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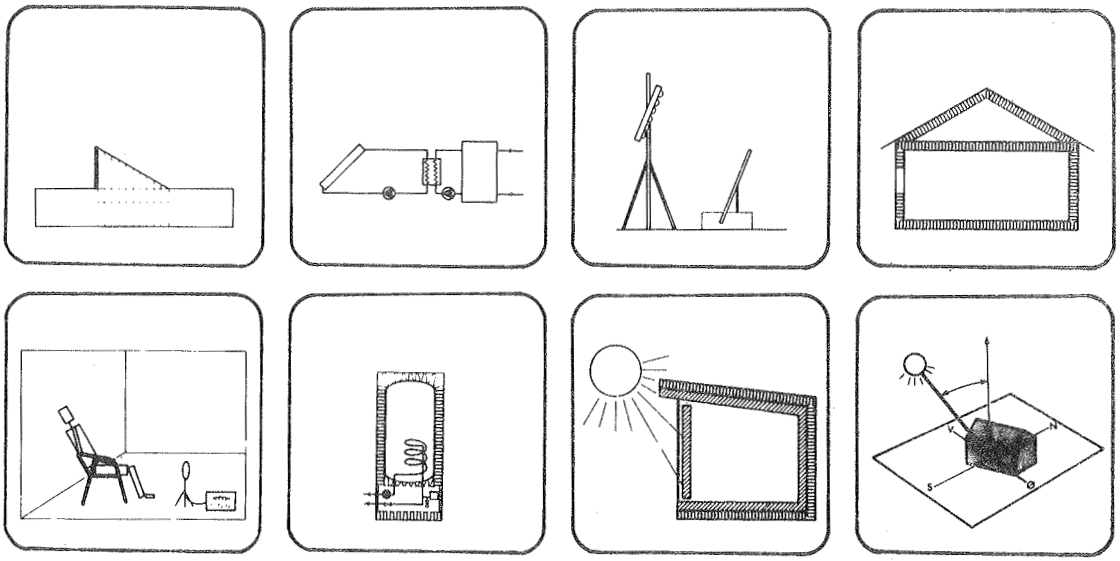
THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK

HEAT STORAGE UNITS USING A SALT HYDRATE AS STORAGE MEDIUM BASED ON THE EXTRA WATER PRINCIPLE.

SIMON FURBO

MEDDELELSE NR. 116

JANUARY 1982



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LIST OF SYMBOLS

Q_s:	Heat content of the heat storage unit, Wh
τ:	Time, h
Q_t:	The power which is transferred from the solar collector fluid to the heat storage, W
Q_{loss}:	Thermal loss from the heat storage unit, W
$\dot{m}$:	The solar collector fluid flow through the heat storage, m^3/s
C_p:	Specific heat of the solar collector fluid, J/kg ^oC
ρ:	Density of the solar collector fluid, kg/m^3
T_{in}:	Temperature of the solar collector fluid entering the heat storage, ^oC
T_{out}:	Temperature of the solar collector fluid leaving hte heat storage, ^oC
T_s:	Mean temperature of the heat storage, ^oC
T_a:	Temperature of the ambient air, ^oC
$(UA)_s$:	Thermal loss coefficient for the heat storage, $W/^oC$
ΔQ_s:	Heat content of the heat storage unit in the heating temperature interval, Wh
$\tau_{heating}$:	Duration of heating period, h
$(UA)_{cs}$:	Heat transfer power per ^oC temperature difference between the solar collector fluid and heat storage, $W/^oC$
η:	Efficiency of the solar collector, abstract
T_m:	Mean temperature of the solar collector fluid in the solar collector, ^oC
T_o:	Outdoor temperature, ^oC
I:	Solar radiation on the solar collector, W/m^2
Q_u:	Power gained from the solar collector, W
T_c:	Temperature of the cold water entering the heat storage during tapping, ^oC

T_w: Mean temperature of the hot water mixed of cold water and water from the heat storage during a tapping period, ^{o}C

M_{tap}: Tapped volume of hot water mixed of cold water and water from the heat storage during a tapping period, l

L: Energy tapped off the heat storage during a tapping period, Wh

N: Number of days in the summer time with the oil burner turned off, days

SSF: The fraction of the summer time heat requirement which is received from the solar heating system, abstract

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ABSTRACT

This report describes the work of the research project No. ESA-S-040-DK-(G), Heat storage units using a salt hydrate as storage medium based on the extra water principle. The project was carried out with support from the European Communities.

A heat of fusion storage unit for solar heating systems for domestic hot water supply was constructed. The unit was examined experimentally with five different storage materials. The storage materials were salt hydrates based on the extra water principle, a heat of fusion storage method demonstrated in two earlier projects supported by the Commission of the European Communities. The experiments resulted in knowledge of the thermal behaviour of the heat storage unit, and hereby knowledge of how to construct a heat of fusion storage unit with good thermal qualities. Calculations of the total yearly utilized solar energy for small solar heating systems for domestic hot water supply were carried out, both with hot water tanks and heat of fusion storage units as heat storages. Based on these calculations the advantages by using heat of fusion storage units, instead of hot water tanks in small solar heating systems for domestic hot water supply, were elucidated.

1. INTRODUCTION - THE EXTRA WATER PRINCIPLE

An incongruently melting salt hydrate consists of an anhydrous salt with corresponding crystal water. The solubility of the anhydrous salt in water at the melting point is not great enough to dissolve all the anhydrous salt in the corresponding crystal water. The molten salt hydrate therefore consists of a saturated solution and some anhydrous salt undissolved in the water. When nothing is done this results in sedimentation in the storage tank due to the higher density. By cooling, salt hydrate crystals are formed in the dividing line between sediment and solution, by which a solid crust is formed. This solid crust prevents the anhydrous salt at the bottom and the upper layer of saturated solution from getting in contact. Only a part of the anhydrous salt in the solution is active in the phase change, and the salt hydrate consists of three parts at temperatures lower than the melting point: at the bottom the anhydrous salt, then a layer of solid salt hydrate crystals, and at the top a layer of saturated salt solution. If the salt hydrate is not stirred, the salt hydrate crystals will melt by heating and form a super-saturated solution. The amount of sediment increases, and the heat storage capacity decreases by each melting/crystalization cycle, and due to that the phase separation has to be avoided before it is possible to make use of an incongruently melting salt hydrate as a reliable heat storage medium.

The extra water principle is a method which prevents phase separation, thus resulting in a stable heat of fusion storage using an incongruently melting salt hydrate as storage material. The method has been demonstrated in two projects supported by the Commission of the European Communities and is described in detail in (1) and (2).

The method consists in adding extra water to the salt hydrate so that all the anhydrous salt can be dissolved in the water at the melting point, that is, the storage medium is a saturated salt solution at the melting point. The storage medium is stirred softly while it is cooled or heated. Since crystallization only takes place from a saturated solution, and the solubility of the salt in water for temperatures belove the melting point decreases for decreasing temperatures, solidification takes place by decreasing tempera-

tures. For temperatures below the melting point the storage medium consists of a salt hydrate solid phase and a saturated solution. By heating, some of the solid salt hydrate melts, and due to the soft stirring the solution will still be saturated also at the higher temperature, so that the mixture will remain stable. The soft stirring is necessary due to differences in density between the salt solution and the melted salt hydrates. The stirring could be natural convection caused by temperature differences inside the heat storage as well as forced convection produced by a stirrer. Both melting and solidification take place in the temperature interval from the melting point and downwards. The heat of fusion of the storage medium is situated in the same temperature interval. The heat storage capacity of the storage medium is less than that of the ideally working incongruently melting salt hydrate, since only a part of the anhydrous salt in the salt water mixture is active in the phase change. On the other hand the heat storage remains stable.

In the temperature interval 0-100°C figure 1 shows the theoretical heat storage capacity of an incongruently melting salt hydrate, Glauber's salt, if it could work stably. The heat storage capacity of a salt water mixture consisting of 33% Na_2SO_4 and 67% of water based on weight, that is a storage medium making use of Glauber's salt and the extra water principle, and the heat capacity of water is shown too. The ratio between the heat storage capacity of a salt water mixture and that of water depends on the temperature interval which is chosen for the comparison. For small temperature intervals around the melting point the ratio is great, and for increasing temperature intervals the ratio decreases.

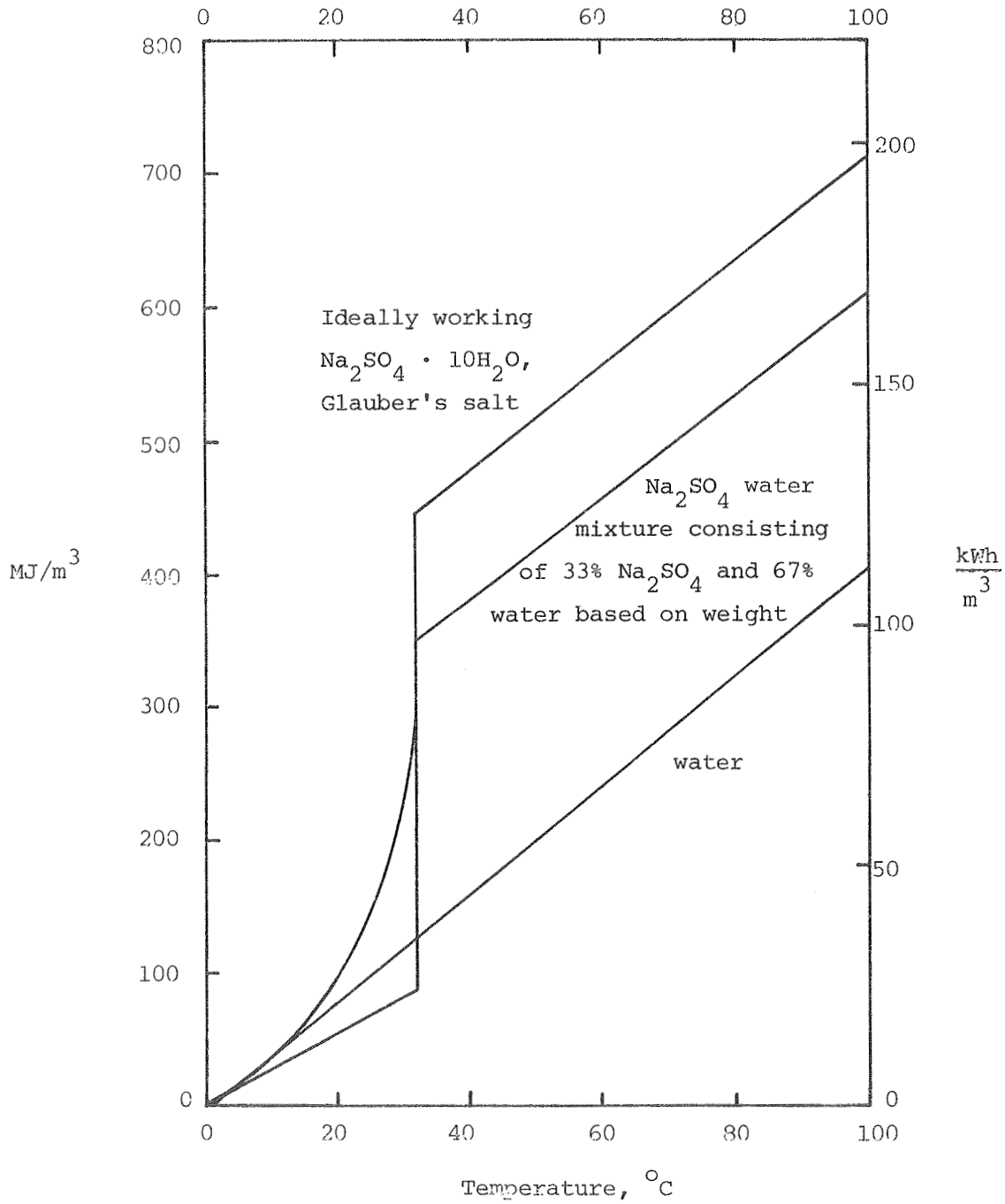


Figure 1. Heat storage capacity in the temperature interval 0-100°C of an ideally working, incongruently melting salt hydrate, a salt water mixture based on the extra water principle, and water. The anhydrous salt is Na_2SO_4.

2. THE HEAT STORAGE

2.1 The heat of fusion storage unit

A heat of fusion storage unit using the extra water principle for a solar heating system for domestic hot water supply was constructed. The storage is shown schematically on figure 2. Photoes of the heat storage unit are shown on figure 3 - 5. Data for the heat storage unit are given in table 1.

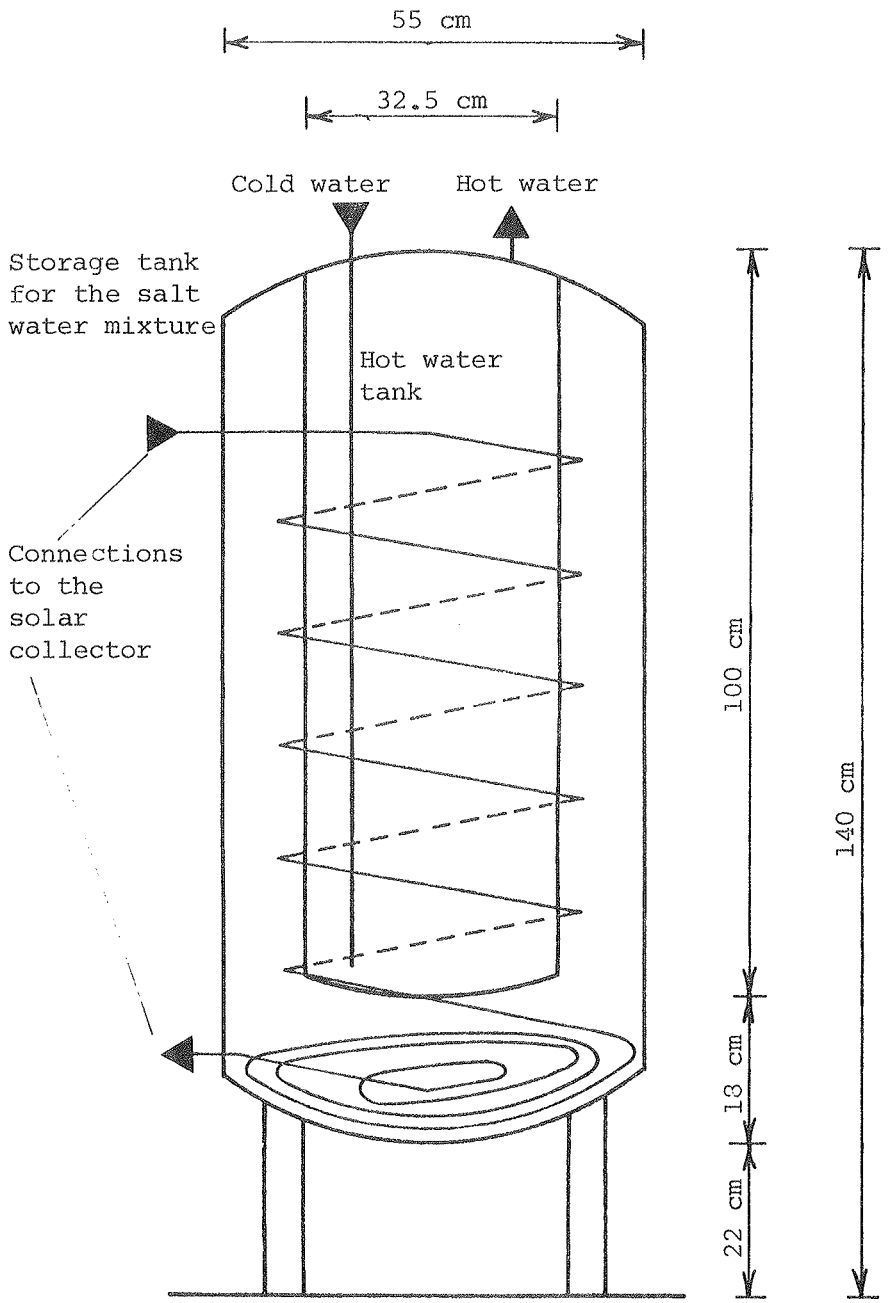


Figure 2. Schematical illustration of the heat storage unit

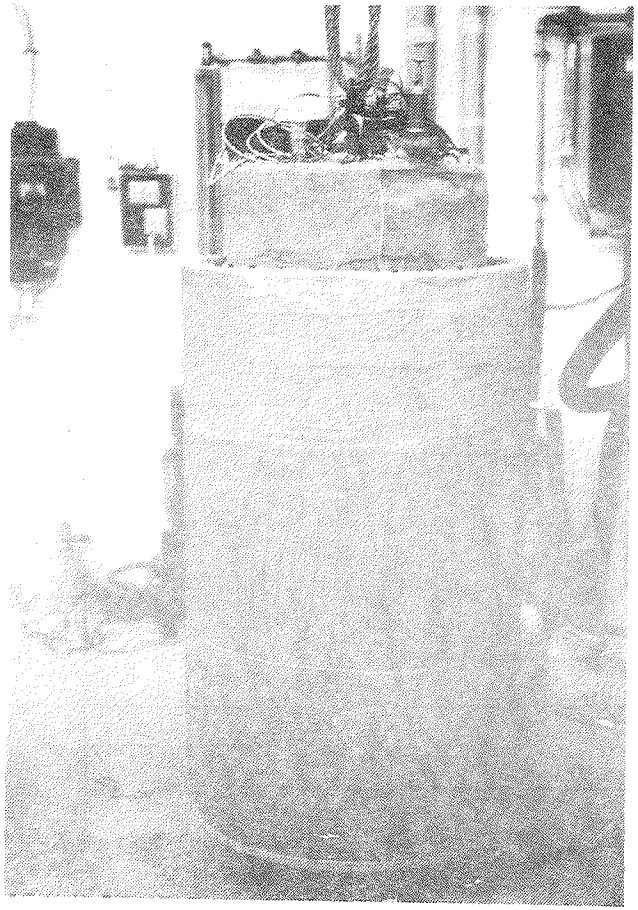


Figure 3.

The insulated heat storage unit.

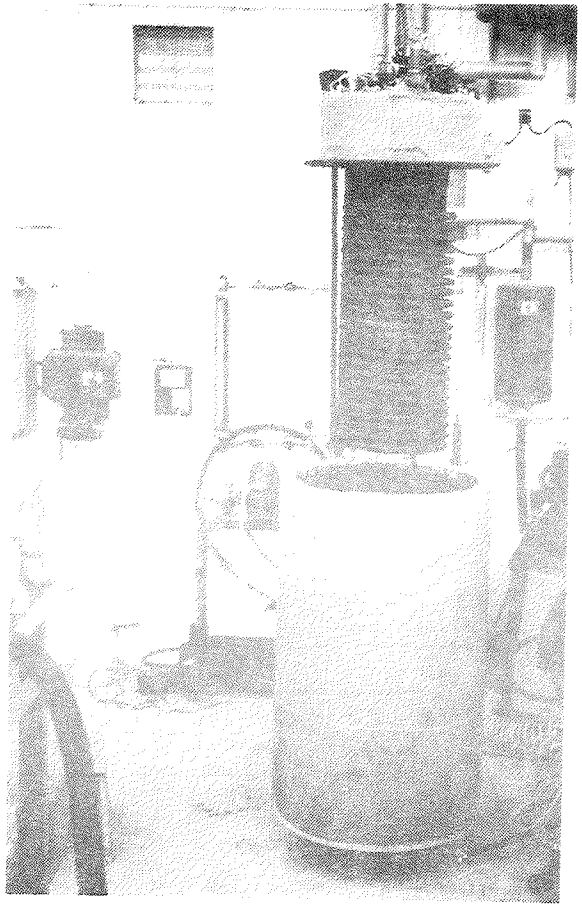


Figure 4.

The hot water tank and the heat storage tank.

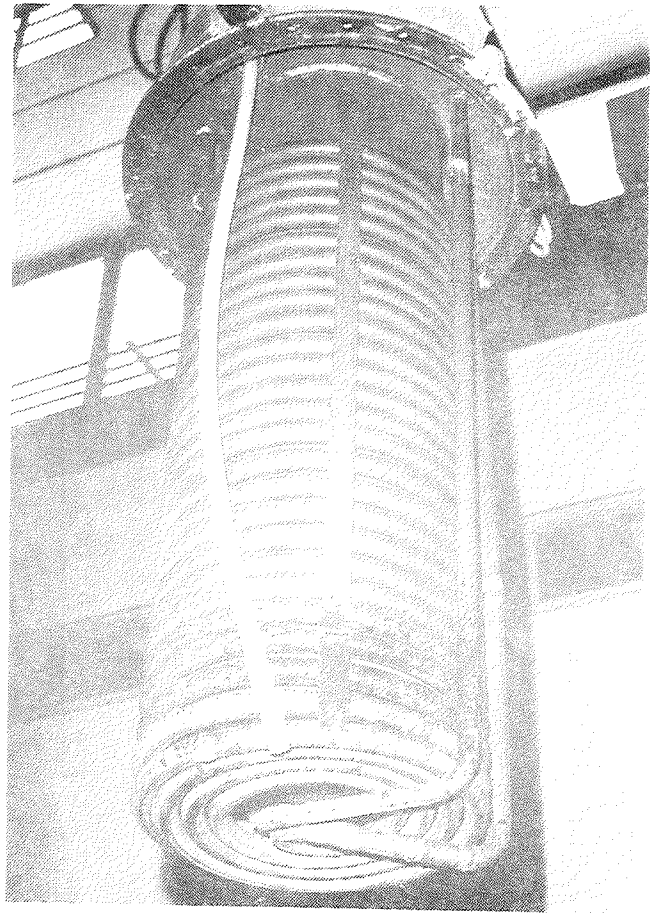


Figure 5.

The hot water tank and the heat exchanger spiral

Volume of hot water tank	82 l
Volume of salt water mixture and air in the heat storage unit	160 l
Volume of solar collector fluid in the heat exchanger spiral	10 l
Mass of the heat storage unit (empty)	277 kg
Dimensions of hot water tank:	
diameter	32.5 cm
height	100 cm
Dimensions of the heat storage unit:	
diameter of tank	55 cm
height of tank	118 cm
total height of heat storage unit	140 cm
Heat exchanger spiral:	
material	steel
length	24 m
dimension	3/4"
heat transfer area	2 m^2
Insulation	
material	mineral wool
thickness	10 cm

Table 1. Data for the heat storage unit

A hot water tank is placed inside the tank which holds the salt water mixture. Heat from the solar collector is transferred to the storage by use of a heat exchanger spiral in which the solar collector fluid is conducted. The heat exchanger spiral is situated at the bottom of the storage tank and around the hot water tank. For storage temperatures above the melting point the salt water mixture is a liquid phase, for storage temperatures below the melting point the salt water mixture consists of a liquid phase and a solid phase. While cold water enters the bottom of the hot water tank, for salt water mixture temperatures above the melting point, a part of the salt solution is cooled, and temperature differences in the salt water mixture produce a soft stirring which, in connection with the extra water principle, makes the heat storage material stable.

The salt solution is stirred softly in this way during cooling as long as solidification has not started, and as long as solidification takes place. The force of the stirring decreases as solidification makes progress.

2.2 The investigated salt water mixtures

The heat storage unit was investigated with five different salt water mixtures based on incongruently melting salt hydrates with different melting points, see table 2.

Anhydrous salt in the salt water mixture	Fraction of anhydrous salt in the salt water based on weight	Salt hydrate crystals	Melting point of the salt hydrate °C	Price Dkr/l salt water mixture 20 t delivery
$NaCH_3COO$	0.58	$NaCH_3COO \cdot 3H_2O$	58	2.60
$Na_2S_2O_3$	0.61	$Na_2S_2O_3 \cdot 5H_2O$	48	2.20
Na_2HPO_4	0.27	$Na_2HPO_4 \cdot 12H_2O$	35	1.60
Na_2CO_3	0.33	$Na_2CO_3 \cdot 10H_2O$	33	0.55
Na_2SO_4	0.33	$Na_2SO_4 \cdot 10H_2O$	32	0.40

Table 2. The investigated salt water mixtures.

The method used for calculation of the heat storage capacity of a salt water mixture as well as the heat storage capacities and the measured densities of the $NaCH_3COO$-, Na_2HPO_4-, Na_2CO_3- and Na_2SO_4-water mixtures are given in (1). The heat storage capacity of the $Na_2S_2O_3$ water mixture was calculated and the density of the salt water mixture was measured. The data used for the calculations of the heat storage capacities for the 5 salt water mixtures are given in table 3. The heat storage capacities of the salt water mixtures based on weight are given in table 4-8. The measured densitsies of the salt water mixtures in the temperature interval 0°C - 100°C are shown in figure 6. The heat storage capacity per volume of the salt water mixture is the product of the heat storage capacity based on weight and the density of the salt water mixture. To make a fair comparison of the heat storage capacity per volume of different materials the minimum density of each material in the temperature interval in which the heat storage operates must be used since this density decides the mass of the storage material which fills up the storage tank. Therefore the densities of the salt water mixtures at the maximum heat storage temperature are used by calculations of the heat storage capacity per volume. In a normal solar heating system the maximum heat storage temperature is about 95°C, and therefore densities at 95°C are used in figure 7, which shows the heat storage capacity per volume of the investigated salt water mixtures and of water in the temperature interval 0°C - 100°C.

Anhydrous salt	Fraction of anhydrous salt in the salt water mixture based on weight	Fraction of anhydrous salt in the salt hydrate based on weight	Solubility of anhydrous salt in water at the temperatur t°C, i.e.: fraction of anhydrous salt in a saturated salt solution based on weight at the temperature t°C	Heat of fusion kJ/kg salt hydrate	Specific heat of the solid salt hydrate J/kg °C	Specific heat of the anhydrous salt J/kg °C
$NaCH_3COO$	0.58	0.60	0°C - 40°C: $0.2646 \cdot e^{0.00983 \cdot t}$ 40°C - 50°C: $0.2313 \cdot e^{0.01345 \cdot t}$ 50°C - 58°C: $0.09667 \cdot e^{0.03089 \cdot t}$	265	2540	1465
$Na_2S_2O_3$	0.61	0.64	0°C - 37.6°C: $0.334 + 0.004013 \cdot t$ 37.6°C - 41.5°C: $0.1484 + 0.008949 \cdot t$ 41.5°C - 45.0°C: $0.1226 + 0.009571 \cdot t$ 45.0°C - 46.9°C: $-0.0175 + 0.012684 \cdot t$ 46.9°C - 47.8°C: $-0.2929 + 0.018556 \cdot t$ 47.8°C - 48.0°C: $-2.728 + 0.0695 \cdot t$	209	1865	924
Na_2HPO_4	0.27	0.40	$0.0130 \cdot e^{0.0865 \cdot t}$	266	1560	1300
Na_2CO_3	0.33	0.37	$0.0701 \cdot e^{0.0469 \cdot t}$	247	1990	1040
Na_2SO_4	0.33	0.44	$0.0404 \cdot e^{0.0652 \cdot t}$	251	1930	880

Table 3. Data for the investigated salt water mixtures.

Temperature °C	Sensible heat kJ/kg	Latent heat kJ/kg	Total heat kJ/kg
0	0.0	0.0	0.0
2	5.2	0.3	5.4
4	10.4	0.5	10.9
6	15.6	0.8	16.4
8	20.8	1.1	21.8
10	25.9	1.4	27.4
12	31.1	1.7	32.9
14	36.3	2.1	38.4
16	41.5	2.5	44.0
18	46.7	2.8	49.6
20	51.9	3.3	55.2
22	57.1	3.7	60.8
24	62.3	4.2	66.5
26	67.5	4.7	72.2
28	72.7	5.3	77.9
30	77.9	5.9	83.7
32	83.0	6.5	89.5
34	88.2	7.2	95.4
36	93.4	8.0	101.4
38	98.6	8.8	107.4
40	103.8	10.2	114.0
42	109.0	11.6	120.6
44	114.2	13.3	127.5
46	119.4	15.2	134.6
48	124.6	17.5	142.1
50	129.8	20.3	150.0
52	135.0	29.1	164.0
54	140.1	44.8	185.0
56	145.3	81.0	226.3
58	150.5	249.2	399.7
60	155.8	249.2	404.9
62	161.0	249.2	410.1
64	166.2	249.2	415.4
66	171.4	249.2	420.6
68	176.6	249.2	425.8
70	181.8	249.2	431.0
72	187.0	249.2	436.2
74	192.2	249.2	441.4
76	197.4	249.2	446.6
78	202.6	249.2	451.8
80	207.9	249.2	457.0
82	213.1	249.2	462.3
84	218.3	249.2	467.5
86	223.5	249.2	472.7
88	228.7	249.2	477.9
90	233.9	249.2	483.1
92	239.1	249.2	488.3
94	244.3	249.2	493.5
96	249.5	249.2	498.7
98	254.8	249.2	503.9
100	260.0	249.2	509.1

Table 4. Heat storage capacity of $NaCH_3COO$ water mixture with 0.58 as the fraction of anhydrous salt in the salt water mixture based on weight.

Temperature °C	Sensible heat kJ/kg	Latent heat kJ/kg	Total heat kJ/kg
0	0.0	0.0	0.0
2	4.0	0.6	4.6
4	8.0	1.2	9.2
6	12.0	1.9	13.8
8	16.0	2.6	18.5
10	20.0	3.3	23.3
12	23.9	4.1	28.0
14	27.9	4.9	32.9
16	31.9	5.8	37.7
18	35.9	6.8	42.7
20	39.9	7.8	47.7
22	44.0	8.9	52.8
24	48.0	10.0	58.0
26	52.0	11.3	63.3
28	56.0	12.7	68.7
30	60.0	14.2	74.2
32	64.0	15.8	79.8
34	68.0	17.6	85.6
36	72.1	19.6	91.6
38	76.1	22.3	98.4
40	80.2	28.2	108.3
42	84.2	36.1	120.3
44	88.3	47.6	135.9
46	92.4	68.5	160.9
48	96.6	187.1	283.8
50	101.0	187.1	288.2
52	105.4	187.1	292.6
54	109.8	187.1	297.0
56	114.2	187.1	301.4
58	118.6	187.1	305.8
60	123.0	187.1	310.2
62	127.4	187.1	314.6
64	131.8	187.1	319.0
66	136.2	187.1	323.4
68	140.6	187.1	327.8
70	145.0	187.1	332.2
72	149.4	187.1	336.6
74	153.9	187.1	341.0
76	158.3	187.1	345.4
78	162.7	187.1	349.8
80	167.1	187.1	354.2
82	171.5	187.1	358.6
84	175.9	187.1	363.0
86	180.3	187.1	367.4
88	184.7	187.1	371.8
90	189.1	187.1	376.2
92	193.5	187.1	380.6
94	197.9	187.1	385.0
96	202.3	187.1	389.4
98	206.7	187.1	393.8
100	211.1	187.1	398.2

Table 5. Heat storage capacity of the $Na_2S_2O_3$ water mixture with 0.61 as the fraction of anhydrous salt in the salt water mixture based on weight.

Temperature °C	Sensible heat kJ/kg	Latent heat kJ/kg	Total heat kJ/kg
0	0.0	0.0	0.0
2	4.9	0.6	5.4
4	9.7	1.3	11.0
6	14.6	2.1	16.7
8	19.5	3.1	22.6
10	24.4	4.3	28.7
12	29.8	5.8	35.1
14	34.2	7.7	41.9
16	39.2	10.0	49.2
18	44.2	12.9	57.0
20	49.2	16.5	65.7
22	54.8	21.2	75.4
24	59.4	27.3	86.7
26	64.6	35.6	100.2
28	69.9	47.1	117.0
30	75.4	63.8	139.2
32	81.1	89.9	171.0
34	87.8	135.4	222.7
36	92.5	176.6	269.2
38	99.5	176.6	276.0
40	106.1	176.6	282.8
42	112.9	176.6	289.6
44	119.8	176.6	296.4
46	126.6	176.6	303.2
48	133.4	176.6	310.0
50	140.2	176.6	316.8
52	147.0	176.6	323.6
54	153.8	176.6	330.4
56	160.6	176.6	337.2
58	167.4	176.6	344.0
60	174.2	176.6	350.8
62	281.0	176.6	357.6
64	187.8	176.6	364.4
66	194.6	176.6	371.2
68	201.4	176.6	378.1
70	208.2	176.6	384.9
72	215.0	176.6	391.7
74	221.8	176.6	398.5
76	228.6	176.6	405.3
78	235.4	176.6	412.1
80	242.2	176.6	418.9
82	249.0	176.6	425.7
84	255.8	176.6	432.5
86	262.7	176.6	439.3
88	269.6	176.6	446.1
90	276.3	176.6	452.9
92	283.1	176.6	459.7
94	289.9	176.6	466.5
96	296.7	176.6	473.3
98	303.7	176.6	480.1
100	311.3	176.6	486.9

Table 6. Heat storage capacity of the Na_2HPO_4 water mixture with 0.27 as the fraction of anhydrous salt in the salt water mixture based on weight.

Temperature °C	Sensible heat kJ/kg	Latent heat kJ/kg	Total heat kJ/kg
0	0.0	0.0	0.0
2	4.5	0.8	5.3
4	9.0	1.7	10.7
6	13.6	2.7	16.3
8	18.1	3.9	22.0
10	22.6	5.4	28.0
12	27.2	7.1	34.3
14	31.8	9.1	40.9
16	36.4	11.7	48.0
18	41.0	14.8	55.8
20	45.6	18.8	64.4
22	50.3	24.1	74.4
24	55.1	31.2	86.3
26	59.9	41.5	101.4
28	64.8	57.4	122.2
30	69.9	85.0	155.0
32	75.4	144.8	220.2
34	80.1	214.1	294.2
36	86.4	214.1	300.5
38	92.7	214.1	306.8
40	99.0	214.1	313.0
42	105.3	214.1	319.3
44	111.6	214.1	325.6
46	117.9	214.1	331.9
48	124.1	214.1	338.2
50	130.4	214.1	344.5
52	136.7	214.1	350.8
54	143.0	214.1	357.1
56	149.3	214.1	363.3
58	155.6	214.1	369.6
60	161.9	214.1	375.9
62	168.2	214.1	382.2
64	174.4	214.1	388.5
66	180.7	214.1	394.8
68	187.0	214.1	401.1
70	193.3	214.1	407.4
72	199.6	214.1	413.6
74	205.9	214.1	419.9
76	212.2	214.1	426.2
78	218.5	214.1	432.5
80	224.7	214.1	438.8
82	231.0	214.1	445.1
84	237.3	214.1	451.4
86	243.6	214.1	457.7
88	249.9	214.1	463.9
90	256.2	214.1	470.2
92	262.5	214.1	476.5
94	268.8	214.1	482.8
96	275.0	214.1	489.1
98	281.0	214.1	495.4
100	287.6	214.1	501.7

Table 7. Heat storage capacity of the Na_2CO_3 water mixture with 0.33 as the fraction of anhydrous salt in the salt water mixture based on weight.

Temperature °C	Sensible heat kJ/kg	Latent heat kJ/kg	Total heat kJ/kg
0	0.0	0.0	0.0
2	5.0	1.0	6.0
4	10.1	2.1	12.2
6	15.1	3.5	18.6
8	20.2	5.1	25.3
10	25.2	7.1	32.3
12	30.3	9.4	39.7
14	35.4	12.3	47.7
16	40.5	15.8	56.3
18	45.7	20.2	65.8
20	50.8	25.7	76.6
22	56.1	33.0	89.1
24	61.3	42.8	104.1
26	66.7	56.5	123.1
28	72.1	76.8	148.9
30	77.8	109.8	187.6
32	83.7	171.9	255.7
34	89.0	181.9	270.9
36	95.2	181.9	277.1
38	101.4	181.9	283.3
40	107.6	181.9	289.5
42	113.7	181.9	295.6
44	119.9	181.9	301.8
46	126.1	181.9	308.0
48	132.3	181.9	314.2
50	138.5	181.9	320.4
52	144.7	181.9	326.6
54	150.8	181.9	332.7
56	157.0	181.9	338.9
58	163.2	181.9	345.1
60	169.4	181.9	351.3
62	175.6	181.9	357.5
64	181.7	181.9	363.7
66	187.9	181.9	369.8
68	194.1	181.9	376.0
70	200.3	181.9	382.2
72	206.5	181.9	388.4
74	212.7	181.9	394.6
76	218.8	181.9	400.7
78	225.0	181.9	406.9
80	231.2	181.9	413.1
82	237.4	181.9	419.3
84	243.6	181.9	425.5
86	249.7	181.9	431.7
88	255.9	181.9	437.8
90	262.1	181.9	444.0
92	268.3	181.9	450.2
94	274.5	181.9	456.4
96	280.7	181.9	462.6
98	286.8	181.9	468.7
100	293.0	181.9	474.9

Table 8. Heat storage capacity of the Na_2SO_4 water mixture with 0.33 as the fraction of anhydrous salt in the salt water mixture based on weight.

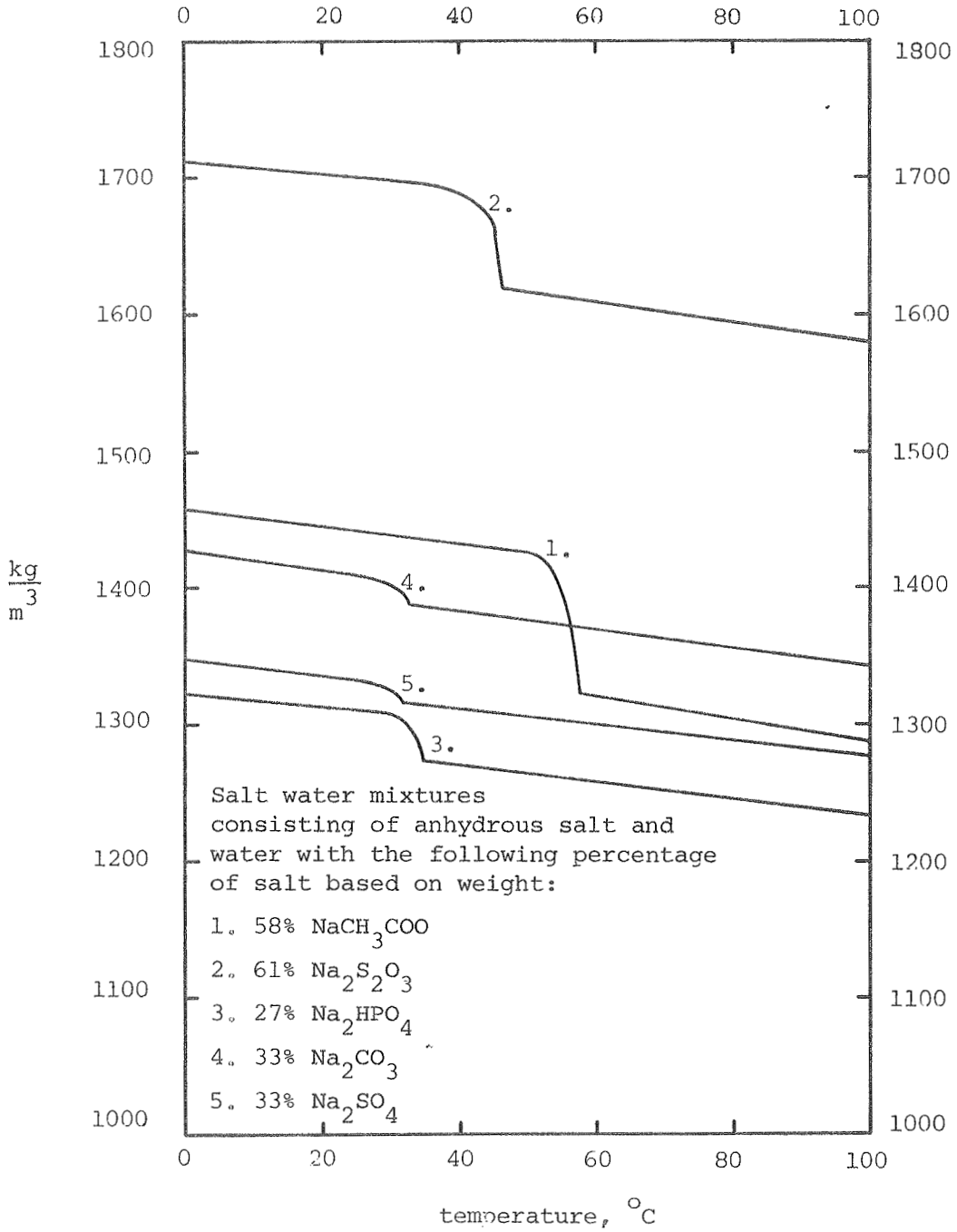


Figure 6. Measured densities of the investigated salt water mixtures in the temperature interval 0 - 100°C.

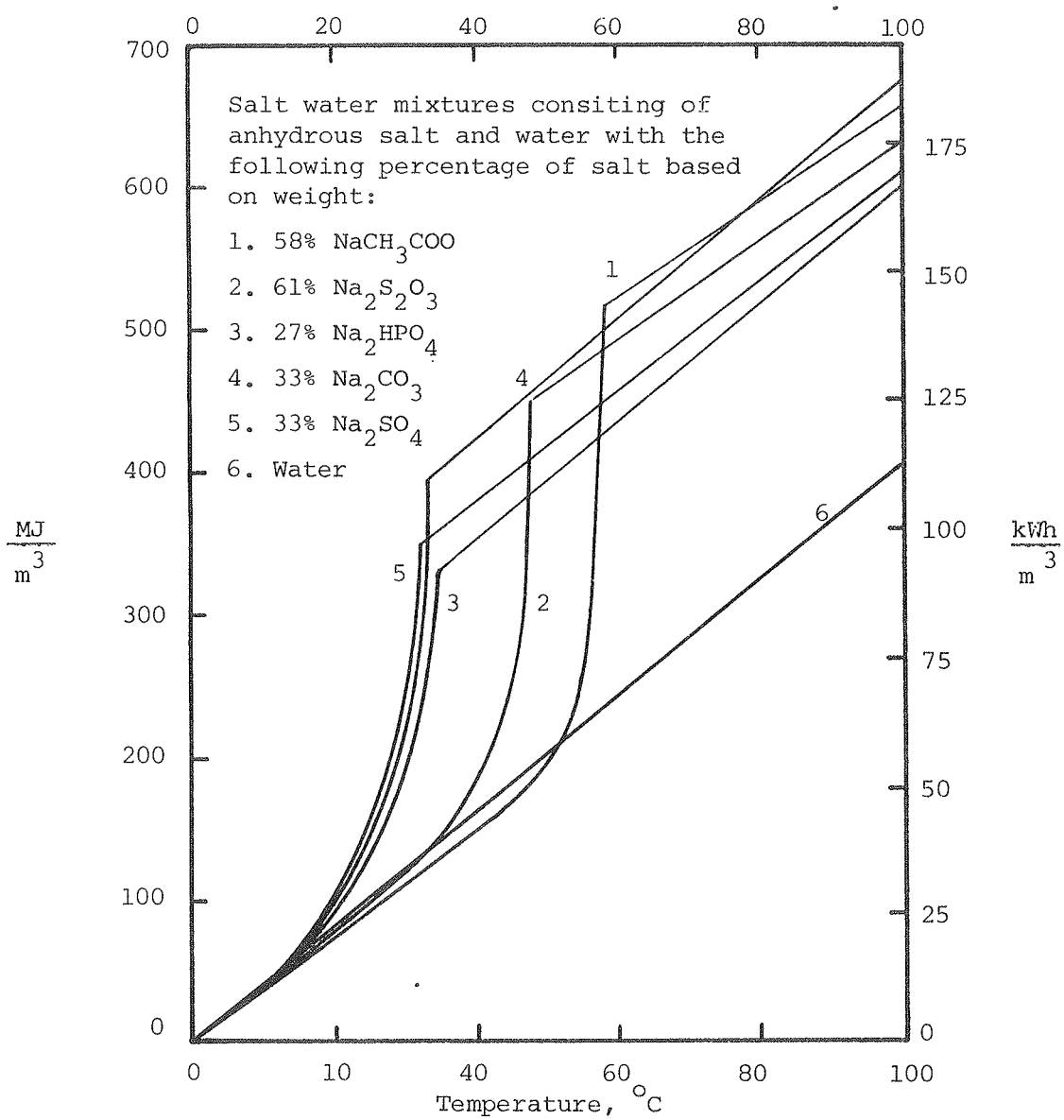


Figure 7. Heat storage capacity of the salt water mixtures used in the heat of fusion storage unit.

The Na_2SO_4-, Na_2CO_3-, Na_2HPO_4- and $NaCH_3COO$-water mixtures are chemically stable. Investigations concerning the chemical stability of liquid sodium thiosulfate pentahydrate were carried out. Section 2.3 is the report from our chemical consultant Erik Pedersen covering this subject.

2.3 The chemical stability of liquid sodium thiosulfate pentahydrate

2.3.1 Introduction

The application of sodium thiosulfate pentahydrate in heat storage systems could be severely limited by chemical reactions in this medium under the temperature conditions imposed on such systems. It has for many years been known by almost every chemist that dilute aqueous solutions of this salt such as used in iodometric titrations decompose slowly in neutral and basic solution and rather rapidly in acid solution.

The result of studies of the stability of the molten salt has to our knowledge not been published in the literature. This report describes such an investigation following reactions at 55°C and 71°C over six months.

2.3.2 Experimental

The sodium thiosulfate pentahydrate, $Na_2S_2O_3,5H_2O$, was delivered by Struers and of "pure quality" without further specifications. Six samples of approximately 40 g of this salt were prepared. 100 mg of sodium hydrogensulfate, $NaHSO_4$, was added to two of the samples. 50 mg of sodium carbonate, Na_2CO_3, was added to another two samples. The two equivalent sets of samples were left in vials with screw caps in ovens at 55°C and 71°C, i.e. above the transition temperature of this incongruently melting salt. After six months the samples were cooled to room temperature, and one month later our analytical work started as described in the following.

From the very beginning it was clear to us that all samples had lost in weight, approx. 0.26 g and 0.36 g at 55°C and 71°C, respectively. This was presumably caused by loss of water through the screw caps. The original material had also been kept in non-ideal containers.

On this background it was decided to limit the investigations to iodemetric titration of reducing material and determination of sulfur and freezing point depression.

Iodometric titrations were performed against potassium dichromate using starch as indicator according to standard procedures. The six samples were melted at 60°C and supercooled to room temperature. The metastable liquids could be transferred to weighing bottles without loss of water by application of pipets. Sulfur was determined gravimetrically after continous extraction with carbon disulfide, CS_2, from the samples diluted with water. The CS_2 phases were subsequently dried with anhydrous sodium sulfate, filtered, and evaporated to dryness.

The freezing-point depressions (transition temperatures) were determined by seeding the supercooled solutions with a few crystals of the pentahydrate and following the temperature vs. time with a thermometer with a resolution of 0.01°C. A molar freezing-point depression of 42.6 was assumed according to Leenhardt and Boutaric, C.r. 154 (1912) 113.

All experimental results are average values of two independant measurements. It was assumed that the loss in weight of the six samples was caused by loss of water and that the original material in two containers was unchanged during the period of the experiments. The analyses of this material showed a composition corresponding to $Na_2S_2O_3,4.69(3)H_2O$. The number in brackets here and in the following is the estimated standard deviation.

The results of the measurements are shown in table 9.

Sample composition	T	Weight loss	Mole fraction by titration	Mole fraction converted to S	ΔT
40.266 g I.M.[a]	55°C	0.261 g	0.998(2)	≤0.0005(5)	≤0.03(3)
42.215 g I.M. +50 mg Na_2CO_3	55°C	0.264 g	0.997(2)	≤0.0005(5)	≤0.03(3)
44.200 g I.M. +100 mg $NaHSO_4$	55°C	0.255 g	1.006(2)	0.0074(5)	0.20(3)
41.083 g I.M.	71°C	0.345 g	0.996(3)	≤0.0005(5)	≤0.03(3)
42.265 g I.M. +50 mg Na_2CO_3	71°C	0.363 g	0.998(2)	≤0.0005(5)	≤0.03(3)
47.561 g I.M. +100 mg $NaHSO_4$	71°C	0.637 g	1.007(3)	0.0085(5)	0.22(3)

[a] I.M: = Initial material with composition $Na_2S_2O_3,4.69(3)H_2O$.

Table 9. Results of measurements of the chemical stability of liquid sodium thiosulfate pentahydrate.

2.3.3 Conclusions

It is evident from the results in table 9 that only those samples with $NaHSO_4$ added showed any sign of decomposition. The degree of this decomposition seems to be independent of the temperature within the experimental uncertainty.

The results of the titrations and the sulfur determinations are in agreement with the following decomposition process

$$S_2O_3^{2-} \rightarrow SO_3^{2-} + S$$

which gives the following reactions during the iodometric titrations

$$2\ S_2O_3^{2-} + I_2 \rightarrow 2\ I^- + S_4O_6^{2-}$$

$$SO_3^{2-} + I_2 + H_2O \rightarrow 2\ I^- + SO_4^{2-} + 2\ H^+$$

This reaction scheme explains why the mole fractions found by titration follow the mole fractions converted into sulfur. These mole fractions correspond to a separation of 1.0 g of sulfur per kg of initial material during six months. The freezing point depressions which are much less accurate give a value approximately one order of magnitude less.

These measurements give almost no information on the kinetics of the reaction. Since the hydrogen ions added with $NaHSO_4$ are not used during the proposed reaction, we suggest as a worst case estimate that the reaction is acid catalyzed and will continue with a rate as observed during the six months. A complete analysis of this system would involve chromatografic separation of all species that might exist, polythionates for example. Such work seems unnecessary, however, on the background that no decomposition was observed in neutral and weekly alkaline media.

3. EXPERIMENTS

Experiments were carried out with each salt water mixture and with water as the heat storage material both in a static and in a dynamic test facility.

3.1 Static test facility

The test facility system is shown schematically in figure 8. The system consists of pipes with 2 pumps for circulation of the solar collector fluid, 2 heating elements, a temperature sensor, a flowmeter and different valves for controlling the solar collector fluid volume flow. The pipe system consists of an inner and an outer circuit, to which the heat storage is connected by means of flexible hoses. The volume flow of the solar collector fluid is large in the inner circuit and has a smaller constant value in the outer circuit.

The temperature sensor, which controls one of the heating elements, is situated just behind the heating elements in the inner circuit with the large volume flow. In this way the temperature of the fluid, which is conducted to the heat storage, can be controlled in a very accurate way. The other heating element is manually operated in such a way that a constant power can be transferred to the collector fluid. In this way it is possible either to obtain a constant temperature of the fluid conducted to the heat storage, or to transfer a constant power to the heat storage.

The test facility is situated in the laboratory where the temperature normally varies in the temperature interval from 20°C to 25°C. Figure 9 shows a photo of the static test facility.

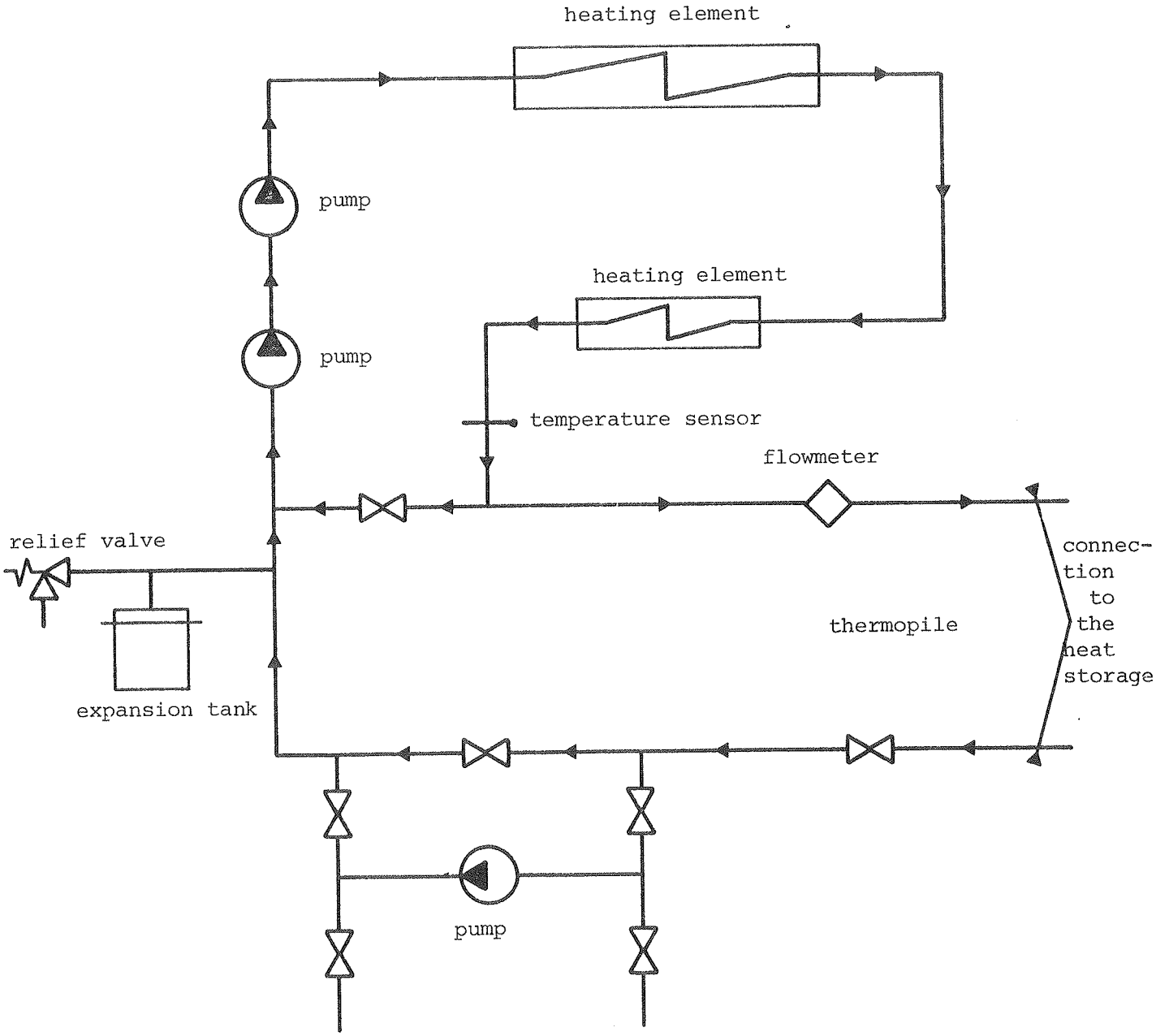


Figure 8. Schematical illustration of the static test facility.

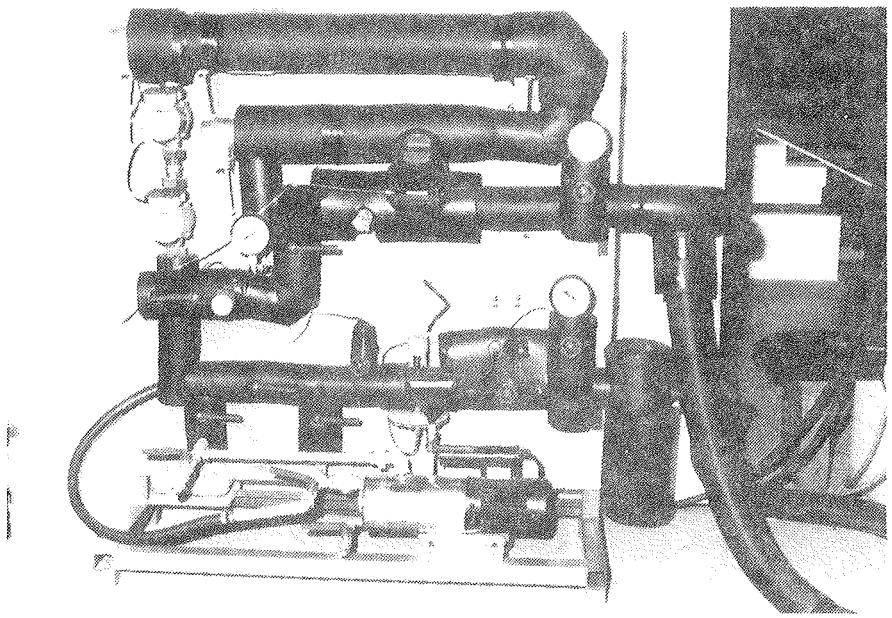


Figure 9. Static test facility.

3.2 Dynamic test facility

The test facility is shown schematically in figure 10. The system consists of a solar collector simulator, a water supply system and a control system. The heat storage is connected to the solar collector simulator and to the water supply system by means of flexible hoses.

The solar collector simulator is a pipe system with valves, a circulation pump which transports the solar collector fluid, a flowmeter, a heating element and a temperature sensor, which is connected to the control system. The solar collector fluid can be circulated through the solar collector simulator and the heat storage with a constant volume flow.

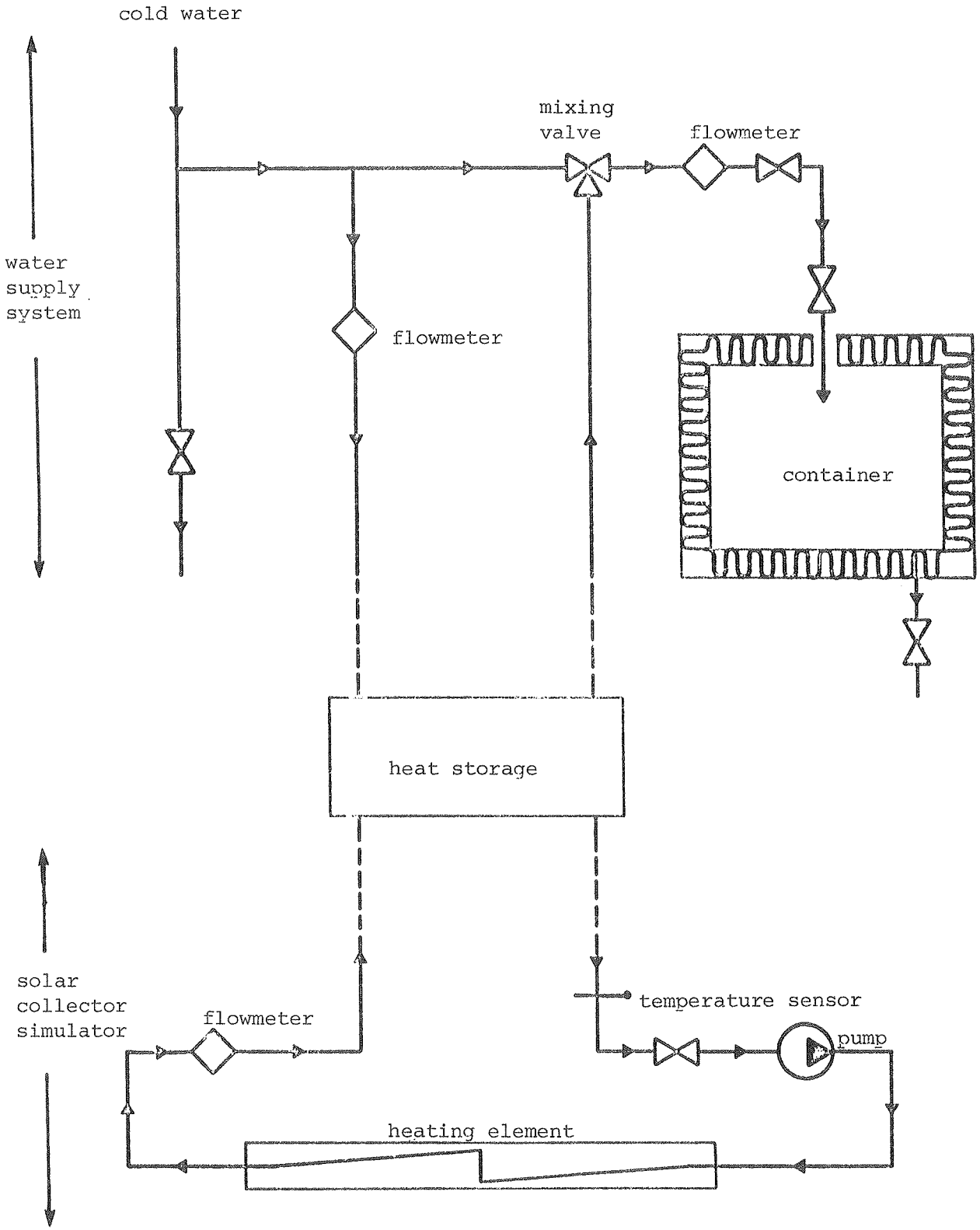


Figure 10. Schematical illustration of the dynamic test facility.

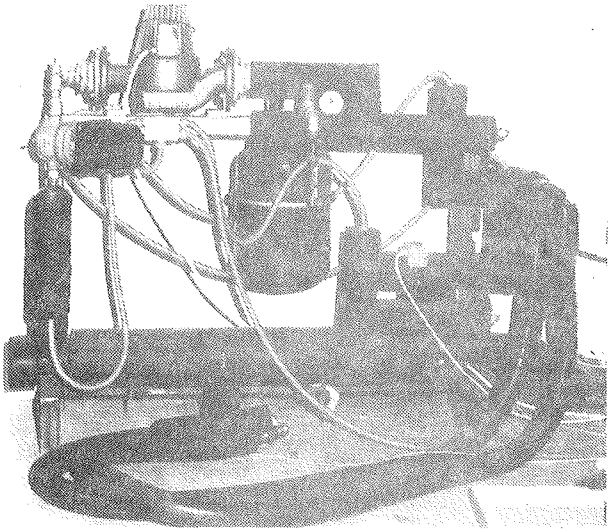
Two flowmeters and different valves for controlling the tapped water volume flow and the temperature of the water entering the heat storage are situated in the water supply system. A mixing valve mixes the cold and the hot water so that a reasonably constant temperature of the tapped water during the period of tapping is the result. The mixed water is conducted to a container where the mean temperature of the water is measured before the water finally is expelled.

The control system is a microprocessor which controls the pump, the valves and the heating element in such a way that the heat storage operates as if it is part of a solar heating system for domestic hot water supply in a period with typical weather conditions. The valves are controlled in such a way that the water entering the storage during tapping periods has a low constant temperature. The power given off from the heating element is found from the weather data fixed in advance, the chosen efficiency of the solar collector and the temperature of the solar collector fluid leaving the heat storage measured by the temperature sensor. Figure 11 shows photoes of the dynamic test facility and the control system.

3.3 Measurements

Temperature measurements are made by use of copper/constantan thermocouples. Temperature differences are measured with copper/constantan thermopiles. Volume flows are measured with Aqua-Metro flowmeters and energy given off from heating elements with kWh-meters. Energy quantities transferred to or drawn off the heat storage are calculated by means of the measured temperature differences and volume flows.

The temperatures are measured at 3 different levels inside the heat storage: at the top, in the middle and at the bottom of the hot water tank and of the salt water mixture. Furthermore, the temperature of the ambient air, the solar collector fluid entering and leaving the heat storage, the cold water entering the heat storage during tapping, the hot water leaving the heat storage during tapping and the mean temperature of the water accumulated in the container during each tapping period.



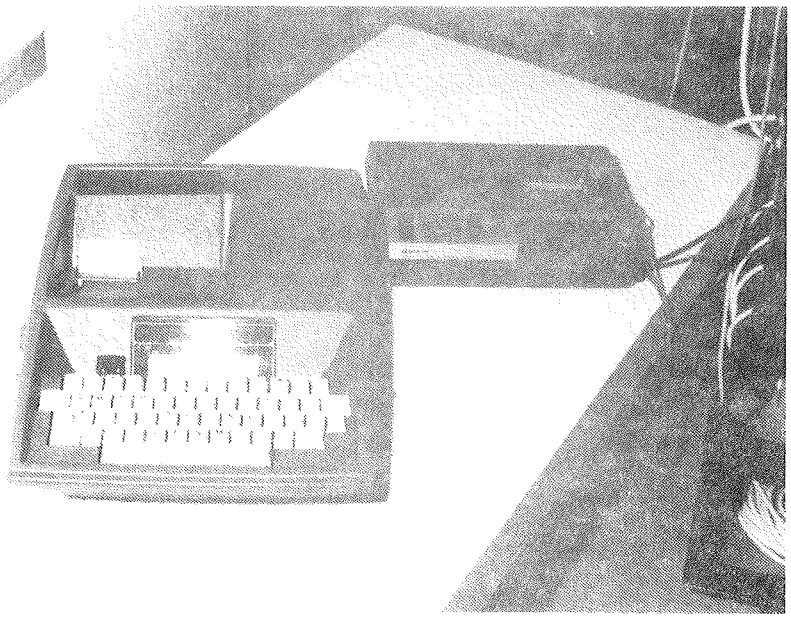


Figure 11. Dynamic test facility and the control system.

Temperature differences are measured between the solar collector fluid entering and leaving the heat storage and between the cold water entering and the hot water leaving the heat storage during tapping.

Volume flows of the solar collector fluid through the heat storage, the cold water entering the heat storage during tapping and the tapped mixed hot water during tapping are measured, as well as the total energy given off from the heating element during the dynamic test period.

3.4 Test procedure

3.4.1 Static test facility

For each salt water mixture the thermal loss from the heat storage unit, the heat content of the storage unit in a temperature interval and the heat transfer power per °C temperature difference between the solar collector fluid and the heat storage material in a period with a constant power supply from the collector fluid to the heat storage, were measured.

The thermal loss is found in the following way. The solar collector fluid is pumped through the heat storage unit with a fluid velocity of about 1 l/min while the temperature of the fluid entering the heat storage is kept constant. After a while the temperature of the storage unit and the temperature difference between the fluid entering and leaving the heat storage will be constant too, if the ambient temperature is constant.

When all temperatures are stable, the energy balance for the heat storage is:

$$\frac{dQ_s}{d\tau} = 0 = Q_t - Q_{loss} = \dot{m} \cdot C_p \cdot \rho \cdot (T_{in} - T_{out}) - Q_{loss}$$

$$= \dot{m} \cdot C_p \cdot \rho \cdot (T_{in} - T_{out}) - (UA)_s \cdot (T_s - T_a)$$

Rearranging this equation, the thermal loss coefficient is found from:

$$(UA)_s = \frac{\dot{m} \cdot C_p \cdot \rho \cdot (T_{in} - T_{out})}{T_s - T_a} \quad W/^oC$$

The thermal loss is measured for different tempreatures since it varies with the temperature.

In order to find the heat content of the storage unit and the heat transfer power per ^oC temperature difference between the solar collector fluid and the heat storage material, the heat storage unit was heated from a temperature below the melting point to a temperature above the melting point. During the heating period both the power transferred from the solar collector fluid to the heat storage and the fluid volume flow were constant. The volume flow was about 6 l/min, and no water was tapped off during the heating. Therefore the energy balance for the heat storage is:

$$\frac{dQ_s}{d\tau} = Q_t - Q_{loss} = \dot{m} \cdot C_p \cdot \rho \cdot (T_{in} - T_{out}) - (UA)_s \cdot (T_s - T_s)$$

The heat content in the temperature interval going from the starting temperature to the final temperature of the heating is found from:

$$\Delta Q_s = \int_0^{\tau_{heating}} [\dot{m} \cdot C_p \cdot \rho \cdot (T_{in} - T_{out}) - (UA)_s (T_s - T_a)] d\tau$$

where $(UA)_s$ is found from the measurements described above and the temperatures and the temperature difference in the equation are measured continously during the heating period.

Provided that the temperature is constant all over the heat storage, the heat transfer power per ^oC temperature difference between the solar collector fluid and the heat storage material $(UA)_{cs}$ is found from the equation:

$$(UA)_{cs} = - \dot{m} C_p \cdot \rho \cdot \ln \left(1 - \frac{T_{in} - T_{out}}{T_{in} - T_s}\right)$$

$(UA)_{cs}$ is found for different points of time during the heating in order to find the influence of the storage temperature on the quantity. Different heating periods were carried out in order to elucidate if $(UA)_{cs}$ varies from one heating period to another.

3.4.2 Dynamic test facility

The heat storage is tested during a period with a duration between 3 and 5 days. Hot water is tapped off the heat storage 4 times every day: at 8, 12, 18 and 20 o'clock. The cold water entering the heat storage during tapping has a constant low temperature. The total consumption of hot water is about 170 l/day. The weather data, that is the solar radiation on the solar collector and the outdoor temperature, which are used for the period, are given in figure 12. The data for the first 3 days are selected from measurements from a solar heating system working in the laboratory in the SPTF-project, which is supported by the Commission. Each parameter has a value for every 10 minutes during the whole period. For simplicity, the last 2 days are identical to the first 2 days.

The solar collector efficiency used in the experiment is

$\eta = 0.80 - 5.5 \frac{T_m - T_o}{I}$ corresponding to the best solar collector which in 1980 was on the Danish market. Provided that the temperature rise of the solar collector fluid across the solar collector is 5°C, the efficiency is found from:

$$\eta = 0.80 - 5.5 \frac{T_{out} + 2.5 - T_o}{I}$$

The heat storage unit will typically be situated in a solar heating system with a collector area of about 6 m^2, and therefore the volume flow of the solar collector fluid during the experiment was fixed to about 6 l/min, and the power from the solar collector calculated from:

$$Q_u = 0.80 \cdot 6 \cdot I - 5.5 \cdot 6 \cdot (T_{out} + 2.5 - T_o) \text{ W}$$

By means of the temperature sensor, the temperature of the solar collector fluid leaving the heat storage, T_{out}, that is the temperature of the solar collector fluid entering the solar collector, is measured every minute during the test period. Using this temperature, the power from the solar collector can be calculated from the formula above.

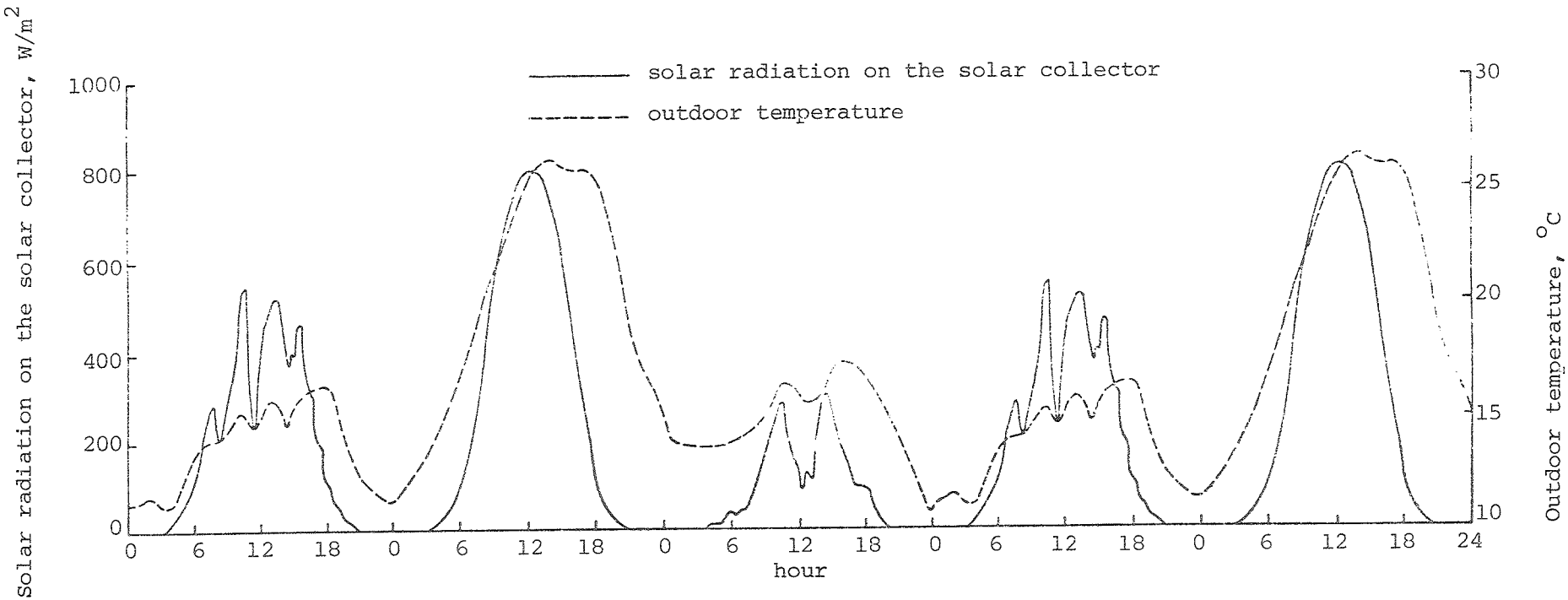


Figure 12. 5 days weather data used in the dynamic investigation of the heat storage unit.

Differences between the construction of the dynamic test facility and a typical solar heating system, for instance pumps, pipes, pipe insulation, etc. exist. Therefore, these differences are taken into consideration in such a way that the power given off from the heating element has such an amount that the power transferred from the test facility to the heat storage is equal to the power which will be transferred to the heat storage from a typical solar heating system with the above described solar collector.

Every minute the temperature sensor measures T_{out}. Every 10 seconds the microprocessor calculates, controls and measures the power given off from the heating element according to the above described method. Any differences between the calculated and measured power, for instance caused by sudden jumps in the electric voltage, are corrected in the next 10 second period, that is the calculated and the measured energy supply from the heating element are identical.

Knowledge of the dynamic behaviour of the heat storage unit in work is obtained by this experiment since storage temperatures and energy quantities added to or drawn off the storage are measured continously during the experiment.

4. RESULTS FROM THE EXPERIMENTS

The heat storage unit was investigated with five salt water mixtures and water as heat storage material, see table 10.

Heat storage material in the storage tank	Material added to the salt water mixture
104.4 kg $NaCH_3COO$ and 75.6 kg water	
134.2 kg $Na_2S_2O_3$ and 85.8 kg water	220 g Na_2CO_3
48.6 kg Na_2HPO_4 and 131.4 kg water	
66.0 kg Na_2CO_3 and 134.0 kg water	
62.7 kg Na_2SO_4 and 127.3 kg water	190 g borax
148.0 kg water	

Table 10. Heat storage materials investigated in the heat of fusion storage unit.

For simplicity water was used as the solar collector fluid in the experiments.

4.1 Results from the experiments with the heat storage unit with the $NaCH_3COO$ water mixture

The thermal loss coefficient was measured at 3 different storage temperatures. The results are given in table 11.

Heat storage temperature, ^oC	35	60	90
Thermal loss coefficient, $W/^oC$	2.0	2.1	2.2

Table 11. Thermal loss coefficient for the heat storage unit with the $NaCH_3COO$ water mixture at different storage temperatures.

The quantity of the thermal loss corresponds to the theoretically calculated thermal loss from a 300 l tank insulated with about 6 cm of mineral wool, see (3). Since the heat storage unit is insulated with 10 cm of mineral wool, the thermal losses caused by thermal bridges are reasonably small.

The heat content was measured by two heating periods, one in the start, and one at the end of the experimental period. The heat content of the heat storage unit was found to be in good agreement with the theoretically calculated heat content, and no decrease in the heat content during the experimental period of about 2 months was observed. The heat content consists of contributions from the salt water mixture, the water, the steel container material and the solar collector fluid situated in the heat exchanger spiral. The theoretically calculated heat content of the heat storage unit in the temperature interval 0 - 100°C is given in table 12 and figure 13. The melting point for $NaCH_3COO \cdot 3H_2O$ is 58°C, and for temperatures above 58°C the heat content increases linearily with the temperature.

The heat transfer power per °C temperature difference between the solar collector fluid and the heat storage material was measured for different heating periods with a volume flow of 6 l/min. The heat transfer power per °C temperature difference between the solar collector fluid and the heat storage increases concurrently with the increase of the heat storage temperature and with the progression of the melting. The quantity of the heat transfer capacity varied from one heating period to another as long as the temperature is below the melting point. Relatively large temperature differences inside the heat storage appear during the heating period, and the differences vary for different locations of the solid an liquid phase inside the storage tank at the start of the heating period. Therefore the heat transfer capacity must be related to the start conditions for the heat storage unit. Applicable heat transfer capacities call for very detailed and timeconsuming measurements where the locations of the solid and liquid phase inside the storage tank at the start of the heating period are well defined. Such detailed measurements were not carried out, and therefore quantities of the heat transfer capacity will not be given.

Temperature °C	Heat content of 180 kg $NaCH_3OOO$ water mixture with 58% anhydrous salt in the mixture based on weight Wh	Heat content of 82 l water Wh	Heat content of 277 kg steel Wh	Heat content of 10 l solar collector fluid Wh	Total heat content of the heat storage unit Wh
0	0	0	0	0	0
2	270	189	74	23	556
4	545	377	148	46	1116
6	820	566	223	69	1677
8	1090	754	297	92	2233
10	1370	943	371	115	2799
12	1645	1131	445	138	3359
14	1920	1320	519	161	3920
16	2200	1508	593	184	4486
18	2480	1697	668	207	5051
20	2760	1885	742	230	5617
22	3040	2074	816	253	6183
24	3325	2262	890	276	6753
26	3610	2451	964	299	7324
28	3895	2639	1039	322	7895
30	4185	2828	1113	345	8471
32	4475	3016	1187	368	9046
34	4770	3205	1261	391	9627
36	5070	3393	1335	414	10213
38	5370	3582	1409	437	10798
40	5700	3770	1484	460	11414
42	6030	3959	1558	483	12030
44	6375	4147	1632	506	12660
46	6730	4336	1706	529	13301
48	7105	4524	1780	552	13962
50	7500	4713	1855	575	14643
52	8200	4902	1929	598	15628
54	9250	5090	2003	621	16964
56	11315	5279	2077	644	19315
58	19985	5467	2151	667	28270
60	20245	5656	2225	690	28816
100	25455	9426	3709	1150	39740

Table 12. Heat content of the heat storage unit with the $NaCH_3COO$ water mixture.

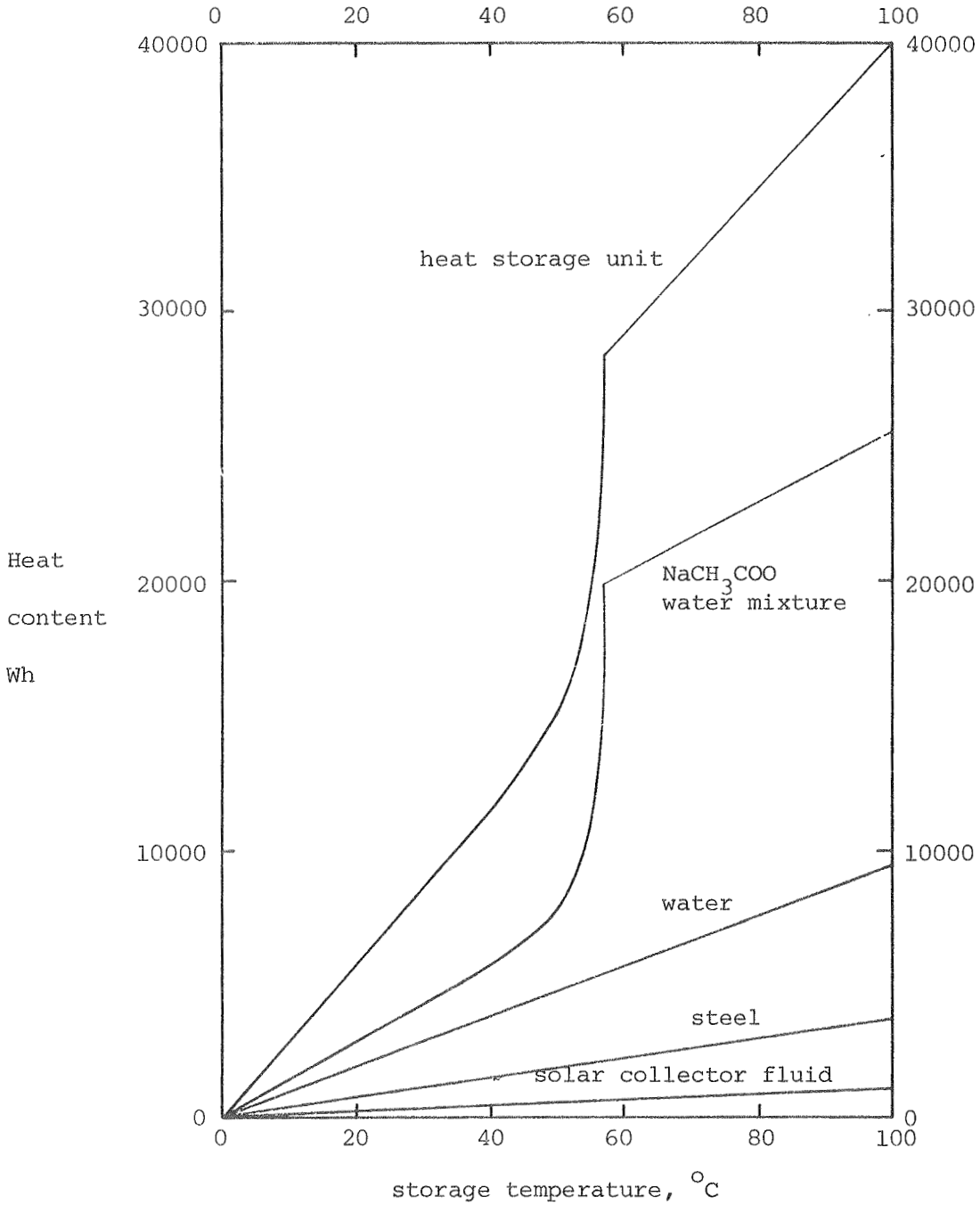


Figure 13. Heat content of the heat storage unit with the $NaCH_3COO$ water mixture versus the heat storage temperature.

The duration of the experiment in the dynamic test facility was 5 days. The measured temperatures during the experiment are shown in figure 14. The temperatures in the top, in the middle and at the bottom of the hot water tank are given. The salt water mixture temperature was measured at 3 locations. As long as the temperature is below the melting point, large temperature differences appear, and therefore the uncertainty of the mean salt water mixture temperature, which is given in the figure, is relatively great. The ambient temperature and the temperature of the solar collector fluid leaving and entering the storage are given in periods with the solar collector in operation. The data for the hot water consumption during the experiment are given in table 13. T_c is the temperature of the cold water entering the heat storage, T_w and M_{tap} are the mean temperature and the volume of the mixed water from the storage system. L is the energy tapped off the heat storage during each tapping.

The important quantities for the heat storage system during the test period are given in table 14. The negative energy supply to the heat storage on the third day with the varying solar irradiation on the solar collector is caused by a failure in the control system. The energy tapped off and lost from the heat storage during the period was 38300 Wh, while the energy supply to the heat storage was 27900 Wh. This change in heat content during the experimental period of -10 400 Wh corresponds to a mean heat storage temperature drop from about 66°C at the start of the period to the final temperature of about 57°C, which is in reasonably good agreement with the heat content given in table 12 and figure 13.

Some observations concerning the dynamic behaviour of the heat storage unit is noticed from figure 14:

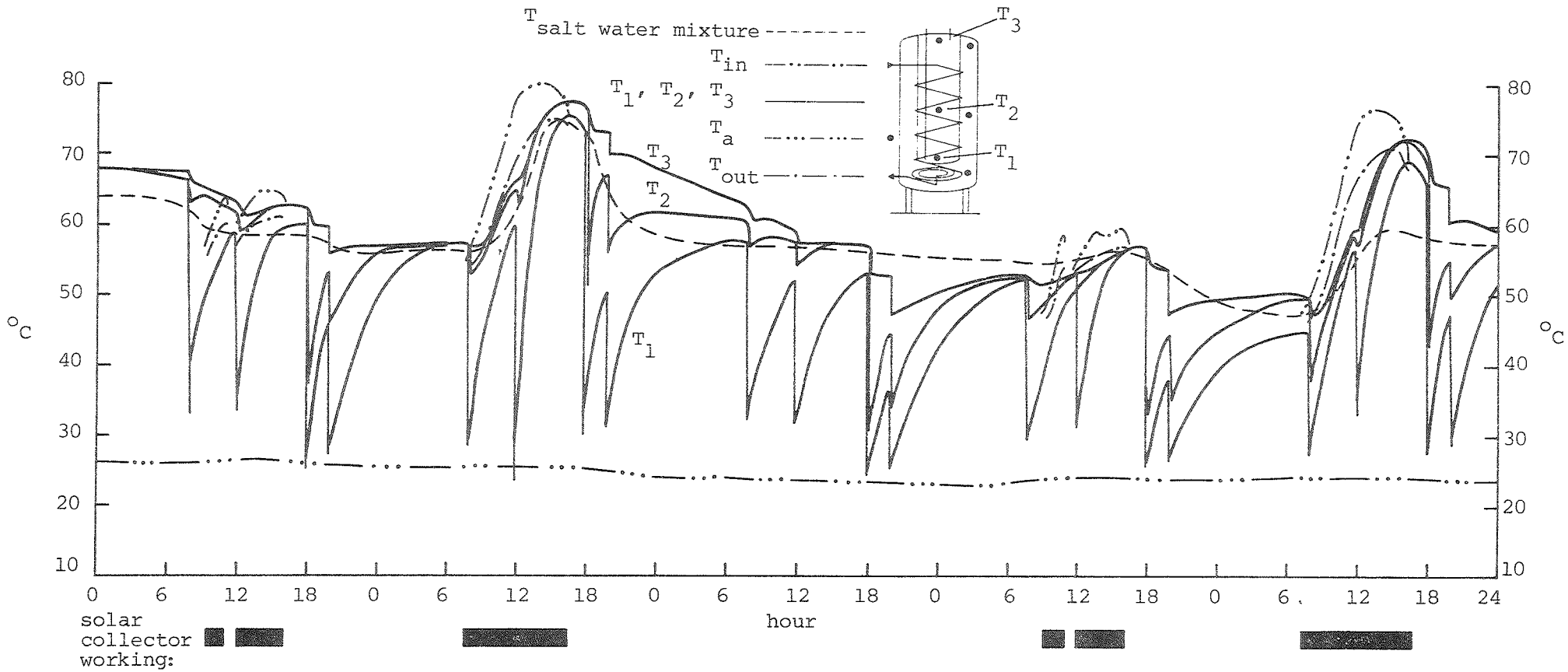


Figure 14. Temperatures for the heat storage unit with the $NaCH_3COO$ water mixture during the experiment.

Time day	Time hour	T_c °C	T_w °C	M_{tap} l	L Wh	Daily hot water consumption l	Energy tapped off the heat storage during the day Wh
1	8	16.1	44.5	35.5	1170	170.6	5920
	12	15.8	44.8	28.6	960		
	18	15.2	46.0	71.0	2530		
	20	15.7	46.3	35.5	1260		
2	8	17.1	45.3	35.5	1160	170.5	6020
	12	16.7	45.3	28.4	940		
	18	17.3	49.8	71.0	2670		
	20	17.8	48.1	35.6	1250		
3	8	16.3	43,8	35.6	1130	171.1	5600
	12	16.7	43.9	28.5	900		
	18	17.8	45.5	71.3	2280		
	20	14.1	45.4	35.7	1290		
4	8	19.3	44.1	35.7	1020	171.2	5190
	12	18.6	44.7	28.5	860		
	18	18.6	45.0	71.3	2180		
	20	18.1	45.4	35.7	1130		
5	8	18.1	42.2	35.5	990	171.7	5860
	12	15.3	43.8	28.4	940		
	18	15.6	48.3	71.9	2720		
	20	16.6	45.8	35.9	1210		

Table 13. Data for the hot water consumption during the dynamic experiment with the $NaCH_3COO$ water mixture.

Time day	Solar irradiation on the solar collector Wh	Energy supply from the solar heating system to the heat storage Wh	Energy tapped off the heat storage Wh	Thermal loss Wh
1	25170	1500	5900	2000
2	37902	10800	6000	2200
3	11904	-300	5600	1900
4	25170	2800	5200	1700
5	37902	13100	5900	1900
Total period	138048	27900	28600	9700

Table 14. Daily energy quantities for the heat storage unit with the $NaCH_3COO$ water mixture during the dynamic experiment.

Since cold water during hot water consumption enters the bottom of the hot water tank, low temperatures appear here in periods after hot water consumption. In such periods with the solar collector in operation, the low water temperatures do no influence the temperature of the solar collector fluid significantly. Like this, the low temperatures inside the heat storage are not optimally utilized to increase the gain from the solar collector. It is also noticed that in the morning of the 5th day, that is in a period with storage temperatures below the melting point of 58°C and energy supply from the solar collector, temperature differences between the salt water mixture and the water appear, but the differences are relatively small. Therefore these temperature differences are not optimally utilized to obtain high hot water temperatures quickly in sunny periods. The dynamic behaviour is, to a certain extent, related to the salt water mixture, but first of all to the design of the heat storage unit. Therefore the dynamic behaviour of the storage will be discussed in detail later in section 4.7.

The duration of the experiments with the $NaCH_3COO$ water mixture was about 2 months. In this period both the steel tanks and the steel heat exchanger were strongly attacked by the $NaCH_3COO$ water mixture. This fact disagrees with the investigations carried out in (2). Therefore the technical grade of $NaCH_3COO$ salt used in the experiment was analysed. The corrosion was caused by small amounts of impurities of acetic acid in the salt. The acetic acid must be neutralized in order to avoid corrosion. This can, for instance, be done by adding a small amount of Na_2CO_3 to the salt water mixture. It is therefore important to know the composition of the impurities in the salt which is used as heat storage material.

4.2 Results from the experiments with the heat storage unit with the $Na_2S_2O_3$ water mixture

The thermal loss coefficient was measured at 3 different storage temperatures. The results are given in table 15.

Heat storage temperature, °C	35	60	90
Thermal loss coefficient, W/°C	1.6	1.7	1.8

Table 15. Thermal loss coefficient for the heat storage unit with the $Na_2S_2O_3$ water mixture at different storage temperatures.

The quantity of the thermal loss corresponds to the theoretically calculated thermal loss from a 300 l tank insulated with about 8 cm of mineral wool, see (3). Since the heat storage unit is insulated with 10 cm of mineral wool, the thermal losses caused by thermal bridges are reasonably small.

The heat content was measured by two heating periods, one in the start and one at the end of the experimental period.

The heat content of the heat storage unit was found to be in good agreement with the theoretically calculated heat content, and no decrease in the heat content during the experimental period of about 2 months was observed. The heat content consists of contributions from the salt water mixture, the water, the steel container material and the solar collector fluid situated in the heat exchanger spiral. The theoretically calculated heat content of the heat storage unit in the temperature interval 0 - 100°C is given in table 16 and figure 15. The melting point for $Na_2S_2O_3 \cdot 5H_2O$ is 48°C, and for temperatures above 48°C the heat content increases linearily with the temperature.

The heat transfer power per °C temperature difference between the solar collector fluid and the heat storage material was measured for different heating periods with a volume flow of 6 l/min. The heat transfer power per °C temperature difference between the solar collector fluid and the heat storage increases concurrently with the increase of the heat storage temperature and with the progression of the melting. The quantity of the heat transfer capacity varied from one heating point. Relatively large temperature differences inside the heat storage appear during the heating period, and the differences vary for different locations of the solid and liquid phase inside the storage tank at the start of the heating period. Therefore the heat transfer capacity must be related to the start conditions for the heat storage unit. Applicable heat transfer capacities call for very detailed and timeconsuming measurements where the locations of the solid and liquid phase inside the storage tank at the start of the heating period are well defined. Such detailed measurements were not carried out and therefore quantities of the heat transfer capacity will not be given.

Temperature °C	Heat content of 220 kg $Na_2S_2O_3$ water mixture with 61% anhydrous salt in the mixture based on weight Wh	Heat content of 82 l water Wh	Heat content of 277 kg steel Wh	Heat content of 10 l solar collector fluid Wh	Total heat content of the heat storage unit Wh
0	0	0	0	0	0
2	281	189	74	23	567
4	562	377	148	46	1134
6	843	566	223	69	1700
8	1131	754	297	92	2273
10	1424	943	371	115	2852
12	1711	1131	445	138	3425
14	2011	1320	519	161	4011
16	2304	1508	593	184	4590
18	2609	1697	668	207	5181
20	2915	1885	742	230	5772
22	3227	2074	816	253	6369
24	3544	2262	890	276	6973
26	3868	2451	964	299	7582
28	4198	2639	1039	322	8198
30	4534	2828	1113	345	8820
32	4877	3016	1187	368	9448
34	5231	3205	1261	391	10088
36	5598	3393	1335	414	10740
38	6013	3582	1409	437	11442
40	6618	3770	1484	460	12332
42	7352	3959	1558	483	13351
44	8305	4147	1632	506	14590
46	9833	4336	1706	529	16404
48	17343	4524	1780	552	24200
50	17612	4713	1855	575	24755
100	24334	9426	3709	1150	38619

Table 16. Heat content of the heat storage unit with the $Na_2S_2O_3$ water mixture.

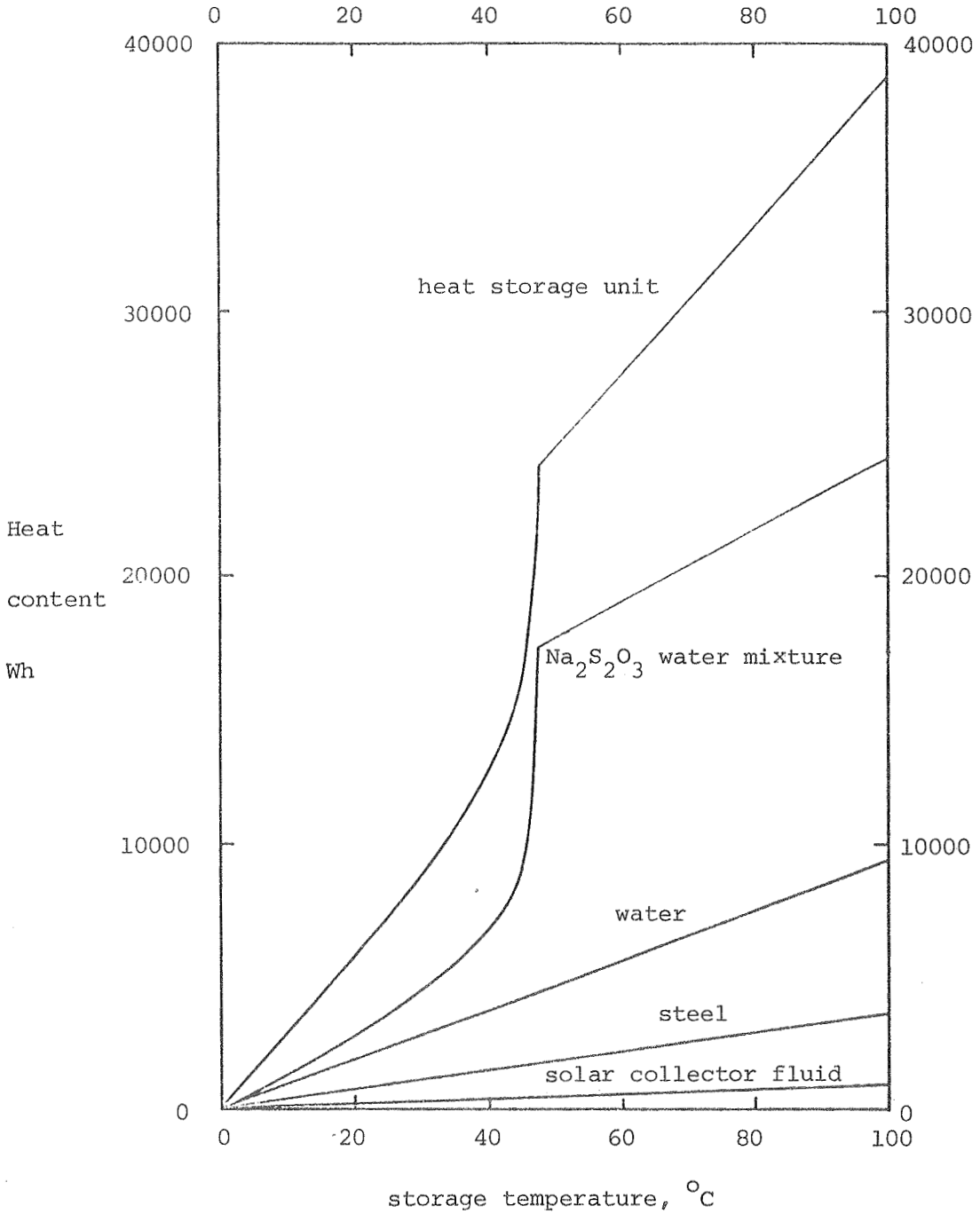


Figure 15. Heat content of the heat storage unit with the $Na_2S_2O_3$ water mixture versus the heat storage temperature.

The duration of the experiment in the dynamic test facility was the first three days of the five days period. The measured temperatures during the experiment are shown in figure 16. The temperatures in the top, in the middle and at the bottom of the hot water tank are given. The salt water mixture temperature was measured at 3 locations. As long as the temperature is below the melting point, large temperature differences appear, and therefore the uncertainty of the mean salt water mixture temperature which is given in the figure is relatively great. The ambient temperatures and the temperature of the solar collector fluid leaving and entering the storage are given in periods with the solar collector in operation. The data for the hot water consumption during the experiment are given in table 17. T_c is the temperature of the cold water entering the heat storage, T_w and M_{tap} are the mean temperature and the volume of the mixed water from the storage system. L is the energy tapped off the heat storage during each tapping.

The important quantities for the heat storage system during the test period are given in table 18. The negative energy supply to the heat storage on the third day with the varying solar irradiation on the solar collector is caused by a failure in the control system. The energy tapped off and lost from the heat storage during the period was 18500 Wh, while the energy supply to the heat storage was 18000 Wh. This change in heat content during the experimental period of -500 Wh corresponds to a mean heat storage temperature drop from about 43°C, at the start of the period, to the final temperature of about 41°C, which is in reasonably good agreement with the heat content given in table 16 and figure 15.

Some observations concerning the dynamic behaviour of the heat storage unit is noticed from figure 16:

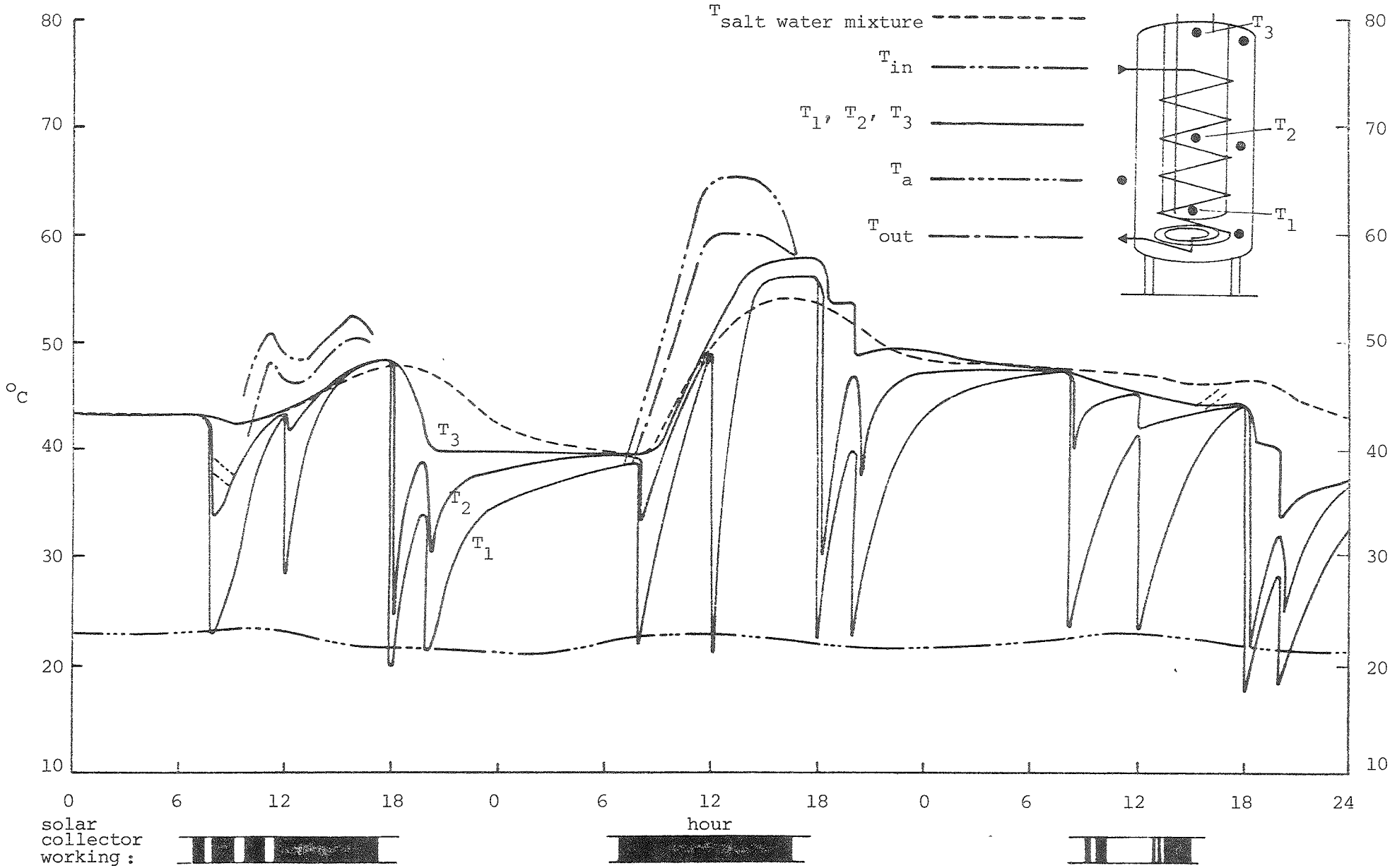


Figure 16. Temperatures for the heat storage unit with $Na_2S_2O_3$ water mixture during the experiment.

Time day	Time hour	T_c °C	T_w °C	M_{tap} l	L Wh	Daily hot water consumption l	Energy tapped off the heat storage during the day Wh
1	8	14.3	37.1	32.9	870	158.8	4880
	12	13.6	38.1	26.2	740		
	18	12.8	42.4	66.6	2280		
	20	12.4	38.3	33.1	990		
2	8	13.3	34.7	32.8	810	167.2	5760
	12	12.1	43.1	35.9	1290		
	18	12.7	44.3	65.7	2400		
	20	12.3	45.4	32.8	1260		
3	8	12.4	40.6	32.7	1070	158.1	4920
	12	12.1	39.4	26.2	830		
	18	12.1	39.8	66.0	2110		
	20	11.9	35.7	33.2	910		

Table 17. Data for the hot water consumption during the dynamic experiment with the $Na_2S_2O_3$ water mixture.

Time day	Solar irradiation on the solar collector Wh	Energy supply from the solar heating system to the heat storage Wh	Energy tapped off the heat storage Wh	Thermal loss Wh
1	25170	4600	4900	900
2	37902	15000	5800	1000
3	11904	-1600	4900	1000
Total period	74976	18000	15600	2900

Table 18. Daily energy quantities for the heat storage unit with the $Na_2S_2O_3$ water mixture during the dynamic experiment.

Since cold water during hot water consumption enters the bottom of the hot water tank, low temperatures appear here in periods after hot water consumption. In such periods with the solar collector in operation, the low water temperatures do not influence the temperature of the solar collector fluid significantly. Like this, the low temperatures inside the heat storage are not optimally utilized to increase the gain from the solar collector. It is also noticed that in the morning of the 2nd day, that is in a period with storage temperatures below the melting point of 48°C and energy supply from the solar collector, temperature differences between the salt water mixture and the water do not exist to a great extent. Therefore such temperature differences are not utilized to obtain high hot water temperatures quickly in sunny periods. The dynamic behaviour is, to a certain extent, related to the salt water mixture, but first of all to the design of the heat storage unit. Therefore the dynamic behaviour of the storage will be discussed in detail later, in section 4.7.

The duration of the experiments with the $Na_2S_2O_3$ water mixture was about 2 months. The $Na_2S_2O_3$ water mixture did not cause any visible corrosion during this period.

4.3 Results from the experiments with the heat storage unit with the Na_2HPO_4 water mixture

The thermal loss coefficient was measured at 3 different storage temperatures. The results are given in table 19.

Heat storage temperature, °C	35	60	90
Thermal loss coefficient, W/°C	2.1	2.2	2.3

Table 19. Thermal loss coefficient for the heat storage unit with the Na_2HPO_4 water mixture at different storage temperatures.

The quantity of the thermal loss corresponds to the theoretically calculated thermal loss from a 300 l tank insulated with about 5 cm of mineral wool, see (3). Since the heat storage unit is insulated with 10 cm of mineral wool, the thermal losses caused by thermal bridges are reasonably small.

The heat content was measured by two heating periods, one in the start and one at the end of the experimental period. The heat content of the heat storage unit was found to be in good agreement with the theoretically calculated heat content, and no decrease in the heat content during the experimental period of about 2 months was observed. The heat content consists of contributions from the salt water mixture, the water, the steel container material and the solar collector fluid situated in the heat exchanger spiral. The theoretically calculated heat content of the heat storage unit in the temperature interval 0 - 100°C is given in table 20 and figure 17. The melting point for $Na_2HPO_4 \cdot 12H_2O$ is 35°C, and for temperatures above 35°C the heat content increases linearily with the temperature.

Temperature °C	Heat content of 180 kg Na_2HPO_4 water mixture with 27% anhydrous salt in the mixture based on weight Wh	Heat content of 82 l water Wh	Heat content of 277 kg steel Wh	Heat content of 10 l solar collector fluid, water Wh	Total heat content of the heat storage unit Wh
0	0	0	0	0	0
2	270	189	74	24	556
4	550	377	148	46	1121
6	835	566	223	69	1692
8	1130	754	297	92	2273
10	1435	943	371	115	2864
12	1755	1131	445	138	3469
14	2095	1320	519	161	4095
16	2460	1508	593	184	4746
18	2850	1697	668	207	5421
20	3285	1885	742	230	6142
22	3770	2074	816	253	6913
24	4335	2262	890	276	7763
26	5010	2451	964	299	8724
28	5850	2639	1039	322	9850
30	6960	2828	1113	345	11246
32	8550	3016	1187	368	13121
34	11135	3205	1261	391	15992
36	13460	3393	1335	414	18603
40	14140	3770	1484	460	19854
100	24345	9426	3709	1150	38630

Table 20. Heat content of the heat storage unit with hte Na_2HPO_4 water mixture.

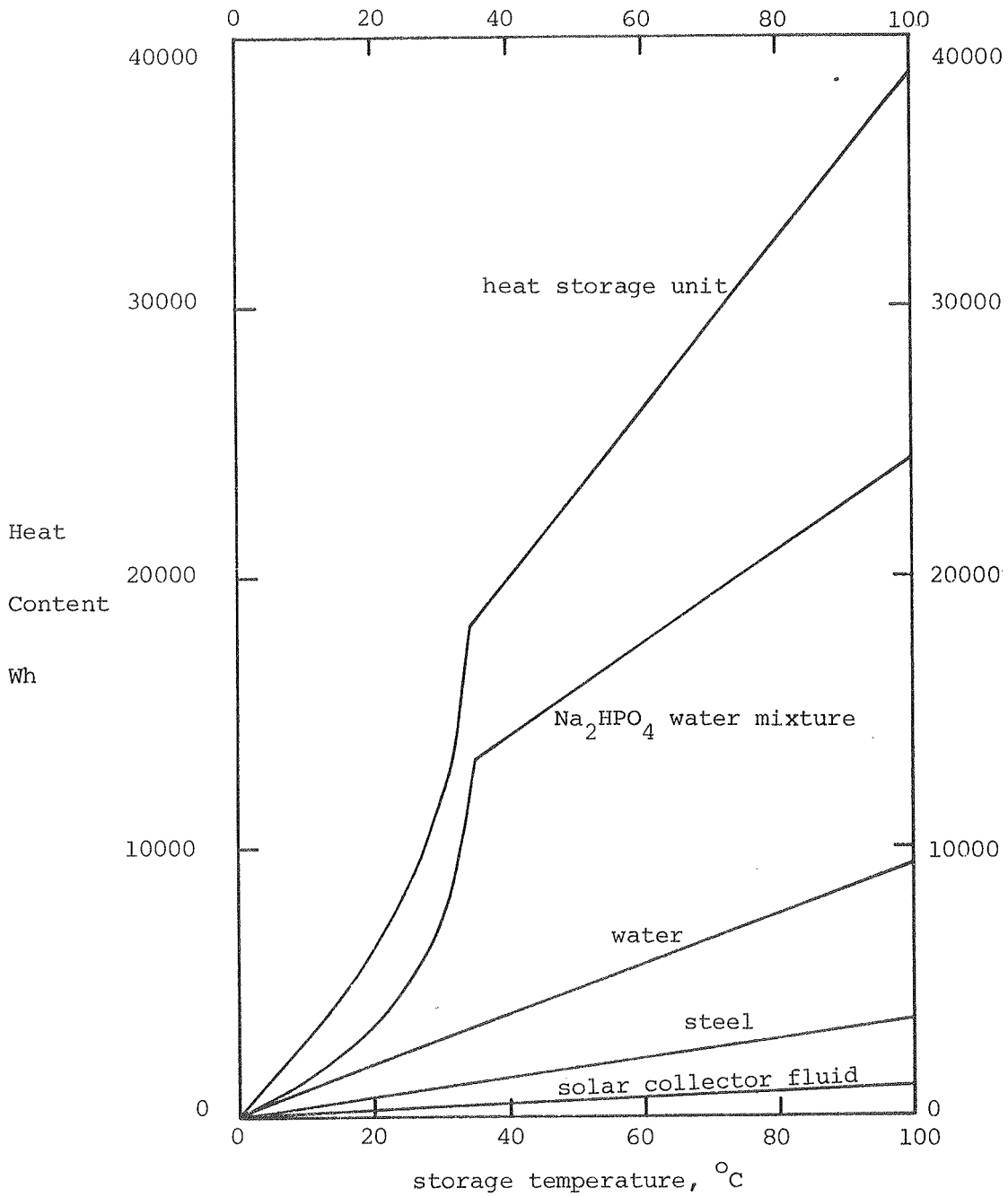


Figure 17. Heat content of the heat storage unit with the Na_2HPO_4 water mixture versus the heat storage temperature.

The heat transfer power per ^{o}C temperature difference between the solar collector fluid and the heat storage material was measured for different heating periods with a volume flow of 6 l/min. The heat transfer power per ^{o}C temperature difference between the solar collector fluid and the heat storage increases concurrently with the increase of the heat storage temperature and with the progression of the melting. The quantity of the heat transfer capacity varied from one heating period to another as long as the temperature is below the melting point. Relatively large temperature differences inside the heat storage appear during the heating period, and the differences vary for different locations of the solid and liquid phase inside the storage tank at the start of the heating period. Therefore the heat transfer capacity must be related to the start conditions for the heat storage unit. Applicable heat transfer capacities call for very detailed and timeconsuming measurements where the locations of the solid and liquid phase inside the storage tank at the start of the heating period are well defined. Such detailed measurements were not carried out, and therefore quantities of the heat transfer capacity will not be given.

The duration of the experiment in the dynamic test facility was 5 days. The measured temperatures during the experiment are shown in figure 18. The temperatures in the top, in the middle and at the bottom of the hot water tank are given. The salt water mixture temperature was measured at 3 locations. As long as the temperature is below the melting point, large temperature differences appear, and therefore the uncertainty of the mean salt water mixture temperature, which is given in the figure, is relatively great. The ambient temperature and the temperature of the solar collector fluid leaving and entering the storage are given in periods with the solar collector in operation. The data for the hot water consumption during the experiment are given in table 21. T_c is the temperature of the cold water entering the heat storage, T_w and M_{tap} are the mean temperature and the volume of the mixed water from the storage system. L is the energy tapped off the heat storage during each tapping.

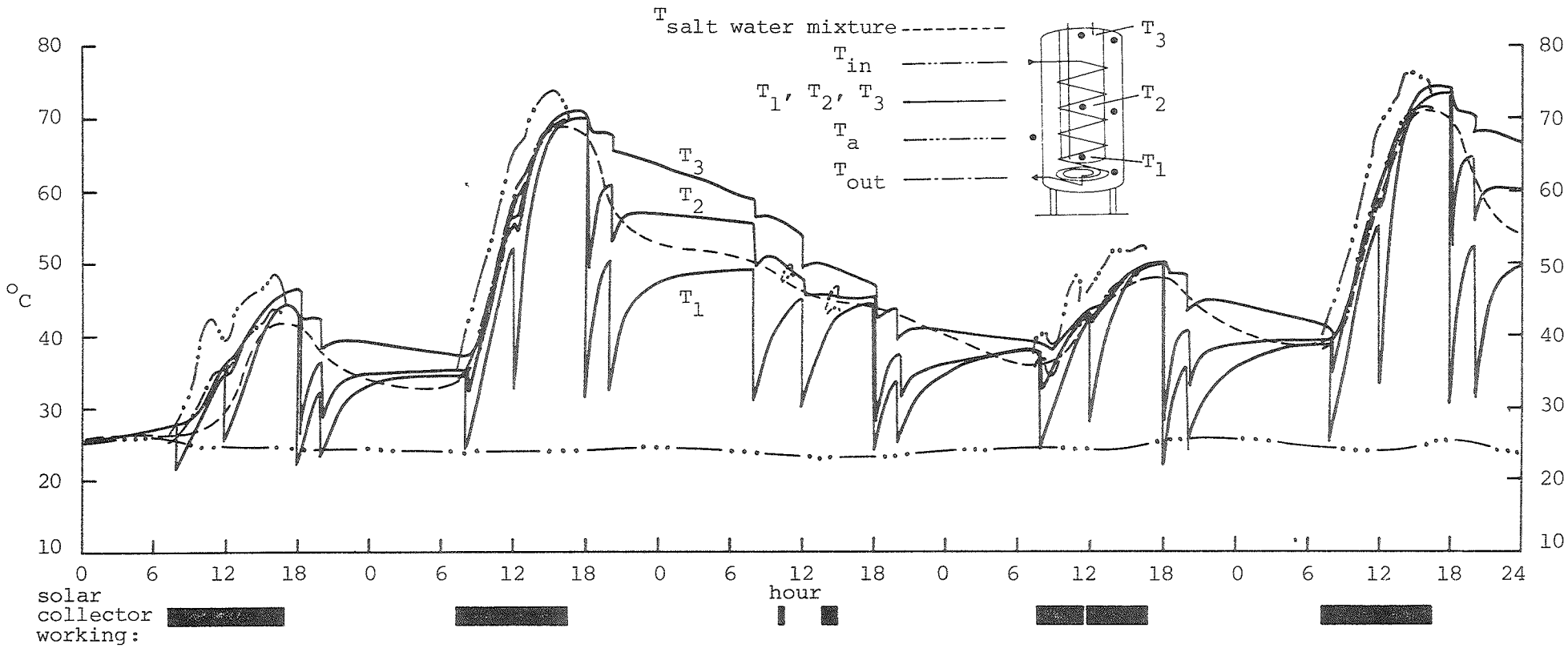


Figure 18. Temperatures for the heat storage unit with Na_2HPO_4 water mixture during the experiment.

Time day	Time hour	T_c °C	T_w °C	M_{tap} l	L Wh	Daily hot water consumption l	Energy tapped off the heat storage during the day Wh
1	8	15.3	27,5	33.5	470	160.8	4130
	12	13.6	33.7	26.8	620		
	18	12.9	40.6	67.0	2150		
	20	14.7	37.7	33.5	890		
2	8	18.0	33.8	33.5	610	160.8	5070
	12	18.3	44.5	26.8	810		
	18	17.1	50.2	67.0	2560		
	20	19.6	47.7	33.5	1090		
3	8	19.6	44.5	33.1	950	158.5	4240
	12	19.7	44.5	26.5	760		
	18	18.8	41.5	65.7	1720		
	20	18.3	39.3	33.2	810		
4	8	16.3	34.5	33.8	710	160.1	4650
	12	14.3	38.0	27.1	740		
	18	16.1	44.8	66.1	2190		
	20	16.1	42.4	33.1	1010		
5	8	17.0	35.9	33.6	730	158.9	5440
	12	12.9	44.5	26.9	980		
	18	15.4	48.3	65.3	2480		
	20	16.3	49.1	33.1	1250		

Table 21. Data for the hot water consumption during the dynamic experiment with the Na_2HPO_4 water mixture.

Time day	Solar irradiation on the solar collector Wh	Energy supply from the solar heating system to the heat storage Wh	Energy tapped off the heat storage Wh	Thermal loss Wh
1	25170	7200	4100	500
2	37902	15700	5100	1500
3	11904	-100	4200	1500
4	25170	5900	4600	1000
5	37902	14400	5400	1600
Total period	138048	43100	23400	6100

Table 22. Daily energy quantities for the heat storage unit with the Na_2HPO_4 water mixture during the dynamic experiment.

The important quantities for heat storage system during the test period are given in table 22. The negative energy supply to the heat storage on the third day with the varying solar irradiation on the solar collector is caused by a failure in the control system. The energy tapped off and lost from the heat storage during the period was 29500 Wh, while the energy supply to the heat storage was 43100 Wh. This change in heat content during the experimental period of 13600 Wh corresponds to a mean heat storage temperature rise from about 26°C at the start of the period to the final temperature of about 51°C, which is in reasonably good agreement with the heat content given in table 20 and figure 17.

Some observations concerning the dynamic behaviour of the heat storage unit is noticed from figure 18:

Since cold water during hot water consumption enters the bottom of the hot water tank, low temperatures appear here in periods after hot water consumption. In such periods with the solar collector in operation, the low water temperatures do not influence the temperature of the solar collector fluid significantly. Like this the low temperatures inside the heat storage are not optimally utilized to increase the gain from the solar collector. It is also noticed that in the morning of the first day, that is in a period with storage temperatures below the melting point of 35°C and energy supply from the solar collector, temperature differences between the salt water mixture and the water appear, but the differences are relatively small. Therefore these temperature differences are not optimally utilized to obtain high hot water temperatures quickly in sunny periods. The dynamic behaviour is to a certain extent related to the salt water mixture, but first of all to the design of the heat storage unit. Therefore the dynamic behaviour of the storage will be discussed in detail later in section 4.7.

The duration of the experiments with the Na_2HPO_4 water mixture was about 2 months. The Na_2HPO_4 water mixture did not cause any visible corrosion during this period.

4.4 Results from the experiments with the heat storage unit with the Na_2CO_3 water mixture

The thermal loss coefficient was measured at 3 different storage temperatures. The results are given in table 23.

Heat storage temperature, °C	35	60	90
Thermal loss coefficient, W/°C	2.1	2.2	2.3

Table 23. Thermal loss coefficient for the heat storage unit with the Na_2CO_3 water mixture at different storage temperatures.

The quantity of the thermal loss corresponds to the theoretically calculated thermal loss from a 300 l tank insulated with about 5 cm of mineral wool, see (3). Since the heat storage unit is insulated with 10 cm of mineral wool, the thermal losses caused by thermal bridges are reasonably small.

The heat content was measured by two heating periods, one in the start and one at the end of the experimental period.

The heat content of the heat storage unit was found to be in good agreement with the theoretically calculated heat content, and no decrease in the heat content during the experimental period of about 2 months was observed. The heat content consists of contributions from the salt water mixture, the water, the steel container material and the solar collector fluid situated in the heat exchanger spiral. The theoretically calculated heat content of the heat storage unit in the temperature interval 0 - 100°C is given in table 24 and figure 19. The melting point for $Na_2CO_3 \cdot 10H_2O$ is 33°C, and for temperatures above 33°C the heat content increases linearily with the temperature.

The heat transfer power per °C temperature difference between the solar collector fluid and the heat storage material was measured for different heating periods with a volume flow of 6 l/min. The heat transfer power per °C temperature difference between the solar collector fluid and the heat storage increases concurrently with the increase of the heat storage temperature and with the progression of the melting. The quantity of the heat transfer capacity varied from one heating period to another as long as the temperature is below the melting point. Relatively large temperature differences inside the heat storage appear during the heating period, and the differences vary for different locations of the solid and liquid phase inside the storage tank at the start of the heating period. Therefore the heat transfer capacity must be related to the start conditions for the heat storage unit. Applicable heat transfer capacities call for very detailed and timeconsuming measurements where the locations of the solid and liquid phase inside the storage tank at the start of the heating period are well defined. Such detailed measurements were not carried out and therefore quantities of the heat transfer capacity will not be given.

Temperature °C	Heat content of 200 kg Na_2CO_3 water mixture with 33% anhydrous salt in the mixture based on weight Wh	Heat content of 82 l water Wh	Heat content of 277 kg steel Wh	Heat content of 10 l solar collector fluid, water Wh	Total heat content of the heat storage unit Wh
0	0	0	0	0	0
2	294	189	74	23	580
4	594	377	148	46	1166
6	906	566	223	69	1763
8	1222	754	297	92	2365
10	1556	943	371	115	2984
12	1906	1131	445	138	3620
14	2272	1320	519	161	4272
16	2667	1508	593	184	4952
18	3100	1697	668	207	5671
20	3578	1885	742	230	6435
22	4133	2074	816	253	7276
24	4794	2262	890	276	8223
26	5633	2451	964	299	9347
28	6789	2639	1039	322	10789
30	8611	2828	1113	345	12897
32	12233	3016	1187	368	16805
33	16217	3111	1224	380	20931
40	17389	3770	1484	460	23103
100	27872	9426	3709	1150	42157

Table 24. Heat content of the heat storage unit with the Na_2CO_3 water mixture.

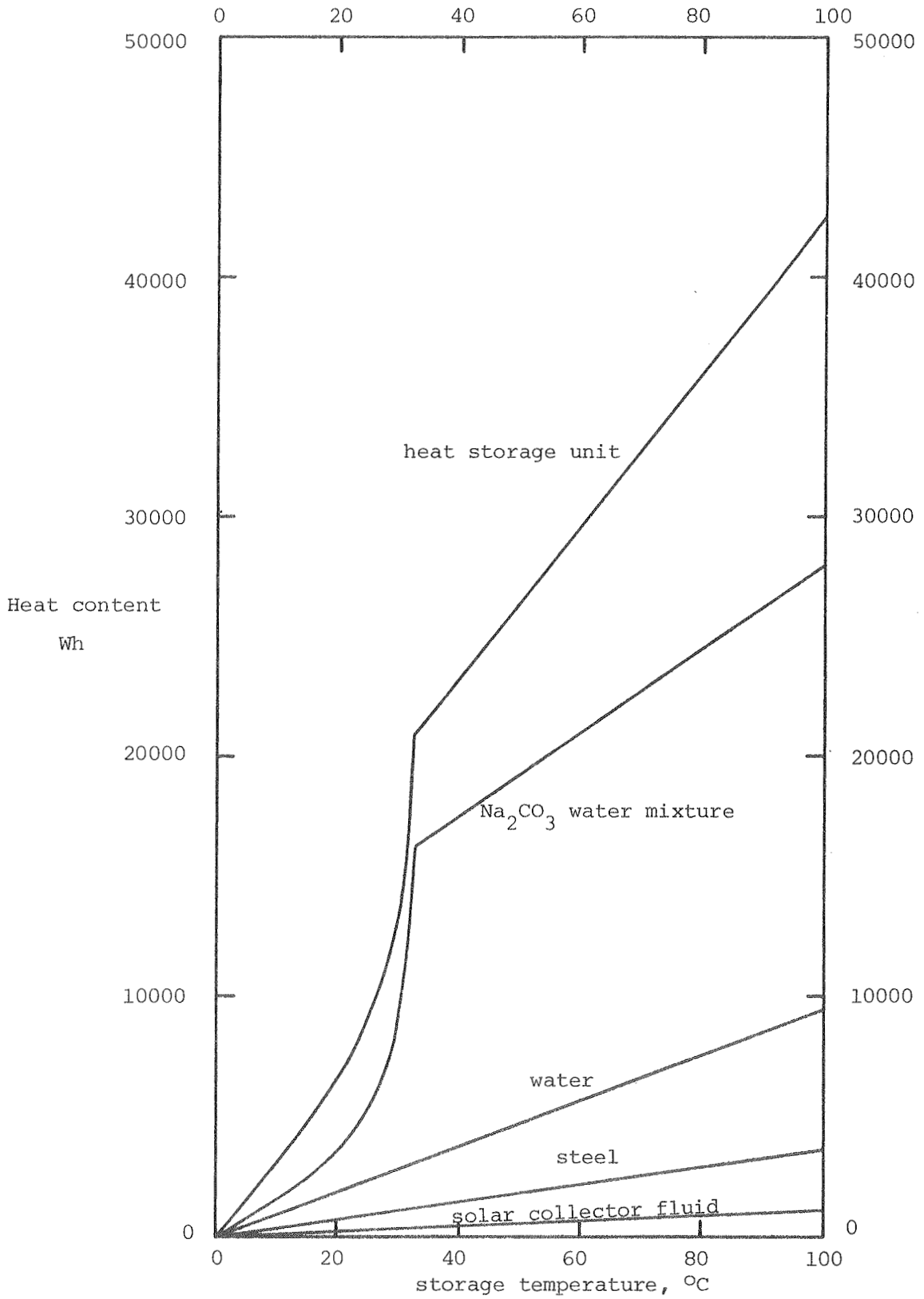


Figure 19. Heat content of the heat storage unit with the Na_2CO_3 water mixture versus the heat storage temperature.

The duration of the experiment in the dynamic test facility was the first three days of the five days period. The measured temperatures during the experiment are shown in figure 20. The temperatures in the top, in the middle and at the bottom of the hot water tank are given. The salt water mixture temperature was measured at 3 locations. As long as the temperature is below the melting point, large temperature differences appear, and therefore the uncertainty of the mean salt water mixture temperature which is given in the figure is relatively great. The ambient temperature and the temperature of the solar collector fluid leaving and entering the storage are given in periods with the solar collector in operation. The data for the hot water consumption during the experiment are given in table 25. T_c is the temperature of the cold water entering the heat storage, T_w and M_{tap} are the mean temperature and the volume of the mixed water from the storage system. L is the energy tapped off the heat storage during each tapping.

The important quantities for the heat storage system during the test period are given in table 26. The negative energy supply to the heat storage on the third day with the varying solar irradiation on the solar collector is caused by a failure in the control system. The energy tapped off and lost from the heat storage during the period was 16000 Wh, while the energy supply to the heat storage was 25500 Wh. This change in heat content during the experimental period of 9500 Wh corresponds to a mean heat storage temperature rise from about 21°C, at the start of the period, to the final temperature of about 32°C, which is in reasonably good agreement with the heat content given in table 24 and figure 19.

Some observations concerning the dynamic behaviour of the heat storage unit is noticed from figure 20:

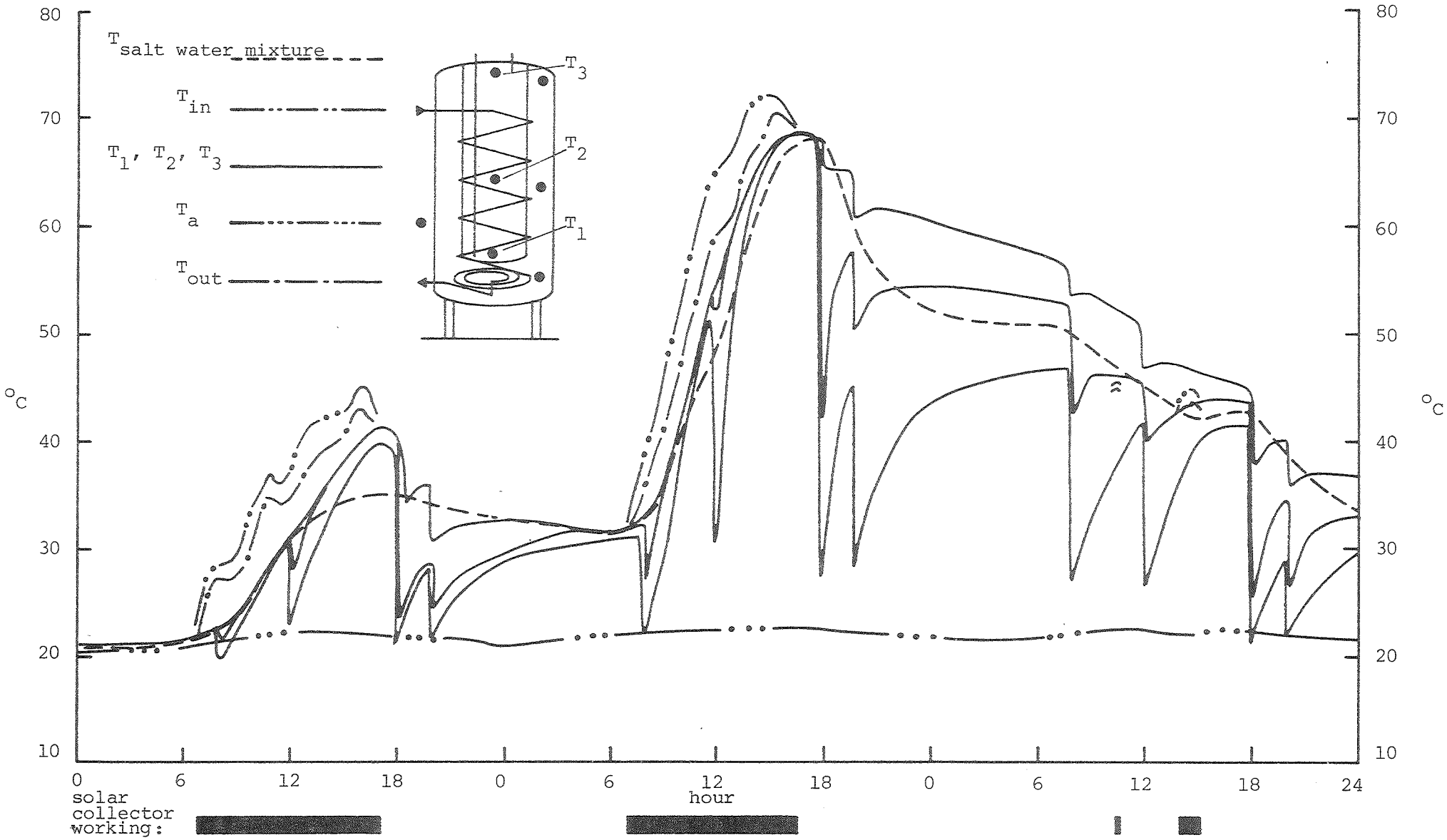


Figure 20. Temperatures for the heat storage unit with Na_2CO_3 water mixture during the experiment.

Time		T_c	T_w	M_{tap}	L	Daily hot water consumption	Energy tapped off the heat storage during the day
day	hour	°C	°C	l	Wh	l	Wh
1	8	17.3	23.5	49.4	350	187.5	3090
	12	17.4	28.8	29.4	390		
	18	16.6	36.7	72.5	1680		
	20	16.6	32.5	36.2	670		
2	8	16.9	29.9	36.2	540	173.7	5420
	12	16.9	44.1	29.2	920		
	18	17.1	49.5	72.2	2700		
	20	16.9	47.1	36.1	1260		
3	8	16.6	46.0	36.4	1240	174.1	4890
	12	16.8	43.4	29.4	900		
	18	16.6	39.8	72.2	1940		
	20	16.3	35.7	36.1	810		

Table 25. Data for the hot water consumption during the dynamic experiment with the Na_2CO_3 water mixture.

Time day	Solar irradiation on the solar collector Wh	Energy supply from the solar heating system to the heat storage Wh	Energy tapped off the heat storage Wh	Thermal loss Wh
1	25170	9800	3100	300
2	37902	15900	5400	1200
3	11904	-200	4900	1100
Total period	74976	25500	13400	2600

Table 26. Daily energy quantities for the heat storage unit with the Na_2CO_3 water mixture during the dynamic experiment.

Since cold water during hot water consumption enters the bottom of the hot water tank, low temperatures appear here in periods after hot water consumption. In such periods with the solar collector in operation, the low water temperatures do not influence the temperature of the solar collector fluid significantly. Like this, the low temperatures inside the heat storage are not optimally utilized to increase the gain from the solar collector. It is also noticed that in the morning of the first day, that is in a period with storage temperatures below the melting point of 33°C and energy supply from the solar collector, temperature differences between the salt water mixture and the water almost do not appear. Therefore such temperature differences are not utilized to obtain high hot water temperatures quickly in sunny periods. The dynamic behaviour is, to a certain extent, related to the salt water mixture, but first of all to the design of the heat storage unit. Therefore the dynamic behaviour of the storage will be discussed in detail later in section 4.7.

The duration of the experiments with the Na_2CO_3 water mixture was about 2 months. The Na_2CO_3 water mixture did not cause any visible corrosion during this period.

4.5 Results from the experiments with the heat storage unit with the Na_2SO_4 water mixture

The thermal loss coefficient was measured at 3 different storage temperatures. The results are given in table 27.

Heat storage temperature, °C	35	60	90
Thermal loss coefficient, W/°C	1.9	2.0	2.1

Table 27. Thermal loss coefficient for the heat storage unit with the Na_2SO_4 water mixture at different storage temperatures.

The quantity of the thermal loss corresponds to the theoretically calculated thermal loss from a 300 l tank insulated with about 6 cm of mineral wool, see (3). Since the heat storage unit is insulated with 10 cm of mineral wool, the thermal losses caused by thermal bridges are reasonably small.

The heat content was measured by two heating periods, one in the start and one at the end of the experimental period. The heat content of the heat storage unit was found to be in good agreement with the theoretically calculated heat content, and no decrease in the heat content during the experimental period of about 2 months was observed. The heat content consists of contributions from the salt water mixture, the water, the steel container material and the solar collector fluid situated in the heat exchanger spiral. The theoretically calculated heat content of the heat storage unit in the temperature interval 0 - 100°C is given in table 28 and figure 21. The melting point for $Na_2SO_4 \cdot 10H_2O$ is 32.4°C, and for temperatures above 32.4°C the heat content increases linearily with the temperature.

Temperature °C	Heat content of 190 kg Na_2SO_4 water mixture with 33% anhydrous salt in the mixture based on weight Wh	Heat content of 82 l water Wh	Heat content of 277 kg steel Wh	Heat content of 10 l solar collector fluid, water Wh	Total heat content of the heat storage unit Wh
0	0	0	0	0	0
2	317	189	74	23	602
4	644	377	148	46	1215
6	982	566	223	69	1839
8	1335	754	297	92	2478
10	1705	943	371	115	3133
12	2095	1131	445	138	3810
14	2518	1320	519	161	4517
16	2971	1508	593	184	5257
18	3473	1697	668	207	6044
20	4043	1885	742	230	6900
22	4703	2074	816	253	7845
24	5494	2262	890	276	8923
26	6497	2451	964	299	10211
28	7859	2639	1039	322	11858
30	9901	2828	1113	345	14187
32	13495	3016	1187	368	18067
32.4	14076	3054	1202	373	18704
40	15279	3770	1484	460	20993
100	25064	9426	3709	1150	39349

Table 28. Heat content of the heat storage unit with the Na_2SO_4 water mixture.

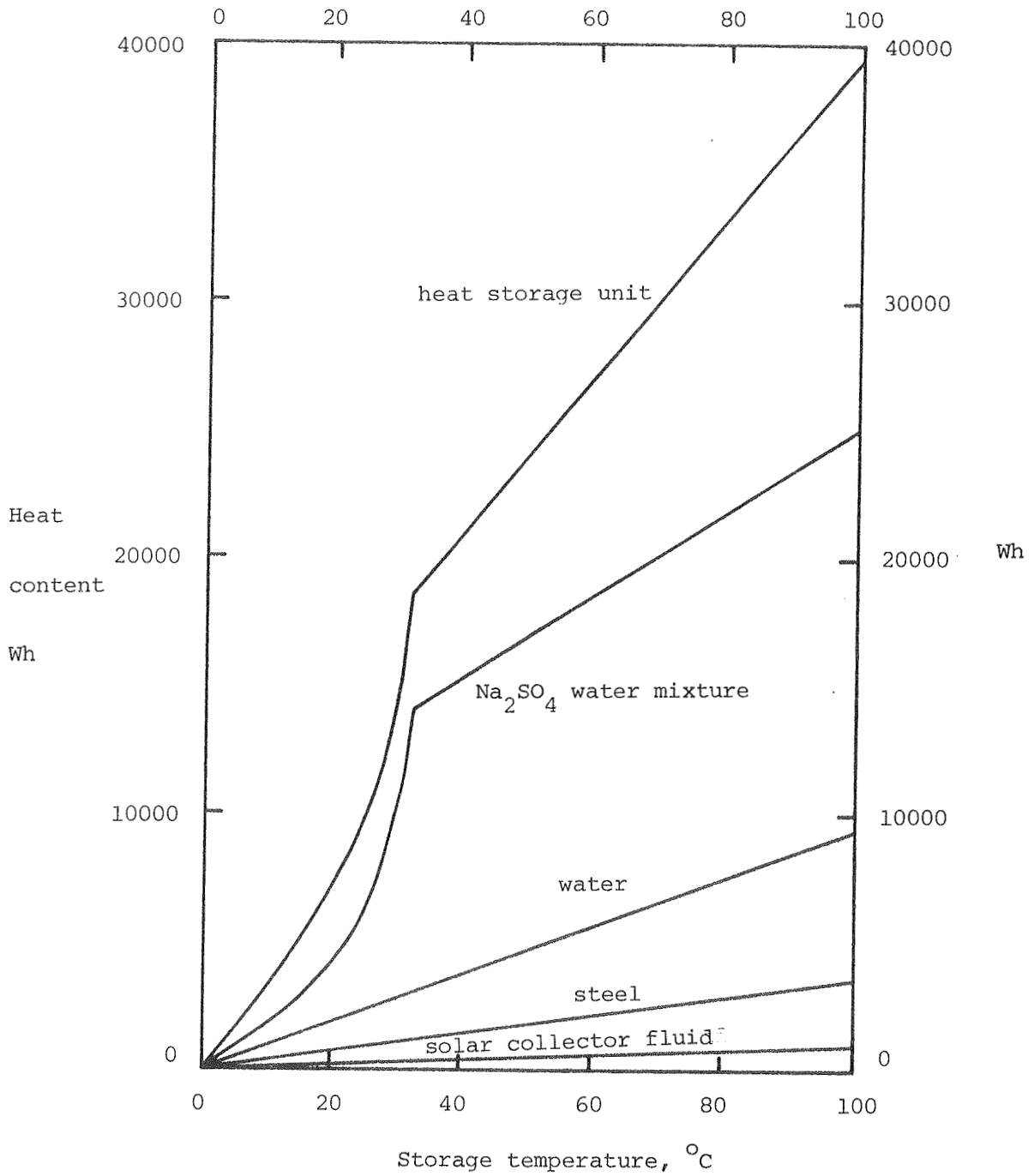


Figure 21. Heat content of the heat storage unit with the Na_2SO_4 water mixture versus the heat storage temperature.

The heat transfer power per ^{o}C temperature difference between the solar collector fluid and the heat storage material was measured for different heating periods with a volume flow of 6 l/min. The heat transfer power per ^{o}C temperature difference between the solar collector fluid and the heat storage increases concurrently with the increase of the heat storage temperature and with the progression of the melting. The quantity of the heat transfer capacity varied from one heating period to another as long as the temperature is below the melting point. Relatively large temperature differences inside the heat storage appear during the heating period, and the differences vary for different locations of the solid and liquid phase inside the storage tank at the start of the heating period. therefore the heat transfer capacity must be related to the start conditions for the heat storage unit. Applicable heat transfer capacities call for very detailed and timeconsuming measurements where the locations of the solid and liquid phase inside the storage tank at the start of the heating period are well defined. Such detailed measurements were not carried out, and therefore quantities of the heat transfer capacity will not be given.

The duration of the experiment in the dynamic test facility was five days. The measured temperatures during the experiment are shown in figure 22. The temperatures in the top, in the middle and at the bottom of the hot water tank are given. The salt water mixture temperature was measured at 3 locations. As long as the temperature is below the melting point, large temperature differences appear, and therefore the uncertainty of the mean salt water mixture temperature which is given in the figure is relatively great. The ambient temperature and the temperature of the solar collector fluid leaving and entering the storage are given in periods with the solar collector in operation. The data for the hot water consumption during the experiment are given in table 29. T_c is the temperature of the cold water entering the heat storage, T_w and M_{tap} are the mean temperature and the volume of the mixed water from the storage system. L is the energy tapped off the heat storage during each tapping.

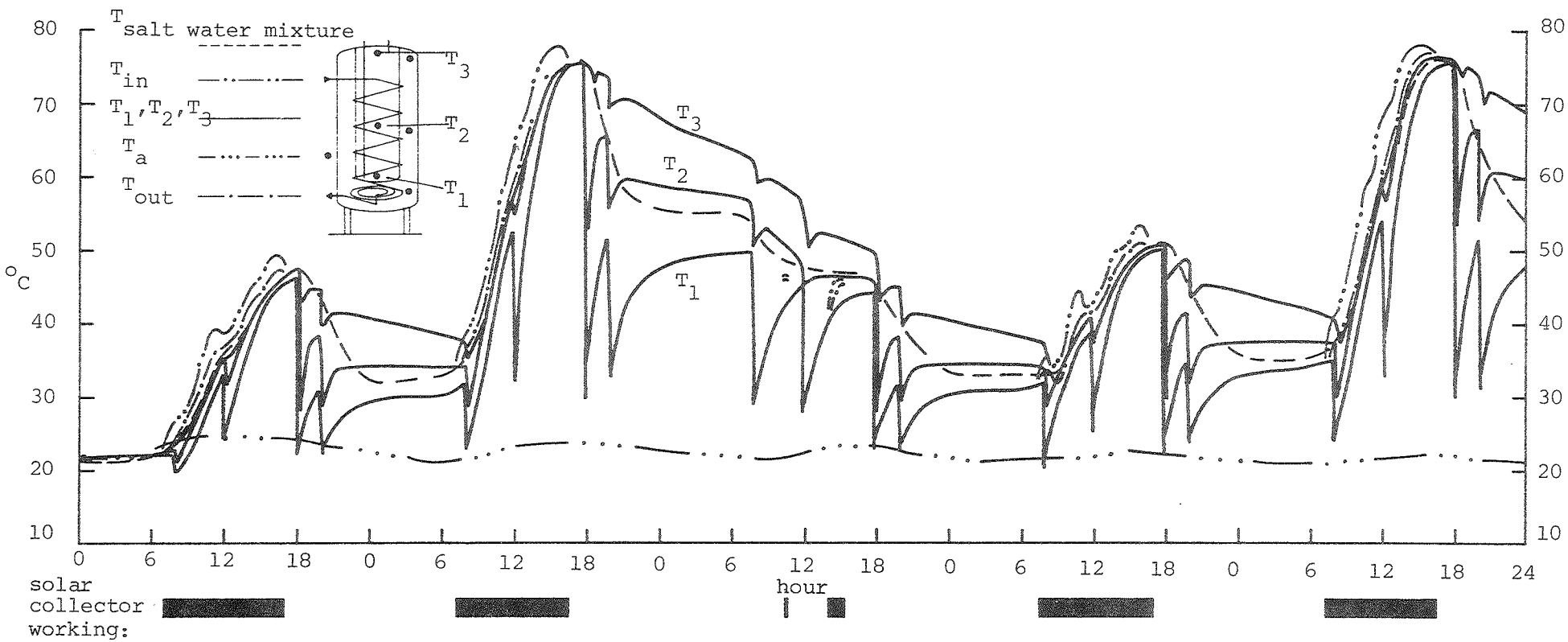


Figure 22. Temperatures for the heat storage unit with Na_2SO_4 water mixture during the experiment.

Time		T_c	T_w	M_{tap}	L	Daily hot water consumption	Energy tapped off the heat storage during the day
day	hour	°C	°C	l	Wh	l	Wh
1	8	16.8	23.5	36.3	280	172.8	3860
	12	16.8	31.6	29.2	500		
	18	16.8	42.4	70.9	2100		
	20	16.3	39.5	36.4	980		
2	8	15.7	33.5	36.3	750	175.0	6070
	12	15.7	44.2	29.2	960		
	18	16.6	50.7	73.0	2880		
	20	16.3	51.3	36.5	1480		
3	8	16.1	44.1	36.3	1170	176.1	5310
	12	15.8	44.7	33.2	1110		
	18	16.9	42.4	71.1	2100		
	20	16.8	39.5	35.3	930		
4	8	16.6	32.8	35.6	670	172.5	4820
	12	16.3	36.6	28.4	670		
	18	16.3	44.8	72.3	2380		
	20	16.1	42.4	36.2	1100		
5	8	16.6	35.5	36.2	790	173.6	6040
	12	16.3	44.1	28.9	930		
	18	16.3	51.4	72.3	2890		
	20	16.6	50.7	36.2	1430		

Table 29. Data for the hot water consumption during the dynamic experiment with the Na_2SO_4 water mixture.

The important quantities for the heat storage system during the test period are given in table 30. The negative energy supply to the heat storage on the third day with the varying solar irradiation on the solar collector is caused by a failure in the control system. The energy tapped off and lost from the heat storage during the period was 31500 Wh, while the energy supply to the heat storage was 45700 Wh. This change in heat content during the experimental period of 14200 Wh should correspond to the mean heat storage temperature rise from about 22°C, at the start of the period, to the final temperature of about 52°C. According to table 28 and figure 21 this temperature rise corresponds to a change in the heat content of 16800 Wh. Therefore these measurements must be defective to a certain extent.

Some observations concerning the dynamic behaviour of the heat storage unit is noticed from figure 22:

Time day	Solar irradiation on the solar collector Wh	Energy supply from the solar heating system to the heat storage Wh	Energy tapped off the heat storage Wh	Thermal loss Wh
1	25170	9300	3900	500
2	37902	14600	6100	1400
3	11904	-100	5300	1200
4	25170	7400	4800	800
5	37902	14500	6000	1500
Total period	138048	45700	26100	5400

Table 30. Daily energy quantities for the heat storage unit with the Na_2SO_4 water mixture during the dynamic experiment.

Since cold water during hot water consumption enters the bottom of the hot water tank, low temperatures appear here in periods after hot water consumption. In such periods with the solar collector in operation, the low water temperatures do not influence the temperature of the solar collector fluid significantly. Like this, the low temperatures inside the heat storage are not optimally utilized to increase the gain from the solar collector. It is also noticed that in the morning of the first day, that is in a period with storage temperatures below the melting point of 32°C and energy supply from the solar collector, temperature differences between the salt water mixture and the water almost do not appear. Therefore such temperature differences are not utilized to obtain high hot water temperatures quickly in sunny periods. The dynamic behaviour is, to a certain extent, related to the salt water mixture, but first of all to the design of the heat storage unit. Therefore the dynamic behaviour of the storage will be discussed in detail later, in section 4.7.

The duration of the experiments with the Na_2SO_4 water mixture was about 2 months. The Na_2SO_4 water mixture did not cause any visible corrosion during this period.

4.6 Results from the experiments with the heat storage unit with water

The thermal loss coefficient was measured at 3 different storage temperatures. The results are given in table 31.

Heat storage temperature, °C	35	60	90
Thermal loss coefficient, W/°C	2.2	2.3	2.4

Table 31. Thermal loss coefficient for the heat storage unit with water at different storage temperatures.

The quantity of the thermal loss corresponds to the theoretically calculated thermal loss from a 300 l tank insulated with about 5 cm of mineral wool, see (3). Since the heat storage unit is insulated with 10 cm of mineral wool, the thermal losses caused by thermal bridges are reasonably small.

The heat content was measured by a heating period, and the measurement was in good agreement with the calculated heat content. The heat content in the temperature interval 0 - 100°C is given in figure 23.

The heat transfer power per °C temperature difference between the solar collector fluid and the hot water tank was measured for a heating period with a volume flow of 6 l/min. The results are shown in figure 24, where the heat transfer capacity is given as a function of the storage temperature. The heat transfer capacity increases for increasing heat storage temperature.

The duration of the experiment in the dynamic test facility was 5 days. The measured temperatures during the experiment are shown in figure 25. The temperatures in the top, in the middle and at the bottom of both the hot water tank and the storage tank are given.

The ambient temperature and the temperature of the solar collector fluid leaving and entering the storage are given in periods with the solar collector in operation. The data for the hot water concumption during the experiment are given in table 32. T_c is the temperature of the cold water entering the heat storage, T_w and M_{tap} are the mean temperature and the volume of the mixed water from the storage system. L is the energy tapped off the heat storage during each tapping.

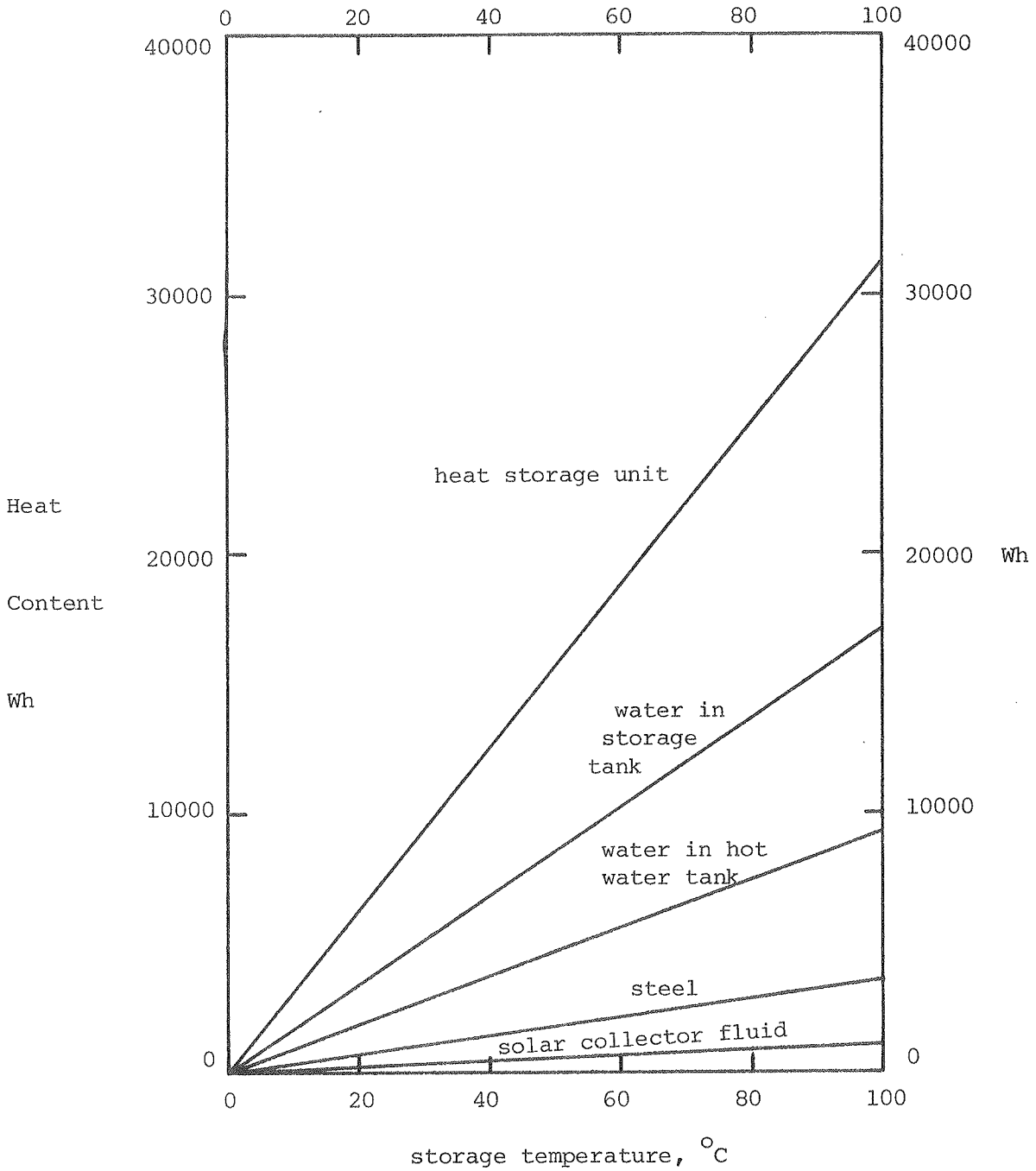


Figure 23. Heat content of the heat storage unit with water versus the heat storage temperature.

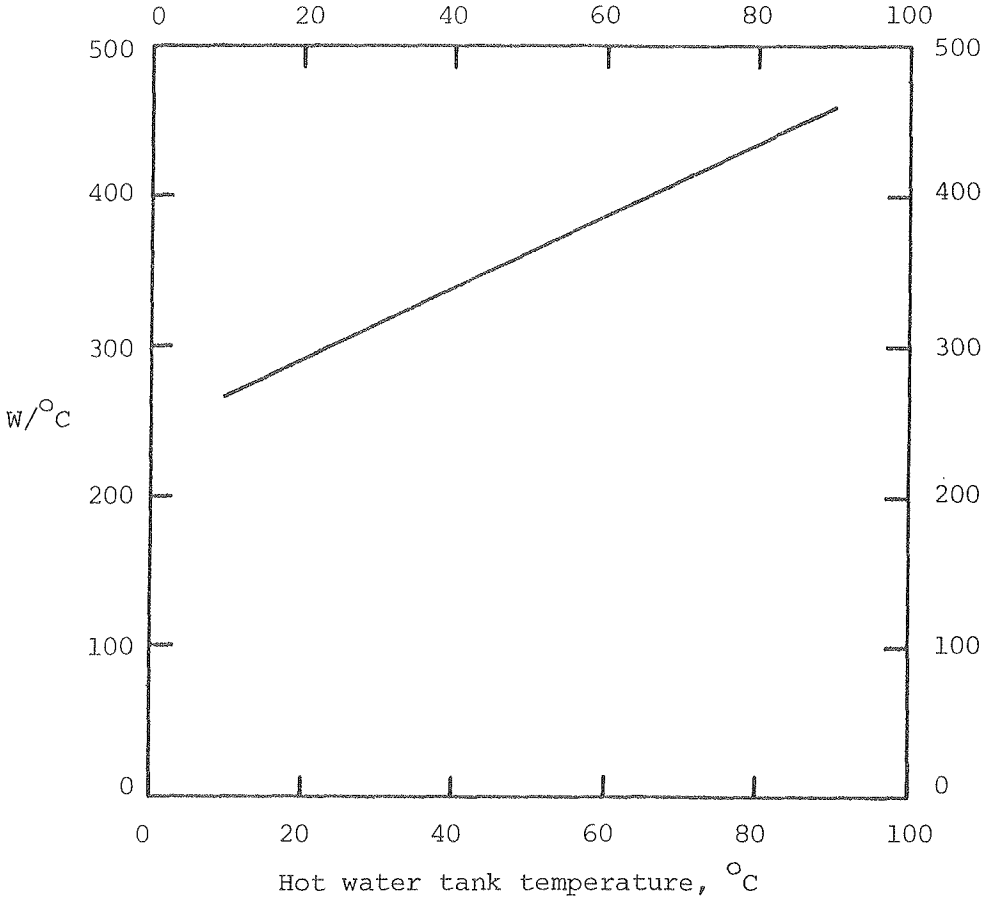


Figure 24. Heat transfer power per °C temperature difference between the solar collector fluid and the hot water tank versus the hot water tank temperature. The storage material is water, the fluid velocity 6 l/min and the power input 1400 W.

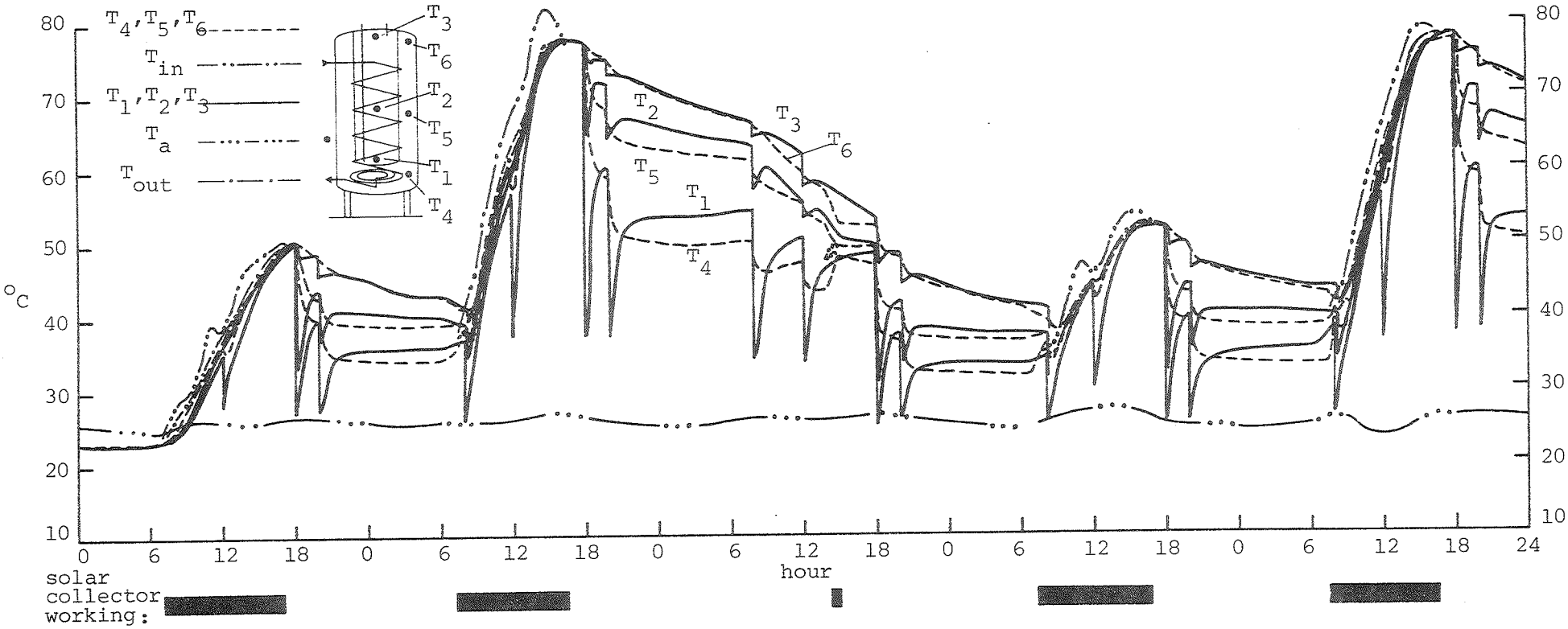


Figure 25. Temperatures for the heat storage unit with water during the experiment.

Time day	Time hour	T_c °C	T_w °C	M_{tap} l	L Wh	Daily hot water consumption l	Energy tapped off the heat storage during the day Wh
1	8	20.9	25.2	26.4	130	142.7	3200
	12	20.1	32.1	21.5	300		
	18	19.1	44.4	63.2	1850		
	20	18.3	43.6	31.6	920		
2	8	17.3	36.7	31.3	700	150.6	5150
	12	16.6	44.8	25.1	820		
	18	17.1	50.1	62.8	2400		
	20	16.8	50.7	31.4	1230		
3	8	17.6	45.5	31.5	1020	160.5	5090
	12	18.1	44.9	25.5	790		
	18	17.4	45.3	69.0	2230		
	20	17.1	43.4	34.5	1050		
4	8	17.6	36.2	34.2	740	163.5	4730
	12	18.1	39.2	27.3	670		
	18	16.6	44.8	68.0	2220		
	20	15.9	43.9	34.0	1100		
5	8	18.1	38.1	34.1	790	164.2	5460
	12	15.8	42.9	27.6	860		
	18	17.8	50.2	68.3	2560		
	20	17.6	49.3	34.2	1250		

Table 32. Data for the hot water consumption during the dynamic experiment with water as storage material.

The important quantities for the heat storage system during the test period are given in table 33. The negative energy supply to the heat storage on the third day with the varying solar irradiation on the solar collector is caused by a failure in the control system. The energy tapped off and lost from the heat storage during the period was 30000 Wh, while the energy supply to the heat storage was 41600 Wh. This change in heat content during the experimental period of 11600 Wh corresponds to the mean heat storage temperature rise from about 23 °C to about 60 °C, which is in good agreement with the heat content given in figure 23.

Time day	Solar irradiation on the solar collector Wh	Energy supply from the solar heating system to the heat storage Wh	Energy tapped off the heat storage Wh	Thermal loss Wh
1	25170	8200	3200	500
2	37902	13900	5200	1700
3	11904	-300	5100	1500
4	25170	6100	4700	800
5	37902	13700	5500	1800
Total period	138048	41600	23700	6300

Table 33. Daily energy quantities for the heat storage unit with water as storage material during the dynamic experiment.

Some observations concerning the dynamic behaviour of the heat storage unit is noticed from figure 25:

Since cold water during hot water consumption enters the bottom of the hot water tank, low temperatures appear here i periods after hot water consump-

tion. In such periods with the solar collector in operation, the low water temperatures do not influence the temperature of the solar collector fluid significantly. Like this the low temperatures inside the heat storage are not optimally utilized to increase the gain from the solar collector. The dynamic behaviour of the heat storage unit is incidentally related to the design of the storage, which will be discussed in section 4.7.

4.7 Summary of the results from the experiments and the dynamic behaviour of the heat storage unit

The measured thermal losses from the heat storage unit with the different heat storage materials were of a reasonably small amount. The differences between the storage losses with the different storage materials are caused by changes in the insulation of the pipes breaking the insulation. The thermal loss from thermal bridges depends very much of how carefull the insulation work is carried out. This explains the changes in the thermal loss from one experimental period to another.

The measured heat contents of the heat storage unit with the 5 different salt water mixtures and water as the storage material are shown in figure 26. These quantities are in good agreement with the calculatied values. No decrease in the heat storage capacity during the experimental period of about two months for each salt water mixture was observed.

For temperatures below the melting point the quantity of the heat transfer capacity from the solar collector fluid to the heat storage varies from one heating period to another. This is caused by different locations of the solid and liquid phase inside the storage tank.

At first, the lowest part of the heat exchanger spiral was located a little above the bottom of the storage tank. This location was changed before the experiments were carried out because it is not possible to melt all the salt hydrate crystals during a heating period if the heating does not take place from beneath. In order to melt all the crystals during a heating period, it

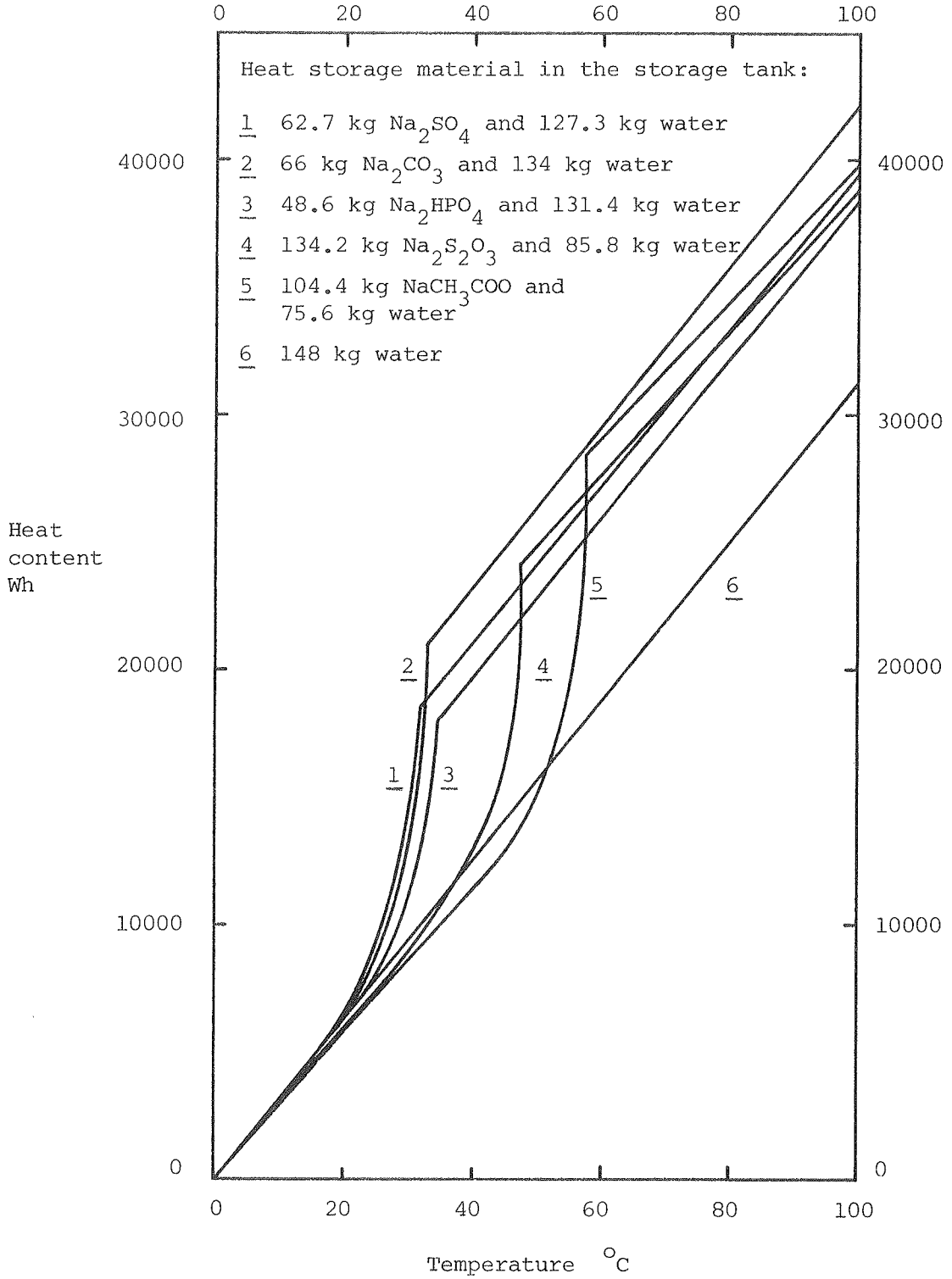


Figure 26. Measured heat contents of the heat storage unit.

is essential that the heat transfer area is situated at the bottom of the tank, i.e. beneath the salt hydrate crystals.

No supercooling of importance occurred during the operation of the heat storage unit. This is caused either by impurities in the salts or by the temperatures at the bottom of the hot water tank far below the melting point after hot water consumption. The dynamic behaviour of the heat storage unit was studied by means of dynamic experiments. Concerning the dynamic behaviour, the heat storage unit design, that is the form and volume of the hot water tank and the storage tank and the form and location of the heat exchanger spiral, is more important than the salt water mixture used as storage material.

For storage temperatures below the melting point of the salt hydrate, a large part of the salt water mixture is solid phase salt hydrate crystals. These crystals have a poor thermal conductivity, and they make convective heat transfer impossible. Therefore it is possible during operation to obtain and in a long period preserve large temperature differences inside the heat storage. That is: the basis for temperature differences are better for a salt water mixture storage than for a hot water storage, and a proper heat storage design should secure that the temperature differences are utilized to increase the performance of the solar heating system. The advantage by using a salt water mixture storage is therefore not only related to the increased heat storage capacity, but to the increased use of temperature stratification as well. The experiences with the tested heat storage unit concerning the temperature stratification and a description of how the temperature stratification should be utilized in such a heat storage will be given in the following:

In sunny periods during and after hot water consumption, the temperature of the solar collector fluid, which is conducted through the heat exchanger spiral, did not decrease much. Like this the low temperatures inside the heat storage were not utilized much to increase the enrgy production from the solar collectors. This disadvantage is caused by an inappropriate placing of the heat exchanger spiral. The shortest distance from the heat exchanger

spiral to the hot water tank is about 8 mm, and the spiral is situated around a large part of the height of the hot water tank. The heat exchanger spiral is placed at too long a distance from the hot water tank. For instance, a partially placing of the heat exchanger spiral inside the hot water tank could be a solution. Furthermore, most of the spiral should be placed at the level of the bottom of the hot water tank, where cold water enters the storage during tapping. In any case, it is important that good thermal contact exists between the heat exchanger spiral and the bottom of the hot water tank.

As long as the storage temperatures are below the melting point, temperature stratification in the hot water tank resulting from hot water tapping is preserved to a certain extent, because the convection in the salt water mixture, which for temperatures above the melting point is responsible for a quick equalization of the temperature differences, does not exist for low storage temperatures. This preservation would have been utilized with a proper design of the heat exchanger spiral.

During heating periods at temperatures below the melting point, the temperature of the water in the hot water tank was not much higher than the temperature of the salt hydrate crystals. In this way almost all the heat storage is heated equally during the heating period, and high usable hot water temperatures are not reached quickly. This is caused by the inappropriate placing of the heat exchanger spiral. The spiral is situated in such a way that salt hydrate crystals surround all the surface area of the spiral. The spiral should be designed in such a way that the heat transfer area surrounded by crystals is as small as possible, considering that all crystals should melt as soon as the melting point has been reached. With such a well designed heat storage unit, only the water in the hot water tank and a small part of the salt hydrate crystals are heated as long as the temperatures are below the melting point due to the poor thermal conductivity of the crystals. Hot water temperatures, equal the melting point, are quickly produced. When the water temperature has reached the melting point, the heat transfer from the solar collector and the water to the salt water mixture should increase rapidly, resulting in the melting of all salt hydrate crystals. This is pos-

sible due to natural convection in the melted salt water mixture. In this way the heat storage capacity of the heat storage unit varies with the storage temperature and with that with the ratio between the hot water consumption and the available quantity of solar energy. For low storage temperatures, that is in periods with a large ratio between the hot water consumption and the available quantity of solar energy, the heat storage capacity is small. For high storage temperatures, that is in periods with a small raito between the hot water consumption and the available quantity of solar energy, the heat storage capacity is large. In this way both short and long sunny periods are utilized in a more efficient way than for traditional hot water storages. This advantage will decrease with an increase in the duration of the period from the energy production to the hot water consumption.

During a long period with a large ratio between the hot water consumption and the quantity of available solar energy, the heat transfer from the salt solution to the hot water tank is small due to the crystals situated on the surface of the hot water tank. By the careful design of the heat storage unit this disadvantage must be taken into consideration as well as the advantage described in this section.

The steel tanks and the steel heat exchanger were strongly attacked by the $NaCH_3COO$ water mixture. The corrosion was caused by small amounts of impurities of acetic acid in the salt. The acetic acid must be neutralized, for instance by adding small amounts of Na_2CO_3 to the salt, in order to avoid corrosion. It is therefore important to know the impurities in the salt that is used as storage material. None of the other salt water mixtures caused any visible corrosion.

5. THE YEARLY THERMAL PERFORMANCE OF SOLAR HEATING SYSTEMS FOR DOMESTIC HOT WATER SUPPLY WITH HEAT OF FUSION STORAGE AND HOT WATER STORAGES

5.1 Assumptions for the calculations

The yearly thermal performance of small solar heating systems for domestic hot water supply is found by use of computer calculations. The solar heating systems which are used in the calculations are shown schematically in figure 27. The auxiliary energy source is an oil fired boiler because this is the kind of systems, which are used most in Denmark. Two different storage types are used: a traditional hot water storage and the heat of fusion storage unit making use of a salt water mixture as storage material based on the extra water principle, designed as described in the previous sections.

The computer program simulates the solar heating system. On the basis of the data of the Danish Test Reference Year (1980 version) the solar radiation and the heat balance for the heat storage is calculated every half hour. The three parts in the heat balance are: the useful solar energy from the solar collector circuit, the heat for the hot water consumption and the thermal loss from the heat storage to the environment. For every half hour these quantities of heat are calculated, and they are summed up for the year, and the yearly thermal performance of the solar heating system is found.

The assumptions for the calculations are listed in table 34. The efficiency of the solar collector corresponds to the efficiency of the best solar collector which in 1981 was on the Danish market. In order to elucidate the suitability of the different salt water mixtures, calculations were carried out with no thermal stratification inside the heat storage. In section 5.3 considerations concerning this assumption are given.

The total utilized solar energy from the solar heating system consists of the utilized solar energy from the solar heating system and the saved thermal loss from the oil fired boiler in the summer time, where the oil burner can

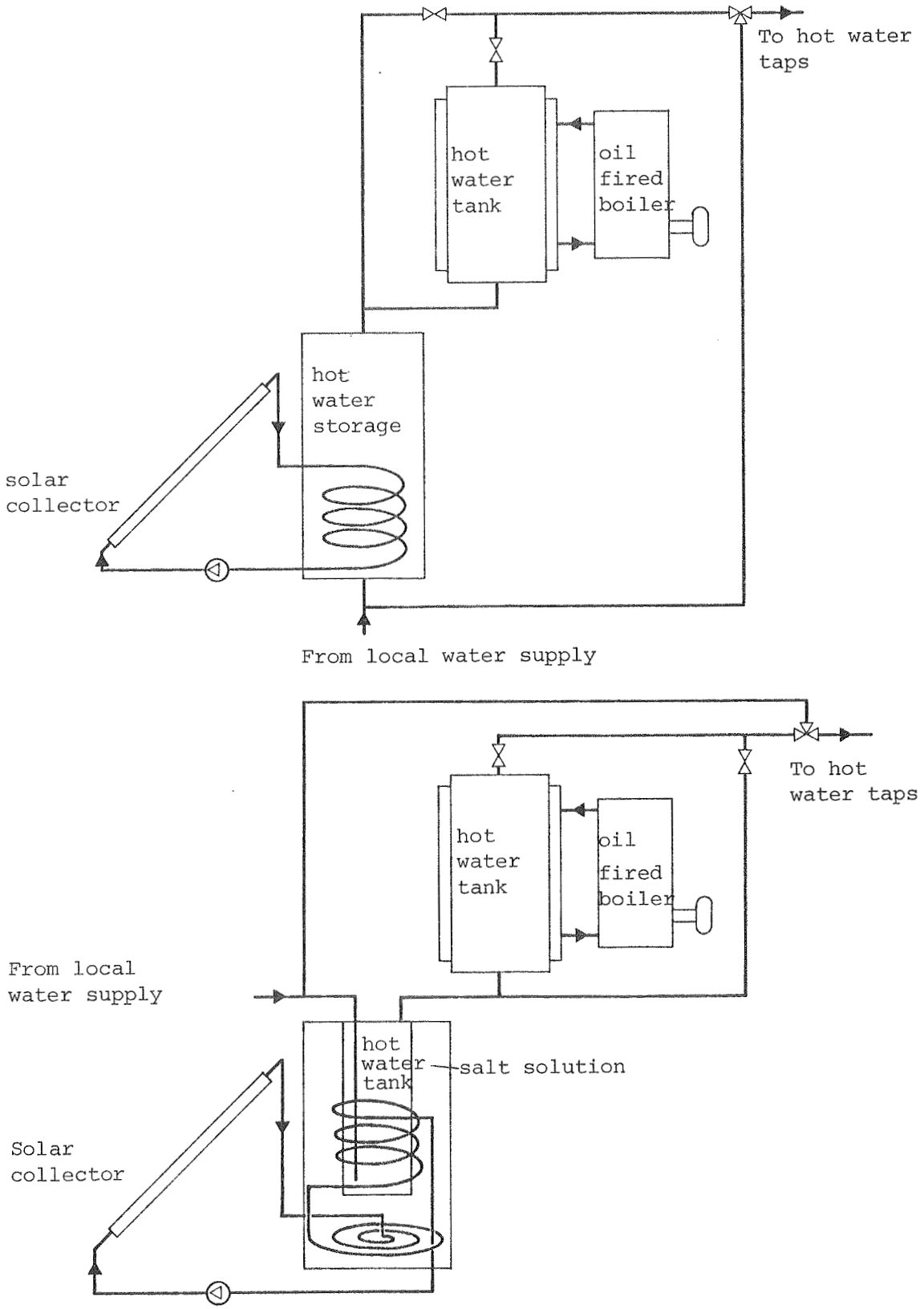


Figure 27. Schematical illustration of the solar heating systems with a hot water storage and a heat of fusion storage.

Solar collector:

Efficiency for small angles of incidence:

$$\eta = 0.80 - 5.5 \frac{T_m - T_a}{I}$$

T_m is the temperature of the solar collector fluid in the solar collector, °C
T_a is the ambient temperature, °C
I is the solar radiation on the solar collector, W/m^2

Tilt: 45°
Orientation: Facing south
Solar collector fluid: Glycol/water solution anti-freezed down to -20°C
Solar collector fluid rate: A l/min

A is the solar collector area, m^2

Heat storage:

	Hot water storage:	Heat of fusion storage:
Storage material:	Water	Partly a salt water mixture based on the extra water principle according to table 2, partly 100 l water situated in a hot water tank inside the storage tank.
Form:	Cylindrical tank	Cylindrical tank
Insulation:	5 cm of mineral wool	5 cm of mineral wool
Thermal bridges:	None	None
Stratification:	None	None
Heat transfer power per °C temp.dif. between the storage and the solar collector fluid:	200 + 5 T_s W/°C	200 + 5 T_s W/°C

T_s is the storage temperature, °C

Pipes in the solar collector circuit:

Material: Steel
Dimension: 3/4"
Insulation: 3 cm of mineral wool
Length: 6 m indoor at 20°C
10 m outside the house

cont.

Control system: Start and stop temperature difference between solar collector fluid inlet and outlet of the heat storage: 1°C
Hot water consumption: Required hot water temperature: 45°C cold inlet water temperature: 10°C
Auxiliary energy source: Efficiency of the oil fired boiler: 0.85 Thermal loss of the boiler: 350 W Heating value of oil: 9.84 kWh/l oil

Table 34. Assumptions used in the calculations

be turned off due to the lack of space heating demand and the high performance of the solar heating system for domestic hot water supply. As described in (4), a reasonable assumption is that the number of days in the summer time with the oil burner turned off is found from:

$$N = \begin{cases} 150 & \text{for SSF} \geqq 95\% \\ \frac{150}{20}(\text{SSF}-75) & \text{for } 75\% < \text{SSF} < 95\% \\ 0 & \text{for SSF} \leqq 75\% \end{cases}$$

SSF is the summer solar fraction, that is the fraction of the summer time heat requirement which is received from the solar heating system. The summer time is the months: May, June, July, August and September, where well insulated houses have no space heating demands.

5.2 Results from the calculations

Calculations were carried out with 5 different salt water mixtures. The mass of the salt water mixtures in the storage tank used in the calculations are calculated on the basis of the densities at 95°C according to figure 6. An example of the results will be given in the following.

The yearly net utilized solar energy from a 6 m^2 solar heating system with a daily hot water consumption of 200 l is shown in figure 28 as a function of the total storage volume and the heat storage material in the storage tank around the 100 l hot water tank. For simplicity, only the results for water and for three of the five salt water mixtures are shown. The results for the Na_2CO_3 water mixture with a melting point of 33°C are very close to the results for the Na_2SO_4 - and Na_2HPO_4-water mixtures with melting points of 32°C and 35°C respectively. Therefore the results for the Na_2SO_4- and Na_2HPO_4-water mixtures are not given in the figure. In addition to the yearly net utilized solar energy, the utilized solar energy in the summer, that is in the five months: May, June, July, August and September is shown. The differences between the yearly net utilized solar energy with the different heat storages are small. The largest differences are about 5%. The $Na_2S_2O_3$ water mixture results in the largest net yearly utilized solar energy, the Na_2CO_3- and the $NaCH_3COO$-water mixture results in about the same net yearly utilized solar energy, and the water results in the smallest net yearly utilized solar energy. In the summer months, the order of the storage materials with decreasing utilized solar energy is: $Na_2S_2O_3$ water mixture, $NaCH_3COO$ water mixture, Na_2CO_3 water mixture and water. Almost all the increase in the yearly net utilized solar energy by using a $Na_2S_2O_3$- or $NaCH_3COO$-water mixture storage with high melting points instead of a water storage is found in the summer, while most of the increase in the yearly net utilized solar energy by using a Na_2CO_3 water mixture storage with a low melting point instead of a water storage is found in the winter. These facts are important since a relatively large part of the total utilized solar energy from a small solar heating system for domestic hot water supply is the saved thermal loss from the oil fired boiler in the summer time, where the oil burner can be turned off.

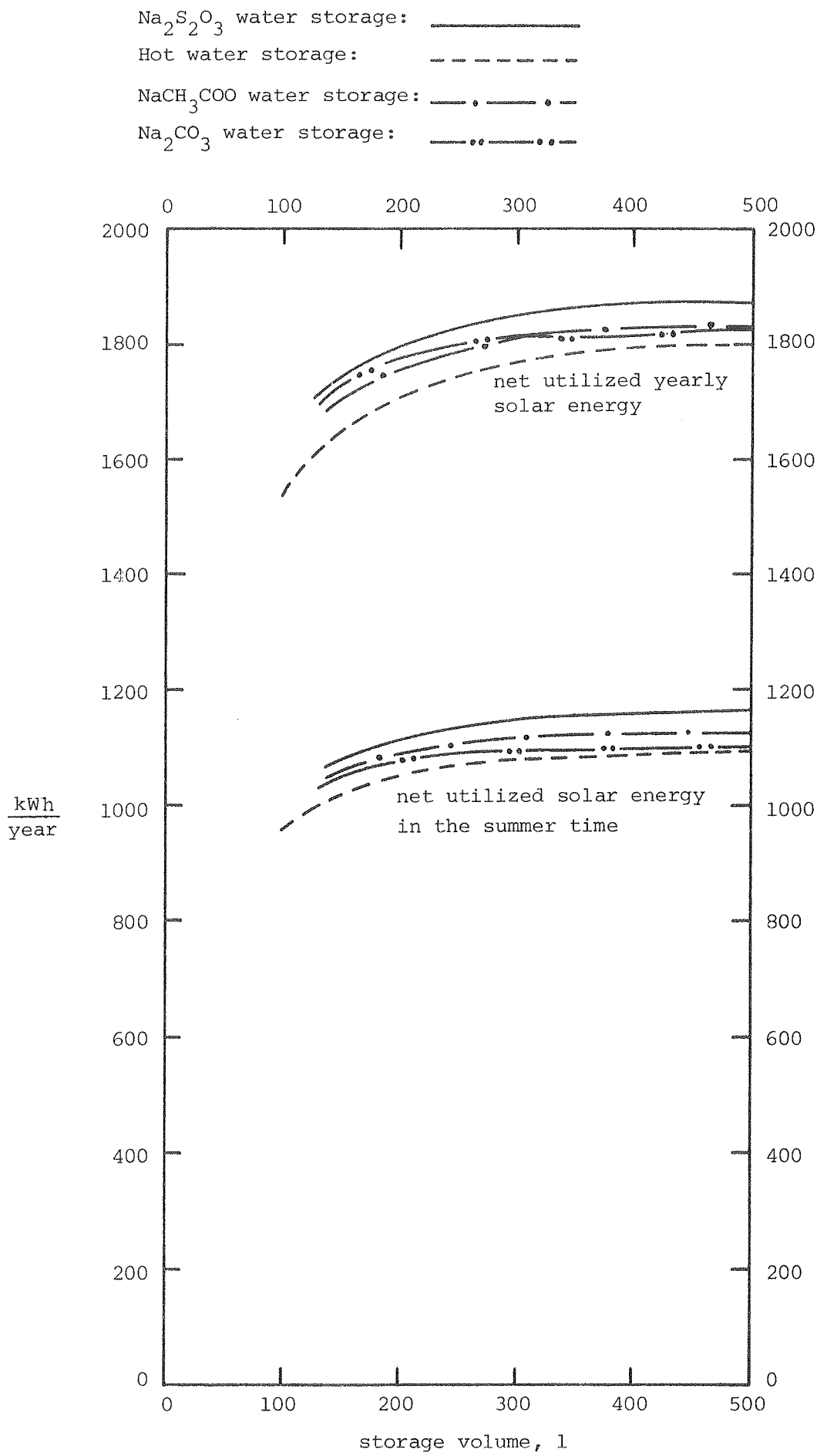


Figure 28. Net utilized solar energy from 6 m^2 solar heating systems for domestic hot water supply as a function of storage type and volume.

In figure 29 the total saved energy by using the solar heating system is shown for the same solar heating system as a function of the heat storage type and volume. The total saved energy from the solar heating system consists of the reduced energy consumption by turning off the oil boiler and the total gross utilized solar energy from the solar heating system. The total yearly gross utilized solar energy is the total yearly net utilized solar energy divided by the efficiency of the oil fired boiler. Relatively large differences between the reduced energy consumption by turning off the oil boiler and with that the total yearly saved energy from the solar heating system exists for the different storage types and volumes. The number of days with the oil burner turned off and with that the reduced energy consumption from the oil fired boiler increases for increasing storage capacity. Therefore the saved energy increases for increasing storage volume and the salt water mixture storages are favourable compared with the hot water storage. The best salt water mixture is based on $Na_2S_2O_3 \cdot 5H_2O$ with the melting point of 48°C just above the required hot water temperature. The $NaCH_3COO$ water mixture with the melting point 58°C situated 13°C above the required hot water temperature is not as favourable as the $Na_2S_2O_3$ water mixture. This is mainly caused by the fact that the solar collector efficiency decreases for increasing temperature. The Na_2CO_3 water mixture with the melting point 33°C situated 12°C below the required hot water temperature is favourabele in the winter, but in the important summer time the temperature in the storage often, like for the water storage, decreases to temperatures below the required hot water temperature, which results in decreased energy savings. A melting point above the required hot water temperature results in the best yearly thermal performance of the solar heating system. The $Na_2S_2O_3$ water mixture with a melting point of 48°C is suitable. The rest of the analysis is therefore concentrated on the comparison of $Na_2S_2O_3$ water mixture storages and hot water storages. In this example the increase of the total saved energy from the solar heating system by using a $Na_2S_2O_3$ water storage instead of a hot water storage is about 15%. For solar heating systems with the same yearly saved energy from each system, the volume of a hot water storage will be about twice as big as for a $Na_2S_2O_3$ water mixture storage.

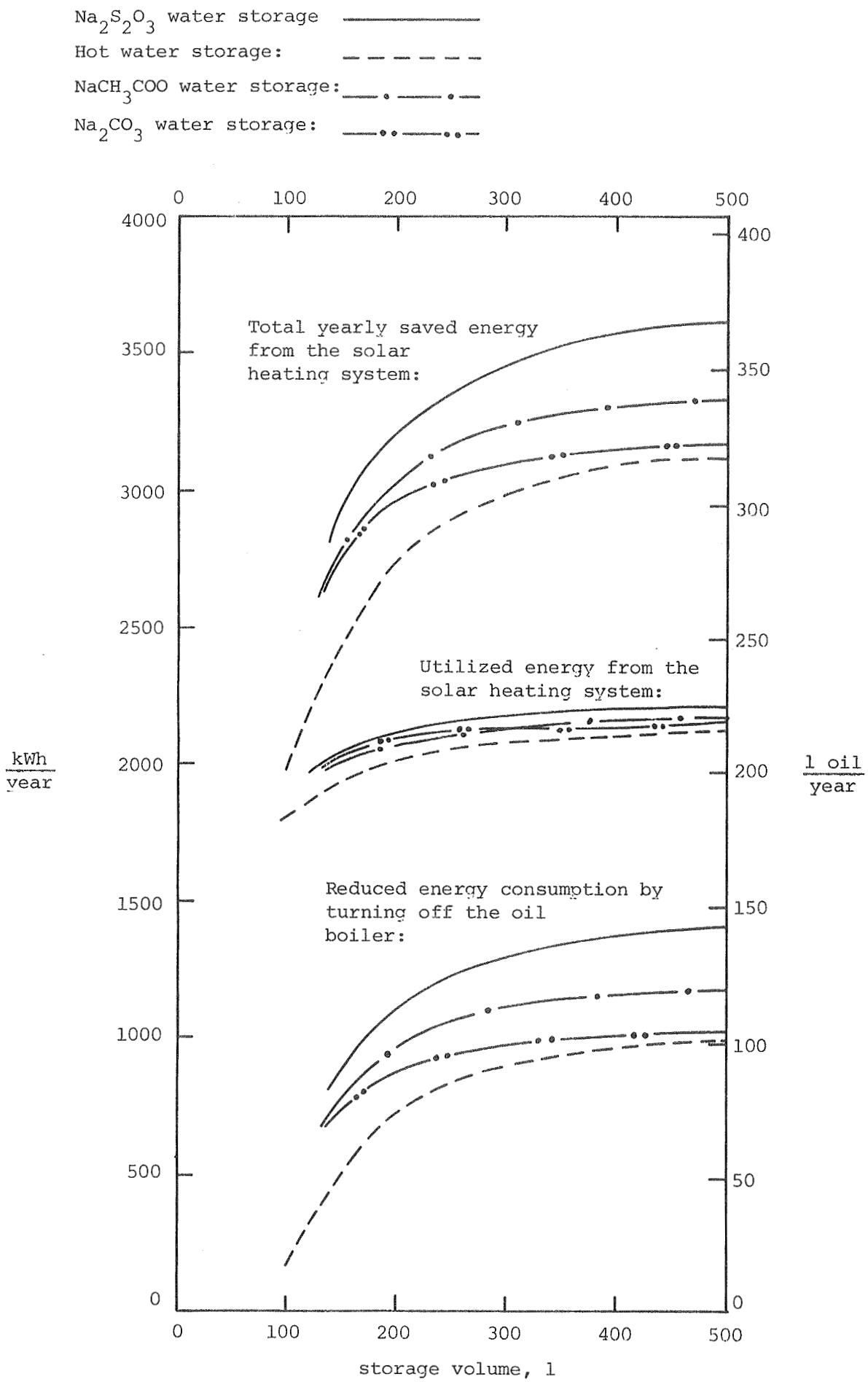
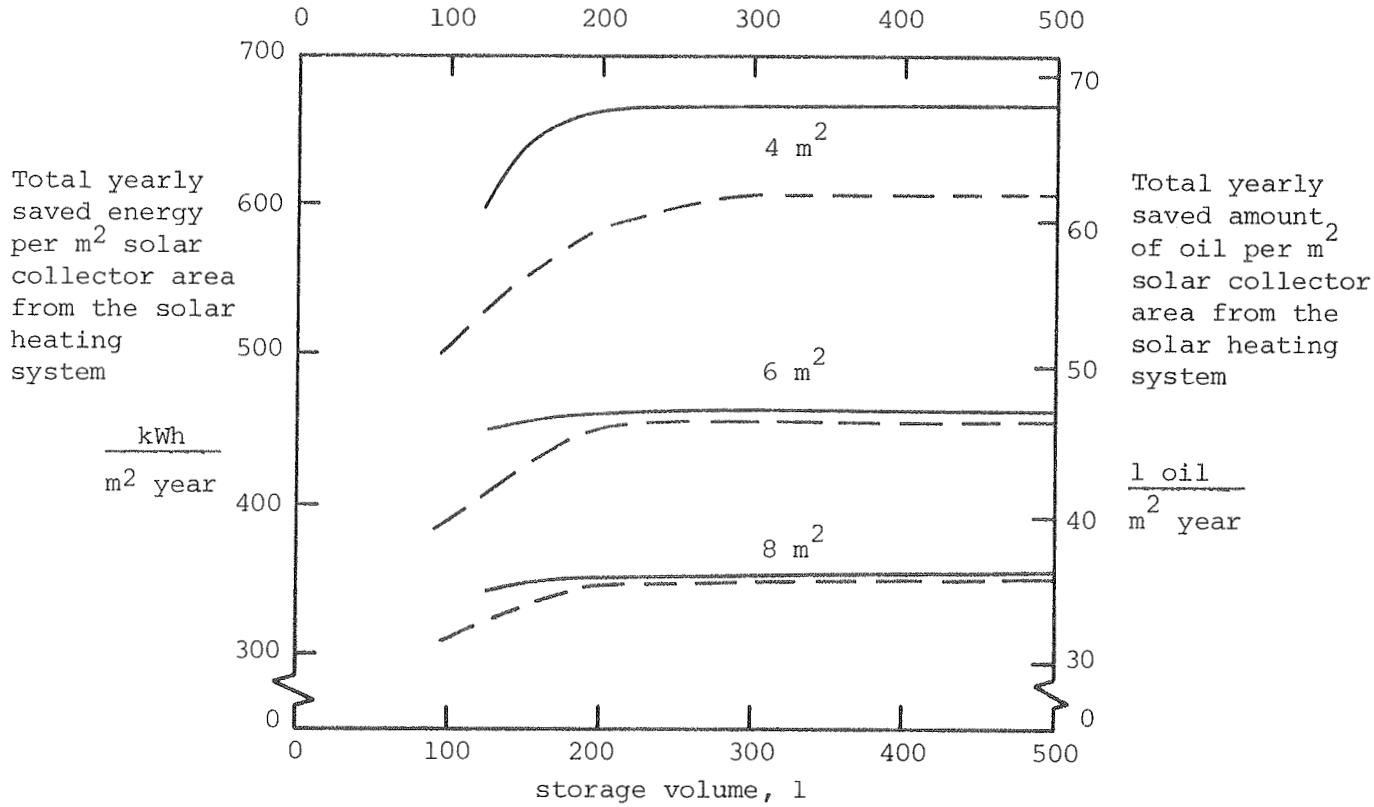


Figure 29. Total yearly saved energy from a 6 m^2 solar heating system for domestic hot water supply as a function of storage type and volume.

The total yearly saved energy from solar heating systems was calculated as described above. Some of the results are shown in figures 30, 31 and 32. The total yearly saved energy from solar heating systems and the total yearly saved energy per m^2 collector area from solar heating systems are shown as functions of the solar collector area and the storage volume for two storage types: a traditional hot water storage and a $Na_2S_2O_3$ water storage unit as described in table 2 and 34 for daily hot water consumptions of 100, 200 and 300 l in figure 30, 31 and 32 respectively. The total yearly saved energy increases for increasing collector area and normally for increasing storage capacity, that is for increasing storage volume and by using the salt water storage instedad of the hot water storage. Both the quantity of the change in the total yearly saved energy and in the total yearly saved energy per m^2 collector area by changes of the collector area and the storage capacity vary with the daily hot water consumption. It is therefore important to know the hot water consumption in order to find the optimum collector area and storage. For a hot water consumption of 100 l/day the total yearly saved energy does not increase much by increase of the collector area for areas greater than 4 m^2, see figure 30. The total yearly saved energy per m^2 area therefore increases much for decreasing collector area. For the 6 m^2 and 8 m^2 solar heating systems, the heat storage type and volume do not influence the performance much, that is: as long as the collector area is oversized, the heat storage is not important. For a hot water consumption of 200 l/day, the differences in the performance of solar heating systems with different collector areas and storage capacities are relatively great, see figure 31. The collector areas are neither too great nor too small. For a hot water consumption of 300 l/day the differences in the performance of the solar heating systems with different collector areas are relatively great, see figure 32. For collector areas greater than or equal to 6 m^2 the differences in the performance vary with changes in the storage. For 4 m^2 the storage does not influence the performance much, that is for undersized collector areas the heat storage is not important. Summarizing the above mentioned observations: The storage does not influence the performance to a great extent as long as the collector area is undersized or oversized, but with a proper collector area the storage has a large influence on the performance of the system.



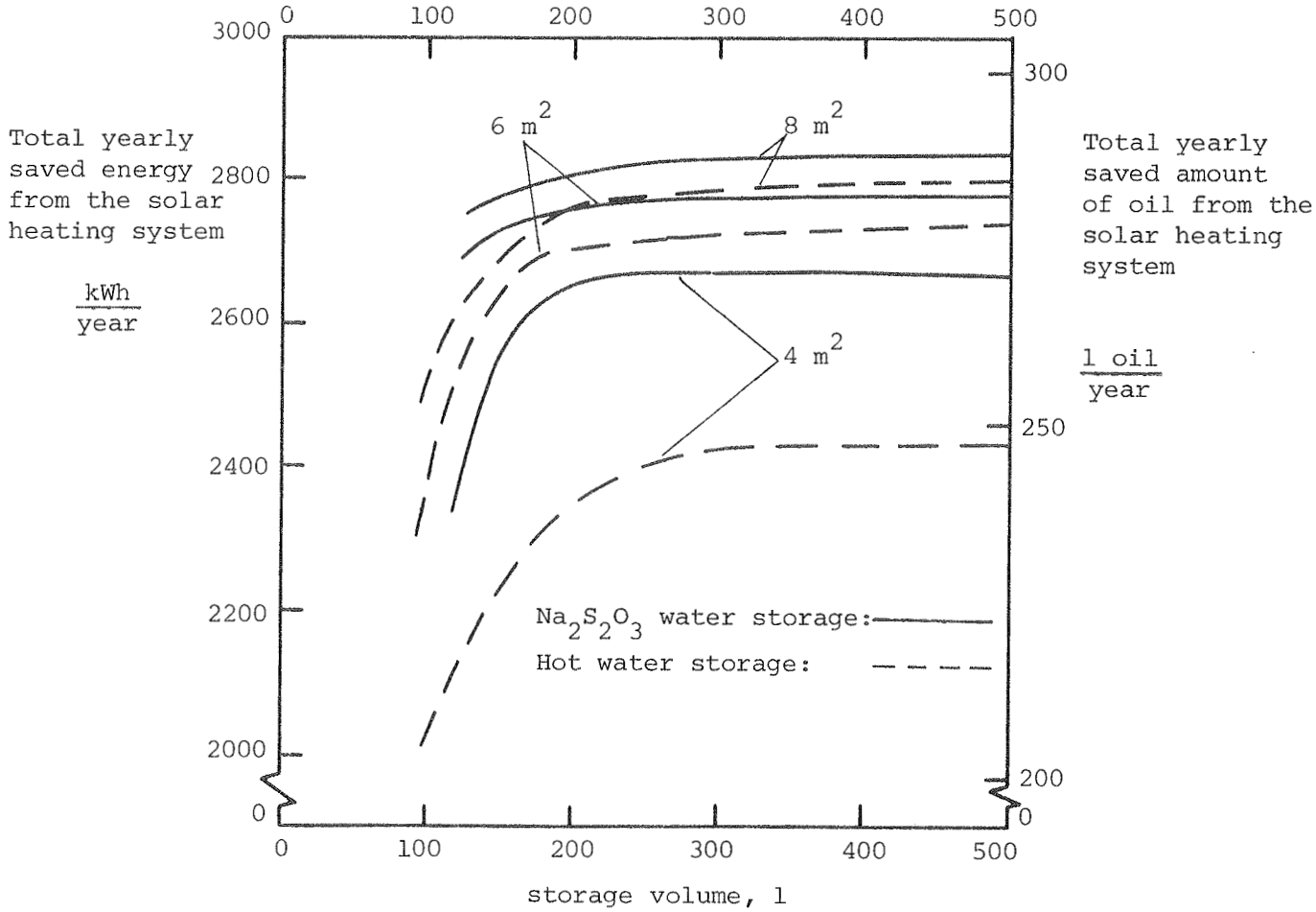
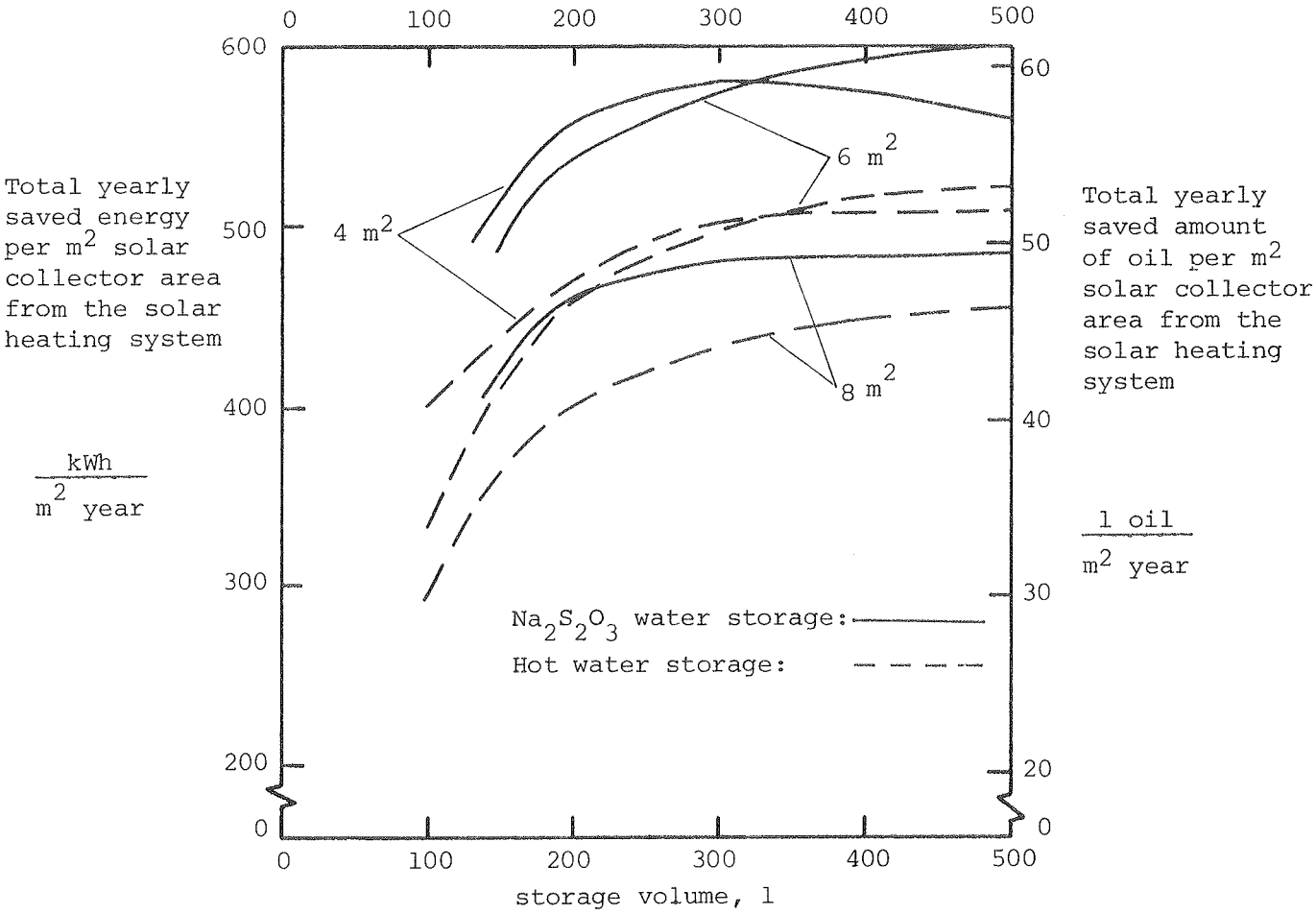


Figure 30. Total yearly saved energy from solar heating systems for domestic hot water supply for a hot water consumption of 100 l/day as a function of collector area, storage type and volume.



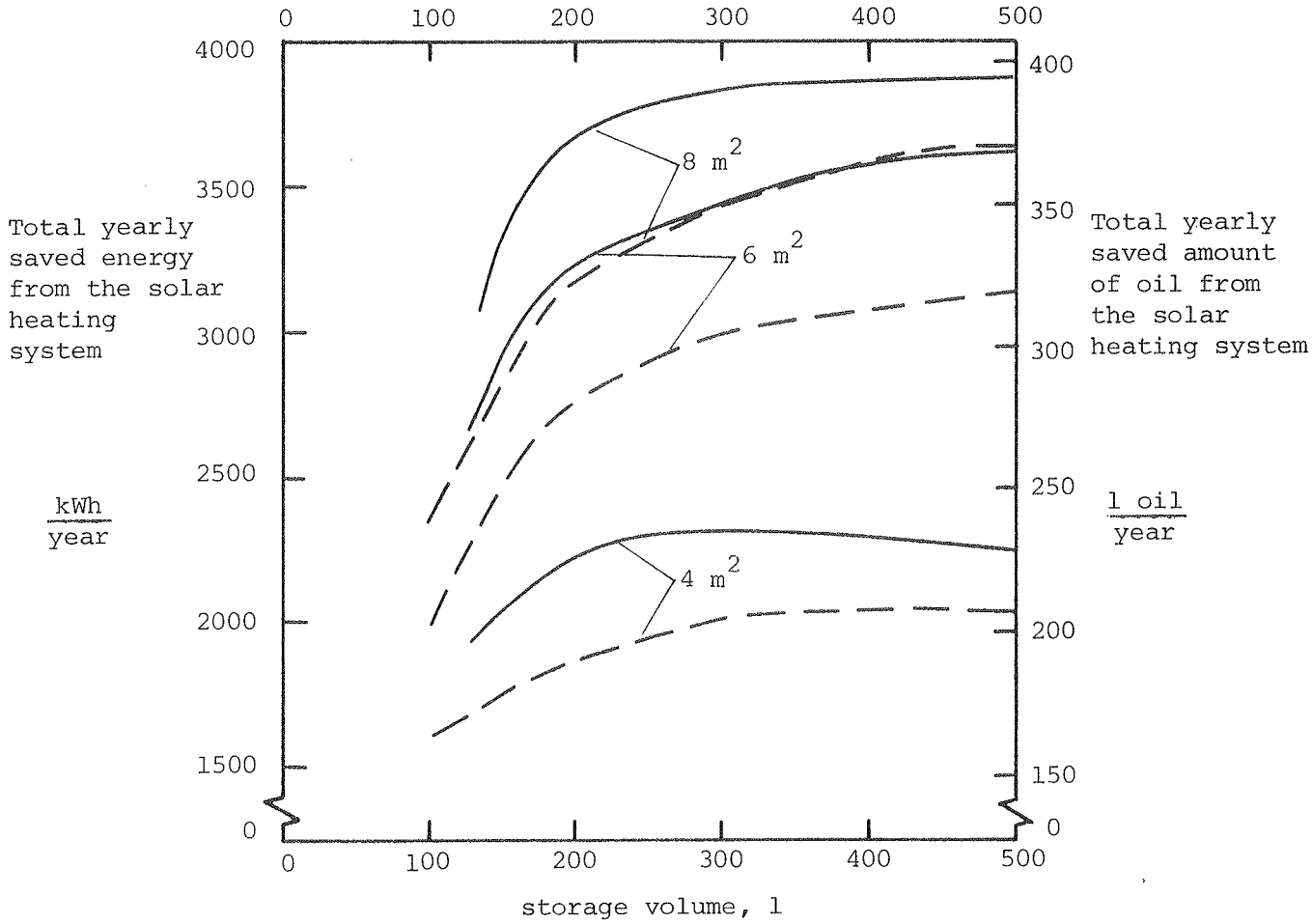


Figure 31. Total yearly saved energy from solar heating systems for domestic hot water supply for a hot water consumption of 200 l/day as a function of collector area, storage type and volume.

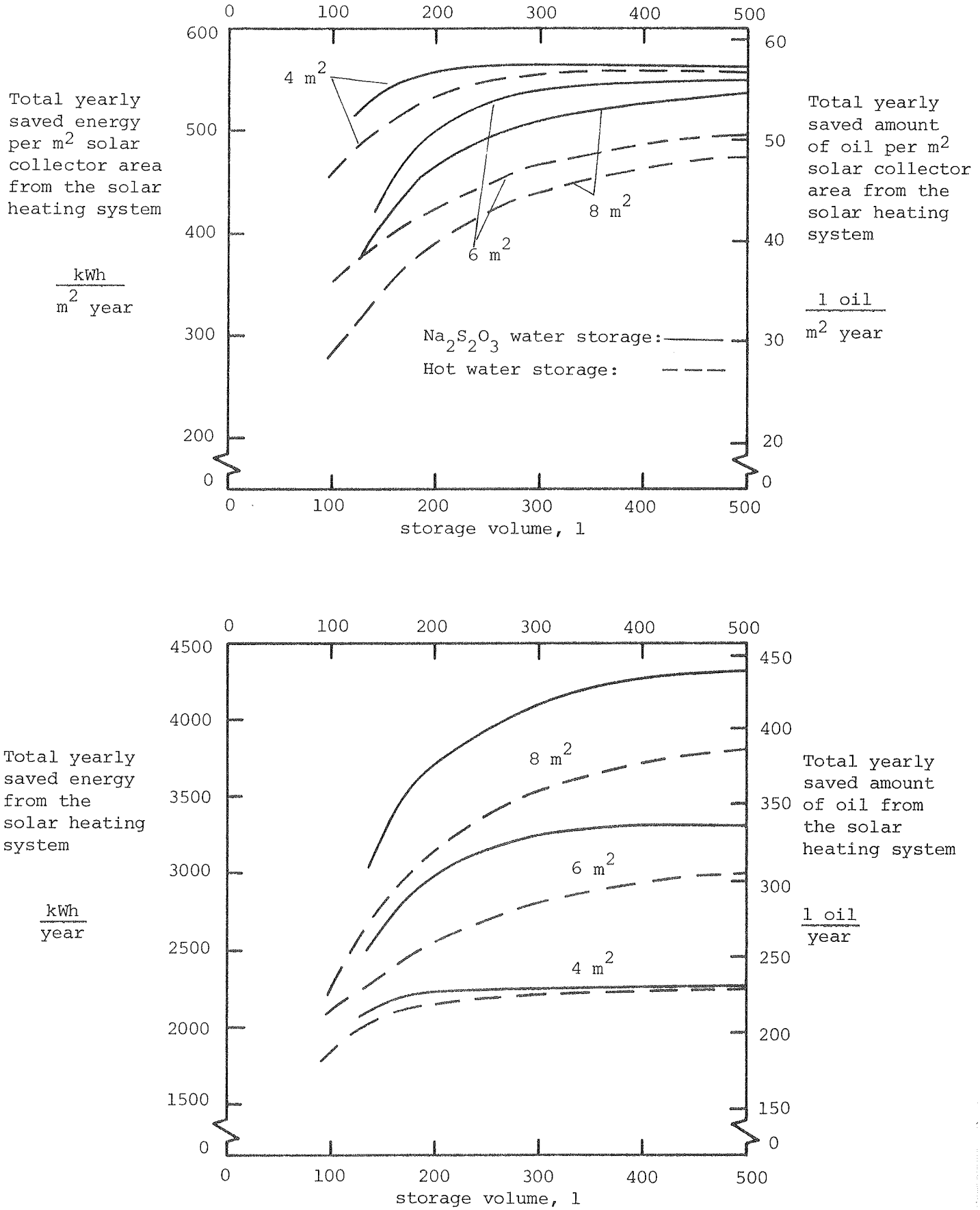


Figure 32. Total yearly saved energy from solar heating systems for domestic hot water supply for a hot water consumption of 300 l/day as a function of collector area, storage type and volume.

With a hot water consumption of 200 l/day, the total yearly energy per m^2 collector area is shown as a function of the the collector area and the storage type both with a storage volume of 150 l and 300 l in figure 33. The performance of the systems increases for decreasing collector area and increasing storage capacity, that is for increasing storage volume or by using the $Na_2S_2O_3$ water storage unit instead of a hot water tank. The increase of the performance is about 15% by using a $Na_2S_2O_3$ water storage unit instead of a hot water storage of the same volume. The decrease of the performance per m^2 per increase of collector area is small as long as the collector area is less than $6m^2$. For collector areas above $6m^2$ the decrease of the performance per m^2 increase of collector area is great.

With a 6 m^2 collector area the total yearly saved energy per m^2 collector area is shown as a function of the daily hot water consumption and the storage type for storage volumes of 150 l and 300 l in figure 34. The performance increases for increasing storage capacity, that is for increasing storage volume or by using the $Na_2S_2O_3$ water storage instead of a hot water storage. The influence of the daily hot water consumption on the performance is not simple, because the system for small consumptions of 100 l/day is oversized, for a hot water consumption of 200 l/day the system is well dimensioned , resulting in great energy savings from turning off the oil boiler during the summer time, and for great consumptions the system is undersized, resulting in small energy savings from turning off the oil boiler during the summer.

For a careful optimization of the system, both the performance and the costs of the system must be taken into consideration. Examples of such optimization will be given in section 5.4.

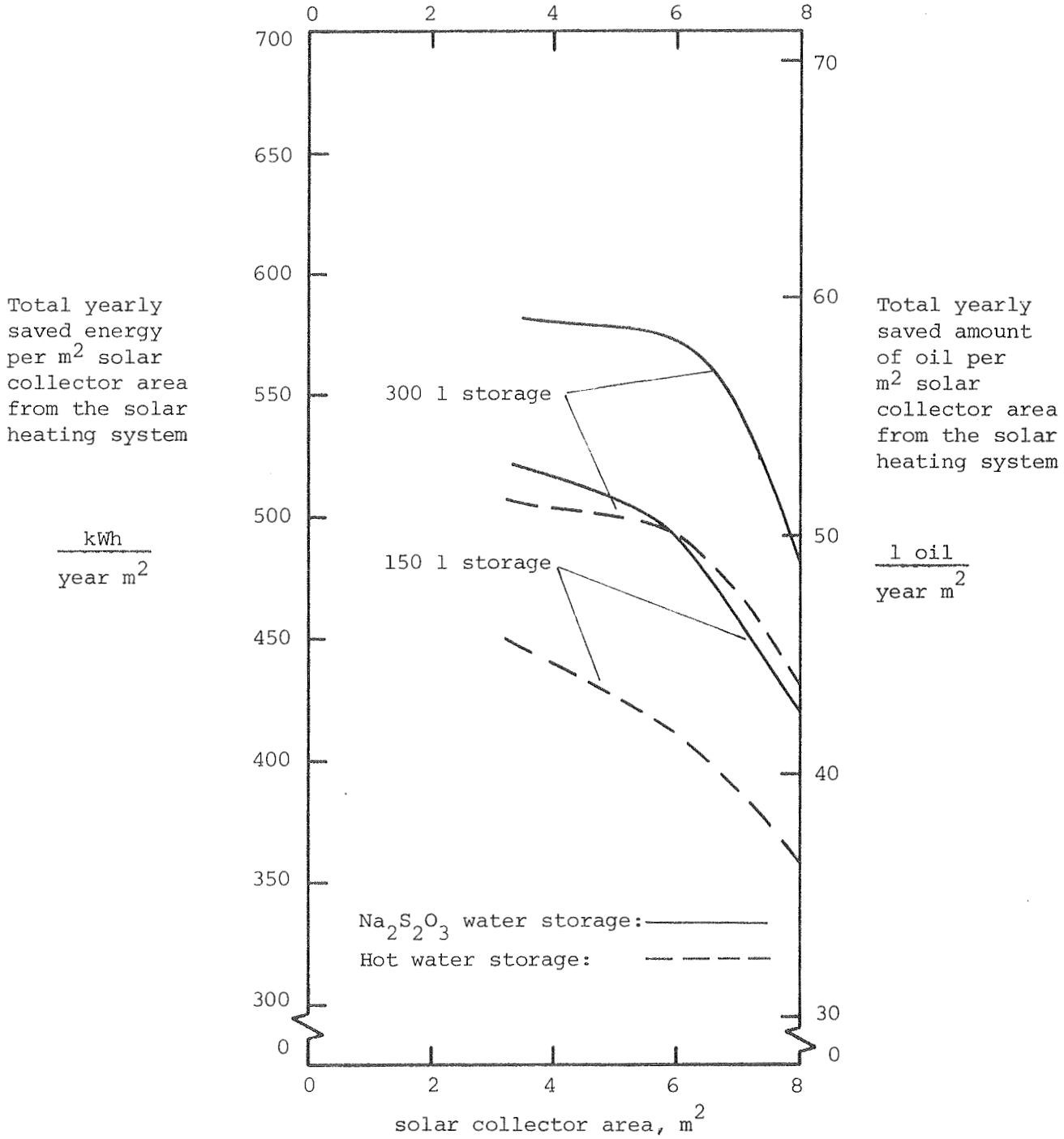


Figure 33. Total yearly saved energy from solar heating systems, with storage volumes of 150 l and 300 l, for domestic hot water supply for a hot water consumption of 200 l/day as a function of solar collector area and the storage type.

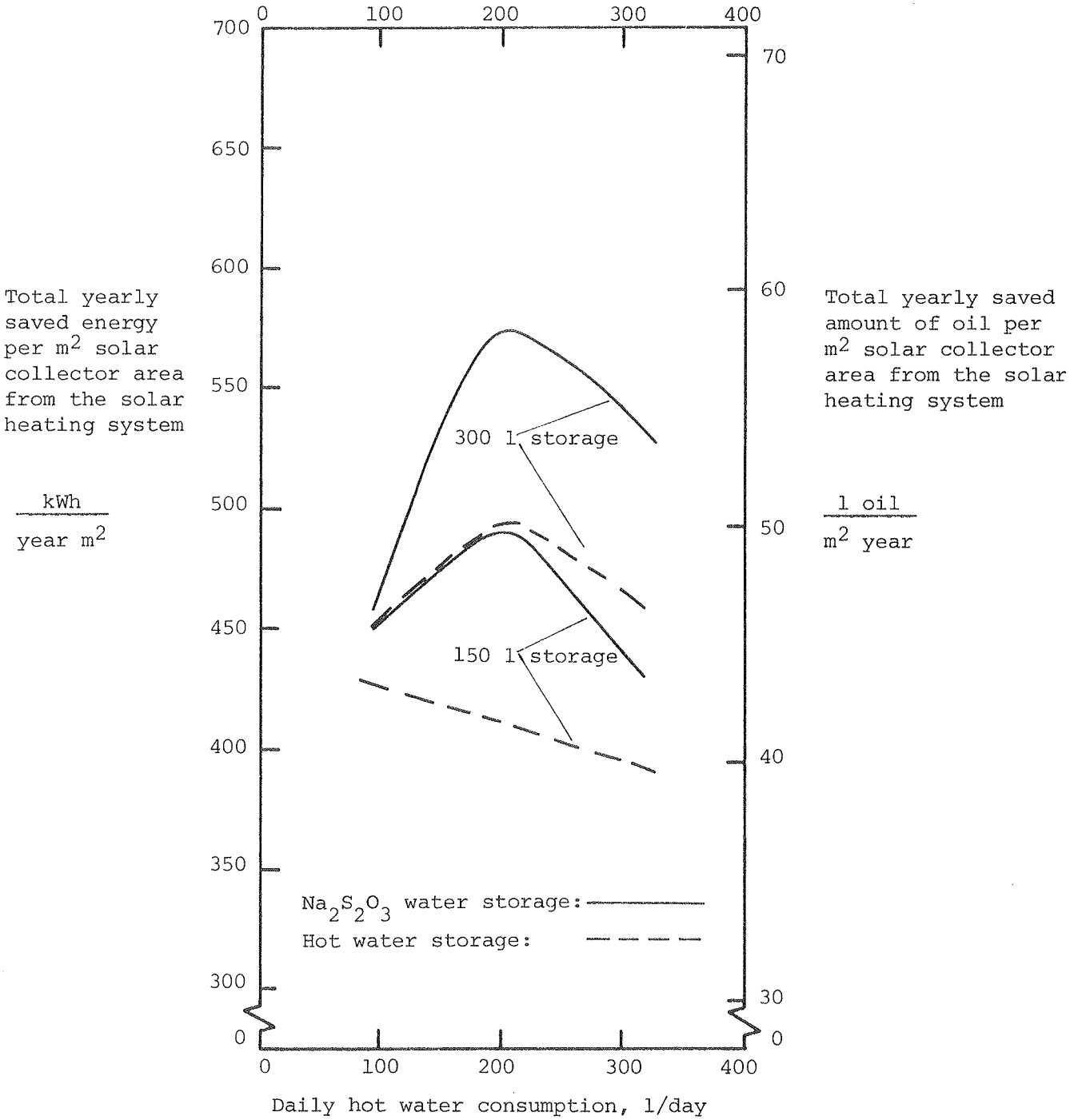


Figure 34. Total yearly saved energy from 6 m^2 solar heating systems with storage volumes of 150 l and 300 l for domestic hot water supply as a function of the daily hot water consumption and the storage type.

5.3 Comparison of calculations with the mathematical model and measurements from the dynamic experiments

As described in section 4.7 the investigated heat storage unit can be improved, first of all by a change of the placing of the heat exchanger spiral. Further the placing of the heat exchanger spiral is difficult to incorporate in a computer model, which takes temperature differences inside the heat storage into consideration. This is especially the case when the thermal contact between the hot water tank and the heat exchanger spiral is poor, which is the case in the investigated heat storage unit. Therefore such detailed computer calculations were not carried out with the unfavourably investigated heat storage unit. Instead the computer model with no temperature differences inside the storage described in section 5.1 was compared with measurements from the dynamic experiments. The computer model was changed in such a way that the heat storage unit described in section 2.1 was included in the calculation. Using the same conditions, that is weather parameters, solar collector efficiency, control system, volume of water tapped from the storage and temperature of the cold water entering the storage, as in the dynamic experiments calculations of the performance of the heat storage were carried out. For simplicity, only the results with the advantageous $Na_2S_2O_3$ water mixture as heat storage material will be given. The heat transfer capacity from the solar collector fluid to the heat storage used in these calculations is a function of the heat storage temperature T_s: $100 + T_s$ W/°C. This quantity was measured with a great uncertainty and was therefore not given in section 4.2. The results of these calculations for the first 3 days of the test period, as well as the measurements with the $Na_2S_2O_3$ water storage unit from table 18, are given in table 35. The calculated heat storage temperature during the experiment has not as great fluctuations as the measured temperatures given in figure 16. The calculated temperature is for the whole period close to the measured mean salt water mixture temperature.

Time	Energy supply from the solar heating system to the heat storage, Wh		Energy tapped off the heat storage, Wh		Thermal loss Wh	
day	measured	calcul.	measured	calcul.	measured	calcul.
1	4600	4200	4900	4700	900	800
2	15000	15200	5800	5300	1000	900
3	-1600	-1800	4900	5300	1000	1000
Toal period	18000	17600	15600	15300	2900	2700

Table 35. Measured and calculated daily energy quantities for the heat storage unit with the $Na_2S_2O_3$ water mixture during the dynamic experiment.

For the total period the measured energy supply to the storage and energy tapped off the heat storage are a little greater than the calculated quantities. Relatively large differences between the calculated and measured energy quantities exist for each of the 3 days. These differences are caused by the temperaturte stratification in the heat storage unit. The first and the third day, the measured energy supply to the storage is greater than the calculated quantity, mainly because the low temperature of the hot water tank is utilized to a certain extent as described in section 4.7.

The measured energy tapped off the heat storage the second day is greater than the calculated quantity, mainly because the water in the hot water tank in this period is heated to temperatures higher than mean salt water mixture temperature. On the third day the measured energy tapped off the heat storage is less than the calculated quantity. The explanation is that in periods without sunshine which follows after sunny periods the temperature of the water in the hot water tank is less than the temperature of the salt water mixture. The measured and calculated thermal loss are close to each other during the whole period.

The differences between the daily measured and calculated energy quantities vary with the weather conditions. On the basis of these calculations it is not possible to estimate the yearly difference between the calculated and a possible measured performance of the heat storage. However, it is shown that thermal stratification in the storage can result in a relatively great increase in the energy production, even with the unfavourable, investigated heat storage unit. In other periods the thermal stratification can also result in decreased thermal performance of the heat storage. Therefore it is important to design the heat storage unit in such a way that the use of thermal stratification in the storage is optimized carefully, both by means of experiments and theoretical calculations. The calculations carried out in section 5.2, in connection with economic considerations, gives an estimnate of the advantages obtained by using a heat of fusion storage unit instead of a hot water tank. These considerations are given in section 5.4.

5.4 Economic considerations concerning heat of fusion storages and hot water storages

The advantage by using a heat of fusion storage instead of a hot water tank depends on the quantity of the yearly utilized solar energy and the costs of investment. Economic considerations for the solar heating systems, which were included in the calculation in section 5.2, will be given here. The costs used are given in table 36. The prices are typical for Danish solar heating systems in January 1982. The costs of the storages are obtained from a Danish container producer.

Solar collector, delivered and installed	2000 Dkr/m^2 collector area
Solar collector fluid circuit inclusive pump, valves and other components, delivered and installed	4000 Dkr + 300 DKr/m^2 collector area
Control equipment, solar collector fluid, hot water installations, insulation of hot water installations and solar collector fluid circuit, etc., delivered and installed	9000 Dkr
Insulated hot water tank, delivered and installed	200 Dkr + 19 Dkr/l hot water tank
Insulated salt water mixture tank, delivered and installed	1600 Dkr + 21 Dkr/l total volume of storage
$Na_2S_2O_3$ water mixture, delivered and installed	2.50 Dkr/l salt water mixture
Required house volume	0 Dkr/m^2 basement storage

Table 36. Costs used in the calculations.

Figures 35, 36 and 37 show the total yearly utilized solar energy per cost of investment for solar heating systems as functions of storage type, storage volume and collector area for daily hot water consumptions of 100 l, 200 l and 300 l respectively. The maximum of each curve gives, with the used

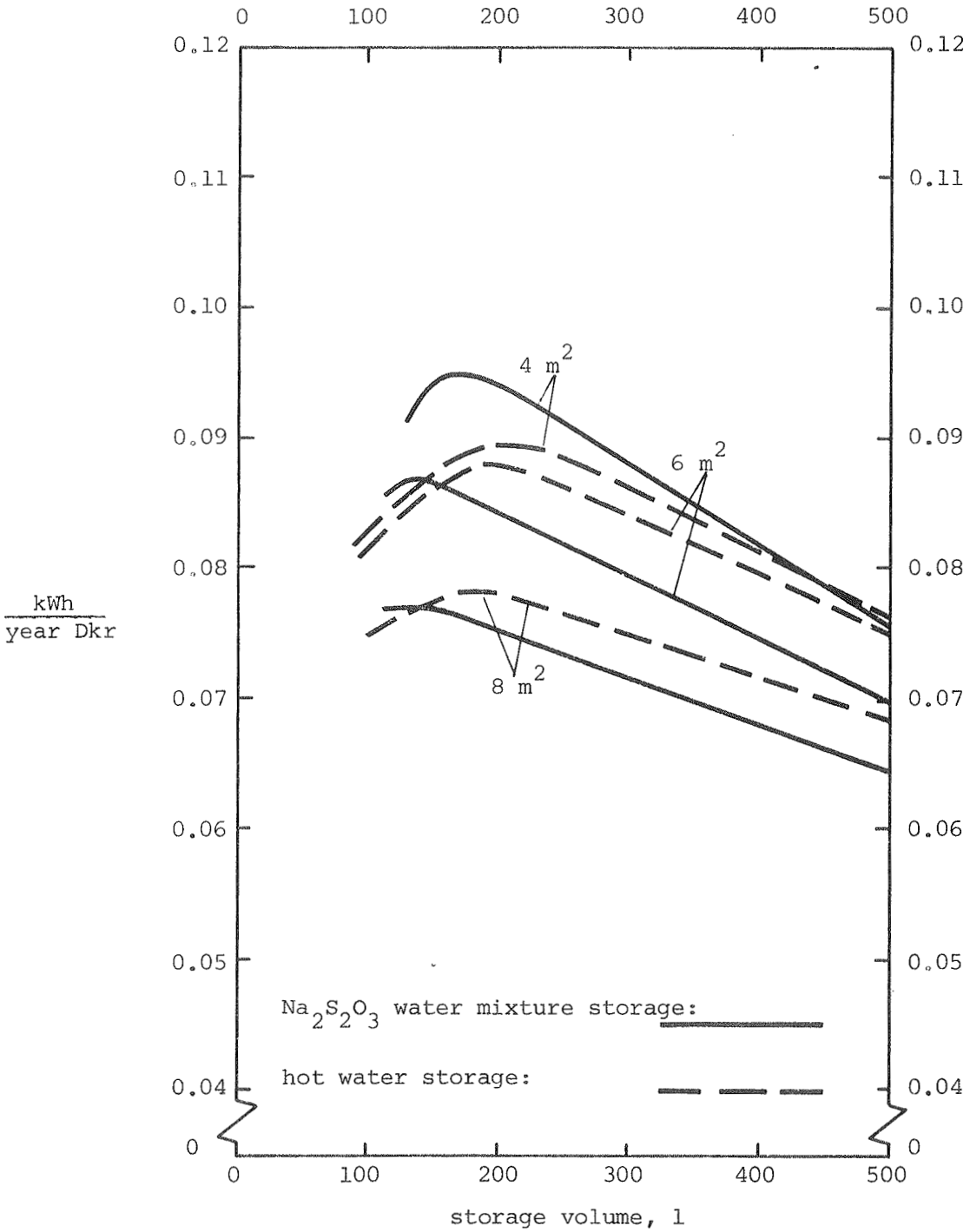


Figure 35. Yearly utilized solar energy per cost of investment for solar heating systems as a function of storage type, storage volume and solar collector area. The daily hot water consumption is 100 l.

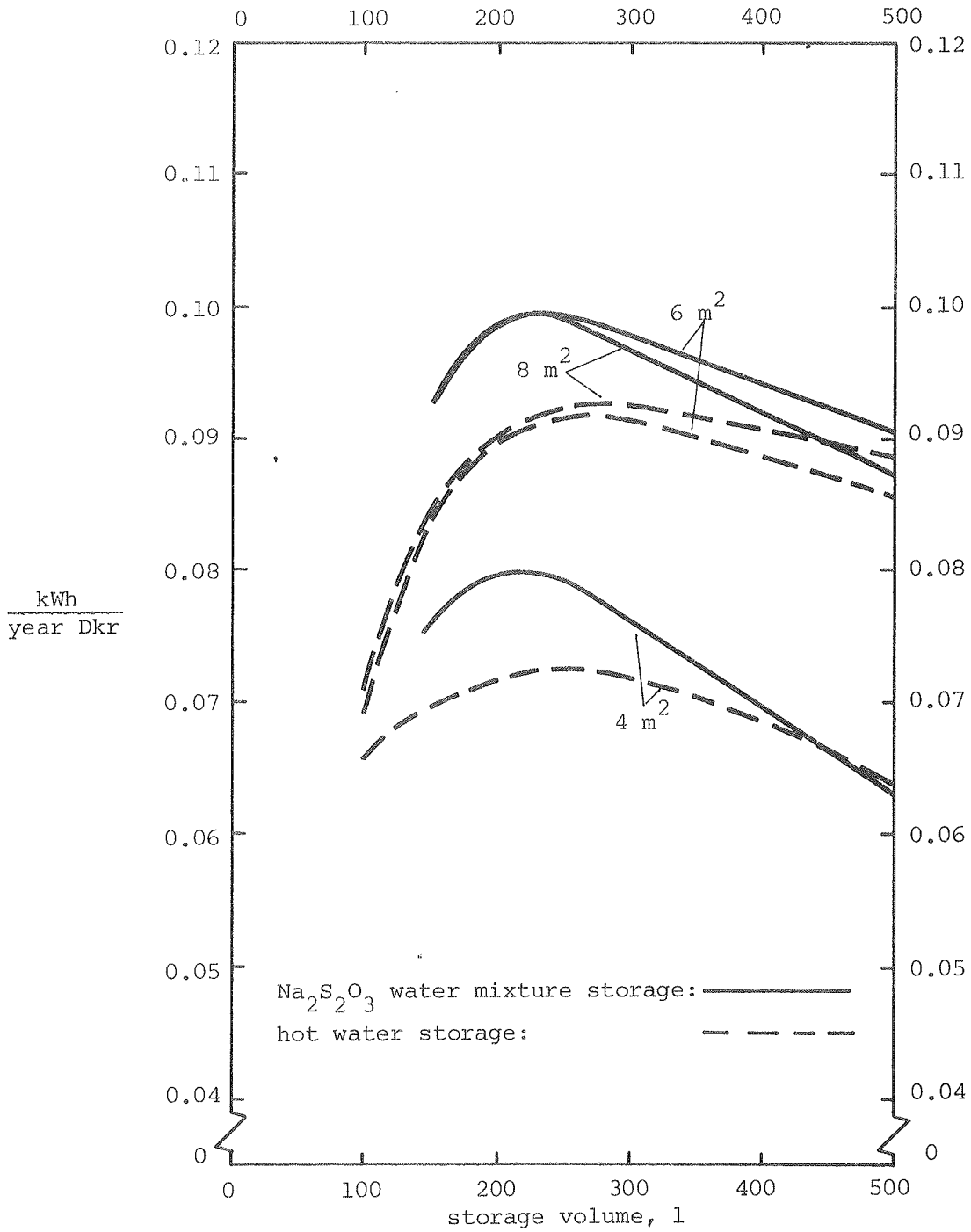


Figure 36. Yearly utilized solar energy per cost of investment for solar heating systems as a function of storage type, storage volume and solar collector area. The daily hot water consumption is 200 l.

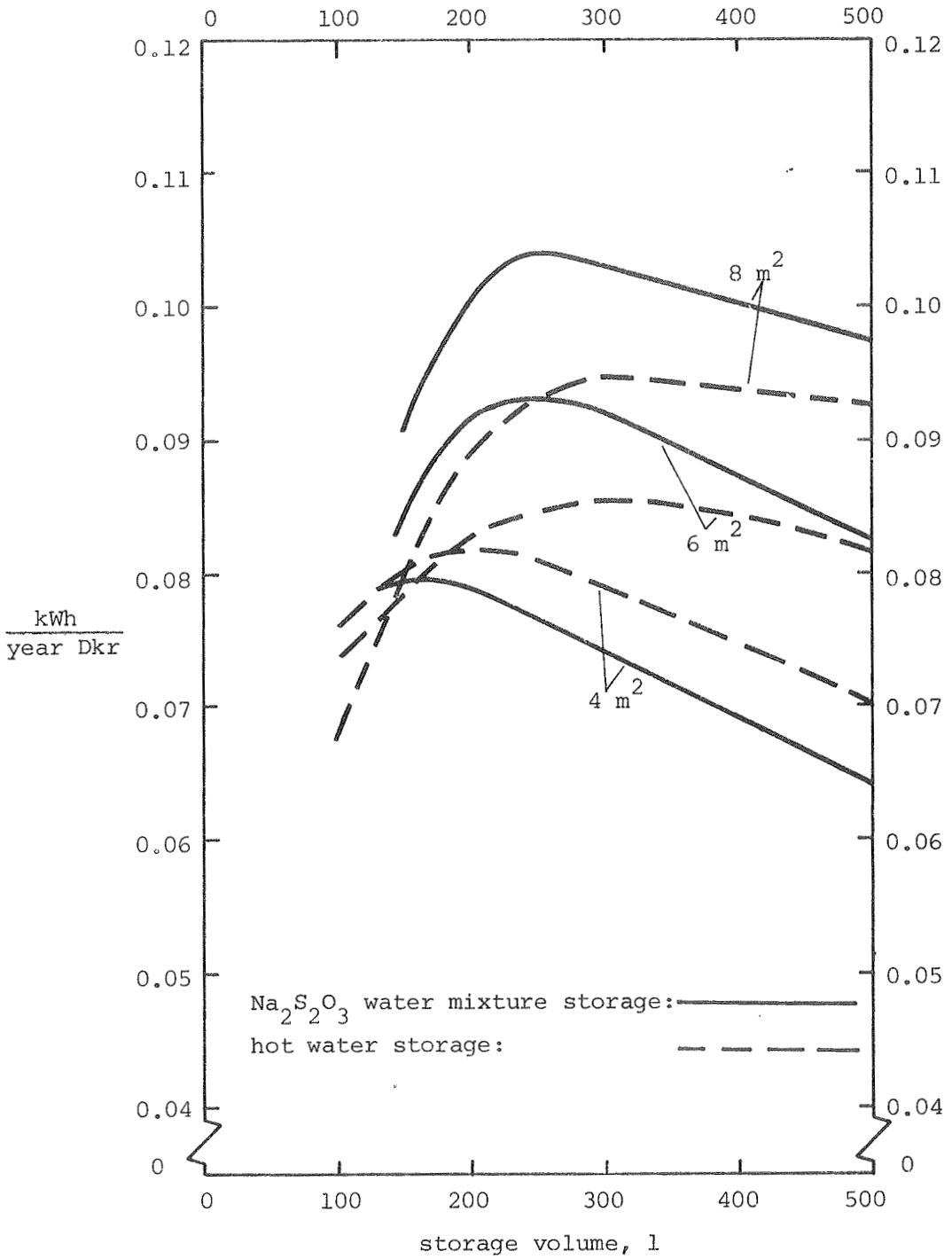


Figure 37. Yearly utilized solar energy per cost of investment for solar heating systems as a function of storage, type, storage volume and solar collector area. The daily hot water consumption is 300 l.

assumptions, the best volume of the storage. The best volume of the storage is a little smaller for solar heating systems with heat of fusion storages than for solar heating systems with hot water tanks. The difference between the yearly utilized solar energy per cost of investment for solar heating systems with different storage types depends on the solar collector area, the storage volume and the daily hot water consumption. For oversized and undersized systems, the hot water storage is more favourable than the heat of fusion storage. For well sized systems the $Na_2S_2O_3$ water storage is more favourable than the hot water storage. For a hot water consumption of 100 l/day, 4 m^2 gives the best result, for 200 l/day, 6 or 8 m^2 gives the best result, and for 300 l/day, 8 m^2 gives the best result.

Figures 38 and 39 show, as functions of the collector area and the daily hot water consumption, the yearly utilized solar energy per cost of investment for solar heating systems with hot water storages respectively $Na_2S_2O_3$ water storages with the best volume, from an economic point of view, found from figures 35, 36 and 37. The economically best solar collector area increases for increasing hot water consumption. The fat stroked curves show the yearly utilized solar energy per cost of investment for solar heating systems with the economically best solar collector areas and storage volumes as functions of the hot water consumption. These quantities are also shown in figure 40 for both storage types. The quantities increases for increasing hot water consumption. The yearly utilized solar energy per cost of investment is about 7% and 10% greater for systems with $Na_2S_2O_3$ water storages than for systems with hot water storages for daily hot water consumption of 100 l and 300 l respectively. Additionally, a decrease of storage volume of about 15-20% is obtained by using a $Na_2S_2O_3$ water storage instead of a hot water storage.

The advantages described above do of course depend on the assumptions used for the calculations. With other assumptions the results would be different. First of all, no temperature stratification inside the storages was assumed. Calculations with detailed computer models with temperature stratification inside the storages will increase the performance of the systems. For systems with hot water storages, the increase will be about 15%. For systems

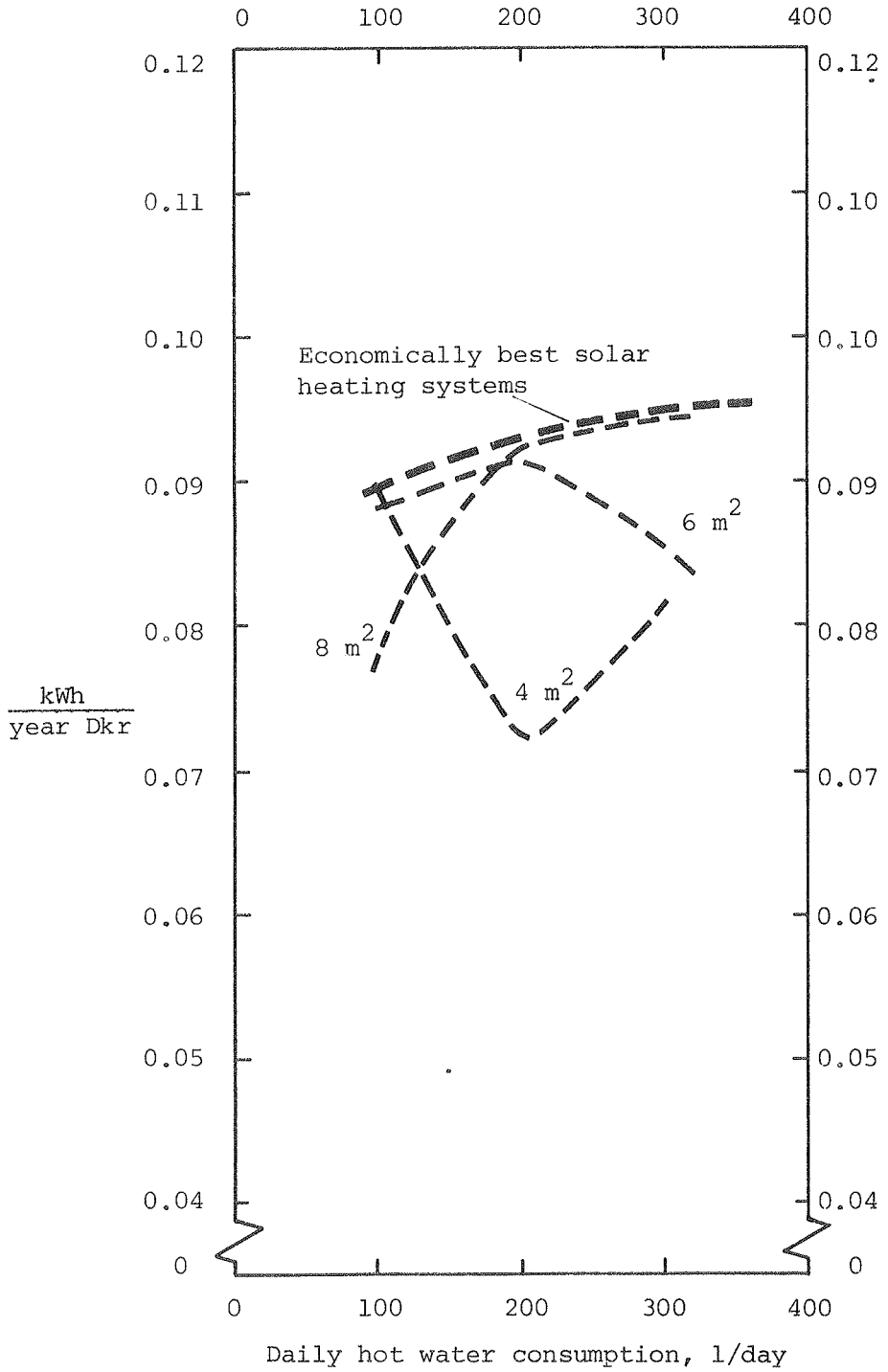


Figure 38. Yearly utilized solar energy per cost of investment for solar heating systems with hot water storages of an economically best volume as a function of solar collector area and the daily hot water consumption. Furthermore, the quantity for economically best solar heating systems is given.

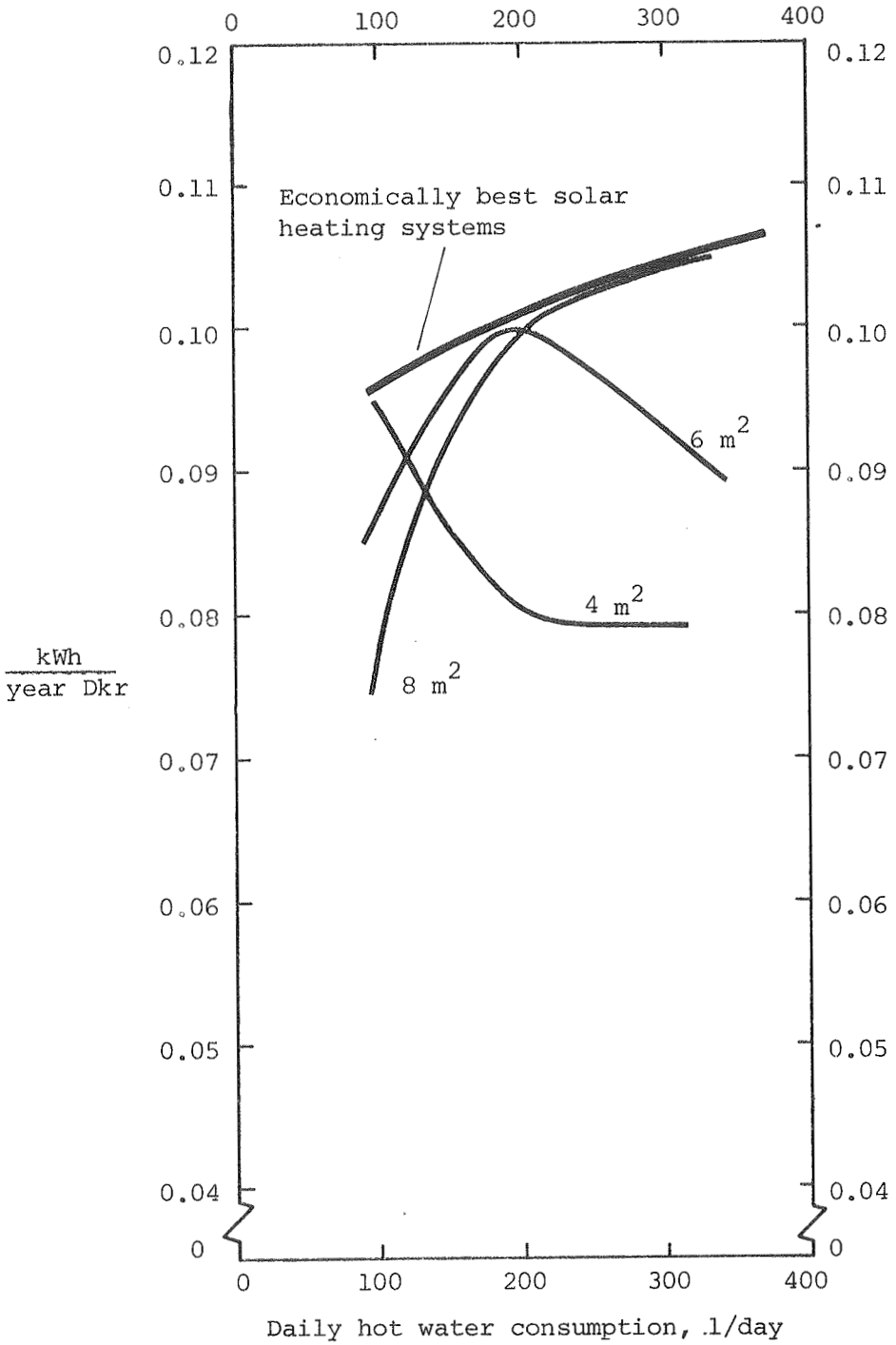


Figure 39. Yearly utilized solar energy per cost of investment for solar heating systems with $Na_2S_2O_3$ water mixture storages of an economically best volume as a function of solar collector area and the daily hot water consumption. Furthermore, the quantity for economically best solar heating systems is given.

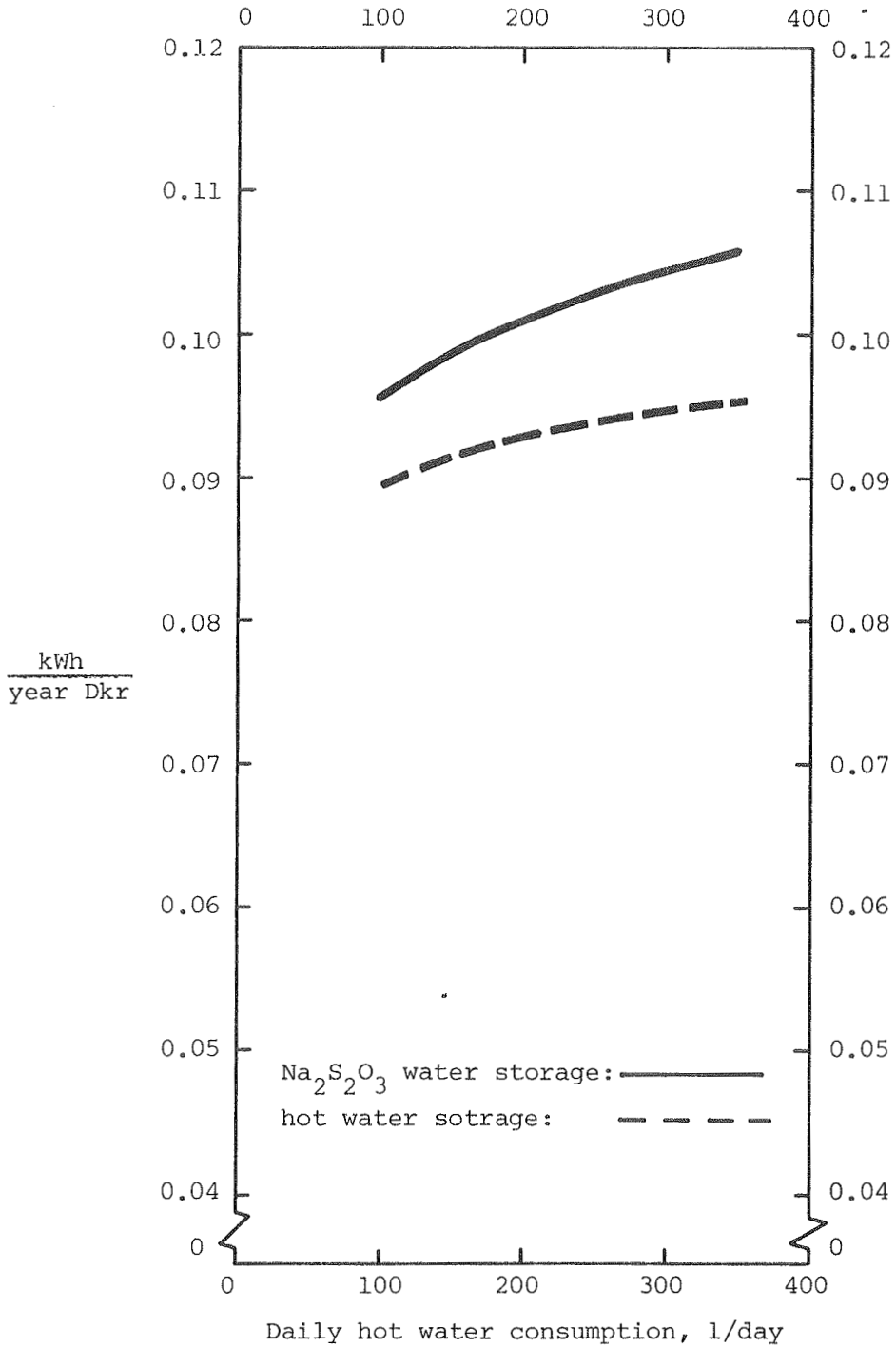


Figure 40. Yearly utilized solar energy per cost of investment for the economically best solar heating systems as a function of the daily hot water consumption and the storage type.

with heat of fusion storages, the increase will probably be even greater due to the advantageous utilization of the poor thermal conductivity of the salt hydrate crystals as described in section 4.7. That is: the performance of the solar heating systems will be greater than mentioned in this section. Furthermore, the advantages by using a $Na_2S_2O_3$ water storage instead of a hot water tank will probably be greater than mentioned in this section.

6. CONCLUSION

By using the experiences gained in this project, it is possible to construct a relatively inexpensive, stable heat of fusion storage unit for domestic hot water supply with advantageous thermal quantities.

The advantages by using a storage like this, for instance with a $Na_2S_2O_3$ water mixture as storage material, instead of a traditional hot water tank in a solar heating system are: a decrease of the storage volume, an increase of the heat production, of the duration of the period during which the oil burner can be turned off during the summer and of the yearly utilized solar energy per cost of investment.

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