Project "Solar Keymark"

Final Report
Subtaks 1.D

(Databases for computer models and test sequences)

In the European Standards EN 12975, EN 12976 and ENV 12977 numerical computer models and mathematical procedures for the determination of certain parameters based on measured data are included. The aim of this subtask is to set up a data base for computer models and measured data (test and verification sequences) in order to validate these models and procedures.

1.D.1: Computer models

It was decided to take the following computer models into account:

Collector:

The equation how the thermal behaviour of a solar collector is described is given in EN 12975. This equation is directly implemented in the collector model from Bengt Perers which is available as **TRNSYS Type 132**.

Store:

The basic equations which are necessary to describe the thermal behaviour of a hot water store are in principle given in EN 12977-3. Since there are several ways to implement these equations in a numerical model, different store models are available. The ones considered in this project are:

- TRNSYS **Type 60** (Standard TRNSYS Type)
- TRNSYS **Type 140** (**MULTIPORT** store model)

1.D.2: Validation

The validation can be carried out based on two approaches.

1.D.2.1 Analytical validation:

The analytical validation is performed by a comparison of the results calculated by the model with the results of analytical calculations. Examples of this approach are given in ENV 12977-3, Annex B2 (temperature in the store during stand-by) and ENV 12977-3, Annex B3 (store considered as a heat exchanger)

1.D.2.1.1 Collector:

The benchmark tests described in this chapter shall ensure that the collector model fulfils fundamental requirements. Hence, for simplified operating cases the results calculated by the model shall be compared with the analytical solutions of the differential equations.

a) Temperature of a collector during stand-by

A collector with an aperture area of 1 m² is assumed.

The temperature decay of the collector during stand-by can be calculated by equation (2.1.1).

$$\vartheta(t) = \vartheta_{am} + (\vartheta_0 - \vartheta_{am}) \cdot e^{\frac{-(UA)_{s,a}}{C_s} t} \qquad (2.1.1)$$

The temperature as a function of time ($0 \leq t \leq 8$ h) shall be calculated by equation (2.1.1) (*analytical*) and by the collector model (*numerical*) with the following parameters :

- constant ambient temperature : ϑ_{am} = 20 °C
- initial temperature : ϑ_0 = 100 °C
- thermal capacity of the collector (constant) : C_s = 10,0 kJ/K
- a heat loss capacity rate : $(UA)_{s,a}$ = 7,0 W/K

This benchmark test shall be considered as valid if the maximum difference between the temperatures calculated in an analytical and numerical way is less then ± 0,2K.

The analytic calculation If the model is part of a simulation program which enables the use of different time steps, this benchmark test shall be carried out for time steps of 0.01 h and 0.1 h.

b) Stagnation temperature

For checking the correct implementation of the steady-state performance of the collector the stagnation temperature is calculated analyticaly and numerical using the collector model with the following parameters.

- constant ambient temperature : ϑ_{am} = 20 °C
- constant hemispharical solar irradiance : G = 1000 W/m²
- conversion factor : η_0 = 0.8
- heat loss coefficient at (Tm –Ta) = 0 : c_1 = 3.5 W/m²K
- temperature dependence of the heat loss coefficient at (Tm –Ta) = 0 : c_2 = 0.01 W/m²K²

For the parameters given the results of the analytical solution is 177.6 °C.

This benchmark test may be considered as valid if the maximum difference between the calculation in an analytical and numerical way is less then ± 0,1K of the stagnation temperature.

c) Collector output

For checking the correct implementation of the solar and the conversion into useful heat of the of the collector the collector output is calculated analyticaly and numerical using the collector model with the following parameters.

- constant ambient temperature : ϑ_{am} = 20 °C
- constant collector inlet temperature : ϑ_{in} = 40 °C
- constant collector outlet temperature : ϑ_{e} = 46 °C
- constant beam solar irradiance : G_b = 680 W/m²
- constant diffuse solar irradiance : G_d = 120 W/m²
- conversion factor : η_0 = 0.8
- heat loss coefficient at (Tm –Ta) = 0 : c_1 = 3.5 W/m²K
- temperature dependence of the heat loss coefficient at (Tm –Ta) = 0 : c_2 = 0.01 W/m²K²
- incident angle of the beam irradiance : θ = 30°
- incident angle modifier of the diffuse irradiance : Kθd = 0.7032
- parameter for the calculation of the incident angle modifier of the beam irradiance : b0 = 0.2852

For the parameters given the results of the analytical solution is 501.72 W/m².
This benchmark test may be considered as valid if the maximum difference between the calculation in an analytical and numerical way is less then ± 0,1 W/m² collector output.

1.D.2.1.2 Store:

The benchmark tests described in this chapter shall ensure that the store model fulfils fundamental requirements. Hence, for simplified operating cases the results calculated by the model shall be compared with the analytical solutions of the differential equations.

a) Temperature of a store during stand-by

It is assumed that a fully mixed store with homogeneous insulation exists.
The temperature decay of the store during stand-by can be calculated by equation (2.1.1).

$$\vartheta(t) = \vartheta_{am} + (\vartheta_0 - \vartheta_{am}) \cdot e^{\frac{-(UA)_{s,a}}{C_s} \cdot t} \qquad (2.1.1)$$

The temperature as a function of time ($0 \le t \le 400$ h) shall be calculated by equation (2.1.1) (*analytical*) and by the store model (*numerical*) with the following parameters :

- constant ambient temperature : ϑ_{am} = 20 °C
- initial temperature : ϑ_0 = 60 °C
- thermal capacity of the store (constant) : C_S = 2,0 MJ/K
- a heat loss capacity rate : $(UA)_{s,a}$ = 7,0 W/K

This benchmark test shall be considered as valid if the maximum difference between the temperatures calculated in an analytical and numerical way is less then ± 0,001K.
If the model is part of a simulation program which enables the use of different time steps, this benchmark test shall be carried out for time steps of 1 min and 60 min.

b) Heat transfer from heat exchanger to store

For checking the correct implementation of the heat transfer from the heat exchanger to the store tank, the store may be considered as a twin tube heat exchanger. For this benchmark test it shall be operated as a counter-flow heat exchanger (see Figure 1.D.2.1.2.1).

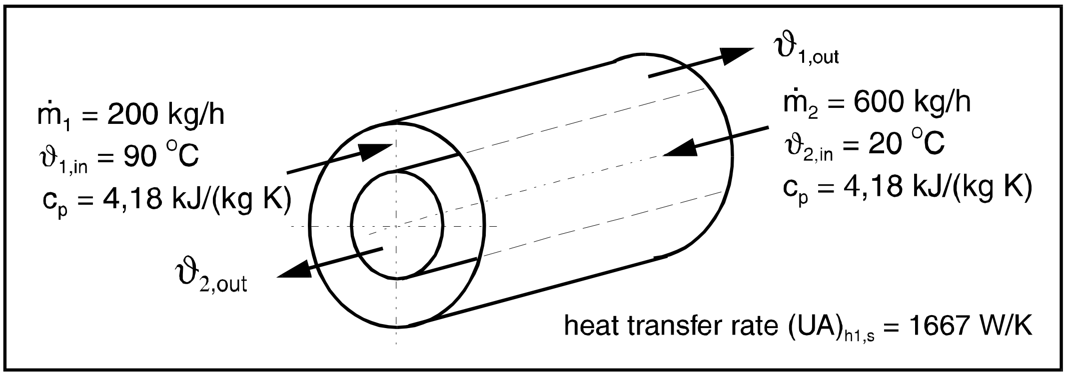

Figure 1.D.2.1.2.1: Store considered as a twin tube heat exchanger

For the parameters given in Figure 1.D.2.1.2.1 the results of the analytical solution are listed in
Table 1.D.2.1.2.1.

Table 1.D.2.1.2.1: Results of the analytical solution

$\vartheta_{1,out}$ °C	$\vartheta_{2,out}$ °C	$\dot{Q}$ kW
20,391	43,202	16,165

This benchmark test may be considered as valid if the maximum difference between the calculation in an analytical and numerical way is less then ± 0,2K of the temperatures and less then ± 1 % (based on the analytical solution) for the transferred power.

1.D.2.2 Comparison with measured data:

The validation is performed by a comparison of the results calculated by the model with the results of measurements. If this approach is used, there is the problem that the results of the calculation depend on both, the model itself and the parameters used in combination with the model. Hence it is necessary to perform this validation in the following steps:
- determination of the parameters necessary to describe the thermal behaviour of the specific component. The determination of these parameters has to be performed as described in the standard based on a set of measured test data.
- validation of the model (in combination with the determined parameters) by ‘re-simulation‘ of an other set of measured data. Figure 1.D.2.2.1 shows as an example the re-simulation of one collector test sequence.

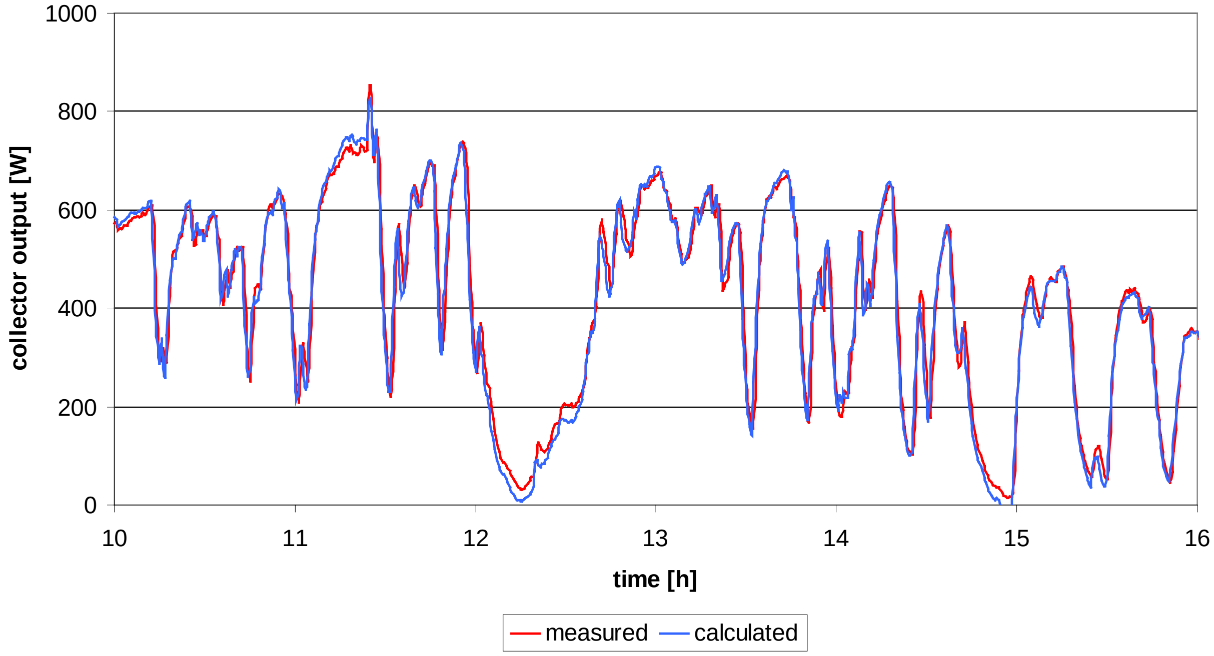

Figure: 1.D.2.2.1: Comparision of measured and calculated collector output

Following this approach allows for a validation of the model and the procedure used for the determination of the parameters. In order to ensure that the parameters determined are not only valid for the data used for the parameter determination it is necessary to use two sets of measured data. One for the determination of the parameters (test sequence) and one for the validation (validation sequence).

However, since the numerical models that are used in combination with the standards are quite complex, a general validation will never be possible.

1.D.2.3 Criteria for acceptance:

For the comparison of calculated (predicted) results with measured data the following acceptance criteria can be used ('x' indicates a flow loop defined by a pair of corresponding inlet and outlet connection; e. g. collector in- and outlet, store charge loop in- and outlet, store discharge loop in- and outlet):

Difference in transferred energy $\varepsilon_{x,Q}$:

$$\varepsilon_{x,Q} = \frac{Q_{x,p} - Q_{x,m}}{Q_{x,m}} \cdot 100\%$$

with: $Q_{x,p}$ = calculated (predicted) energy [kJ]

$Q_{x,m}$ = measured energy [kJ]

Difference in transferred power:

Every time step during the simulation for each flow loop 'x' the absolute difference between the transferred predicted and measured power ΔP_x shall be calculated by

$$\Delta P_x = \left| P_{x,p} - P_{x,m} \right|$$

with: $P_{x,p}$ = calculated (predicted) power [W]

$P_{x,m}$ = measured power [W]

The mean difference in transferred power $\Delta\overline{P}$ shall be calculated by

$$\Delta\overline{P} = \frac{\int_t \sum_x \Delta P_x \, dt}{\sum_x t_{x,t}}$$

with: $t_{x,t}$ = transfer time [s]. Time period during which energy is transferred through the corresponding flow loop. The transfer time is calculated over one or more test or verification sequences, excluding time periods used for conditioning at the beginning of the sequences.

The mean transferred power $\overline{P}$ shall be calculated by

$$\overline{P} = \frac{\int_t \sum_x P_x \, dt}{\sum_x t_{x,t}}$$

The relative error in transferred power ε_p shall be calculated by

$$\varepsilon_p = \frac{\Delta\overline{P}}{\overline{P}} \cdot 100\%$$

1.D.3: Database of test and validation sequences

The database with test and validation sequences shall include the following:
- Description of the component (collector, store)
- Description of the data format
- Test sequences for the determination of the parameters
- Validation sequences for the verification of the determined parameters
- Address of the person responsible for the data

An example of the structure of the database with test and validation sequences for collectors and stores is shown in Annex !

1.D.4: Deliverables

As the final deliverable of this work package a CD containing the "Databases for computer models and test sequences for solar collectors and hot water stores" was produced (see Figure 1.D.4.1).

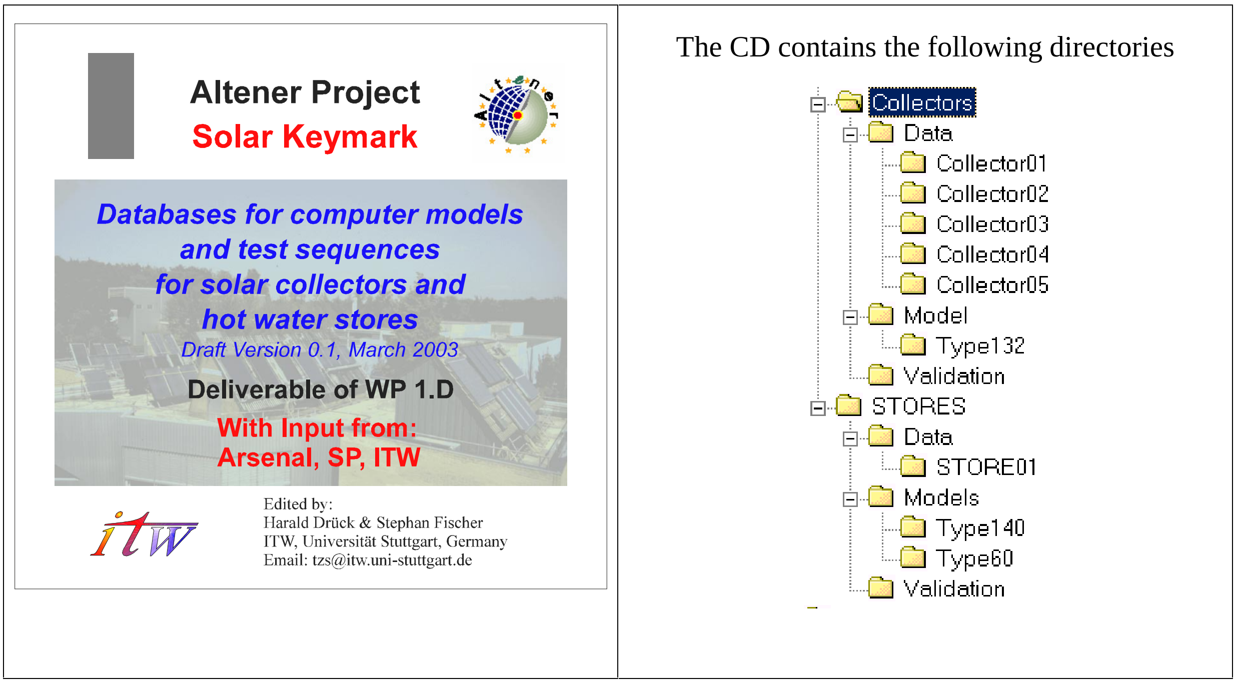

Figure 1.D.4.1: First version of the "Databases CD"

A draft version of the CD was distributed to the participants of the 5th Solar Keymark meeting held in Lisbon, Wednesday 5th of March 2003.

Database of test and validation sequences for collectors and stores

Note: This is an example how the database should be structured in order to present your input in the same way

1. Introduction

In the European Standards EN 12975, EN 12976 and ENV 12977 numerical computer models and mathematical procedures for the determination of certain parameters based on measured data are included. The aim is to set up a data base for measured data (test and verification sequences) in order to validate the numerical models and evaluation procedures described in the standards.
This database is containing measured data for solar collectors and heat stores.
The following information should be included in the data base
- Description of collector
- Description of the location and orientation of the test site (only required for collectors)
- Information about the test sequences required for the determination of the parameters and the verification sequences
- Information about the format of the data files included.
- Address of the person responsible for the data

Solar Collectors

1.C Collector COL1

1.C.1 Description of the collector

The absorber consists out of 10 absorberstrips (Teknoterm, selective coated). The absorberstrips are divided into two serial bunches with 5 parallel stripes each. The collector case is build up out of aluminium profile and a 0.5 mm aluminium back. The insulation at the back is 30 mm PU foam and 20 mm mineral wool. Side insulation is 30mm mineral wool. The collector has the gross area of 5.85 m² (length 4063 mm, width 1440 mm) and was mounted horizontal. The transparent cover consists out of 4 structured glass sheets (structure pointing towards the absorber). The aperture area of 5.09 m² is thus divided by 3 vertical aluminium bars to hold the glass covers. The test was performed with water as heat carrier and the mass flow rate during the test was adjusted to 50 kg/(m²h).

1.C.2 Description of the location and orientation of the test site

Location: Stuttgart, Germany
Local Latitude: 48.78°
Local Longtitude: 9.2°
Standard Longtitute: 15.0°
Collector tilt: 48°
Collector azimuth: 5.71° west

1.C.3 Test and verification sequences

The test and verification sequences were performed on the basis of prEN 12975:2000 6.3.4.6.2 Description of test days.

The verification sequences are selected among the sequences not used for parameter identification. It should be used at least 2 sequences showing enough variability within the surrounding conditions. The mean temperature of the two sequences shall differ by at least 30 K.

sequence	name of data file
Day type 1 according to 6.3.4.6.2	750205tf.30
Day type 2 according to 6.3.4.6.2	750105tf.30
1st Day type 3 according to 6.3.4.6.2	751704tf.30
2nd Day type 3 according to 6.3.4.6.2	7524041t.30
Day type 4 according to 6.3.4.6.2	7524042t.30
Verification day type 2	7517041t.30
Verification day type 4	752304tf.30

Table 1.C3.1: Test and verification sequences for collector COL1

1.C.4 Data files

To ensure the maximum flexibility in the evaluation of the data the selection does not strictly follow the requirements of the prEN 12975-2. The only criterion for the data selection has been a positive collector output.
All data files (ASCII-Format) are located in the directory COL_DATA\COL1*.*.
The time step of the data points is equidistant (30 seconds). The format of the data files is listed in Table 2. Has a quantity not been measured during the test the channel is denotetd by "9999".

column	quantity	unit
1	time	[s]
2	hemispherical solar irradiation	[W/m²]
3	direct solar irradiation	[W/m²]
4	diffuse solar irradiation	[W/m²]
5	long wave irradiance	[W/m²]
6	surrounding air temperature	[°C]
7	collector inlet temperature	[°C]
8	collector outlet temperature	[°C]
9	mean collector temperature	[°C]
10	collector mass flow rate	[kg/(m²h)]
11	useful power extracted from collector	[W/m²]
12	incidence angle of the direct solar irradiance	[°]
13	angle between the normal of the collector surface and the projection of the line of sight to the sun into the longitudinal (east –west) plane	[°]
14	angle between the normal of the collector surface and the projection of the line of sight to the sun into the transvers (north –south) plane	[°]
15	surrounding wind speed	[m/s]
16	time derivative of the mean fluid temperature	[K/s]

Table 1.C.4.1: Format of the data files for collector COL1

1.C.5 Contact person

The measured data of the test and verification sequences are provided by:

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Stores

1.S Store STO1

1.S.1 Description of the store

The store is discharged in a direct way and charged via a solar loop or an auxiliary loop heat exchanger. Hence, according to the classification of stores given in Table 1 of ENV 12977,3 the store belongs to group 2.

The nominal volume is 280 litres. The store vessel as well as the heat exchangers are made of steel that is enamelled for corrosion protection. Both the solar loop heat exchanger and the auxiliary loop heat exchanger consist of a smooth tube with a fluid content of 5,7 litres. Design drawings of the store are shown in Figure 1.S.1.1 to Figure 1.S.1.3.

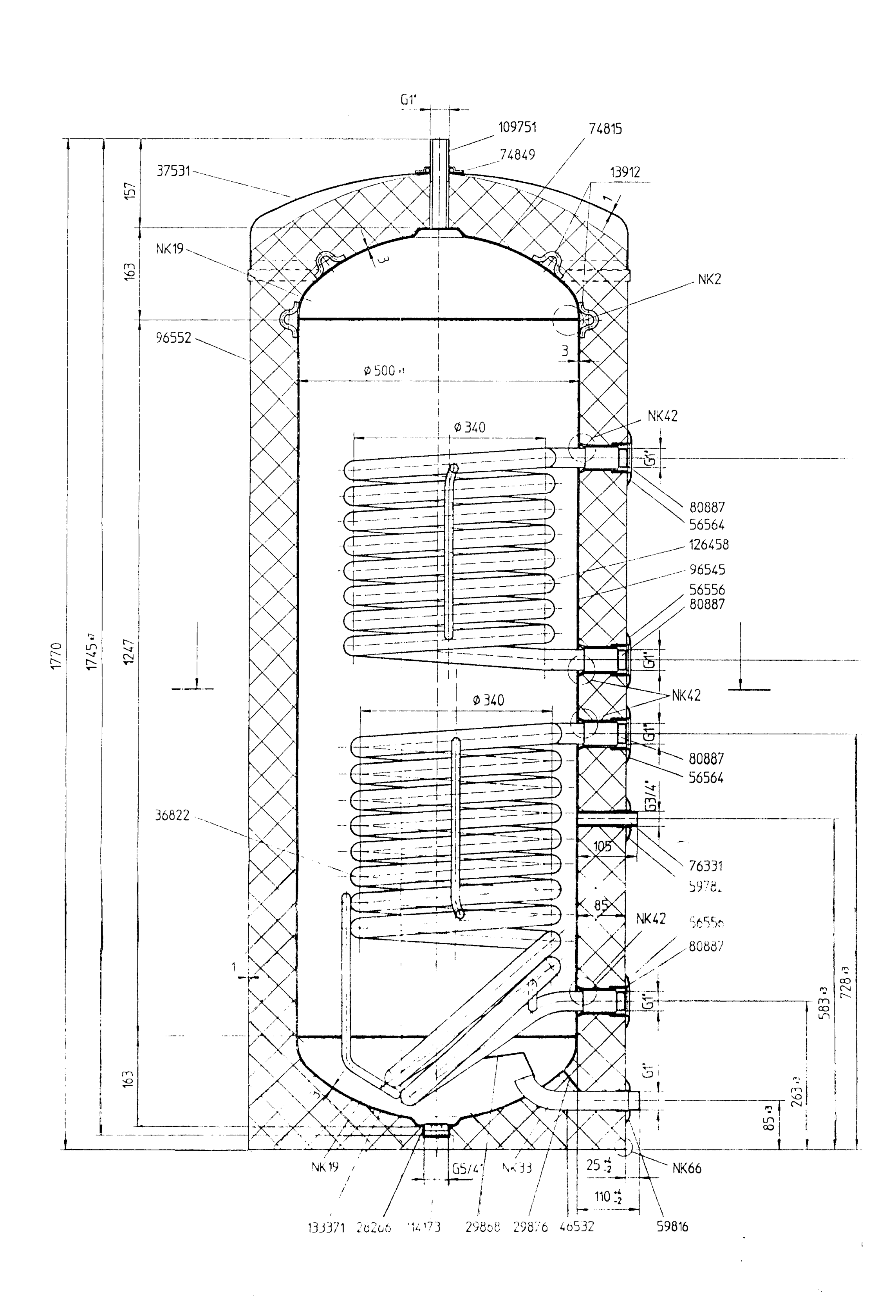

Figure 1.S.1.1: Front view of store STO1

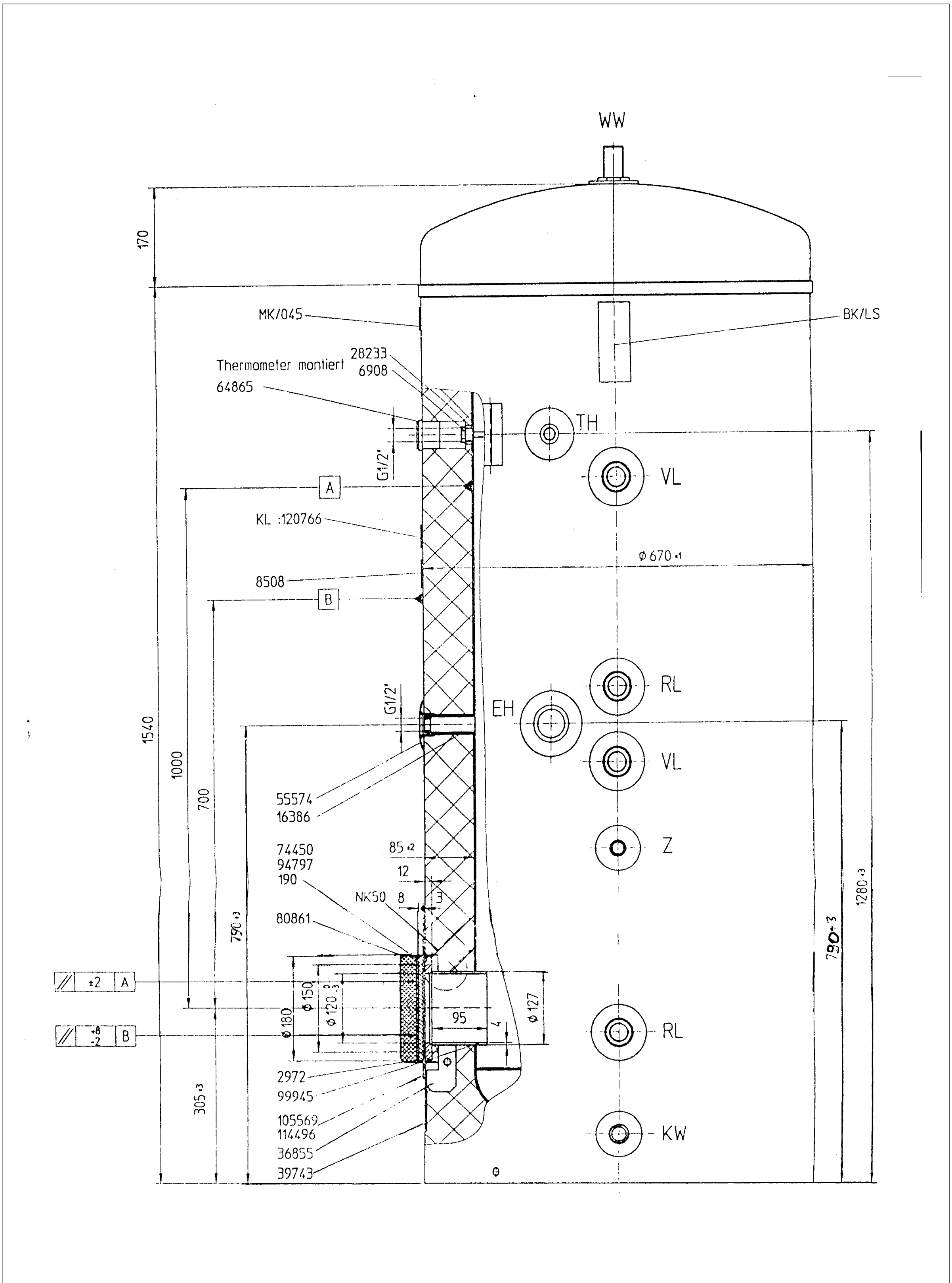

Figure 1.S.1.2: Side view of store STO1

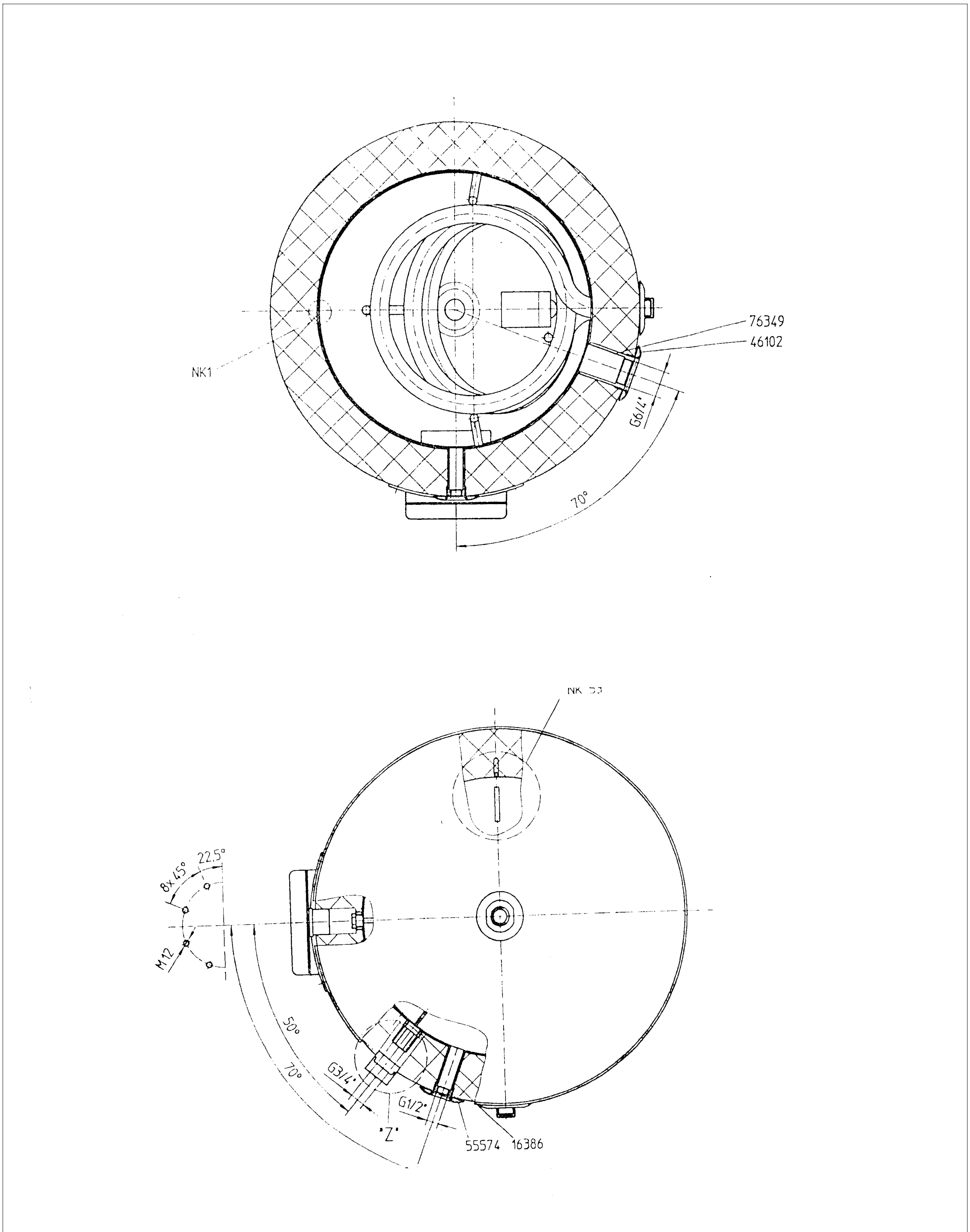

Figure 1.S.1.3: Bird's view of store STO1

1.S.2 Test and verification sequences

The test and verification sequences were performed on the basis of prEN 12977. The numbers for the sequences given in Table C1 refer to the corresponding section of prEN 12977. For the tests water was used inside the store and as heat transfer fluid for both heat exchangers.
The store was connected to the test facility in the following way:

Tap water inlet at the bottom (connection KW) and outlet at top (connection HW).

Solar loop heat exchanger and auxiliary loop heat exchanger:
Inlet at the upper connection (VL) and outlet at the lower connection (RL).

Conditioning was performed via the inlet at the bottom (connection KW) and the outlet at top (connection HW). *This means that the "tap water connections" were used.*

sequence	name of data file
Test C according to 6.3.2.1.1.2	CX_0610.DAT
Test S according to 6.3.2.1.2	SX_0809.DAT
Test L according to 6.3.2.1.3.2	LX_0627.DAT
Test NiA according to 6.3.2.1.4	AXN_0327.DAT
Test NB according to 6.3.2.1.6.2	BXN_0528.DAT
Test V according to 8.2.1.1.3	DX_0612.DAT
Test NiV according to 8.2.1.2	DXN_0530.DAT

Table 1.S2.1: Test and verification sequences of store STO1

1.S.3 Data files

All data files (ASCII-Format) are located in the directory STO_DATA\STO1*.*. The time step of the data points is equidistant (1.5 minutes). The format of the data files is listed in Table C2.

column	quantity	unit
1	time	[h]
2	ambient temperature	[^{o}C]
3	tap water inlet temperature (cold) of the store	[^{o}C]
4	tap water outlet temperature (hot) of the store	[^{o}C]
5	tap water volume flow rate*	[m^3/s]
6	solar loop heat exchanger inlet temperature	[^{o}C]
7	solar loop heat exchanger outlet temperature	[^{o}C]
8	solar loop heat exchanger volume flow rate*	[m^3/s]
9	not used	-
10	auxiliary loop heat exchanger inlet temperature	[^{o}C]
11	auxiliary loop heat exchanger outlet temperature	[^{o}C]
12	auxiliary loop heat exchanger volume flow rate*	[m^3/s]
13	not used	-

Table 1.S.3.1: Format of the data files for store STO1

*** Note:** The flow meter for the determination of the flow rates was located at the inlet. Hence, if required, the corresponding inlet temperature has to be used for the calculation of the mass flow rate.

1.S.4 Contact person

The measured data of the test and verification sequences are provided by:

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