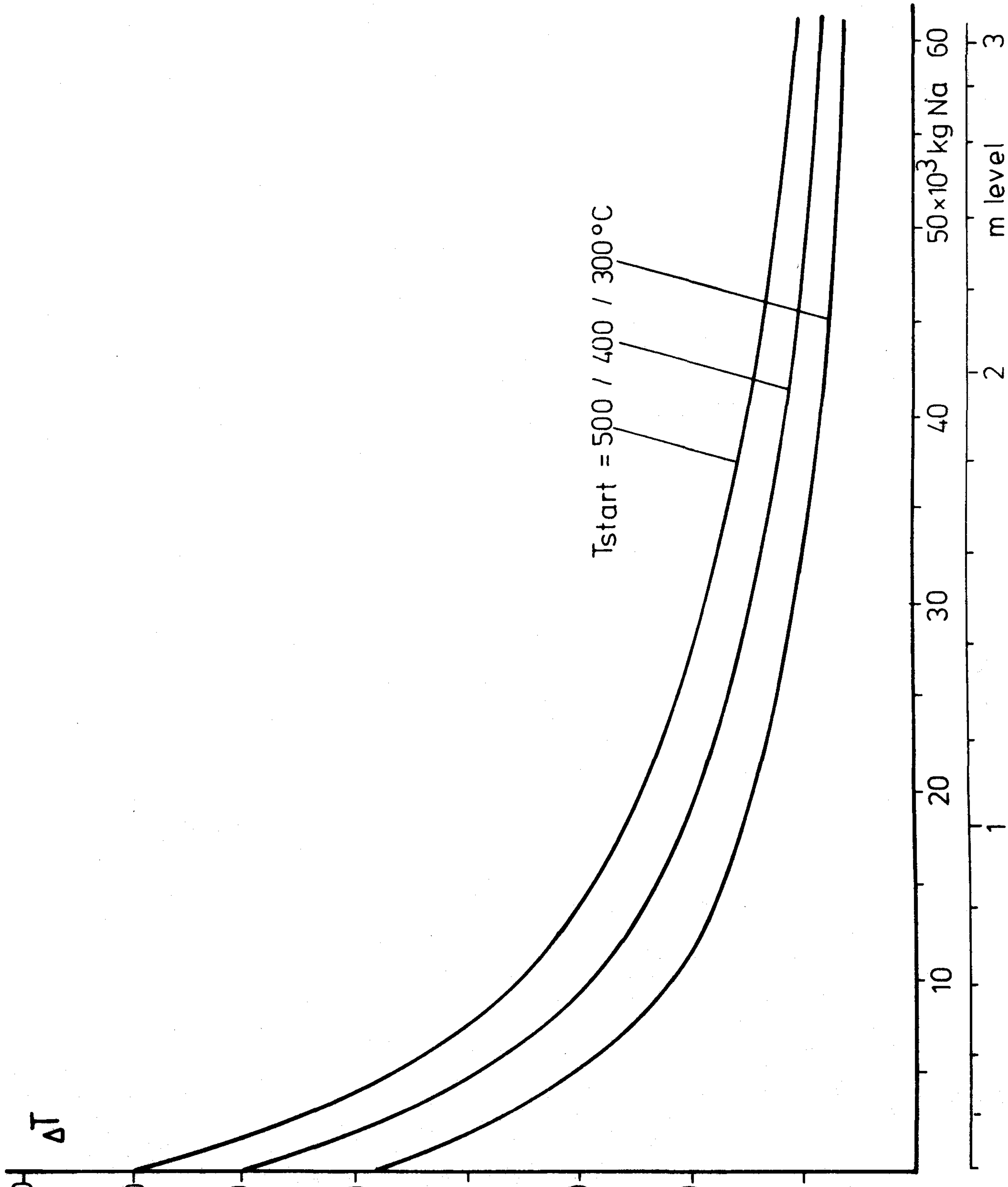
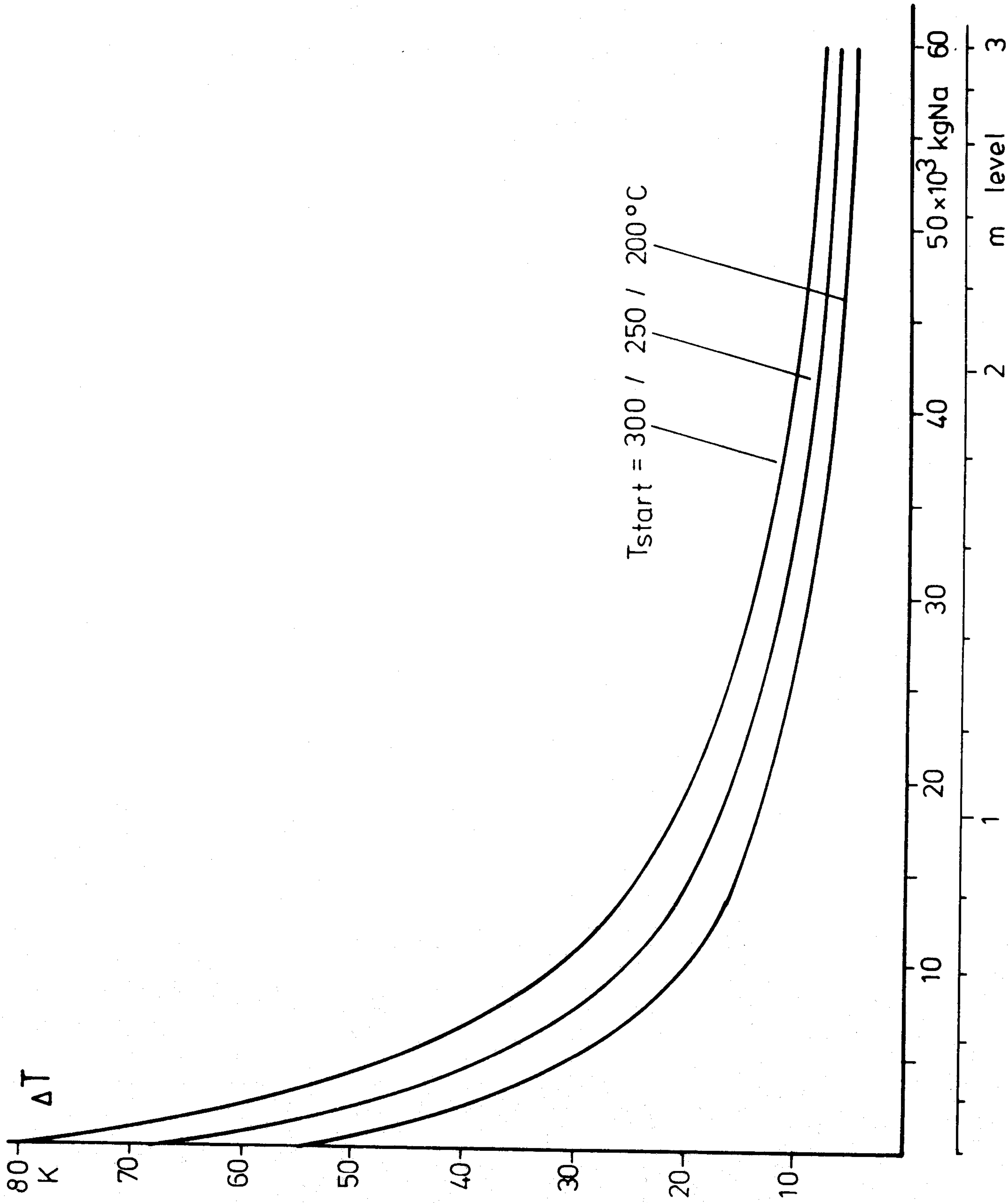

thermal losses of
the sodium tanks
losses
kW
25
20
15
10
5
COLD STORAGE
HOT STORAGE
$Q = A_t k \cdot (T_{Na} - T_{amb})$
T_{amb} = 20 °C
K_{hot} = 0,452 W / m^2 / K
K_{cold} = 0,570 W / m^2 / K
sodium temperature
100
200
300
400
500 °C

fig. 4



temperature drop in the hot storage during 12 hours

figure 5



temperature drop in the cold storage during 12 hours

figure 6

6. Reference list

1. CRS - Final Documentation file 8
   Document no. 2512 and 2412.2

2. Analysis of Heat and Mass-transfer
   International Student Edition page 75 f.f.

3. VDI - Wärmeatlas 2. Auflage 1974
   pages:

3a	Bc	1
3b	Ca	1
3c	Cb	2
3d	Db	7
3e	Ea	7
3f	Ec	3
3g	Fa	4

4. Mannesmannröhren - Werke AG Düsseldorf

   4a Werkstoffblatt 440B W-Nr. 1.4948
   4b Werkstoffblatt 405R W-Nr. 1.5415

5. DIN 17155 Kesselbleche

6. Carlos Gómez Camacho
   Determination of Sodium Tank's volume as a function of level
   SSPS Report R-5/82 CGC 4.2.1982

7. T. van Steenberghe
   A general purpose polynominal regression program
   SSPS Report R-41/82 TVS 3221 - 11.5.1982

8. Carlos Gómez and Ricardo Carmona
   CRS-PCS Gross Efficiency
   SSPS Report R-44/82 CGC/RC 14.5.1982

7. Annex

```
10 REM ****************************************************************
20 REM *                        PROGRAM COOLHS                        *
30 REM * THIS PROGRAM CALCULATES THE LOSSES OF THE HOT STORAGE VESSEL. *
40 REM * ALL THE INPUT - DATA ARE AT THE END OF THE PROGRAM IN SEVERAL *
50 REM * DATA - LINES.  IT IS POSSIBLE TO ADD MORE DATA FOR ADDITIONAL *
60 REM *                        CALCULATIONES.                        *
70 REM *                   PREPARED BY HEINZ JACOBS                   *
80 REM ****************************************************************
90 \
100 N$-"COOLHS    23-FEB-83"
110 \
120 REM ****************************************************************
130 REM * PRINT HEADLINE                                               *
140 REM * READ DATA FROM THE DATA- LINES                               *
150 REM * CALCULATE THE AMBIENT TEMPERATURE                            *
160 REM ****************************************************************
170 \
200 OPEN "LP:" FOR OUTPUT AS FILE #1
210 F1$-"  ##,##   ##   ##.#   ###.##   ###.##   #.###   ##.#   #####   ###.#   #.###
211 F2$="  ##. average :                ###.##   #.###   ##.#   #####   ###.#   #.###
212 G1$="   date  time  T amb  Na temp. change   level   Q th   m Na     HVT     k
213 G2$="              h    deg     deg      deg       m     kW      kg       h   W/m^2/K
220 PRINT #1,N$ \ PRINT #1 \ PRINT #1,G1$ \ PRINT #1,G2$ \ PRINT #1
230 DIM U(50),D(50),T(2,50),L(50),H(50),Z(50)
240 READ X
250 IF X=-9 THEN PRINT #1 \ CLOSE 1 \ STOP
260 IF X<>-1 THEN 240
270 READ Q \ P-P+1 \ N=0
280 READ D(N+1) \ IF D(N+1)<0 THEN 400
290 N=N+1 \ READ L1,T(1,N),L2,T(2,N),Z(N),U \ L(N)=(L1+L2)/2
300 U(N)=12.7395+U*.8434
310 IF P>3 THEN U(N)=U(N)-7
320 GO TO 280
330 REM ****************************************************************
340 REM * CALCULATE THE K- VALUE AND THE HVT                           *
350 REM * CALCULATE THE AVERAGE                                        *
360 REM * CALCULATE THE VALUES FROM THE INPUT- AVERAGES                *
370 REM * PRINT THE RESULT                                             *
380 REM ****************************************************************
390 \
400 X=D(N+1) \ FOR I=0 TO 9 \ S(I)=0 \ NEXT I \ FOR I=1 TO N
410 T=(T(1,I)+T(2,I))/2 \ L=L(I) \ GOSUB 900 \ Z=Z(I)*3600
420 K=(M1+M*C+Q*Z/(T(1,I)-T(2,I)))*LOG((T(1,I)-U(I))/(T(2,I)-U(I)))
430 K=K/(100*Z) \ H=(M1+M*C)*LOG(2)/100/K \ Y=Z(I)
440 S(0)-S(0)+Y \ S(1)=S(1)+T*Y \ S(2)=S(2)+L(I)*Y \ S(3)-S(3)+Q*Y
450 S(4)=S(4)+M*Y \ S(5)=S(5)+H*Y \ S(6)=S(6)+K*Y
460 PRINT #1,USING F1$,D(I),Z(I),U(I),T(1,I),T(2,I),L(I),Q,M,H/3600,K*1000
470 NEXT I \ FOR I=1 TO 9 \ S(I)=S(I)/S(0) \ NEXT I
480 T=S(1) \ GOSUB 900 \ K1-(M1+S(4)*C)*LOG(2)/S(5)/100
490 PRINT #1,TAB(31);"-------------------------------------------"
500 PRINT #1,USING F2$,P,S(1),S(2),S(3),S(4),S(5)/3600,S(6)*1000,K1*1000
510 PRINT #1 \ GO TO 250
590 \
```

```
800 REM ***********************************************************************
810 REM * CALCULATE THE PROPERTIES OF SODIUM                                  *
820 REM * CALCULATE THE PROPERTIES OF THE TANK                                *
830 REM ***********************************************************************
840 \
900 R=950.1+T*(-.22976+T*(-1.46000E-05+T*5.63800E-09))
910 C=4.18680E-03*(343.24+T*(-.13868+T*1.10440E-04))
920 V-.9181+L*(11.1062+L*(11.7256-L*2.585))
940 M=R*V \ M1=7985.02+9.6205*T
950 RETURN
990 \
1000 REM **********************************************************************
1010 REM * DATA LINES:                                                        *
1020 REM * SWITCH {-1=START,-9=END} , Q [KW]                                  *
1030 REM * DATE, LEVEL 1, TEMP 1, LEVEL 2, TEMP 2, DELTA TIME, T OUT          *
1040 REM * DATE, LEVEL 1, TEMP 1, LEVEL 2, TEMP 2, DELTA TIME, T OUT          *
1050 REM **********************************************************************
1060 \
2000 DATA -1,10.4
2010 DATA 19.07,.2997,203.6,.2999,204.9,3,26.1
2020 DATA 20.07,.3,205.8,.2902,215.1,21,25.5
2100 DATA -1,10.4
2130 DATA 23.07,.2916.212.5,.3007,215.9,7,27.2
2140 DATA 24.07,.3003,216.6,.2977,224.3,22,26.7
2150 DATA 25.07,.2965,225.2..2980,229.7,16,25.3
2200 DATA -1,19.6
2220 DATA 9.09,2.912,400.4,2.912,401.6,18,20.5
2230 DATA 10.09,2.912,401.6,2.913,402.7,21,20.5
2240 DATA 11.09,2.911,402.7,2.911,403.9,21,20.6
2250 DATA 12.09,2.911,404,2.912,405.2,19,20.4
3000 DATA -1,10.4
3030 DATA 8.01,3.070,110,3.070,113.8,17,2.82
3040 DATA 9.01,3.070,113.8,3.070,118.8,24,1.46
3050 DATA 10.01,3.070,118.8,3.070,119.7,5,6.7
3051 DATA -1,10.4
3060 DATA 17.01,3.070,111.1,3.070,116.3,24,8.99
3070 DATA 18.01,3.070,116.3,3.070,119.5,18,9.51
3071 DATA -1,10.4
3110 DATA 26.01,3.070,110.2,3.070,112.8,12,10.23
3120 DATA 27.01,3.070,112.8,3.070,115,12,11.07
3121 DATA -1,10.4
3130 DATA 4.02,3.070,110.4,3.070,114,18,7.92
3140 DATA 5.02,3.070,114,3.070,119,24,10.86
3141 DATA -1,10.4
3150 DATA 12.02,3.030,118.3,3.070,123.5,24,1.15
3160 DATA 13.02,3.070,123.5,3.070,128,24,1.96
3170 DATA 14.02,3.070,128,3.070,130,13,1.59
10000 DATA -9
20000 END
```

SSPS TECHNICAL REPORTS

1/79	HELIOSTAT FIELD AND DATA ACQUISITION SUBSYSTEM FOR CRS (BY MARTIN MARIETTA)	DECEMBER 1979
2/79	CRS-HELIOSTAT FIELD, INTERFACE CONTROL AND DATA ACQUISITION SYSTEM (BY MCDONNELL DOUGLAS)	DECEMBER 1979
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