TECHNICAL REPORT

No. 6/91

HIGH TEMPERATURE
THERMAL ENERGY STORAGE
ACTIVITIES 1988 - 1990

IEA SSPS TASK IV OPERATING AGENT
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REPORT

IEA - SSPS Task IV

High Temperature Thermal Energy Storage

Activities 1988 - 1990

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October 1991

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Contents

1. Performance Improvement and Availability Enhancement of Solar Thermal Power Plants by Means of High Temperature Thermal Energy Storage

The use of the sun's radiation to cover man's energy needs has two basic advantages over the fossil or nuclear conversion techniques:

It is **renewable** - no raw materials are consumed and it is **clean** - no pollutants or radiation can be emitted. However, nature does not provide these advantages for free. In order to make use of them, solar engineers must overcome the inherent drawbacks of solar radiation: It's **low power density** and it's **intermittent supply**. Both properties conflict with currently available conversion techniques which require a constant high power supply for economical operation. To achieve immediate high power levels, solar energy must be integrated over large surfaces, concentrated to the desired power level and then delivered to the consumer at the place and time desired. These two basic functions, **energy storage** and **energy transport** determine the choice of the energy conversion system and the energy carrier used. In solar plants, the seasonal solar radiation supply is distributed to seasonal loads through long term storage, while short term storage is required for evening out the daily intermittent flux conditions, prolong operation after sunset and shift energy sales from low revenue off-peak hours to high revenue peak demand hours.

1.1 Impact of Storage Systems on Solar Plants

On it's output side, a solar plant must face the conditions of the existing energy market like any other conventional plant: If the demand exceeds the offer, high prices are paid for the output; additional credit is awarded for guaranteed output during peak demand periods.

On it's input side, a solar plant must deal with the basic solar characteristics of the diurnal, seasonal an weather-related changes. The three alternatives to cope with these changes are: Follow these changes with the plant cycle, back up solar energy by fossil-fuel firing or smooth out the changes with buffer storage. The choice depends on specific system and site conditions, and is always complicated by cost/benefit considerations and questions about optimum storage system size. If storage is chosen, it can serve as

- a <u>plant internal buffer</u> for steady state cycle operation by smoothing out insolation changes and for operational purposes such as blanketing steam production, component preheating and freeze protection, and as
- an <u>output management tool</u> to shift output production to periods with highest revenues and to contribute to guarantee output when no solar input is available.

In solar thermal plants, a fossil backup burner can be used as internal buffer as well as for output management instead of thermal storage. Photovoltaic plants do not require internal buffers; output management can only be achieved by an "electricity" storage system as pumped hydro, batteries or fuel cells.

1.1.1 Capacity Factor and Solar Multiple

A simple measure of storage capacity is the "storage hour": the <u>storage hour</u> is defined as the storage capacity necessary to run the process connected to it at the rated output for one hour. Increasing concentrator field and storage hours increase solar plant annual operating time, as expressed in terms of the <u>capacity factor</u>, term created by conventional power plant technology. However, a solar plant cannot always operate at rated power due to the intermittency of radiation. Therefore, "virtual" power hours t_{Nel} are defined by dividing the net annual electric power output $W_{el,a}$ by the rated power $P_{el,d}$ of the conversion cycle. (Battleson, 1981). The capacity factor of a solar electric plant is then:

$$c_{el} = \frac{W_{el,a}}{P_{el,d} * 8760}$$

A 'thermal' capacity factor would accordingly be defined by the rated thermal power $P_{t,d}$ of the process connected to it. Fig.1.1 shows the energy flow of a solar plant with storage qualitatively on the ideal design day (no clouds), for example, June 21st. Between sunrise at t_{SR} and receiver start-up at t_{ON}, incoming radiation is too low. During τ_{RD}, receiver output is still insufficient to run the process at its rated output, but during τ_{DC}, receiver output exceeds nominal required input power and surplus energy E_C charges the storage system with a charging utilization factor γ_C. During τ_{DD}, receiver power is again too low, but the difference required to run the consumer at rated power is retrieved from storage with a discharge utilization factor γ_d. From sunset at t_{SS} throughout τ_{DO} the process runs at its nominal load from storage only. With storage, only the receiver must be designed for peak loads $P_{Re,d}$ and the cycle need only be designed for $P_{Cy,d}$. Due to losses in storage and heat exchanger, charge and discharge utilization factors are naturally less than 1, so the solar plant transfers less energy over the year to the cycle via the storage system than it would transfer directly from the receiver. If $\delta_{St,a}$ is the annual fraction of receiver energy sent to storage

$$\delta_{St,a} = \frac{E_{C,a}}{E_{Re,a}}$$

then annual plant system efficiency is reduced by the annual storage loss factor $\gamma_{St,a}$:

$$\gamma_{St,a} = 1 - \delta_{St,a} * (1 - \gamma_{C,a} * \gamma_{d,a})$$

If for example 50% of receiver output is charged in a storage system with 90% annual roundtrip efficiency, then the total direct receiver output is reduced by $\gamma_{St,a}$ = 95%. To compensate for this loss, the leveling effect of storage must improve annual cycle efficiency by 5%. Storage is already profitable, however, if increased revenues in time dependent priced energy sales due to user time changes can pay for additional storage costs.

This ratio of design receiver power $P_{Re,d}$ to nominal cycle inlet power $P_{Cy,d}$, is called the solar multiple (SM) (Gintz 1976):

$$SM = \frac{P_{Re,d}}{P_{Cy,d}}$$

Fig. 1.2 illustrates achievable rated power operating hours on a cloud less December 21st and June 21st for solar multiples ranging from 1.0 to 2.8 in Barstow, California. While the solar multiple of 2.8 is sufficient to operate 24 hours at rated power in summer, only 12 hours are possible with it in winter, and a minimum solar multiple of 5 would be required to achieve 24-hour operation in winter also.

Preliminary storage layout calculations for an Albuquerque, N.M. location, already showed that only the first 9 to 15 storage hours yield a linear increase in annual energy production. This is illustrated in Fig. 1.3, where the achievable solar capacity factor has been plotted over the required storage hours for various solar multiples. These calculations, using 19[illegible] Albuquerque meteorological data, make possible simple energy accounting without basing it on a specific plant (Ianucci 1981). The "critical" solar multiple is that necessary to reach a 100% capacity factor. Although the sizes of the storage systems indicated in Fig.1.3 may not be realistic, two main conclusions are arrived at, none the less:

The first 15 storage hours can increase rated power operation by 4500-5500 hours, yielding a capacity factor of up to 90%. In this range each storage hour provides approximately 350 rated power hours, meaning that each storage hour is used once a day. Each additional storage hour only provides an average of around 11 rated power hours, but the first 15, which equalize the daily day/night cycle, are also used 30 times as often as the next 90 storage hours, which balance seasonal oscillations.

If the surface area of the concentrating field is increased above the critical solar multiple, the storage capacity required for the 100% capacity factor drops again proportionally. With an oversized concentrator field, seasonal irradiation valleys need not be leveled by storage capacity, but are filled by additional concentrator area. Again, however, an oversized field would lead to an unusable energy excess in summer.

1.1.2 Optimization of Solar Multiple and Storage Capacity

For illustration of storage optimization, the study results for a 20 MW_e gas-cooled central receiver plant (GAST-20) with Brayton cycle carried out by a German-Spanish GAST consortium will be chosen as example. This study assumes a northern heliostat field, a gas-cooled metallic tube receiver operating between 500 and 800°C and an open Brayton cycle. Fire-brick filled wind heater modules each with a usable thermal capacity of 100 MWh_t (equivalent to 1.5 hours of rated power operation) were chosen for high temperature thermal storage. Main features of the GAST-20 plant are summarized in Tab. 4.1 for solar multiple 1.0. A detailed description of the GAST system is given in (Becker, et al., 1986). Annual solar multiples of 1.0, 1.2, 1.4, 1.6, 1.8 and 2.0, have been simulated with storage capacity varied 1.5 h at a time in each case from 0 to 9 storage hours, (Geyer, 1987a).

While field and receiver efficiency depend on the solar multiple, but not on the storage capacity, cycle efficiency and resulting system efficiency also depend on the storage capacity. Although, on one hand, added storage hours increase cycle efficiency due to reduced and partload operation, their growing parasitic pumping requirements diminish net electrical output. 5% improvement in cycle efficiency is already observed when the the solar multiple is increased from 1.0 to 1.2 without the addition of storage, and a further increase of 3% can be obtained by adding 1.5 h of storage to it. However, cycle efficiency decreases again with more than 4.5 storage hours, due to the increased parasitics. The greatest cycle efficiency gain, 15%, is possible with 1.5 storage hours at solar multiple 1.4.

Fig. 1.4 shows the resulting annual system efficiencies, the ratio of the net annual electric output to the annual insolation at the aper ture of the heliostat field. Variations in both the solar multiple and the storage capacity affect annual system efficiency since it aggregates all subcomponent efficiencies. When the solar multiple is increased from 1.0 to 1.2. with reduced partload operation, overall system efficiency rises from 13.1% to almost 14% without adding any storage at all. But system efficiency drops below design level at solar multiples higher than 1.5 with no storage when the unused summer insolation surplus exceeds the gains in partload performance, surplus which can be used, however, if storage is added. The highest system efficiency increase of 15.1% is reached with 3 storage hours at a solar multiple of 1.4. Beyond that, overall system efficiency drops again due to increased pumping parasitics. However, with sufficient storage capacity, annual mean system efficiency is above design for all solar multiples up to 2.0.

The resulting annual operating hours and total output are not yet affected by mean annual system efficiency. Therefore, in Fig. 1.5, total annual virtual rated power hours are plotted for the different solar multiples versus storage capacity. Again, a considerable rise in full power hours can be achieved without storage just by increasing the solar multiple to 1.2. With 4.5 - 9 hours of storage, over 4000 virtual rated power hours can be achieved at solar multiples higher than 1.8, bringing this solar system into the range of the intermediate load plants. However, this figure only considers virtual rated power hours obtained by dividing the annual output by the net cycle rating.

The real distribution of power levels achieved is illustrated in Fig. 1.6. 1810 rated power hours may be obtained at a solar multiple of 1.0 with no storage. In reality, though, this plant operates less than 800 hours at rated power and over 800 hours at less than 50% rated power. At a solar multiple of 1.2, still without storage, real rated power operation is almost doubled to 1600 hours while operation below 50% of rated power is reduced to 500 hours. With the addition of storage, rated power operation exceeds 80% and with 4.5 storage hours at solar multiple 2.0, 3700 hours of the total 4000 operating hours run at rated output.

Cost analysis (Geyer, 1987a) showed that original specific electric power costs of the reference case with solar multiple 1.0 and no storage can be cut by up to 15% when the solar multiple is increased to 1.4, even without adding storage. With storage, a specific cost decrease of up to 25% percent is possible. The reason is obvious: With solar multiple 1.0 and no storage, specific costs are due 27% to the heliostat field, 28% to receiver and tower, and 25% to the conversion cycle. With solar multiple 2.0 and 6 storage hours, the heliostat field contributes 26%, receiver and tower 26%, conversion cycle 12% and storage 7% of costs. Fig 1.7 shows the increase of investment costs with the increase of solar multiple and the addition of storage capacity for the 20 MW_e GAST project. Fig. 1.8 shows the resulting decrease of specific electricity generation costs.

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Qualitative Energy Flow in a Solar Plant with Storage

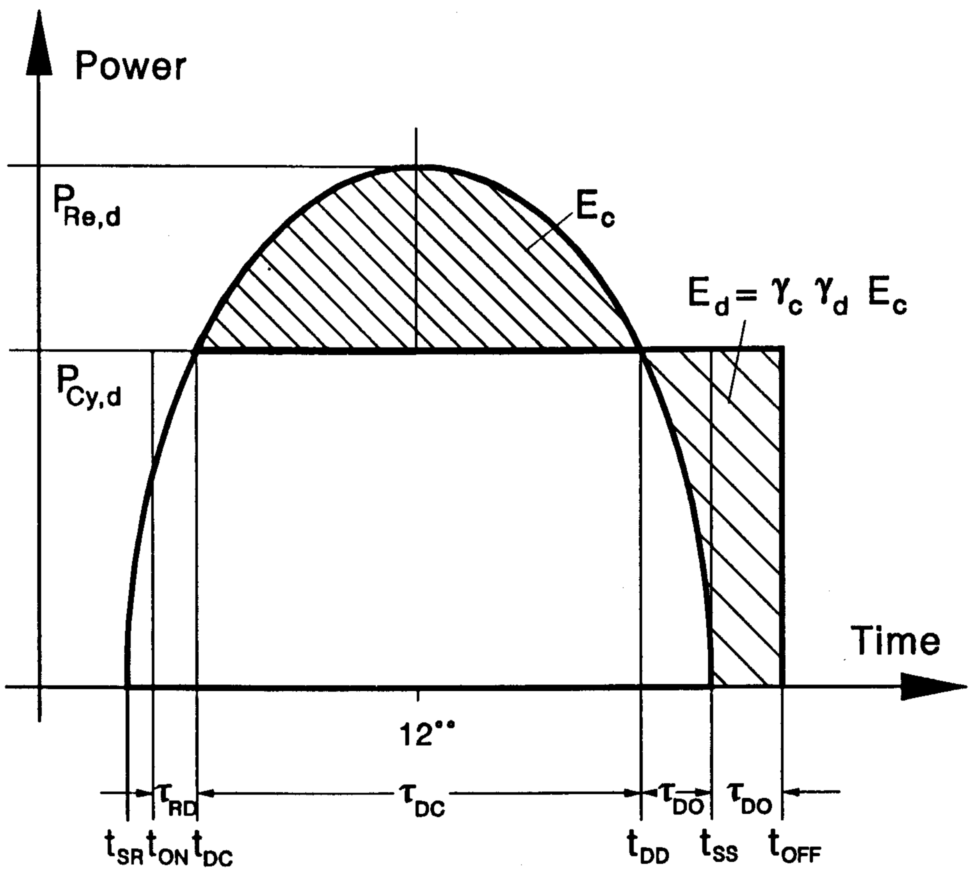


Fig. 1.1

Achievable Rated Power Operating Hours on a Cloudless December 21st and June 21st for Solar Multiples Ranging from 1.0 to 2.8 in Barstow, California

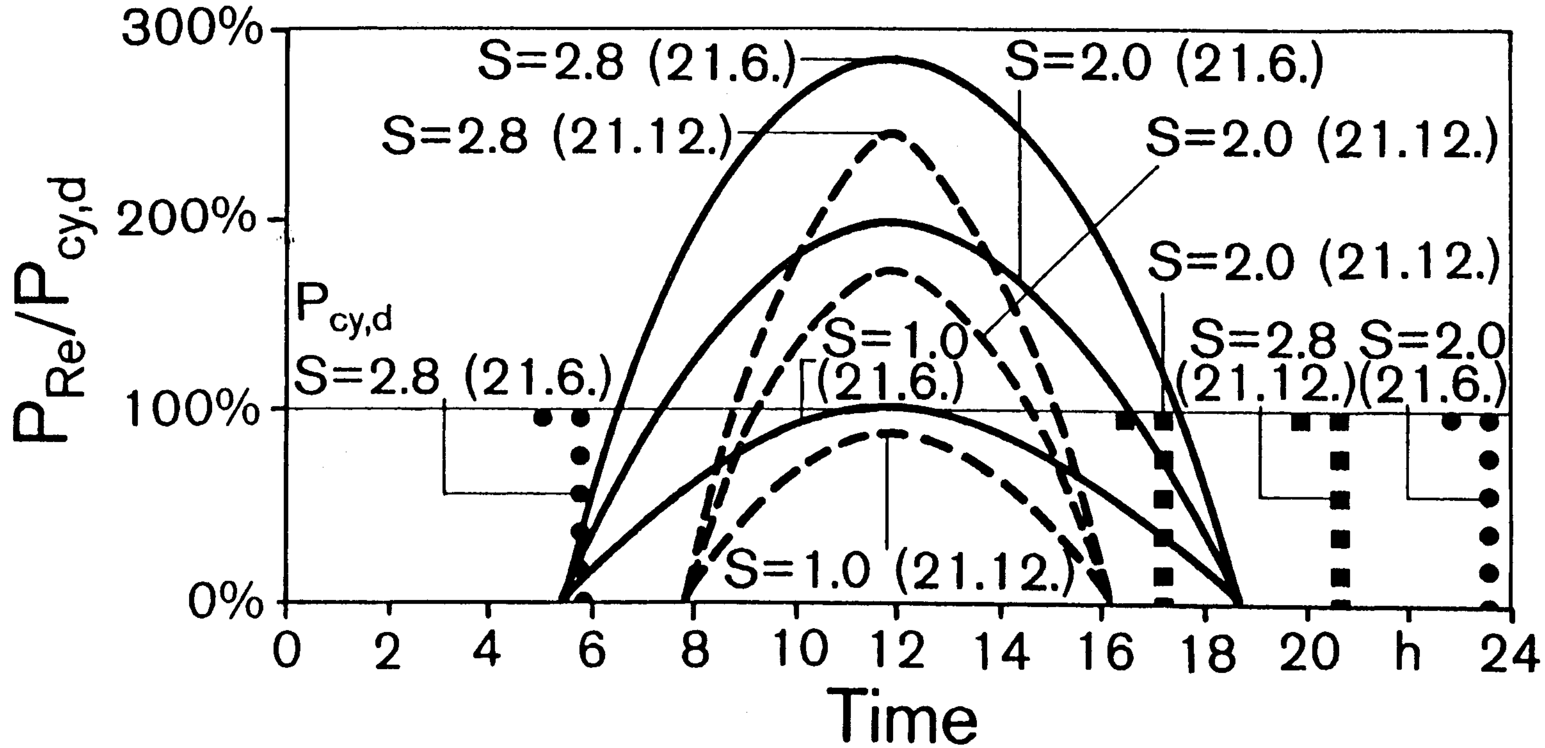


Fig. 1.2

Achievable Solar Capacity Factor as a Function of Solar Multiple and Storage Capacity

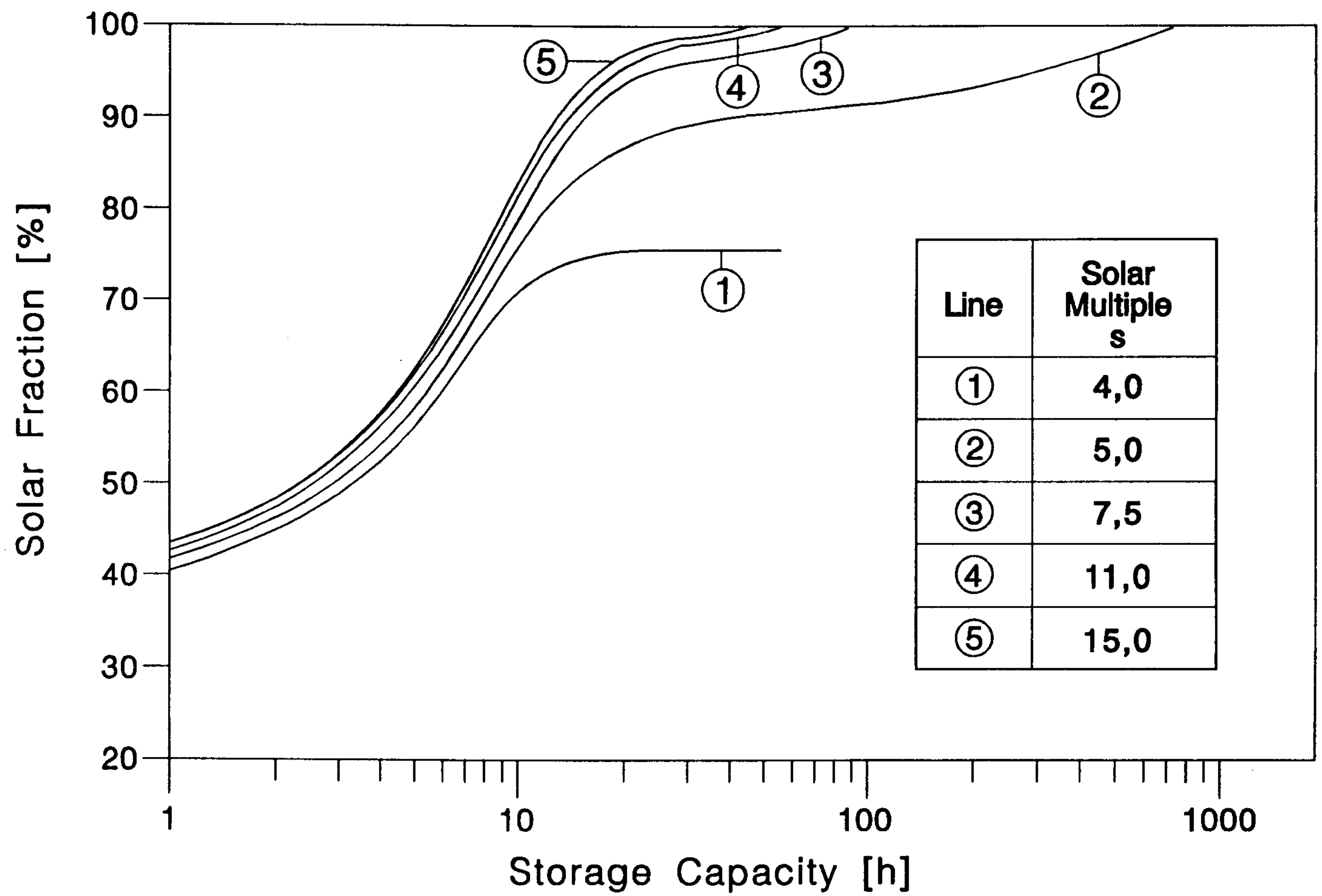
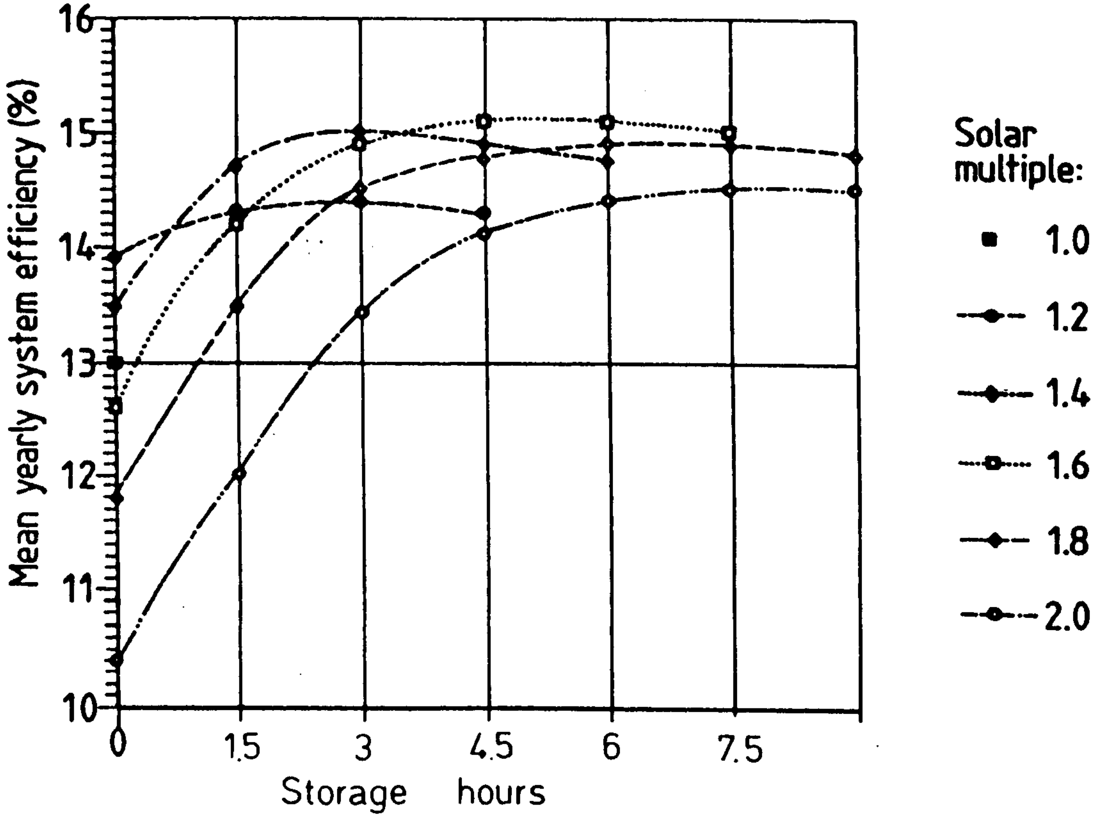


Fig. 1.3

Increase of Annual System Efficiency with Addition of Storage for Different Solar Multiples

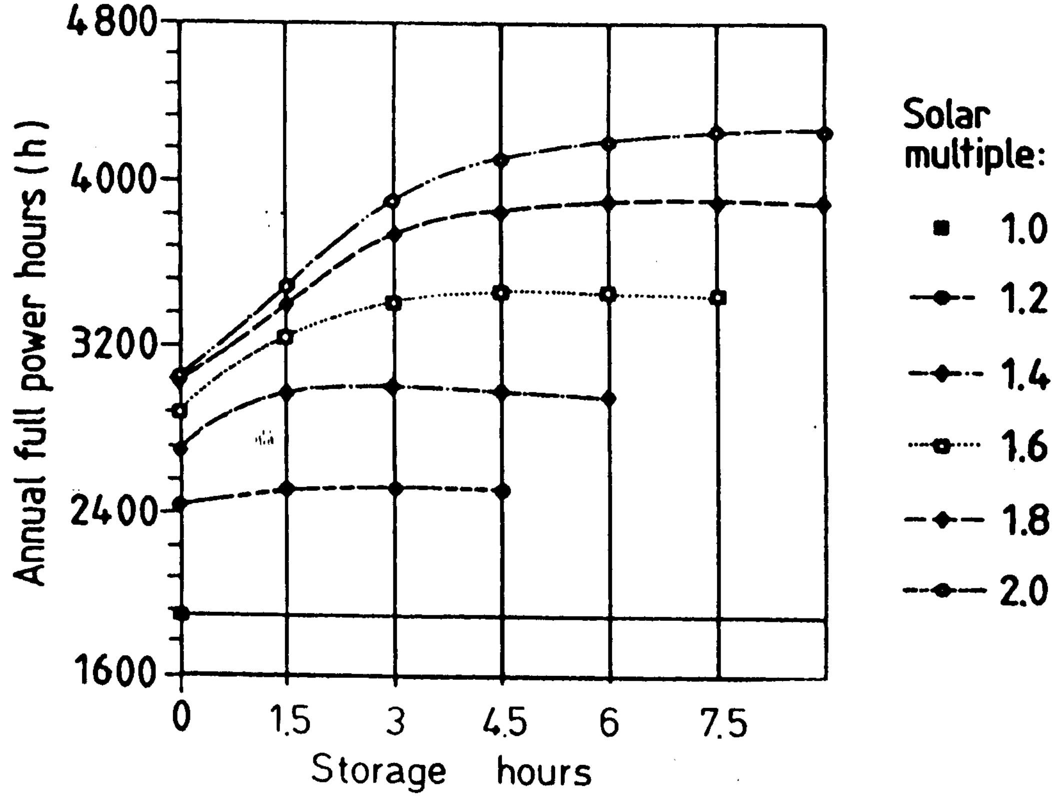


20 MW_{el} Solar Tower Plant
2550 kWh/m^2a direct radiation
115830 m^2 heliostat area at SV=1.0

500/800 °C air cooled receiver
100 MWh_t ceramic storage modules
open Brayton cycle

Fig. 1.4

Increase of Annual Rated Power Hours with Addition of Storage for Different Solar Multiples

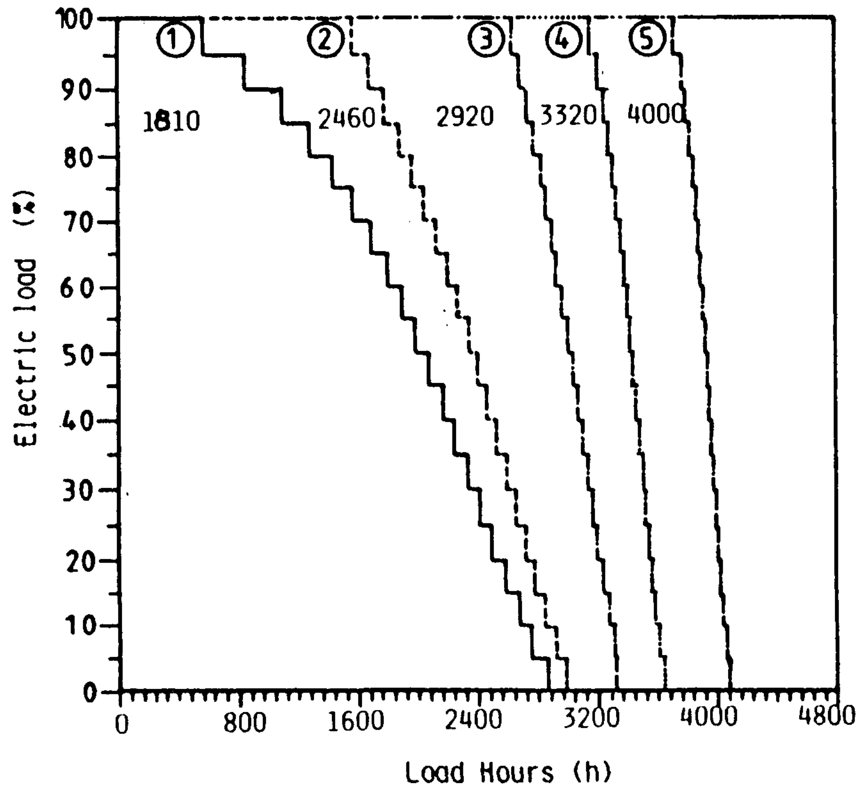


20 MW_{el} Solar Tower Plant
2550 kWh/m^2a direct radiation
115830 m^2 heliostat area at SV=1.0

500/800 °C air cooled receiver
100 MWh_t ceramic storage modules
open Brayton cycle

Fig. 1.5

Classified Annual Load Distribution for Various Solar Multiples and Storage Capacities



case		solar multiple	storage hours
①	———	1,0	0
②	------	1,2	0
③	—·—	1,4	1.5
④	··········	1,6	3.0
⑤	—··—	2,0	4.5

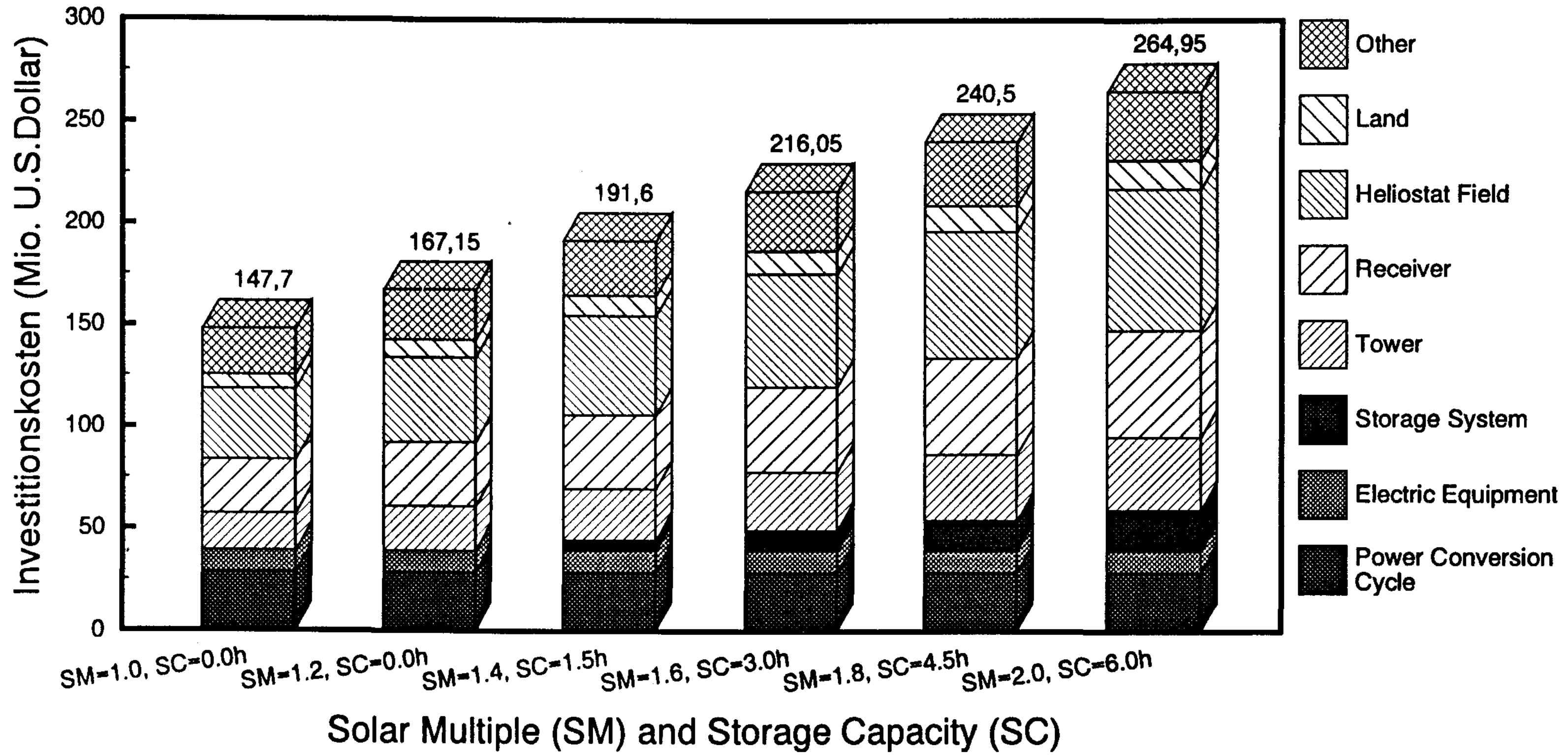
20 MW_{el} Solar Tower Plant
2550 kWh/m^2a direct radiation
115830 m^2 heliostat area at SV=1.0

500/800 °C air cooled receiver
100 MWh_t ceramic storage modules
open Brayton cycle

Fig. 1.6

The Costs of Higher Availability

Capital Cost as a Function of Solar Multiple and Storage Capacity



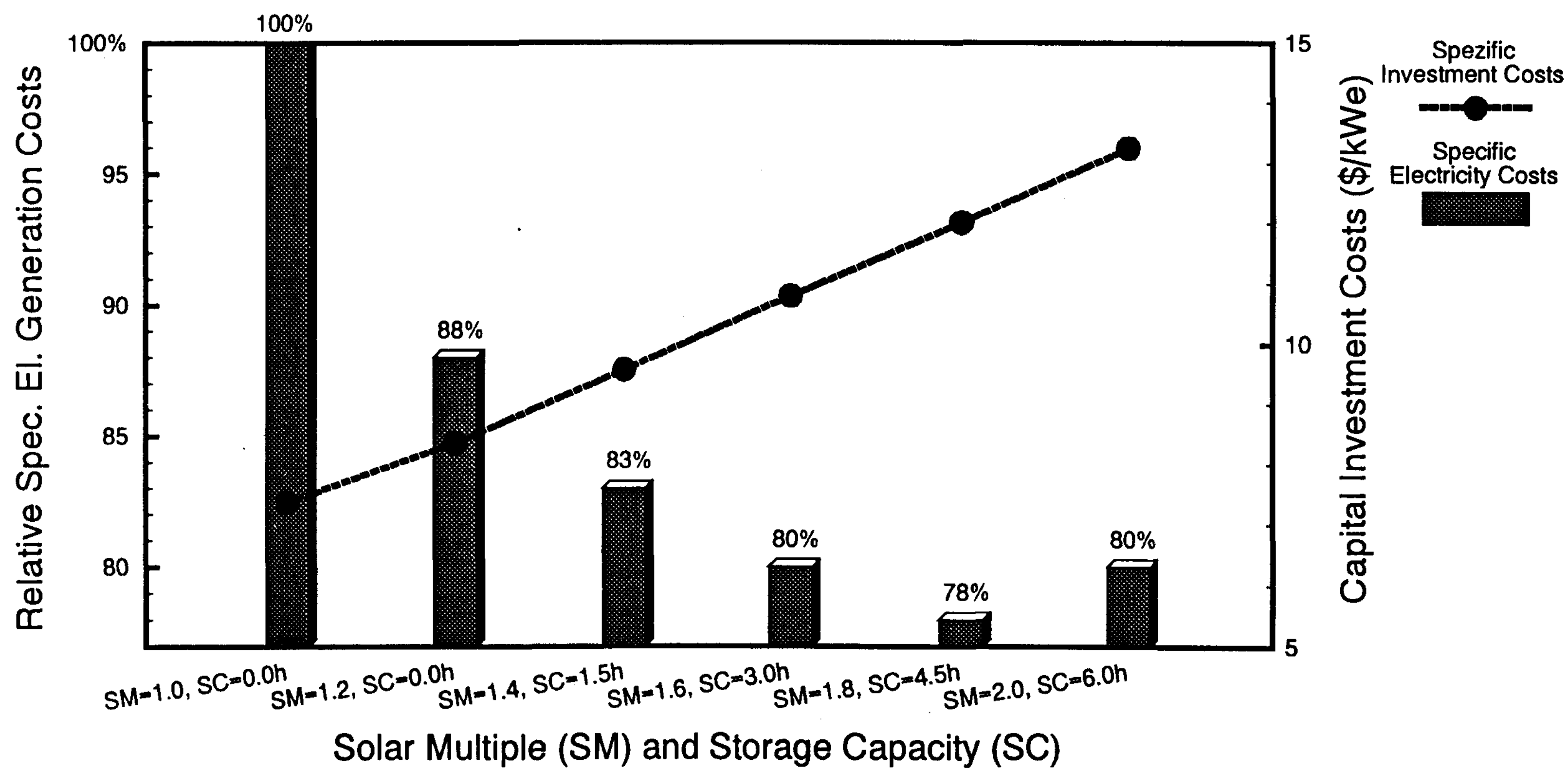
Price Basis 1984
Exchange Rate U.S.$1.00 = 2.00 DM
Heliostat Costs 300 $/m**2

20 MWel Solar Tower Plant
500/800 C Air Tube Receiver
(Source: GAST-Projekt)/a:\vdi\gw\vdi10e.cht

Fig. 1.7

The Gain of Higher Availability

Specific Electricity Generation Costs over Solar Multiple and Storage Capacity



Price basis 1984, Start of Operation 1990
Construction 3 years, depreciation 20 years
Interest rate 8%, inflation 5%, $1.00=2.00DM

20 MWel Solar Tower Plant, 500/800C air receiver
Glass/metal heliostats $300/m**2
Barstow insolation 2645 kWh/m**2/a VDI11E.CHT

Fig. 1.8

2. Progress of Subtasks

2.1 Subtask IV.1 "Pilot Storage Experiment at Almería"

As reported in the Proceedings of the 2nd IEA-SSPS Task IV Status Meeting on "High Temperature Storage", the realization of the High Temperature Pilot Storage Experiment at Almería has been posponed until SSPS Tasks III and V/VI produce a suitable receiver and an attractive chemical process application for it.

In the meantime, the sensible high temperature storage concept with ceramic checkerwork has been selected as the preferred technology for the 30 MWe PHOEBUS Central Receiver Project, where a 2 hour storage module has been designed for 700°C air charging temperature by the Didier Werke AG. Detailed information can be found in the PHOEBUS Feasibility Study Phase I of the European PHOEBUS Consortium.

As the next step, a 2.5 MWt Volumetric Receiver connected to a ceramic buffer storage system will be tested at operating temperatures up to 700°C at the Plataforma Solar.

2.2 Subtask IV.2 "Development of Salt Ceramic Storage Media"

The development of the advanced composite media was significantly supported by funds of the German Ministry of Research and Development and of Didier Werke AG, dedicated to the HTWS program.

Within this project, the DLR Institute of Technical Thermodynamics in Stuttgart is responsible for laboratory development and the industrial partner Didier Werke AG is responsible for manufacturing those materials in full scale geometries. The presently used method of preparation of lab scale materials is a cold pressing of the pulverized base materials. The typical test probes were cylindrical pellets of

26mm and 40mm diameter and of 10 to 20 g or 50 to 200 g mass, resp.. They were used to optimize the manufacturing process and to test and qualify the hybrid materials. Main influence on the thermal and mechanical stability of the composites is caused by the particle size of the components, the particle size distribution as well as type and quantity of binders and the burning procedure. Main effort was directed on magnesia, MgO, and silica, SiO2, as the basic ceramic components. As PCM compounds, mainly alkali and alkali earth metal carbonates and sulfates were tested.

Detailed investigations with the salt/ceramic systems Na-BaCO3/MgO and Na2SO4/MgO included analysis of chemical and thermophysical properties, cristal structures and thermal behaviour during the phase transitions. These experiments have proven sufficient thermal and mechanical stability of these composite materials to build up a stacked arrangement of several meters height.

In order to test the full scale checker work elements fabricated by Didier Werke AG with the composite material, a technical scale test facility was built at DLR in Stuttgart as part of the HTWS project. A detailed technical description of the test facility is attached.

2.3 Subtask IV.3 "Intermediate Temperature Densified Storage"

This Sub-Task had beed redifined to cover the intermediate temperature region on the 1987 proposal of M.Bohn from SERI, who had proposed together with ORNL a material, encapsulation and heat exchanger development project with the objective of using an encapsulated metal alloy phase change storage system in a molten nitrate-salt central receiver environment.

In the meantime, a feasibility study on intermediate temperature (200-400°C) thermal energy storage systems for oil and steam cooled parabolic trough plants has been carried out by the DLR and CIEMAT-IER in cooperation with Flachglas

Solartechnik GmbH, Gertec GmbH, Initec S.A., Luz International Ltd. and Siempelkamp Gießerei & Co., funded by the German Ministry for Research and Development, the Spanish Ministry for Industry and Energy and the participating companies. The results of this study have been published.

2.4 Molten Salt Storage Tests at CRTF, Albuquerque

The molten salt storage tests were carried out as planned at the Central Receiver Test Facility (CRTF) of Sandia National Laboratories Albuquerque in spring and summer 1987. The final results of the evaluation were reported at the Task IV Meeting in Denver, 1988 and published as a Sandia Report.

2.5 Molten Salt Storage Tests at CESA-I, Almería

The molten salt storage tests were carried out as planned at the CESA-I central receiver plant of the Plataforma Solar de Almería in 1987 and 1988. The final results of the evaluation were reported at the Task IV Meeting in Denver, 1988 and published in Solar Energy.

3. IEA-SSPS Task IV Status Meeting
Denver, June 22, 1988

3.1 Agenda

1. General Status of Task IV (M. Geyer, DLR)

2. Status and 1988 Results of Subtask IV.2 "Development of Composite Salt/Ceramic Materials" (R. Tamme, DLR)

3. Status of Subtask IV.3 " Intermediate Temperature Increased Density Storage" (M. Bohn, SERI)

4. Status of Subtasks IV.4 and IV.5 "Molten Salt Storage Tests"

5. Discussion of Standardized Storage Evaluation Principles with Example of Data taken from SSPS, CESA-I, Solar I and CRTF Storage Subsystems

6. Report on Storage Activities at the Weizmann Institute of Science (as guest M. Epstein, WIS)

7. Report on Storage Activities at Paul Scherrer Institute (W. Durisch, PSI)

8. New projects:
   - German-Spanish Feasibility Study on Intermediate Temperature Thermal Energy Storage for Commercial Applications (TESCA)
   - Proposal for a 2.5 MWt Volumetric Receiver / Storage Test at the Plataforma Solar de Almeria

3. IEA - SSPS Task IV Status Meeting
Denver, June 22, 1988

3.2 Participants

Name	Institution
B. Gupta	SERI, Golden, Colorado, USA
H. Ries	PSI, Würenlingen, Switzerland
W. Durisch	PSI, Würenlingen, Switzerland
M. Geyer	DLR, Plataforma Solar, Spain
M. Epstein	WIS, Rehovot, Israel
J.M. Andújar	CIEMAT-IER, Plataforma Solar, Spain
M. Sanchez	CIEMAT-IER, Plataforma Solar, Spain
C. Tyner	SNLA, Albuquerque, USA
R. Dahl	KfA-PBE Jülich, Germany
R. Tamme	DLR EN-TT, Stuttgart, Germany
M. Bohn	SERI, Golden, Colorado, USA
M. Pritzkow	DLR WB-BK, Stuttgart, Germany
M. Böhmer	DLR MD-ET, Cologne, DLR
R. Sizmann	University of Munich, Germany

3. IEA - SSPS Task IV Status Meeting
Denver, June 22, 1988

3.3 Reports, Papers, Presentations

3.3.1 High Temperature Thermal Energy Storage Using Salt/Ceramic Hybrid Materials (R. Tamme, DLR)

3.3.2 Intermediate Temperature Increased Density Storage and Direct Contact Heat Exchange (M. Bohn, SERI)

3.3.3 Modelling of the CESA-1 Two Tank Molten Salt Thermal Storage System
(J.M. Andújar, PSA)

3.3.4 Advanced Latent Heat Storage Concepts for Intermediate Temperature Applications (R. Tamme, DLR)

3.3.1

HIGH TEMPERATURE THERMAL ENERGY STORAGE
USING SALT/CERAMIC HYBRID MATERIALS

- Status of Work, New Results, and Proposed Activities -

Rainer Tamme
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presented at

IEA-SSPS Task IV Meeting
June 22, 1988
Denver, CO, USA

ABSTRACT

The present available high temperature thermal energy storage (TES) materials are various oxide ceramics used as pellets, bricks or other shapes in packed bed or chequer work arrangements. Well known are large cowper stoves used in the iron and steel industry. Energy storage occurs in sensible form and, therefore, high temperature differences during charging and discharging are necessary for efficient storage capacities.

For conventional and new industrial applications (e. g. steel, ceramic, glass, chemical industries and solar thermal) storage materials with higher storage capacities and a modified design and construction of cowper-type storage systems are necessary. The advanced "composite salt/ceramic TES media concept" offers the potential for using phase change materials (PCM) via direct contact heat exchange and, therefore, the potential of significant cost improvements through elemination of HX materials and reduction of containment vessel size.

This concept involves either the retention and immobilization of a PCM (salt) within the submicron pores of a ceramic matrix (micro encapsulation) or the use of a heat resistent shell (or honeycomb structure) filled with the PCM (macro encapsulation).

In the micro encapsulation approach, the molten salt is retained within the solid ceramic network by surface tension and cappilary forces. Heat storage occurs in several modes: latent heat of the salt and sensibel heat of the ceramic matrix and of the salt. Therefore, the use of salt/ceramic materials represents not a pure latent heat storage system, but a latent/sensibel hybrid storage concept. Several key problems still need further investigation: Chemical and thermomechanical stability, thermal cycling, heat carrier compatibility, upscaling and economic manufacturing.

The paper presents:

- the status of salt/ceramic hybrid material development at DFVLR,
- new results on TA measurements of the $NaCO_3/BaCO_3/MgO$ system, comparison of the pure eutectic and of the hybrid material,
- results of a "stacked arrangement TES model" for hybrid materials, thermal behaviour of the pure material (as a single cylindrical rod) and of a 10 MWh storage module,
- the cost improvement through salt/ceramic application, and
- the status of the joint DIDIER + DFVLR project "HTWS".

Objective

- Development of several salt ceramic hybrid materials using different salts (with different melting temperatures) for different applications

- Use of salt ceramic hybrid materials in a stacked configuration similar to a chequer work array

- Development and manufacturing of salt ceramic hybrid materials with shape and dimension similar to chequer work bricks

Present Status of Lab-Scale Materials

Na_2CO_3-$BaCO_3$/MgO

45 wt.% salt hybrid material
50 wt.% salt sandwich

cold pressed pellets:
26 mm diameter ~ 20 g

$D = 2.6$ g/cm^3, $T_F \sim 700$ °C

$Q_{\Delta T} = 300$ K ~ 420 kJ/kg

→ ~ 300 kWh/m^3

Compressive strength =
1100 g/cm^2
stacked arrangement of ~ 3 m

NaF-MgF_2/MgO

35 wt.% salt hybrid material

cold pressed pellets:
26 mm diameter - 18 g

$D = 2.4$ g/cm^3, $T_F \sim 825$ °C

$Q_{\Delta T} = 300$ K ~ 580 kJ/kg

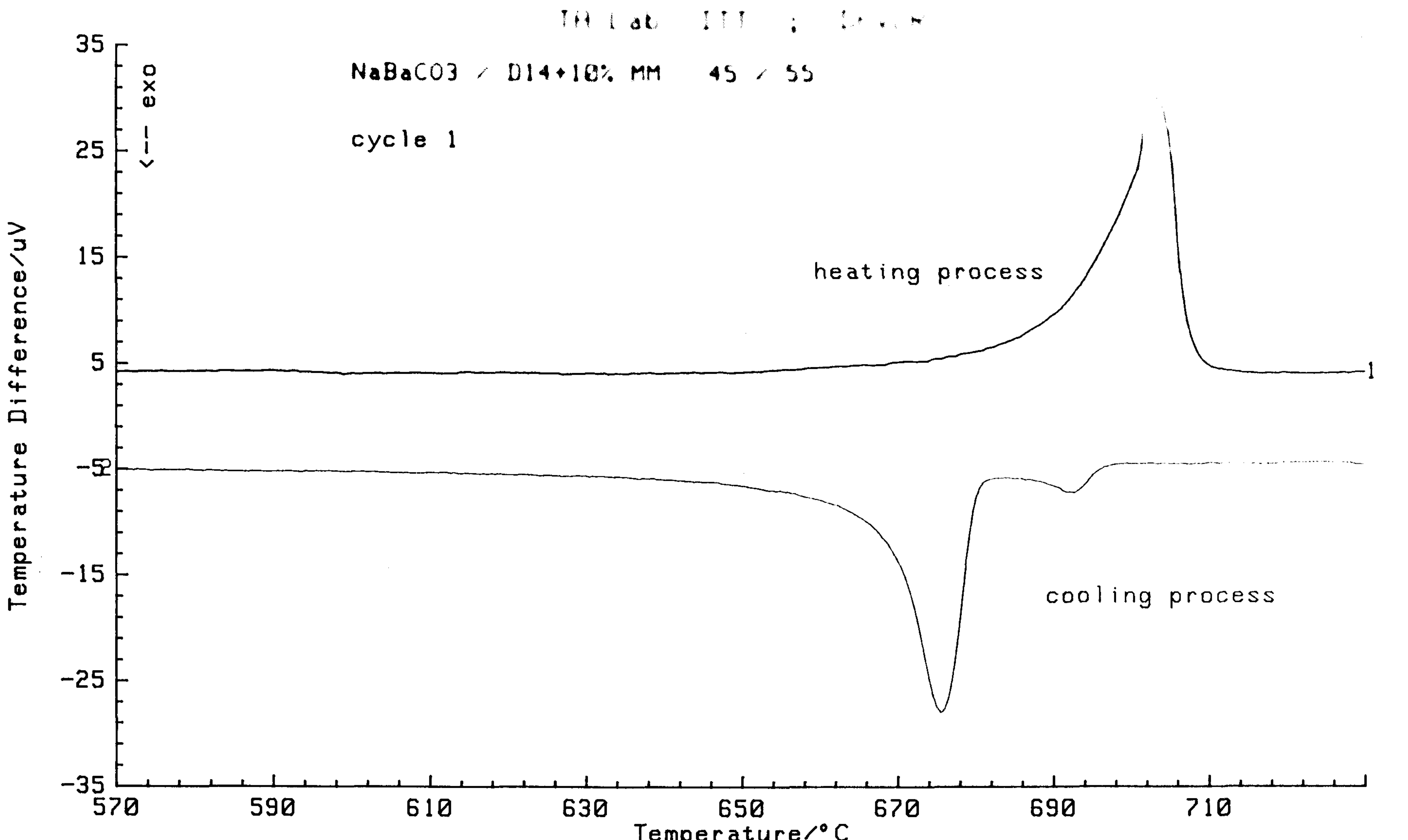
→ ~ 390 kWh/m^3

Compressive strength ~
200 g/cm^3
stacked arrangement of ~ 0,8 m

T A Investigation of the System Na_2CO_3 / $BaCO_3$ / MgO

DSC 404, argon

sample	initial weight m[mg]	m[mg]	fusion temperat. T_F [^0C]	heat of fusion H_F [J/g]		spec. heat [J/g K] solid, 600^0C	liquid, 740^0C
salt mixture (48/52)	61.26	n.e.	708	207		1.1_4	1.3_6
	46.51	n.e.	708	205		1.1_7	1.4_2
eutectic (48/52)	60.54	0.58	699	185		1.1_8	1.4_9
pulverized 0 - 50 um	60.92	0.33	694	196		1.1_9	1.5_7
	59.14	0.57	700	207		-	-
eutectic, multiple melted,pulverized 0 - 50 um	61.55	0.61	698	197		1.1_8	(1.8)
salt/ceramic pellet					100 %-value		
30 / 70	65.89	0.78	695	61.6	205	1.2_0	1.3_4
45 / 55	78.83	0.84	698	93.4	208	1.1_7	1.3_2
50 / 50	70.65	0.76	698	104	208	1.1_8	1.2_9



#	SAMPLE	/ mg	DATE	IDENTITY No.	Seg.	RANGE:	Corr.
1	Eut/D14 45/55	58.1	22 Feb 1988	Pel neu	3:	370/ 5.00/ 820	
2	Eut/D14 45/55	58.1	22 Feb 1988	Pel neu	5:	820/ 5.00/ 570	Bsb5

Thermal Cycling of Composite Salt / Ceramic

45 / 55 NaBaCO3 / D14+10% MM

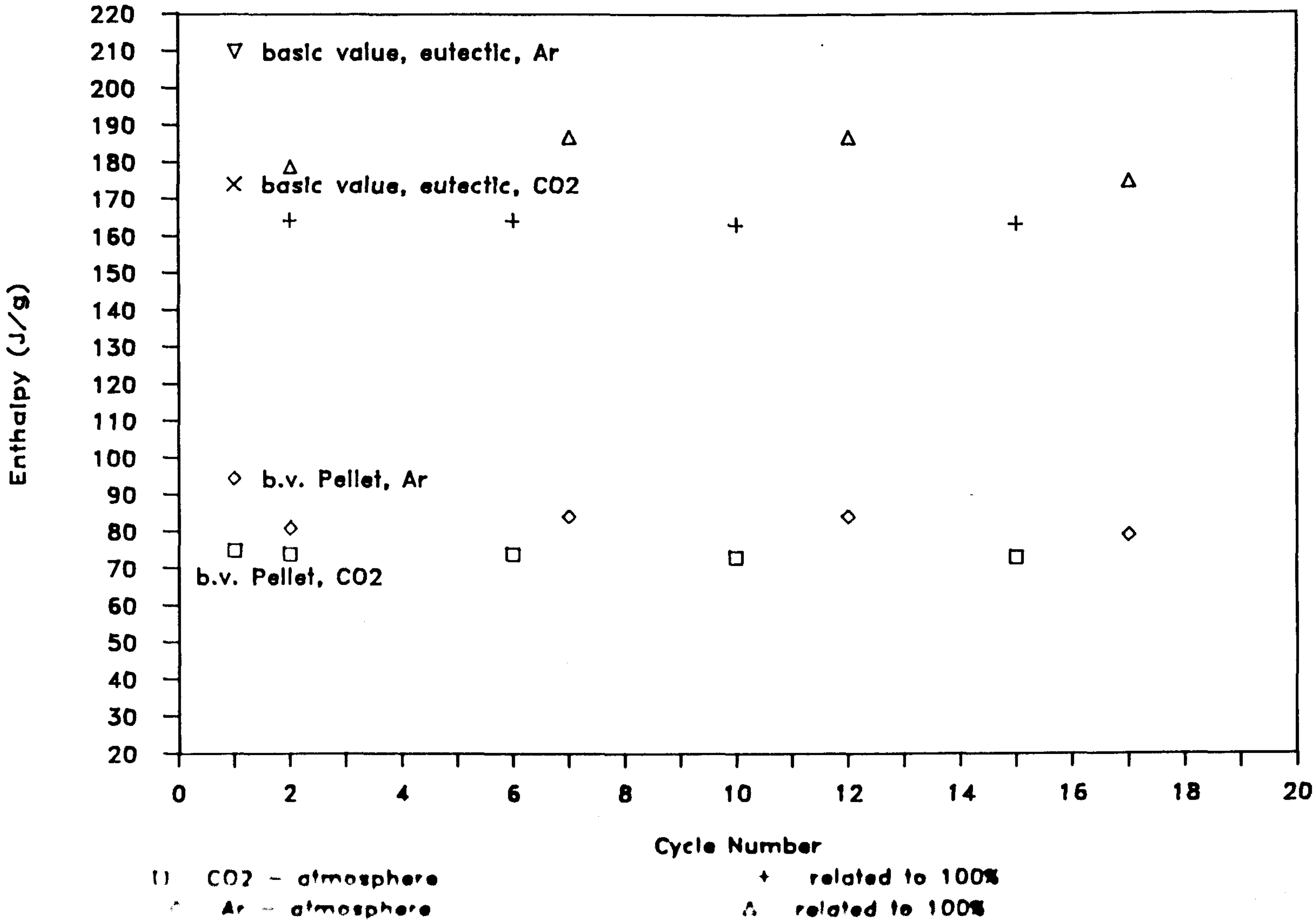
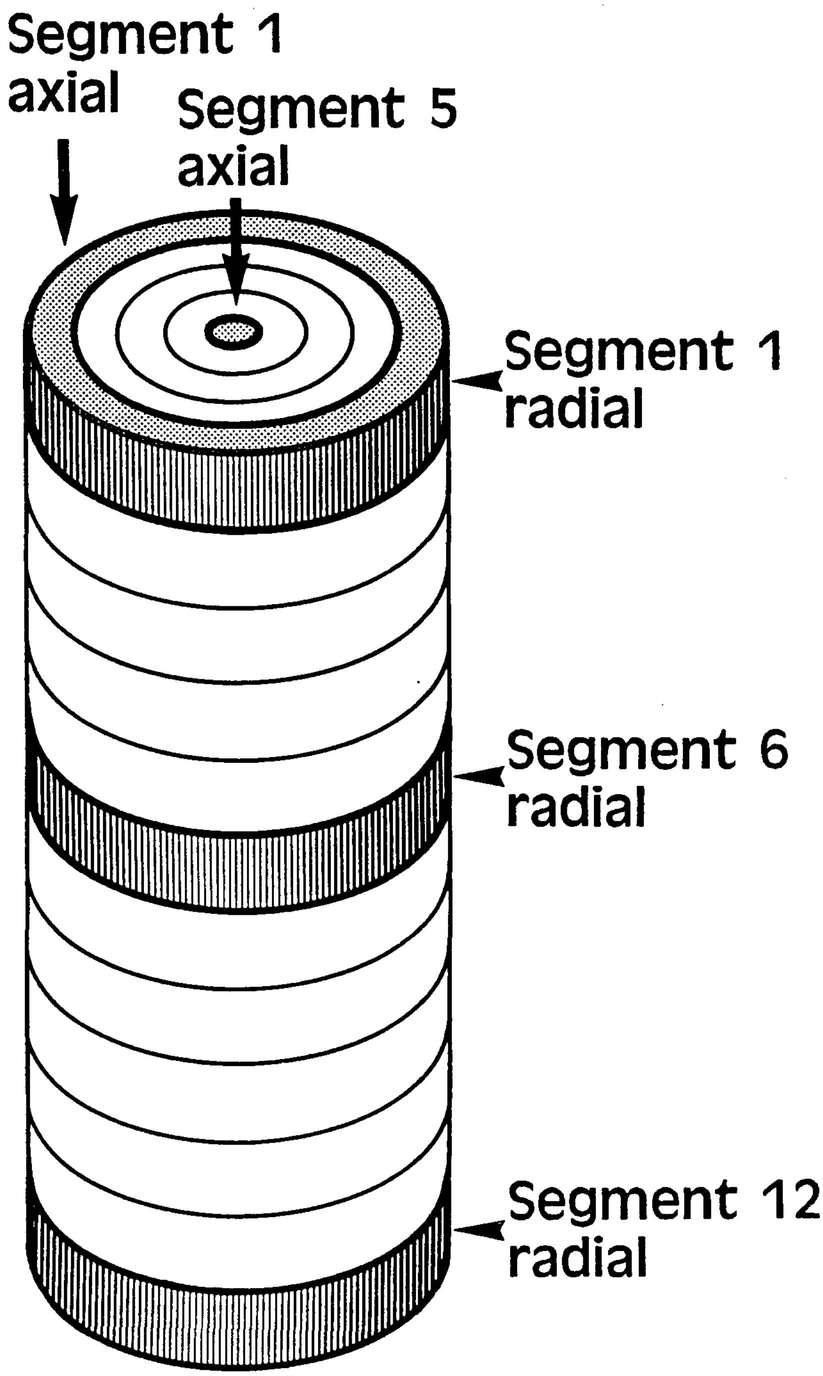


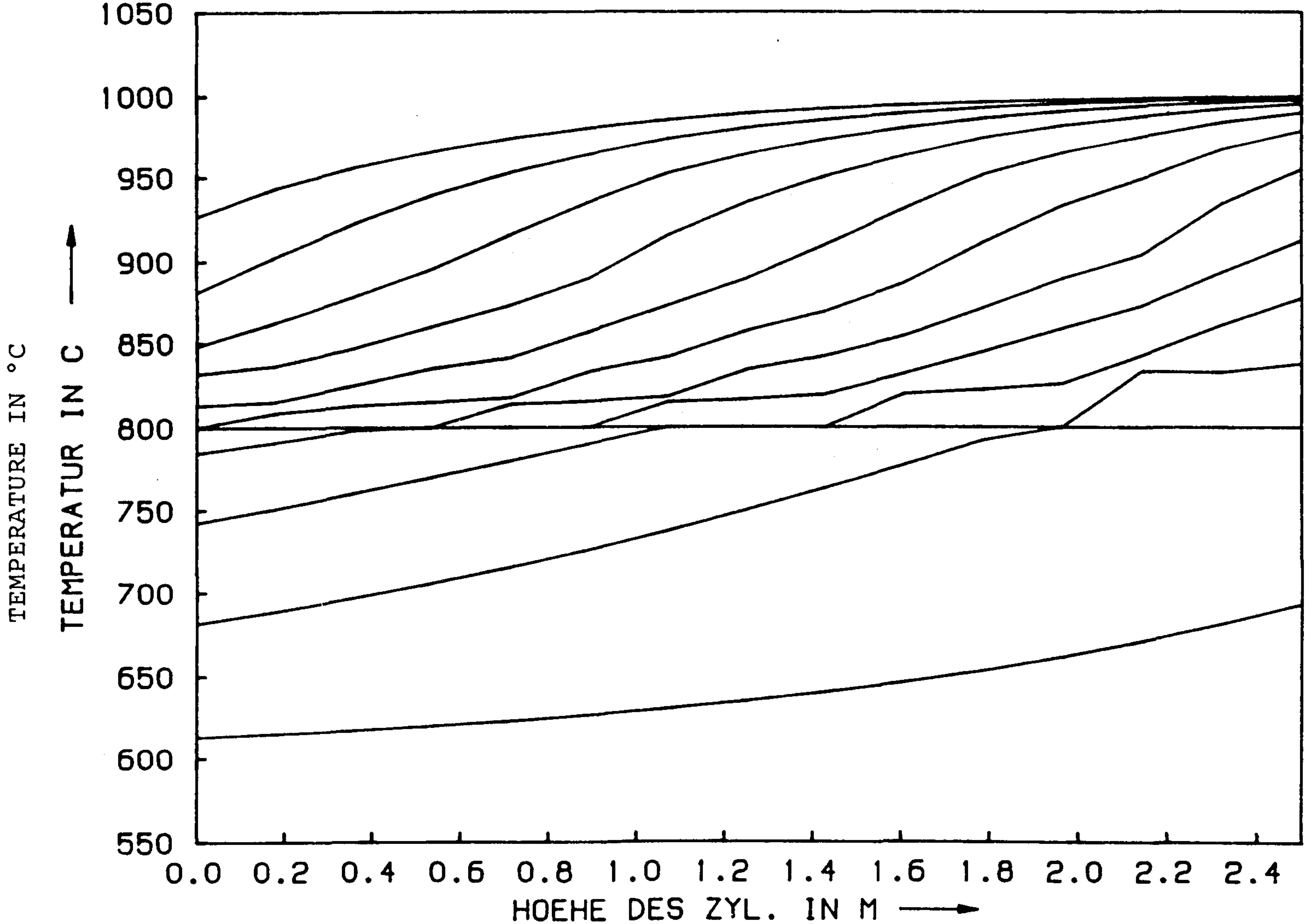
Table: Storage Material Data Used for Hybrid Material Stacked Arrangement Thermal Model

	hybrid material	sensible material
substance	salt/ceramic	MgO
composition	50/50	100
density	2.5 kg/dm^3	2.9 kg/dm^3
spec. heat	1.2 J/g K	1.1 J/g K
heat conductivity	5 W/m K	5 W /m K
heat of fusion	0.5 300 J/g	-
fusion temperature	800 ^{0}C (salt A) 850 ^{0}C (salt B)	


Segment 1
axial
Segment 5
axial
Segment 1
radial
Segment 6
radial
Segment 12
radial

ACHSIALES TEMPERATURPROFIL EINES SPEICHERZYL. MIT ZEIT ALS PARAMETER

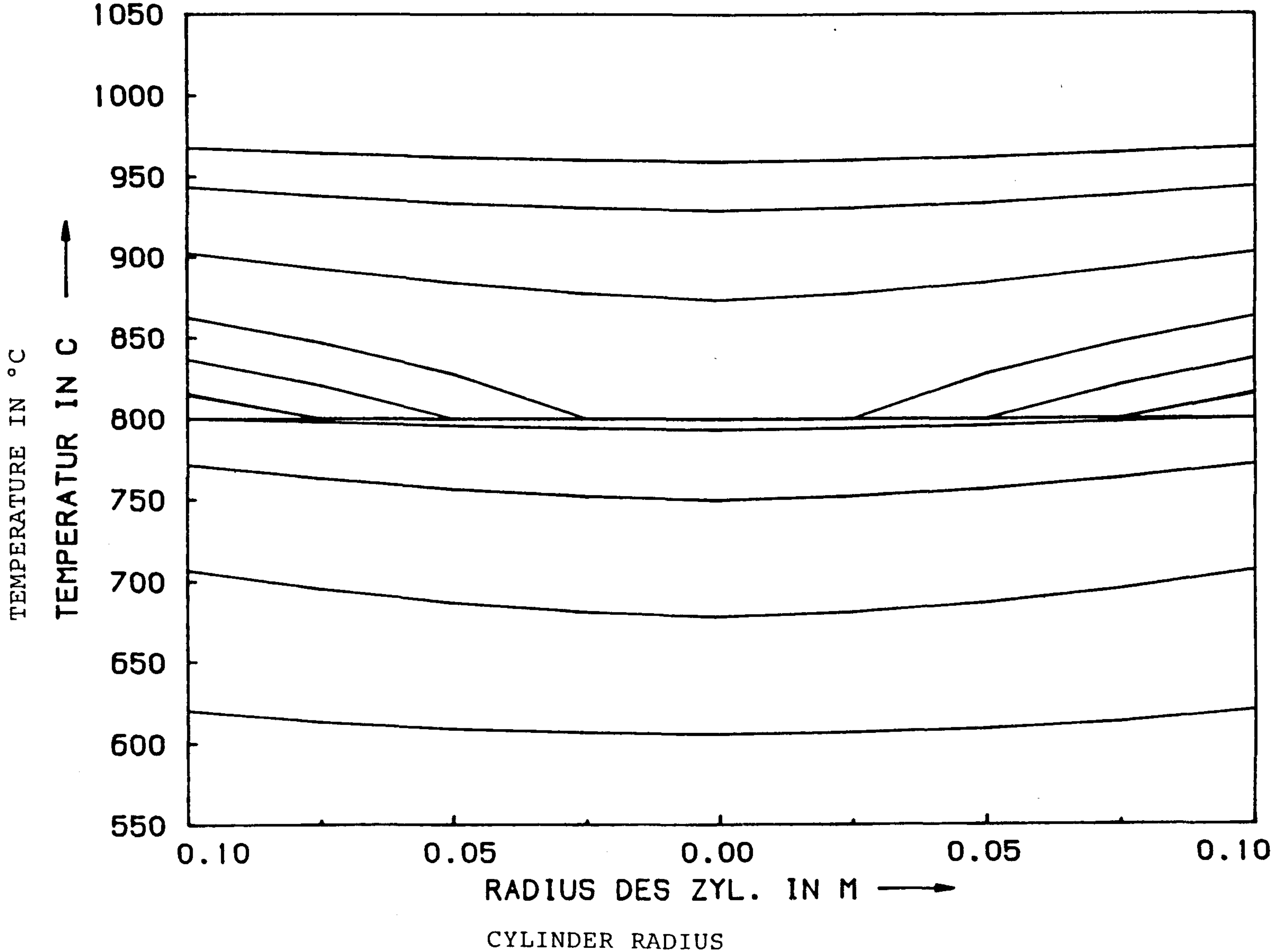
TIME DEPENDENT TEMPERATURE CURVES OF A SINGLE, CYLINDRICAL SALT CERAMIC ROD (SEGMENT 1, AXIAL)



CYLINDER HIGHT

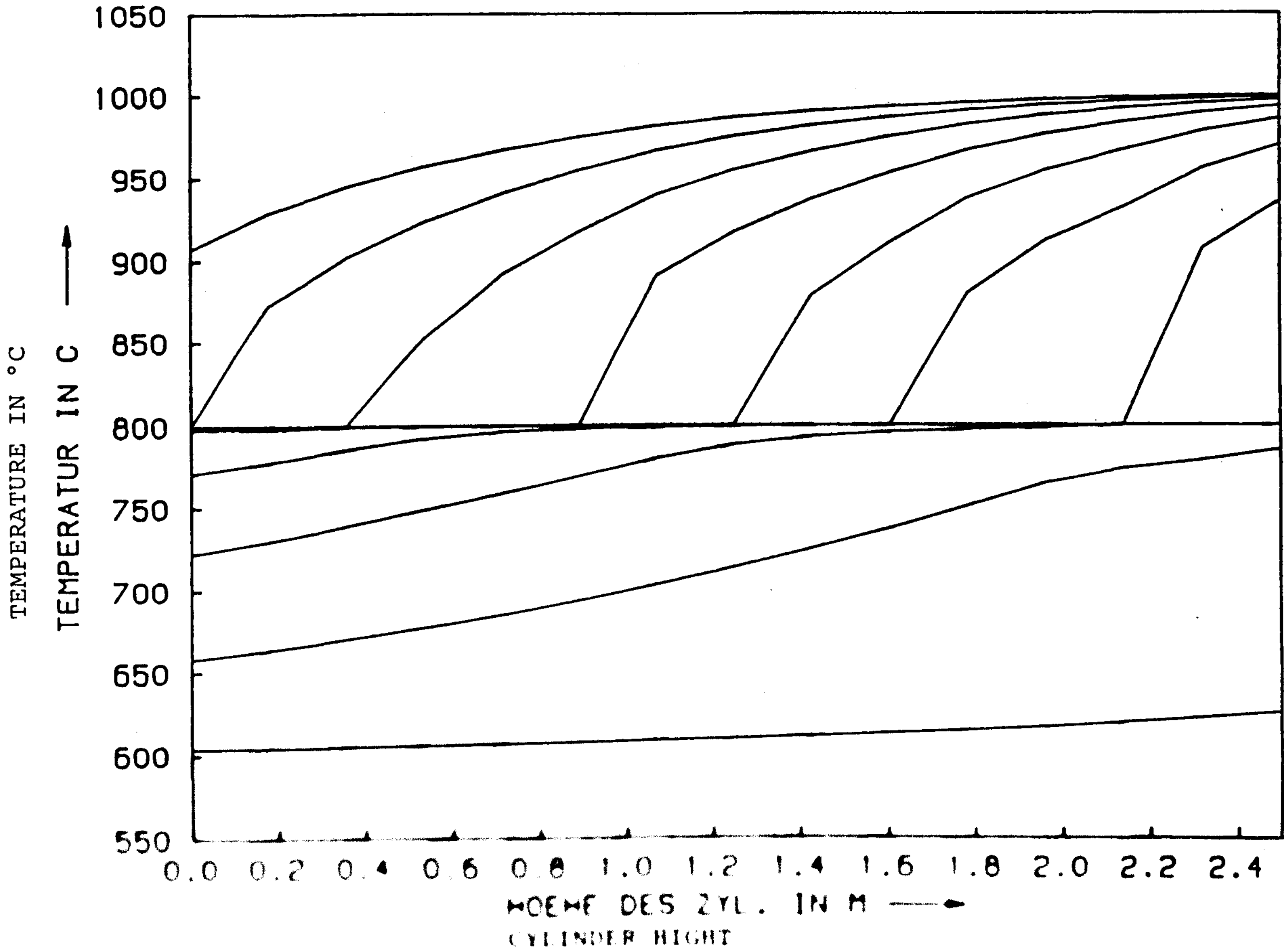
RADIALES TEMPERATURPROFIL EINES SPEICHERZYL. MIT ZEIT ALS PARAMETER

TIME DEPENDENT TEMPERATURE CURVES OF A SINGLE, CYLINDRICAL SALT CERAMIC ROD (SEGMENT 4, RADIAL)



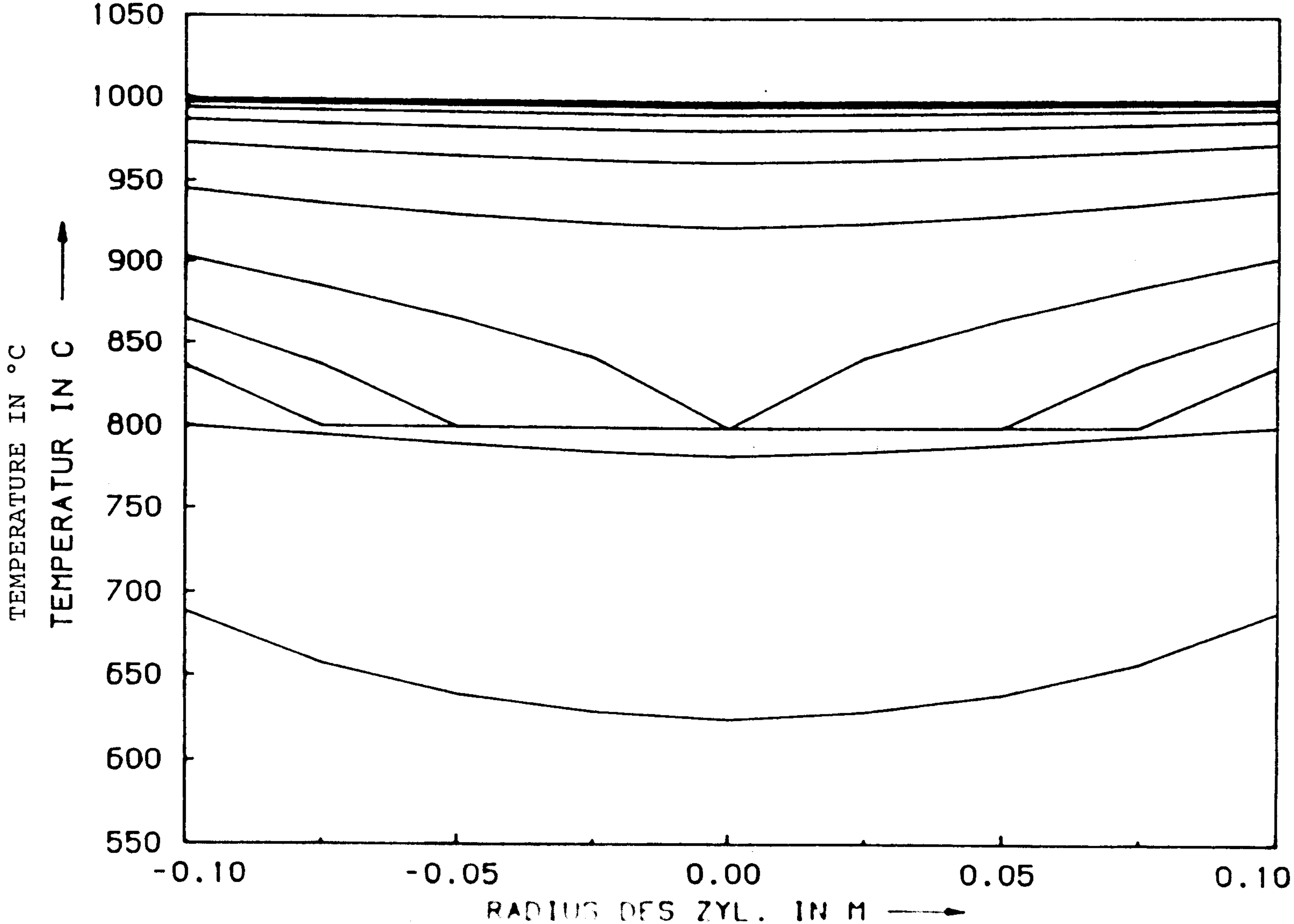
ACHSIALES TEMPERATURPROFIL EINES SPEICHERZYL. MIT ZEIT ALS PARAMETER

TIME DEPENDENT TEMPERATURE CURVES OF A SINGLE, CYLINDRICAL SALT CERAMIC ROD (SEGMENT 5, AXIAL)



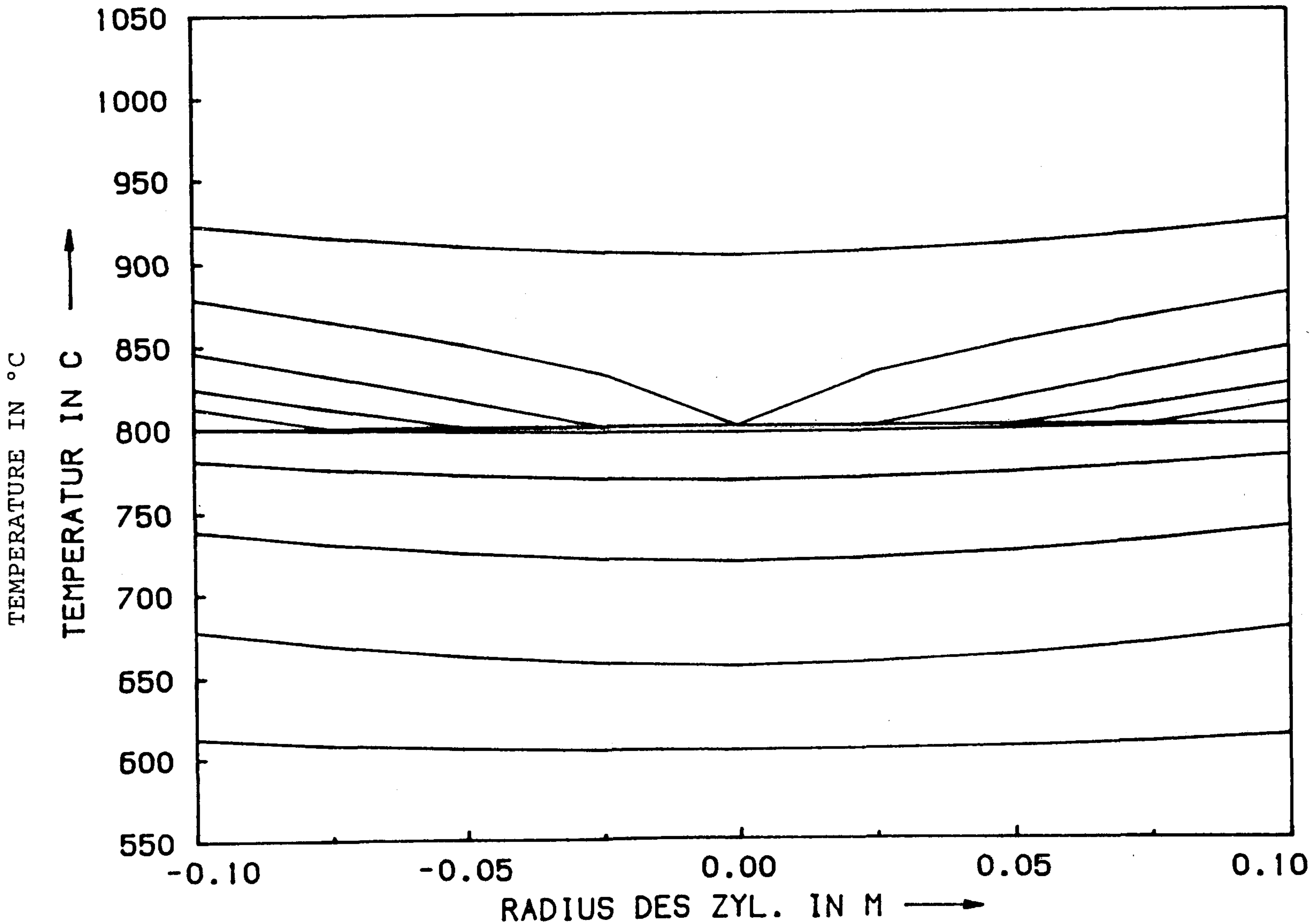
RADIALES TEMPERATURPROFIL EINES SPEICHERZYL. MIT ZEIT ALS PARAMETER

TIME DEPENDENT TEMPERATURE CURVES OF A SINGLE, CYLINDRICAL SALT CERAMIC ROD (SEGMENT 1, RADIAL)



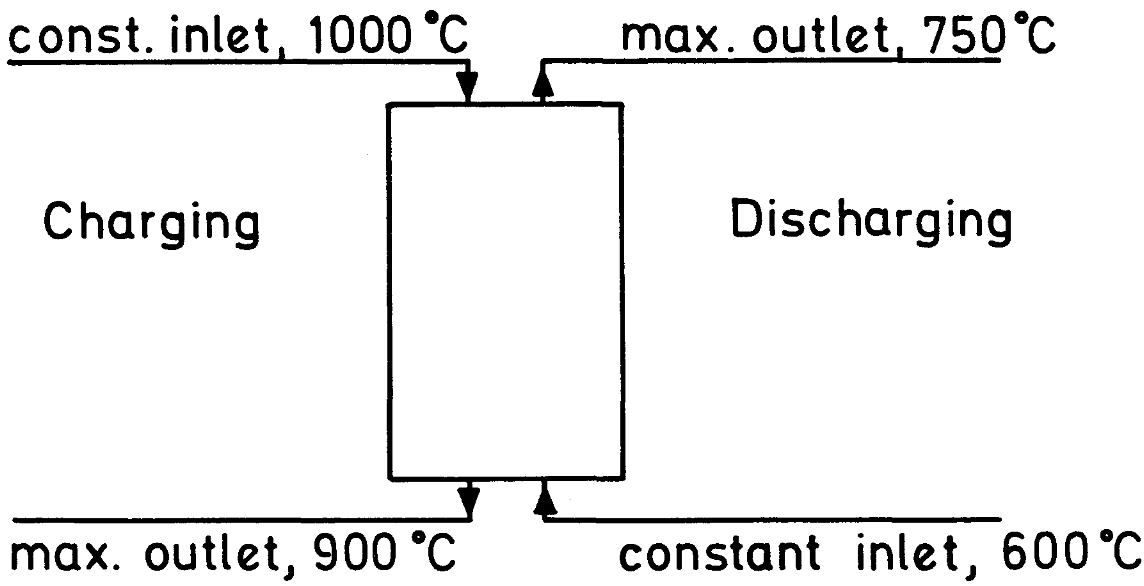
RADIALES TEMPERATURPROFIL EINES SPEICHERZYL. MIT ZEIT ALS PARAMETER

TIME DEPENDENT TEMPERATURE CURVES OF A SINGLE, CYLINDRICAL SALT CERAMIC ROD (SEGMENT 12, RADIAL)



CYLINDER RADIUS

TES MODEL



Design Data

Storage Module, 10 MWh

Storage Module

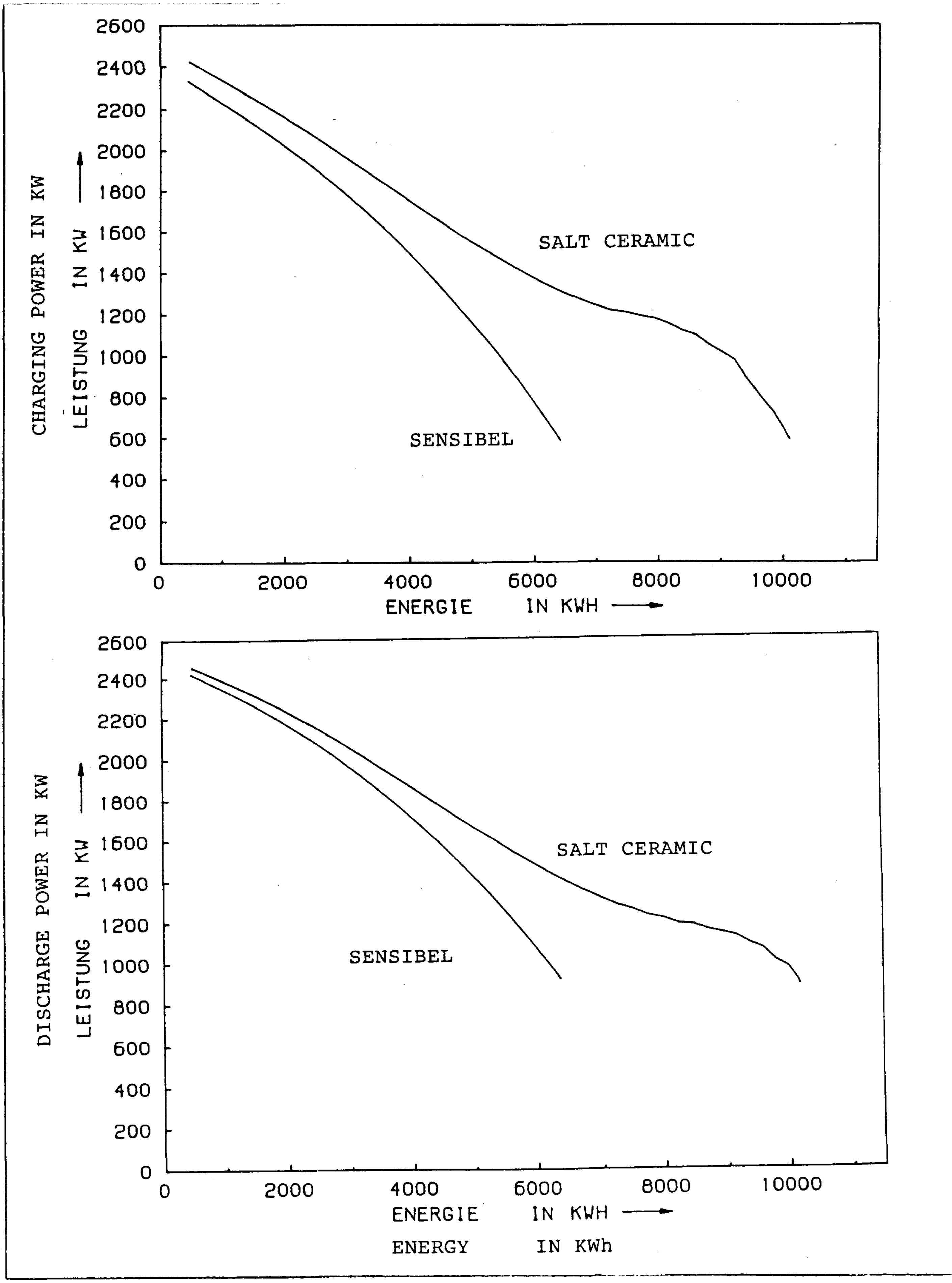
height	10 m
diameter	2 m
volume	31 m^3

Heat Carrier Gas

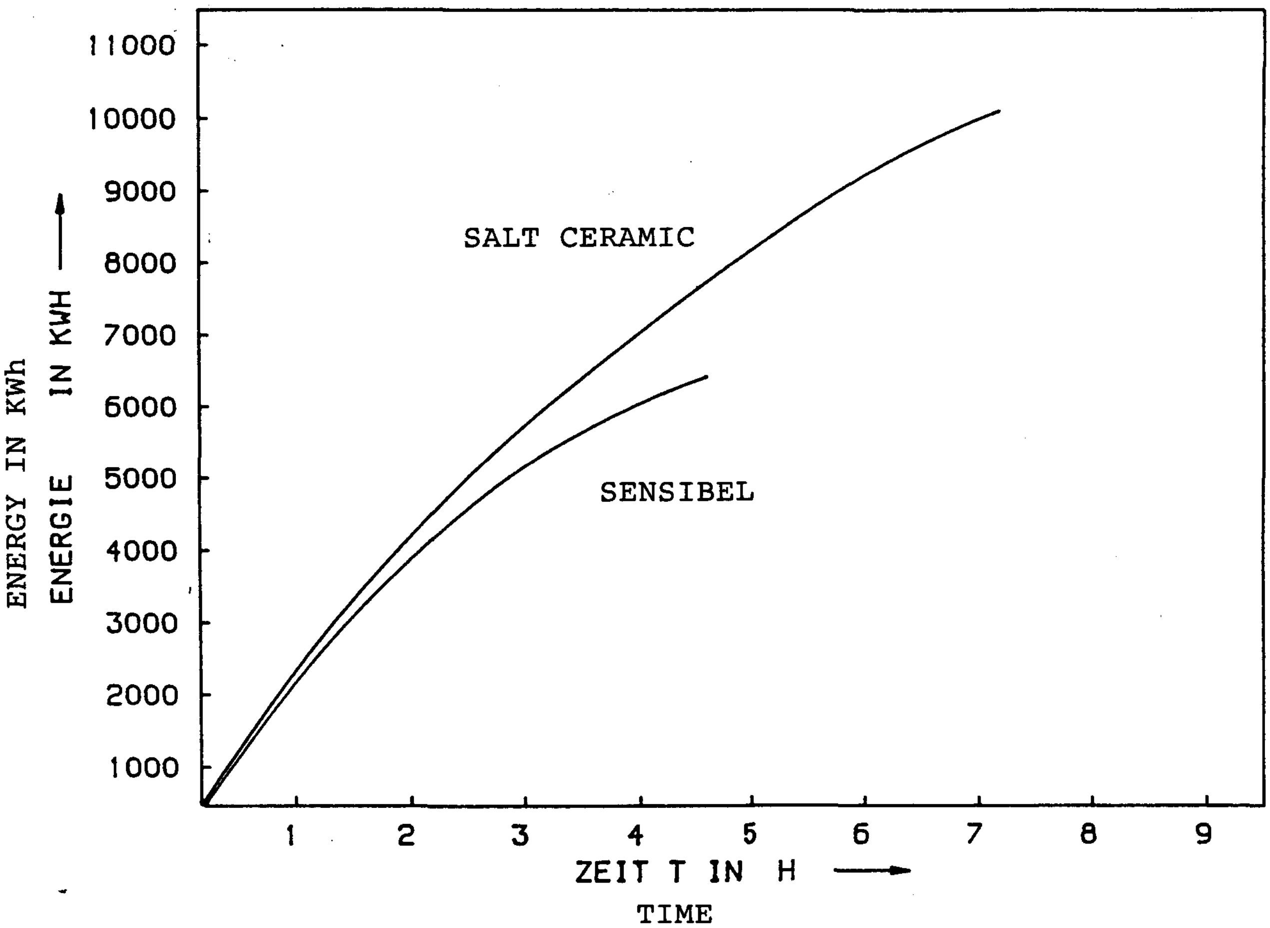
air	
volume flow	3500 m^3/h
pressure	20 bar
specific heat	1 J/g K

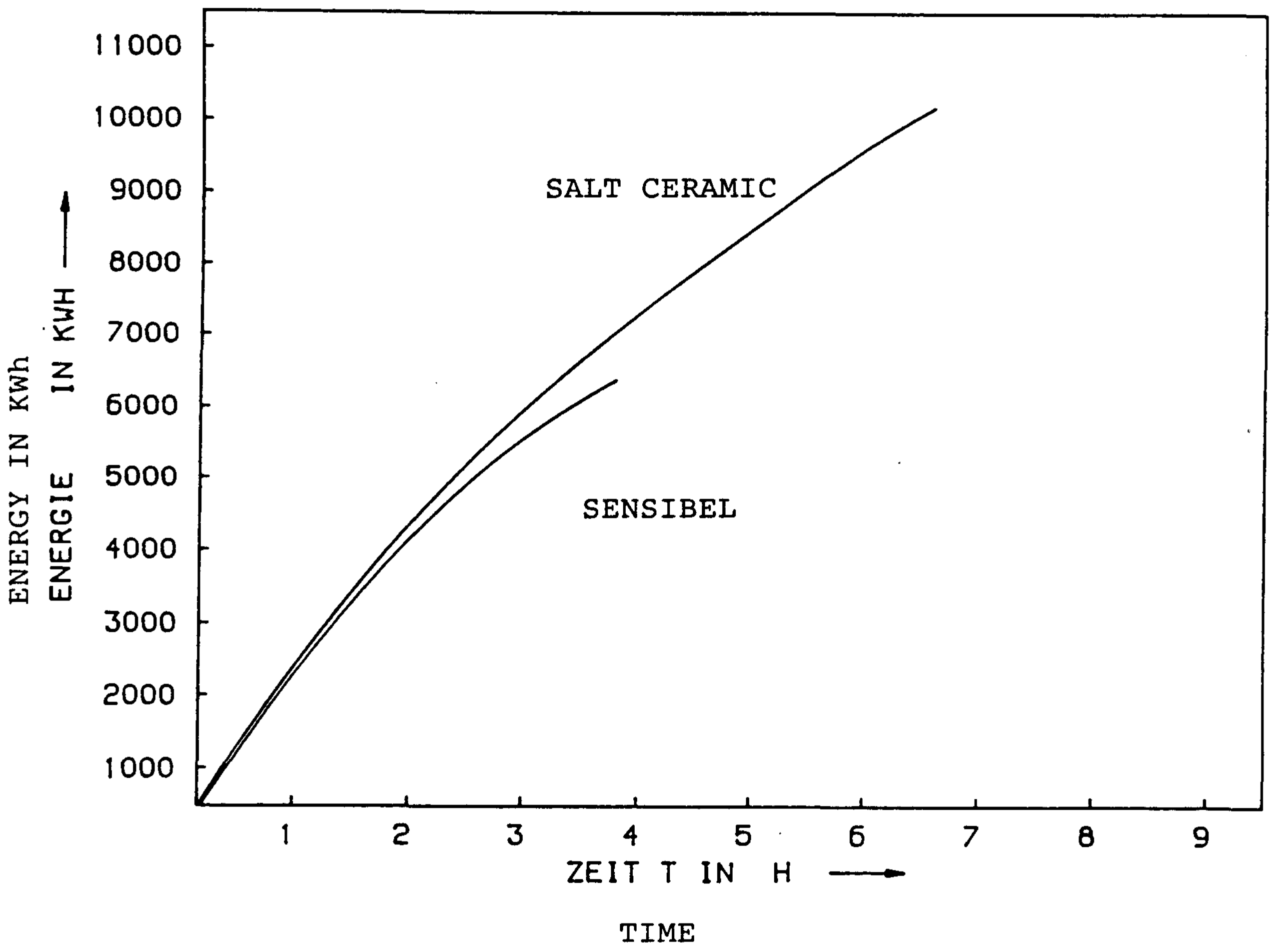
Storage Material

cylindrical shape	
radius	0.1 m
filling factor	0.8
quantity, salt ceramic	62 t
quantity, MgO ceramic	72 t
surface	496 m^2

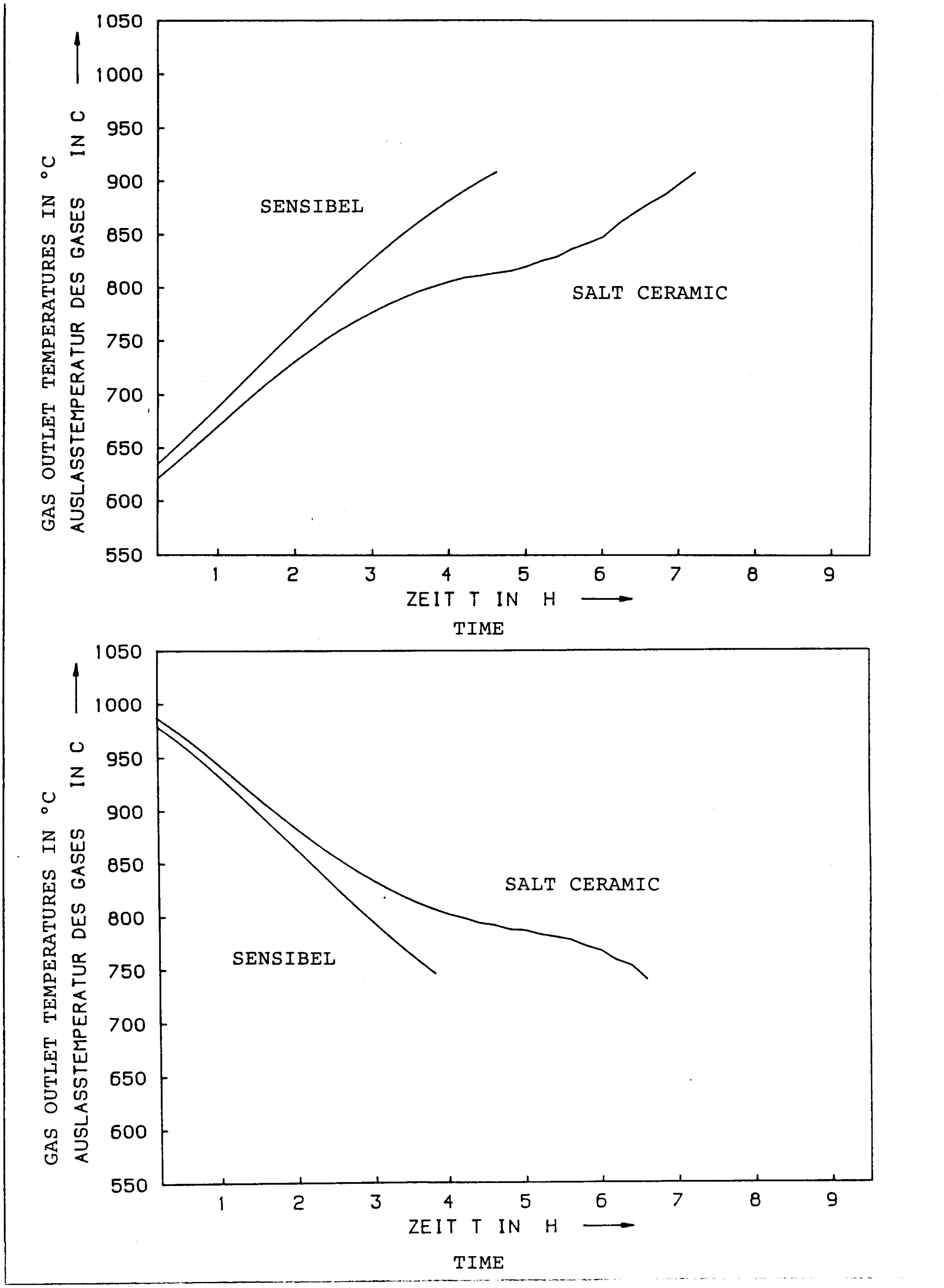


Charge and Discharge Power for the Charging (above) and Discharging (down) Process.

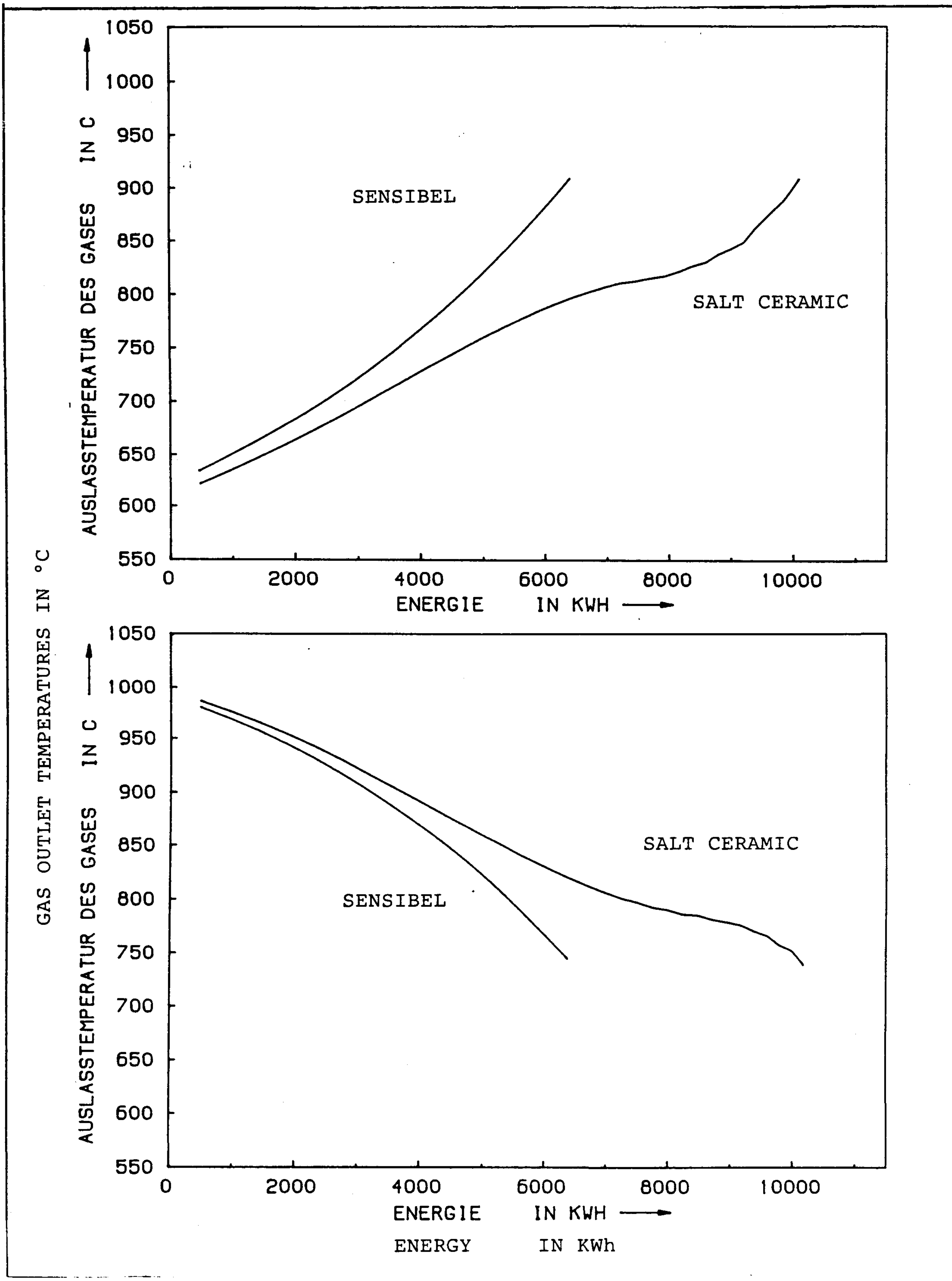




Energy Input for Charging (above) and Energy Output for Discharging (down).



Gas Outlet Temperatures for Charging (above) and Discharging (down) over Time.



Gas Outlet Temperatures for Charging (above) and Discharging (down)

Table: Storage Material Data Used for Cost Evaluation

material	bulk density	spec. heat	volumetric* capacity
	t/m^3	MJ/(t*K)	$MJ/(m^3*K)$
silica	1.82	1.00	1.24
chamote	2.10	1.02	1.45
silimanite	2.40	1.13	1.84
magnesite	3.00	1.15	2.35
cast iron	7.00	0.55	2.62

	fusion temperat.		heat of fusion MJ/(t)	heat of fusion $MJ/(m^3)$
salt/ceramic A1	450 ^0C	2.50	180.00	300.00
salt/ceramic A2	700 ^0C	2.70	70.00	126.00
salt/ceramic B	825 ^0C	2.50	250.00	416.00
salt/ceramic A3	990 ^0C	2.50	330.00	550.00

* filling factor 0.68

Vordr. 2 043

DIDIER-WERKE A.G.

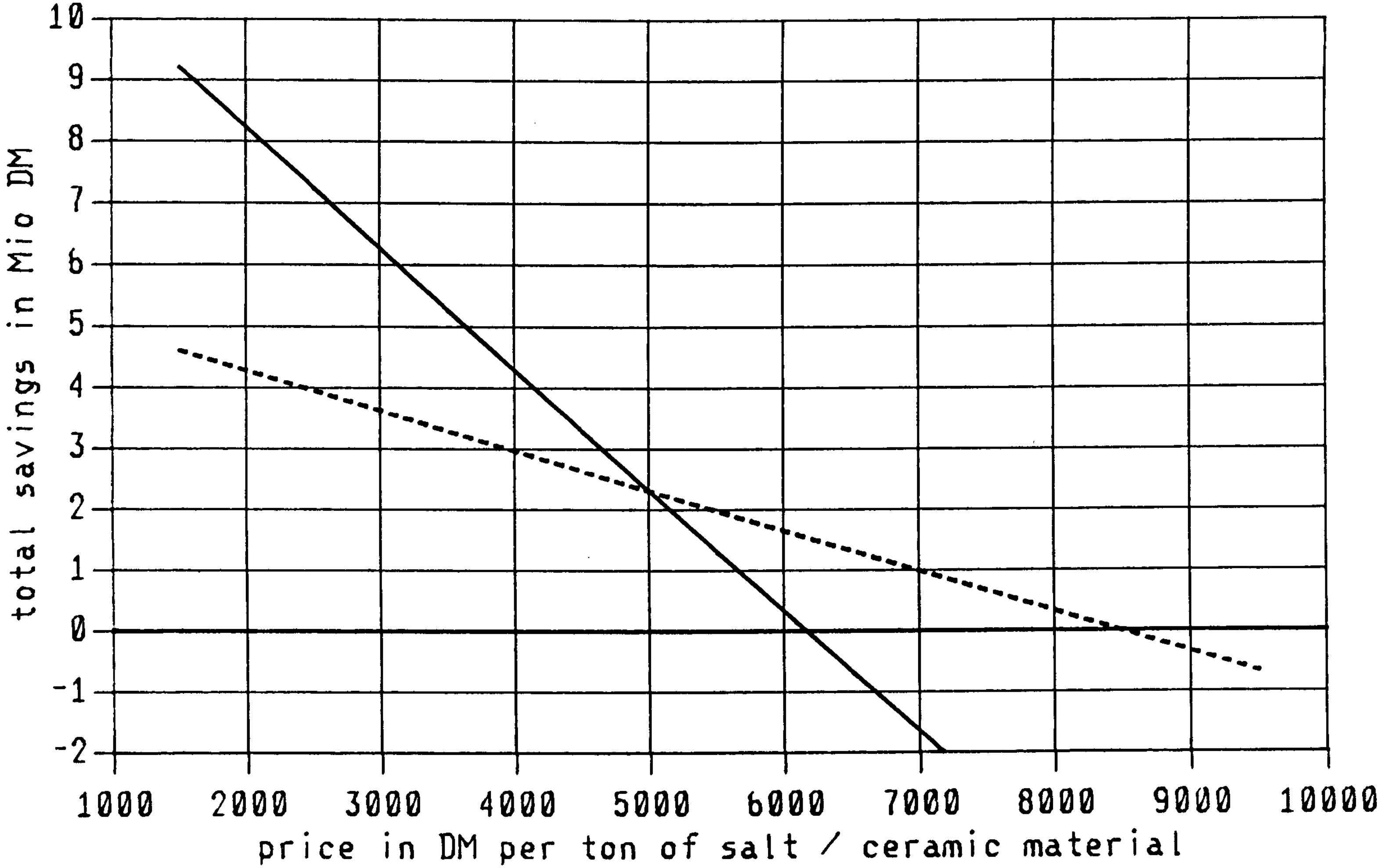
Kunde/Anlage

Maßstab

Datum

Gezeichnet/Gepr

COST IMPROVEMENT THROUGH HYBRIDMATERIAL USE



———	height of checker work 24 m including 9 m salt / ceramic (3 zones)
----	height of checker work 30 m including 3 m salt / ceramic (1 zone)

comparable stove: height 36 m, same performance assumed

PROPOSED TEST STORAGE DESIGN

- high pressure
- low pressure
- different temperatures
- high temperatures also at the bottom of the checker work (700 deg C)
- changing of the checker bricks must be very simple
- time for loading and unloading must be variable
- use of special checkers (hybrid material)

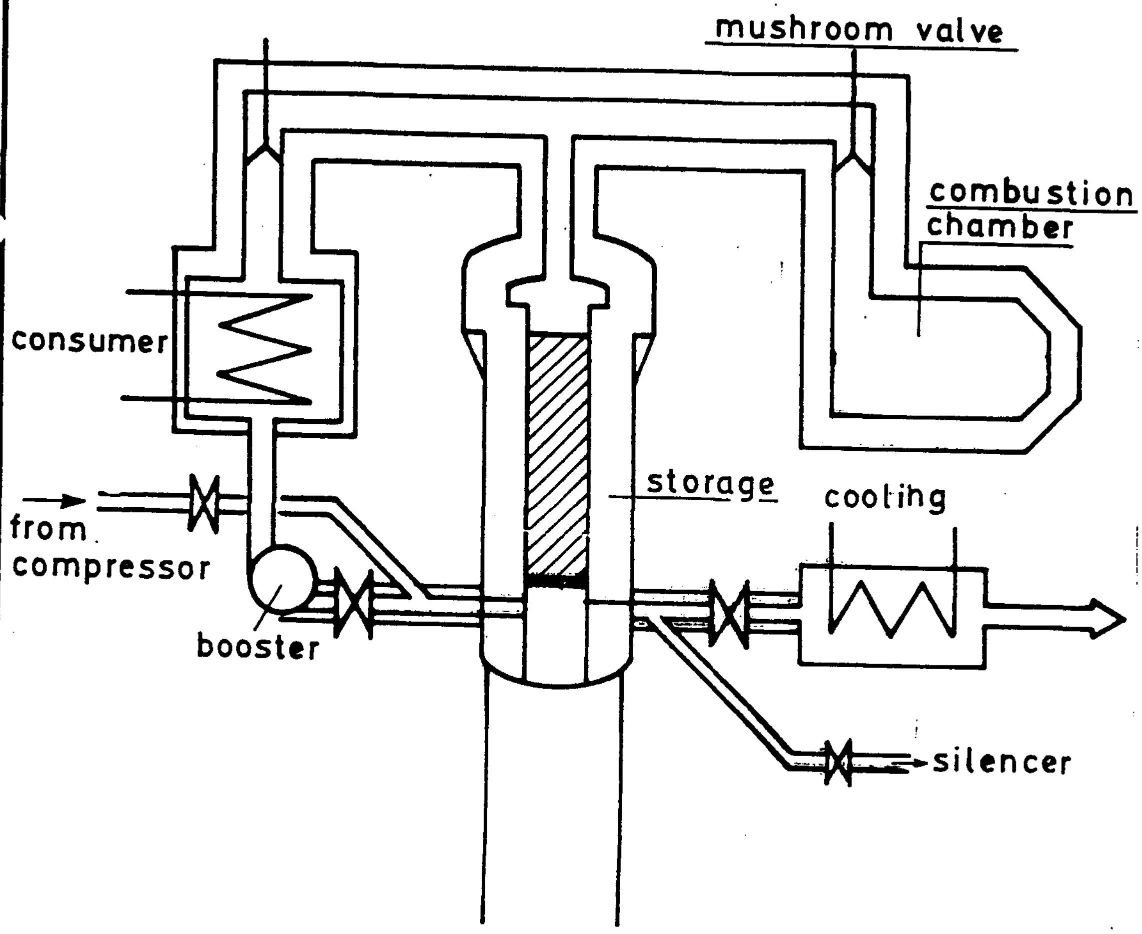
The following data are specified:

maximum temperature at the top	1300 deg C
maximum temperature at the bottom	700 deg C
maximum pressure when unloading	20 bar
pressureless loading with a burner	

The design of the checker is as follwos:

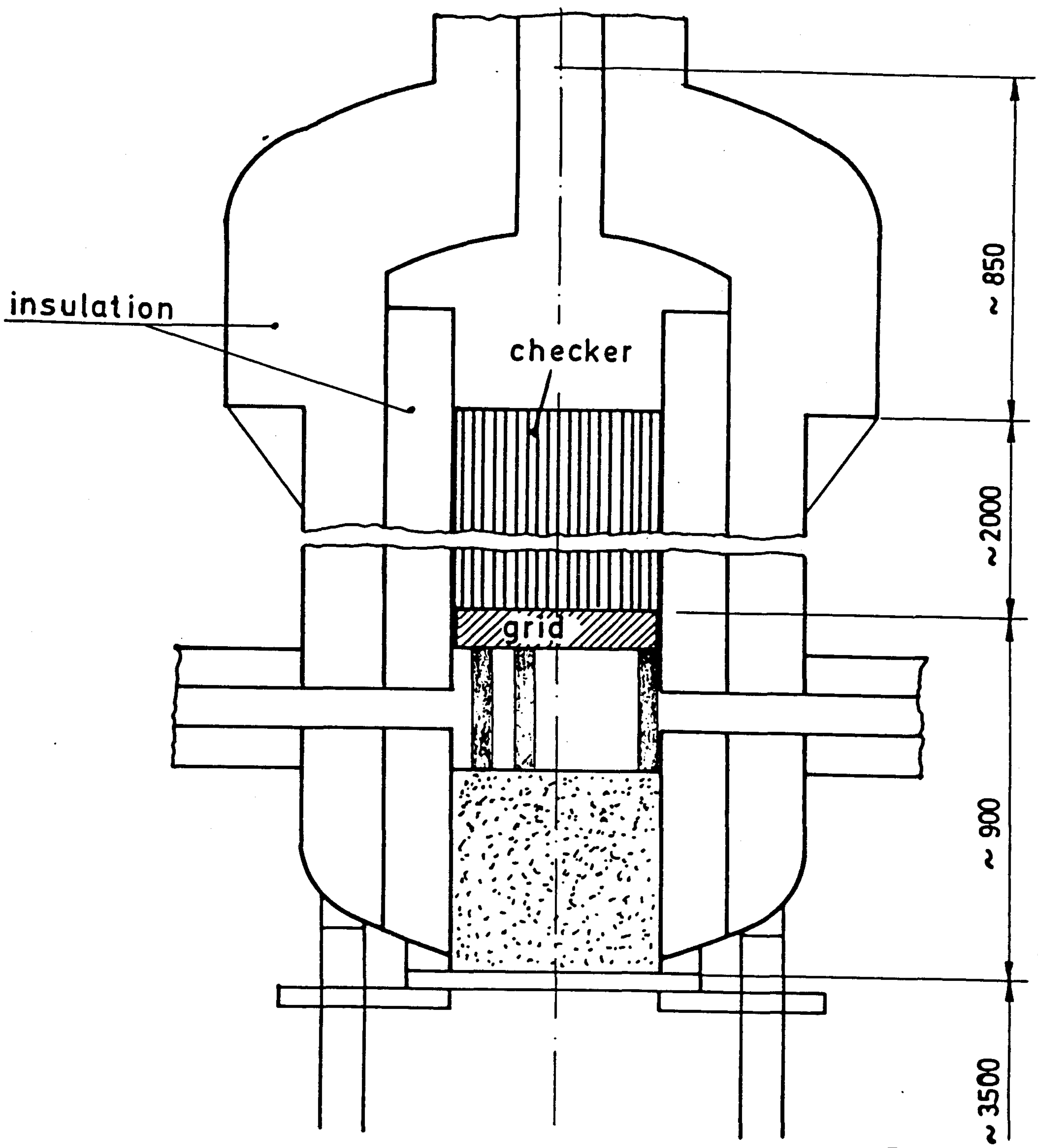
diameter of checker	500 mm
height of checker work	2000 mm
weight of checkers	700 kg
free cross-sectional area	40 %

COMPONENTS FOR TEST STORAGE



DIDIER-WERKE A.G.	Kunde / Anlage	Maßstab	Datum	
	DFVLR			TEP

TEST STORAGE UNIT , PROPOSED



DIDIER-WERKE A.G.	Kunde / Anlage: DFVLR	Maßstab	Datum	TEP

3.3.2

INTERMEDIATE TEMPERATURE INCREASED DENSITY STORAGE

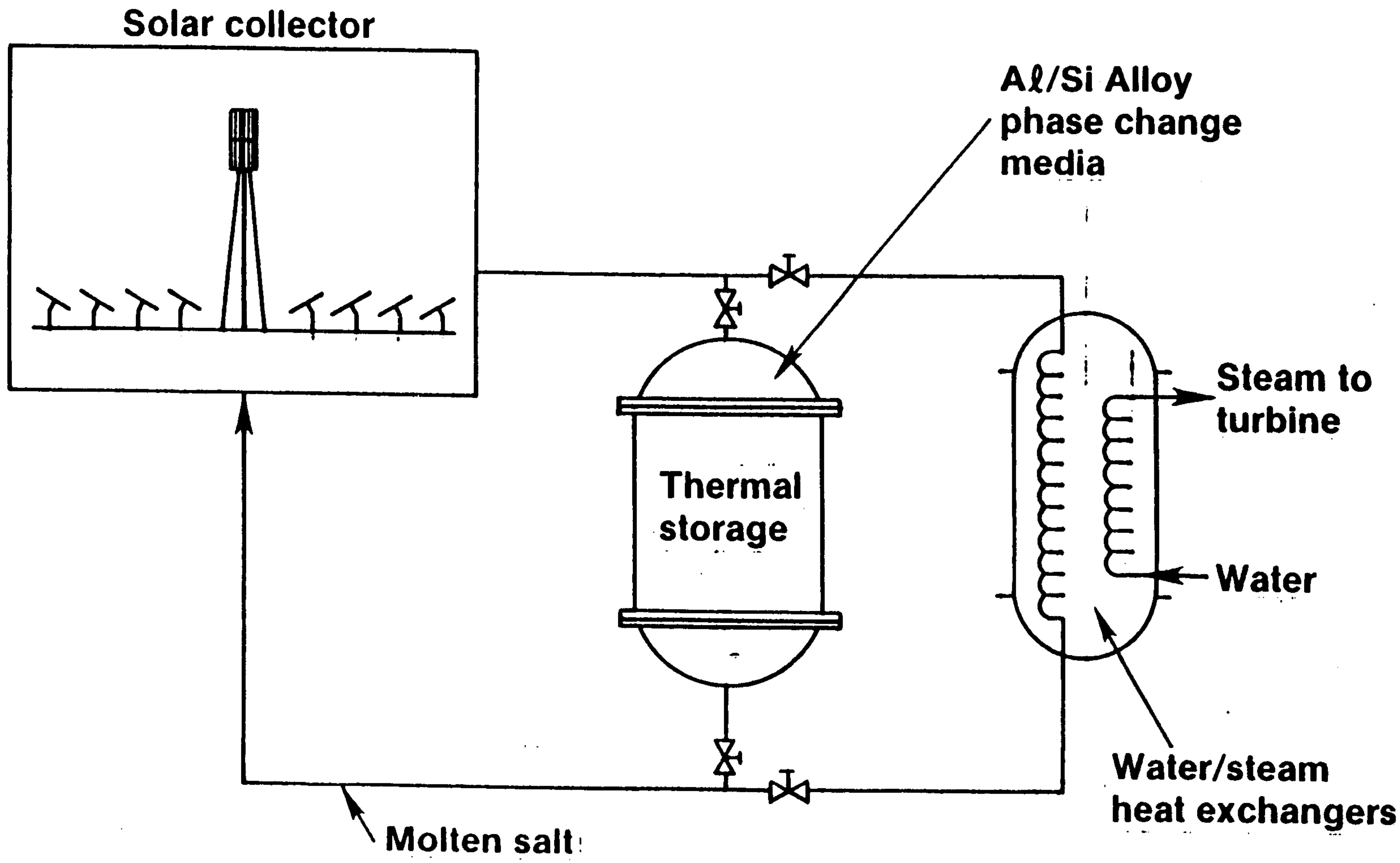
AND

DIRECT CONTACT HEAT EXCHANGE

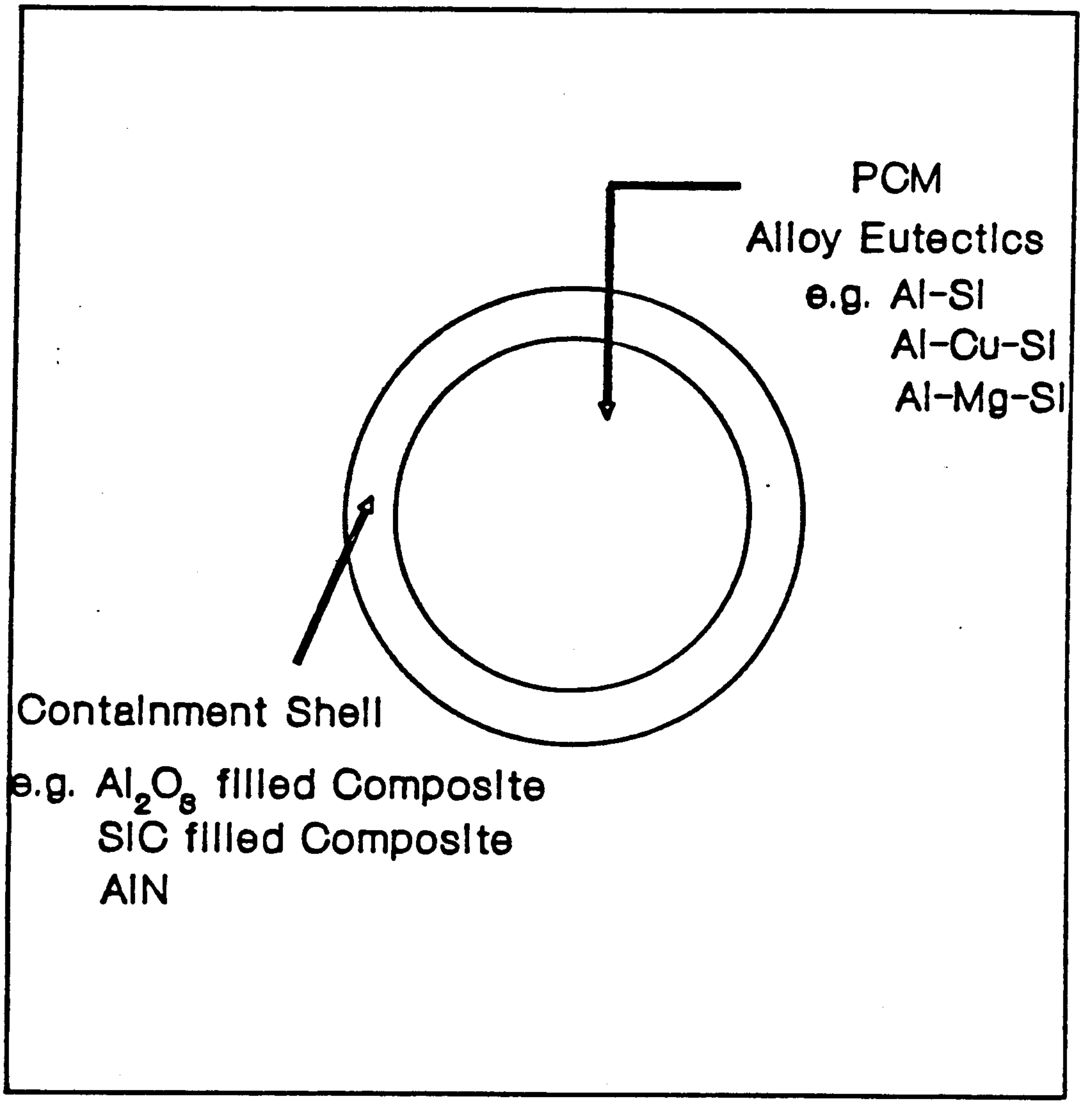
MARK S. BOHN
SOLAR ENERGY RESEARCH INSTITUTE

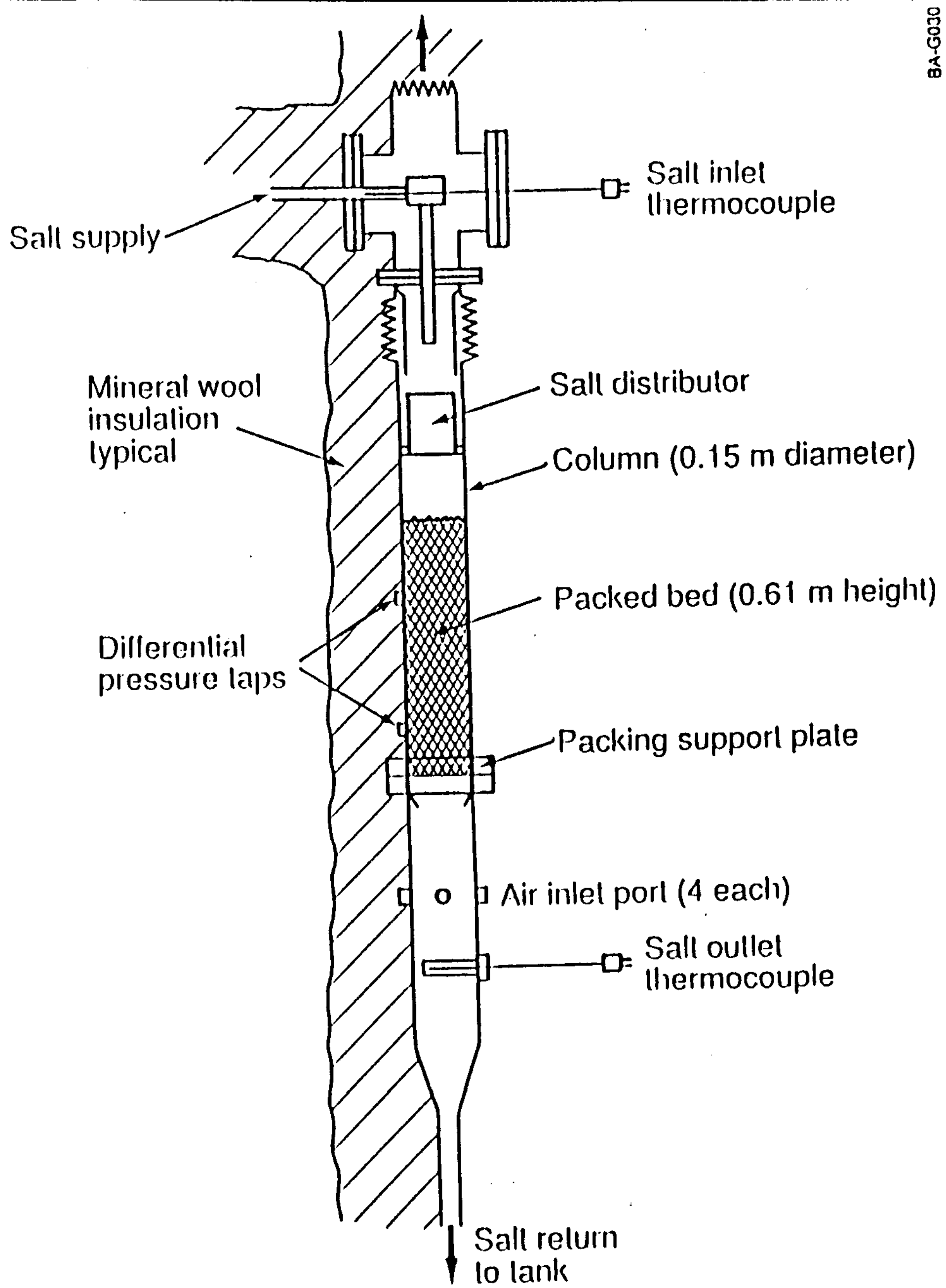
IEA/SSPS TASK IV MEETING
JUNE 22, 1988
GOLDEN, COLORADO

System Schematic

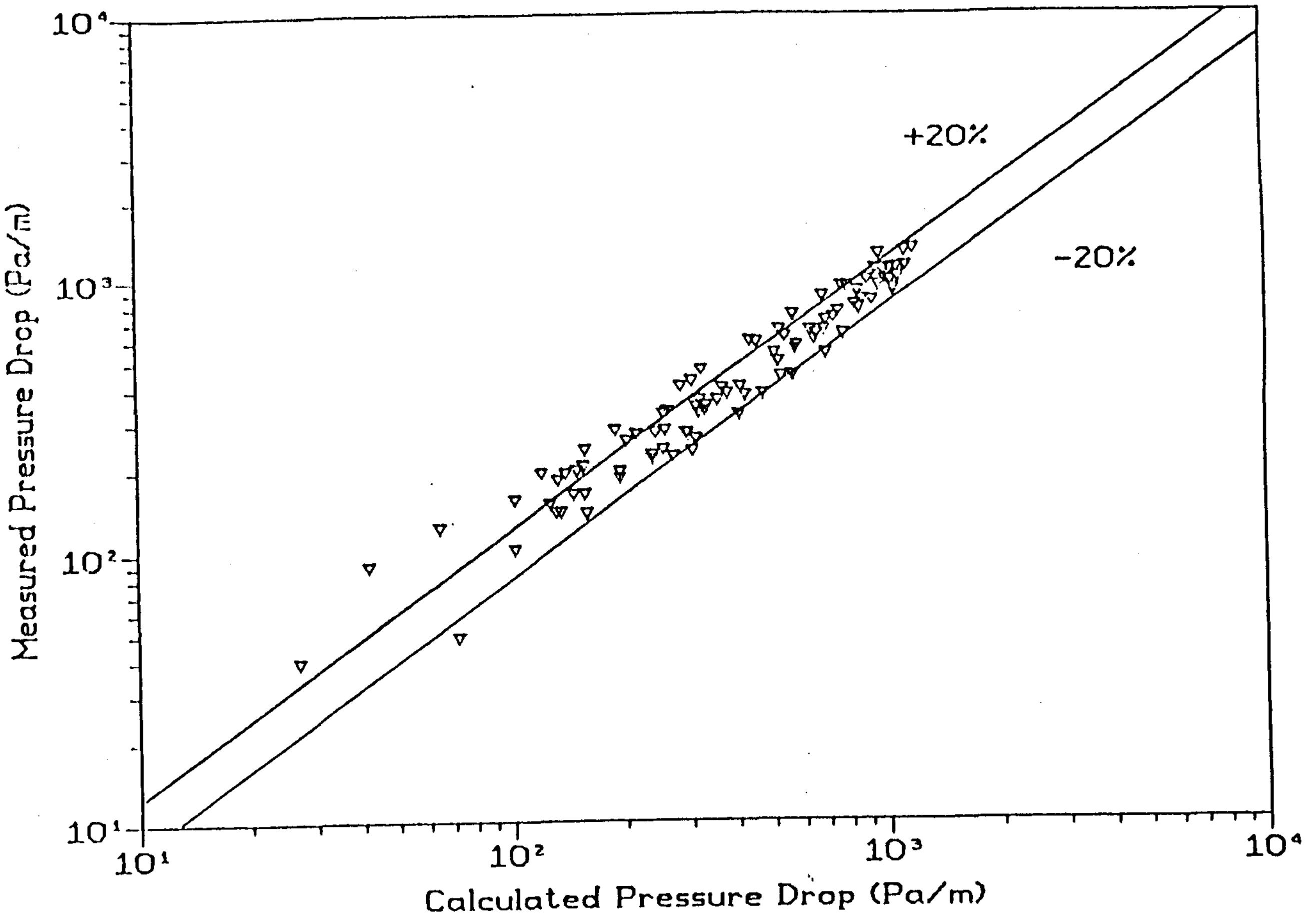


Schematic:
Lanxide™ Heat Storage Media

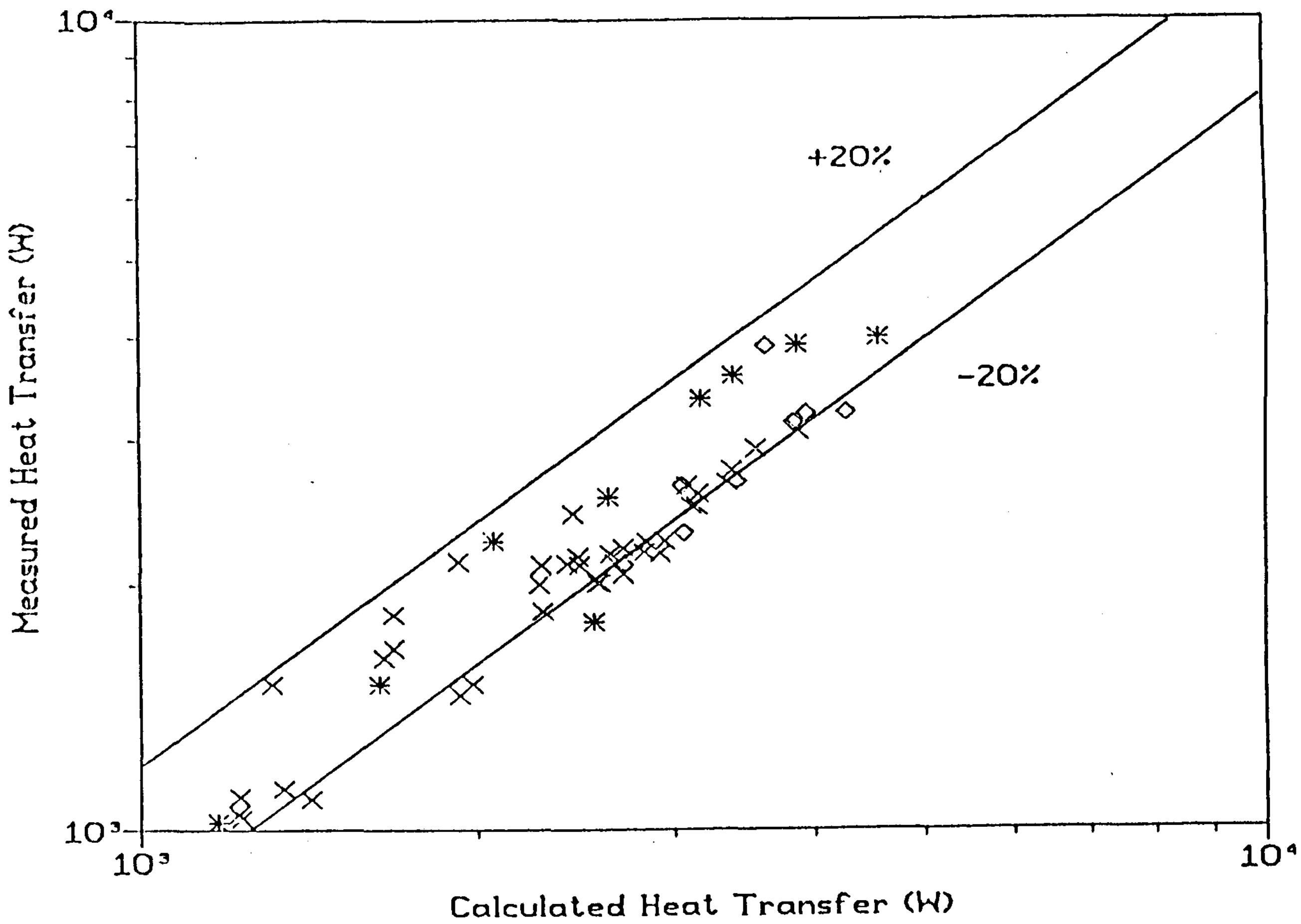




Direct Contact Heat Exchange Column Used for Experimental Determination of Pressure Drop and Heat Transfer in Air/Molten Nitrate Salt System



Comparison of Measured Pressure Drop with Value Predicted by Model (Air/Molten Nitrate Salt System)



Comparison of Measured Heat Transfer with Value Predicted by
Analytical Model
Direct Contact Heat Exchange between Air and Molten Nitrate Salt

3.3.3

Modeling of the CESA-1 Two-Tank Molten Salt Thermal Storage System

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Plataforma Solar de Almería,
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Tabernas, Almería, Spain

INTRODUCTION

The main components of a thermal storage system are the containers, heat exchangers, and the thermal fluid (in the CESA-1 storage system this is an eutectic mixture of salts $NaNO_3$, $NaNO_2$, and KNO_3). The heat exchangers in the CESA-1 storage system are not optimized regarding the energy exchange because of temperature drops inside them (1). Thus, they are not be included in this model, which covers the tanks and salts. In a storage system based on sensible heat, heat losses lower the temperature of the thermal fluid. This temperature drop depends on the mass of storage material inside the tanks, given the geometric and physical characteristics of the tanks, thermal fluid, and insulating material.

Temperature losses of the thermal fluid determine the system's capacity of work production, because:

- The total amount of available heat decreases.
- Engine efficiency (i.e., turbine) converting thermal energy to electricity decreases when the input power or temperature decrease.

The second reason is why it is useful to determine not only the heat available in the storage after a storing period, but also the temperature or temperature distribution at which this heat is available.

Since salt behaves as an insulating material due to its low thermal conductivity (K), and because of its transport properties, it takes a long time for temperature homogenization. On the other hand, the storage tanks are not symmetrical on the Z-axis, hence their heat losses differ due to the Nitrogen layer in the upper part of the tank and the supports in the lower part. Heat losses are different in different regions of the salt bulk, with resulting temperature distribution in the total salt volume.

To calculate this temperature distribution, two different states regarding heat losses have been considered:

- Steady state: There is no salt flow in the system, and there is salt enough in either the hot or cold tank so that the temperature drop in the salt bulk is small enough to be considered constant.

- Unsteady state: There is salt flow in the system and heat is added during the charging process or withdrawn during the discharging process to produce electricity to or from the system, respectively.

A numerical method was used to solve the differential equations governing the heat transfer between the different salt layers, and the ambient through the insulation and supports.

SYSTEM DESCRIPTION

The thermal storage facility of the CESA-1 plant was designed for three hours of plant operation, with 875 kWe output in discharging mode; this requires 4165 kWht as input in the discharging mode. The hot salt temperature is 340°C; the cold salt temperature, 220°C; and ΔT = 120°C for charging/discharging cycle.

The storage facility holds a total of 260 T salt with a $Cp = 1.3039 + 0.6066 \times 10^{-3}$ T kJ/kg°C (T in °C), and a maximum storage capacity of 12772.5 kWht or 2685 kWhe. The heat containers are two 200 m^3 tanks.

This system can be operated jointly with the turbine. It is installed outside the machine hall, between levels 0.2 and 14 m, and consists of:

- Charging system: three heat exchangers; a secondary hot well; water pump (P-04) to send the condensed water ($T \sim 240$°C) to the receiver once the heat exchange between steam/water and salt has taken place; and a salt pump (P-06) to drive the cold salt through the charging circuit.

- Salt storage tanks: two insulated carbon steel tanks, 4 m in diameter and 16 m long; both storage tanks are cylindrical. They are placed adjacently at level 4 m, with their axes oriented N-S on a slight tilt (1%).

- Discharging system: three heat exchangers (two overheaters and one steam generator); two salt pumps (P-04 and P-05) to drive the salt through the discharging circuit; and a feedwater pump (P-03) to supply the water required for steam production.

Two hot salt pumps feed the steam generator and overheaters (discharging circuit) and are located inside the hot tank. A cold pump (charging circuit) is located in the cold tank. They are coupled by a shaft to their drive motors at level 6.22 m.

The steam generator is cylindrical, placed above and between the two storage tanks, just below 8.545 m. Two overheaters are fed by the steam produced in the steam generator and are located above and between the two storage tanks at levels 7.655 m and 8.545 m.

The charging circuit consists in a cylindrical overcooler placed at level 7.867 m; a cylindrical secondary hot well, installed vertically at level 7.1 m; a condenser at level 11.648 m, feeding the secondary hot well where steam condensation takes place at P = 100 bar; and an overheater placed at level 13.394 m, where the salt undergoes its last heating to 340°C.

The receiver feedwater pump (P-02) is located in the next machine hall, at level 0.55 m. It works at 100 bar pressure ($\Delta P = 46.2$ bar). The whole storage system is inertized with a slight Nitrogen overpressure (0.2 - 1 bar).

THEORETICAL BACKGROUND

Different heat flows in the storage system are found between adjacent layers, and from one layer to the ambient through the insulation and tank supports. Two differential equations are used to determine the different heat flows:

- Inside the bulk of salt:

$$\nabla^2 T_s + \dot{Q}_s/K_s = 1/\alpha_s \, \partial T_s/\partial t$$

- Between the salt interface and ambient through the insulation:

$$\nabla^2 T_I + \dot{Q}_I/K_I = 1/\alpha_I \, \partial T /\partial t$$

The following was assumed to solve these differential equations:

- Heat losses through the tank support are balanced by the bottom salt layer.
- Nitrogen temperature is the same as that of the upper salt layer.
- Tanks support ends in an adiabatic floor.
- Heat conduction through the metallic shield of the tank is instantaneous, with regards to the heat conduction inside the salt bulk.
- Temperature of a salt layer is homogeneous.
- Heat generation inside the insulation is zero: $\dot{Q}_I = 0$.

Under these conditions, the following heat balances were assumed for each layer:

- Heat stored in layer i:

$$\dot{Q}_i = Cp_{si} \; \rho_{si} \; V \, (\partial T_{si}/\partial t)$$

- Heat exchanged between adjacent layers:

$$\dot{Q}_{i,\;i+1} = S_{i,i+1} \; (K_s/D)(T_{si+1}-T_{si})$$

$$\dot{Q}_{i,\;i-1} = S_{i,i-1} \; (K_s/D)(T_{si-1}-T_{si})$$

- Heat generation inside the salt bulk when freezing:

$$\dot{Q}_{si} = \dot{m}L$$

- Heat loss through insulatiion material in contact with layer i:

$$\dot{Q}_{i,a} = (K_i, S_i')(T_{is} - T_{Io}) \qquad (7)$$

where S_i is the effective conducting surface calculated for each layer (2).

- Heat loss from the external surface of insulation to the ambient:

$$\dot{Q}_a = h(T_{Io} - T_a)S \qquad (8)$$

A numerical method was used to solve equations (1) and (2), acounting for conditions (3) to (8) in each layer. These layers were constant in volume, and a total of 100 layers were used.

MODEL VALIDATION

The model was applied to both steady state and unsteady state.

Inside the tanks, temperature is measured at three levels--bottom, medium, and upper. The model takes the position of each thermocouple array as half of the height of the salt volume with uniform temperature, and calculates this temperature as the average of the layers included in this volume. For the steady state calculations, input values were the salt temperature distribution at the beginning of the tests. Figure 1 shows the agreement between the predicted and measured values for temperature distribution in the hot tank; similar results were determined for the cold tank.

For unsteady state, a simulation of the salt temperature distribution was made during the charging process. Figure 2 shows the comparison between the predicted and measured values. Maximum differences of [illegible] are found between the measured and predicted values. For this simulation, 40% of the layer volume was considered as perfect mixing due to the penetration of salt beam in the layer.

RESULTS

Temperature profiles of the salt in both hot and cold tanks have been calculated based on this model. Figure 3 shows these temperature profiles for different storage times (1, 6, 12, 18, 24, and 30 days) giving a temperature decrease in 30 days for the upper layer in the hot tank of 70°C from 340°C, or 0.3×10^{-4} °C/s. For the cold tank upper layer, this value is 39°C, or 0.15×10^{-4} °C/s.

Figure 4 shows the average temperature of both tanks for different filling ratios as a function of time; this graph shows the average temperature drop in the hot tank for a filling ratio of 100% as 0.4 x 10^{-4} °C/s. This value agrees well with experimental results (1).

Figure 5 shows the overall system thermal losses per kWht stored as a function of the filling ratio.

Thermal losses of the hot tank with 99% filling ratio are 19.2 kW; for the cold tank with 1 % filling ratio, 8.9 kW. Hence, overall thermal losses of the system for these ratios in the hot and cold tanks are 28.1 kW; the experimental value was 29 kW for these same conditions.

Input for the model are the tanks' geometrical characteristics; heat transport and physical properties of the tanks, insulation, and salts.

CONCLUSIONS

A simulation model of the CESA-1 storage system was developed. Its predictions fit reasonably well with experimental measured values. From this model, thermal energy losses were calculated giving precise information on system capabilities, from an electricity production point of view.

This model allows extrapolation of the results of the CESA-1 storage systems to bigger scale models, and can be used as a tool to calculate the behavior of these systems for industrial purposes.

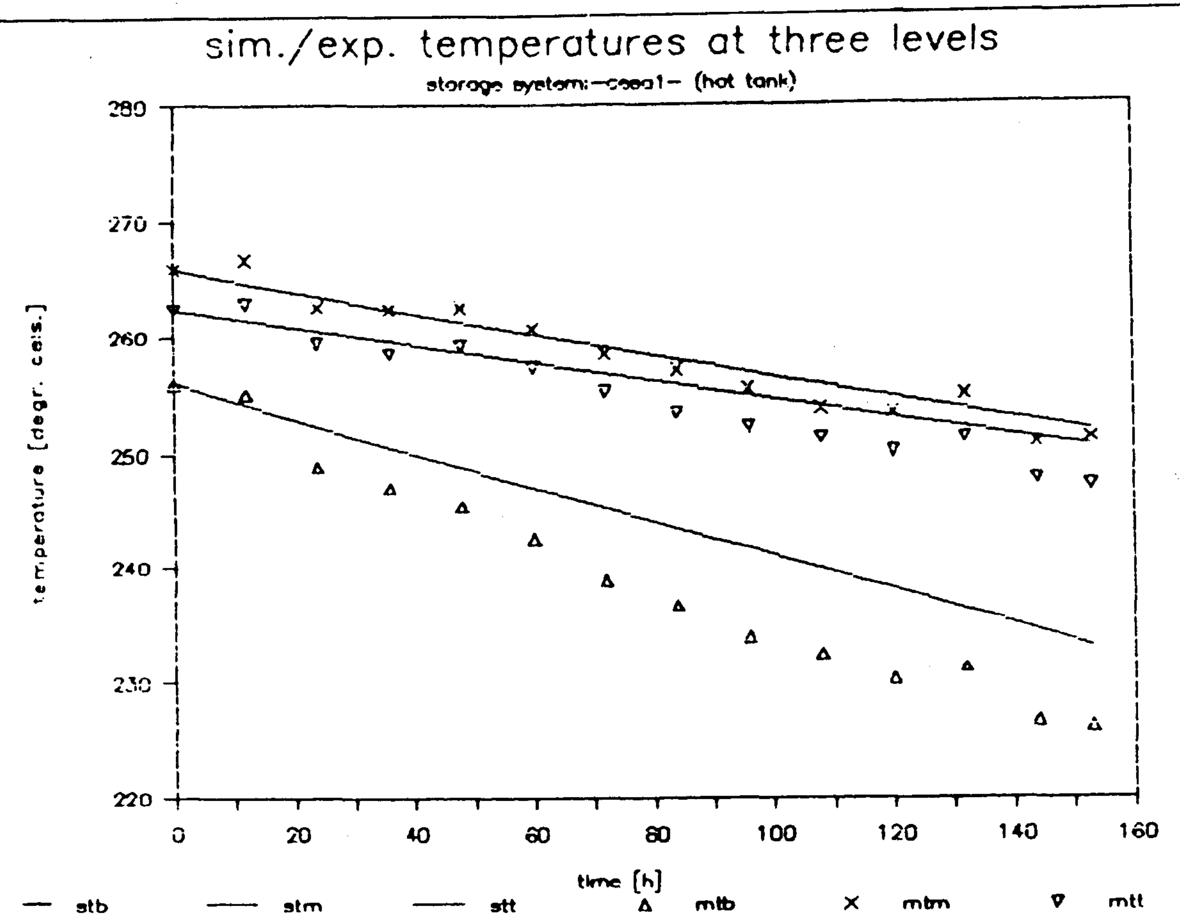
REFERENCES

1. J.M. Andújar, F. Rosa, 'CESA-1 Thermal Storage System Evaluation', Proceedings of the 2nd IEA/SSPS Task IV Status Meeting on High Temperature Thermal Storage, 24-25 August 1987.

2. Bronstein, Mathematischen Formeln, 1980.

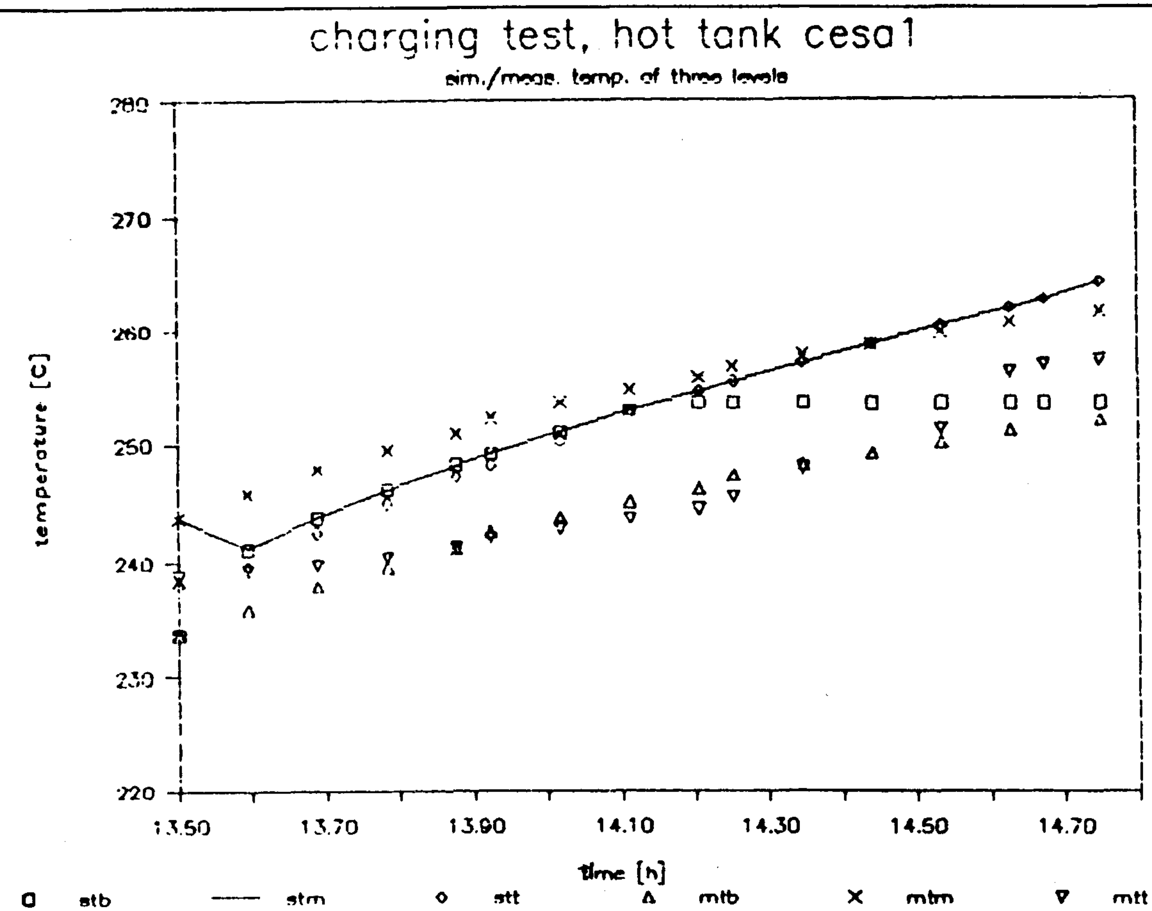
NOMENCLATURE

Cp_s = salt heat capacity
D = distance between the center of two adjacent layers
h = convective heat transfer coefficient
K_s = salt thermal conductivity
K_I = insulation thermal conductivity
L = salt latent heat
$\dot{m}$ = salt freezing rate
$\dot{Q}_I$ = rate of heat generation inside insuation
$\dot{Q}_s$ = rate of heat generation inside salt
Q_i = heat stored in layer i
$\dot{Q}_i$ = heat flow to or from layer i
$\dot{Q}_a$ = heat flow from the insulation to the ambient
S = surface
T_s = salt temperature
T_I = insulation temperature
T_a = ambient temperature
t = time
V = volumne
α_s = salt thermal diffusivity
α_I = insulation thermal diffusivity
ρ = density



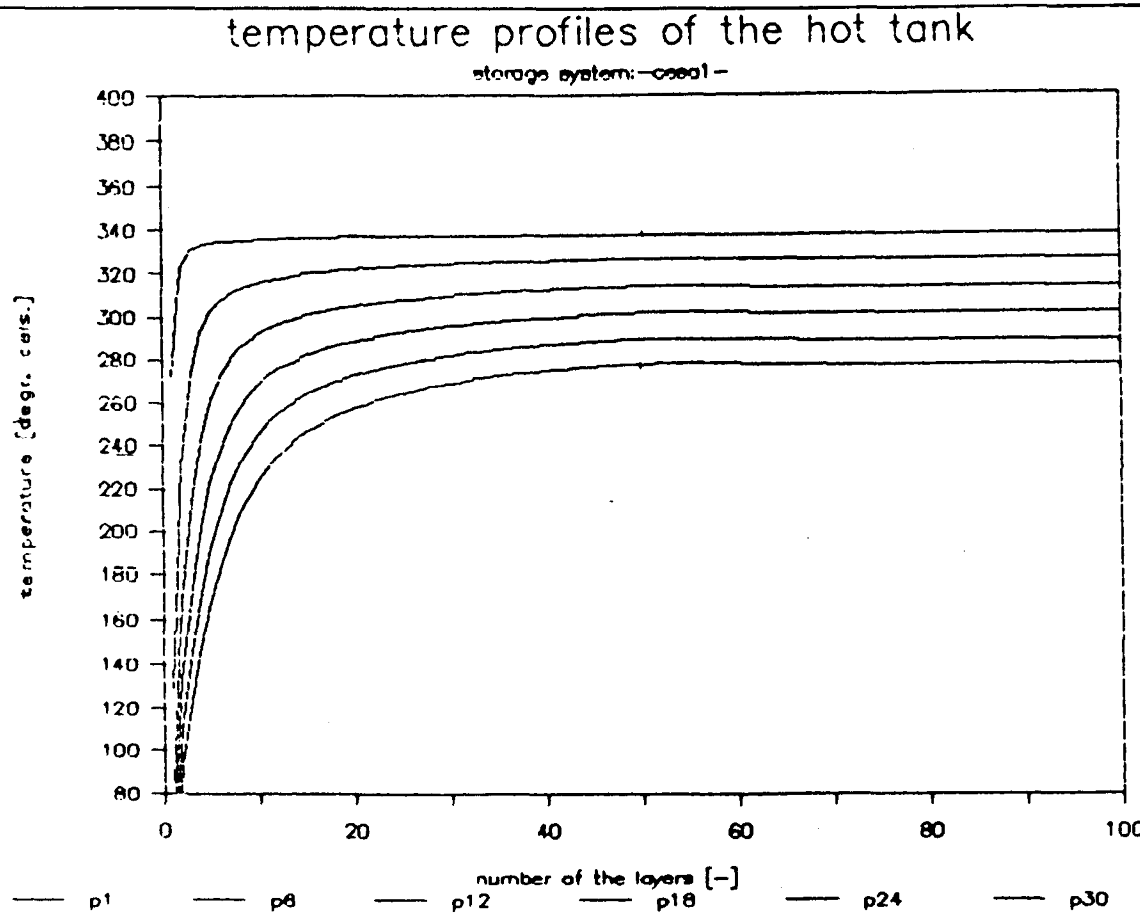
stb = simulated bottom temperature ; stm = simulated medium temperature ; stt = simulated top temperature
mtb = measured bottom temperature ; mtm = measured medium temperature ; mtt = measured top temperature

Figure 1. Simulated and experimental temperatures at three levels



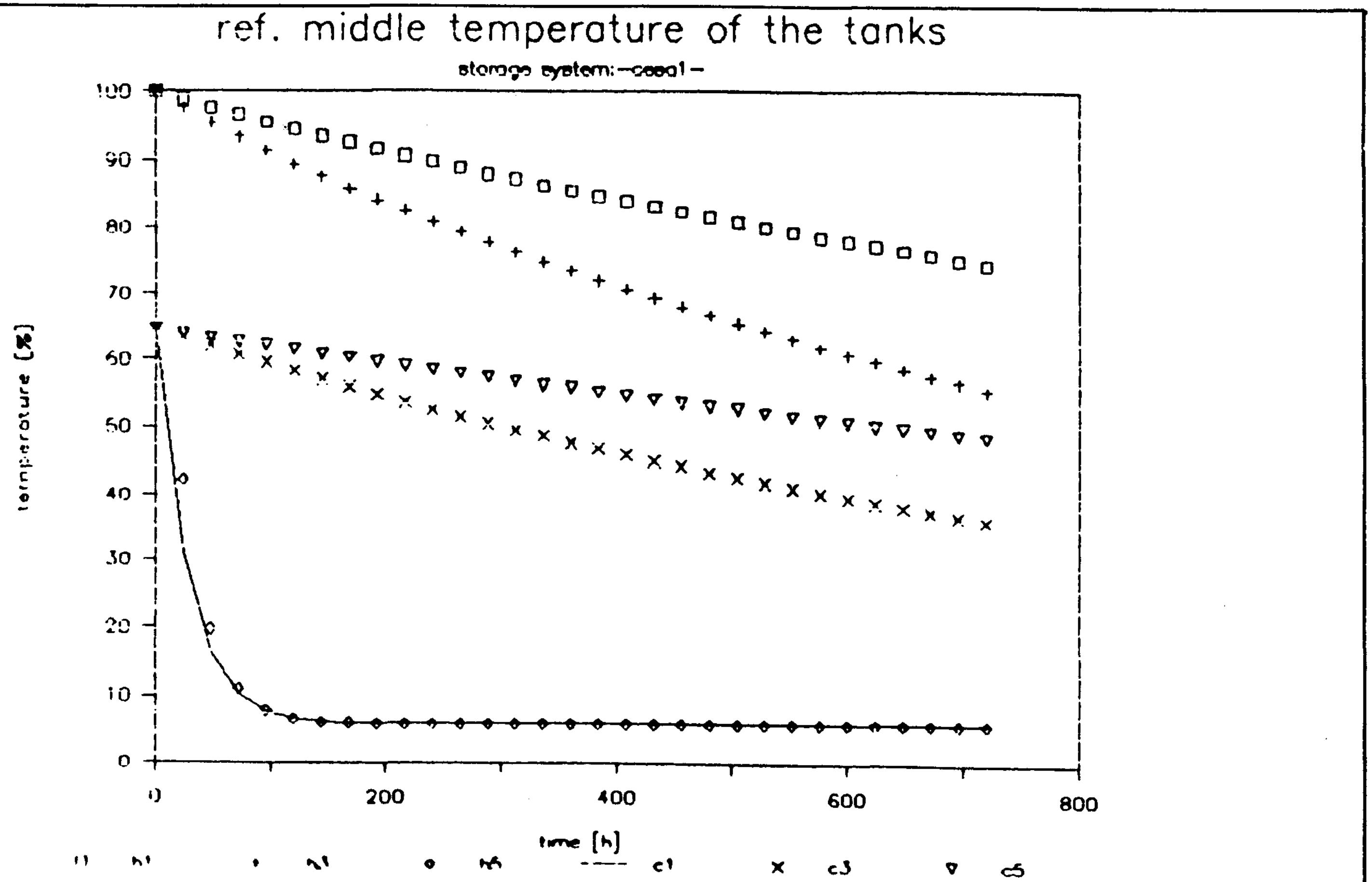
stb = simulated bottom temperature ; stm = simulated medium temperature ; stt = simulated top temperature
mtb = measured bottom temperature ; mtm = measured medium temperature ; mtt = measured top temperature

Figure 2. Charging test, CESA-1 hot tank



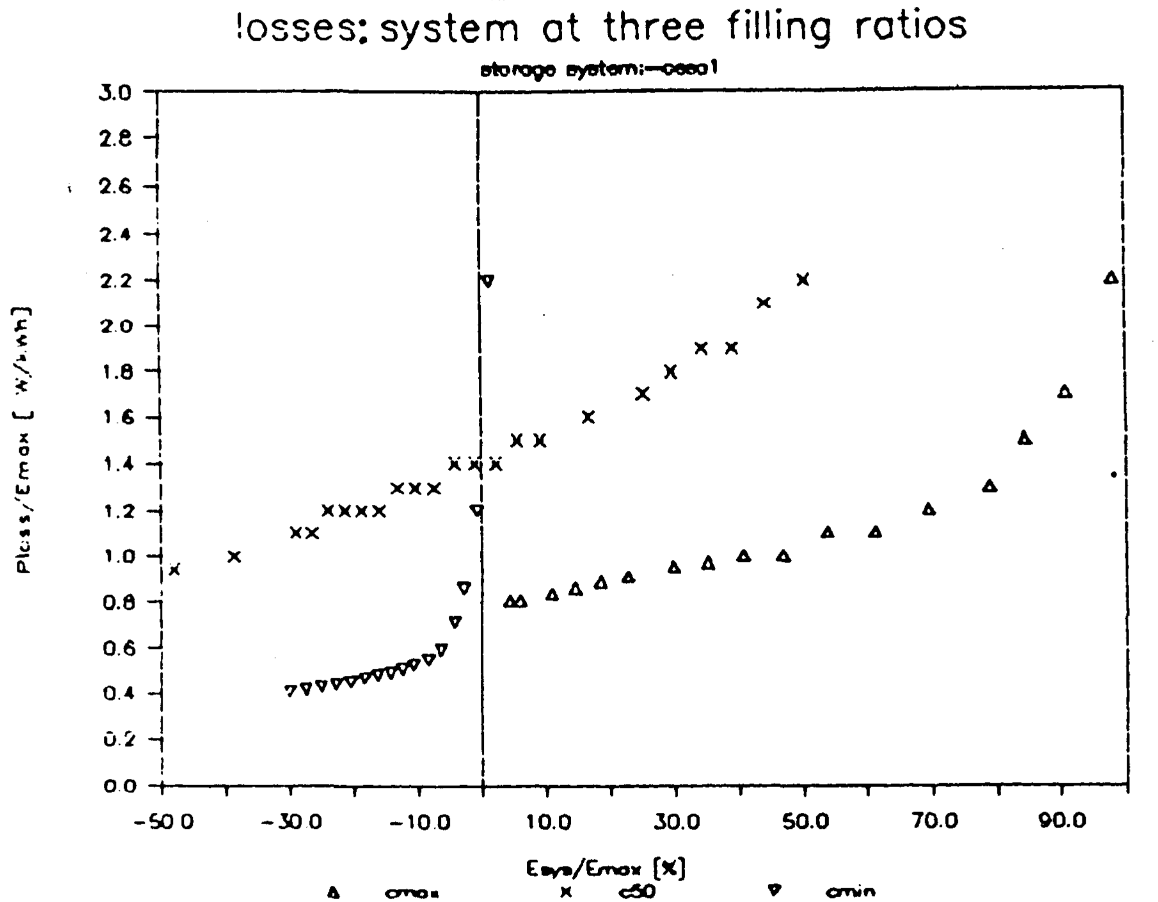
p1 = after one day's storage ; p6 = after six days' storage ; p12 = after twelve days' storage
p18 = after 18 days' storage ; p24 = after 24 days' storage ; p30 = after thirty days' storage

Figure 3. Temperature profiles of the hot tank



h1= 99% salt at 340°C in hot tank; h3= 50% salt at 340°C in hot tank ; h5= 1% salt at 340°C in hot tank
c1= 1% salt at 220°C in cold tank; c3= 50% salt at 220°C in cold tank; c5= 99% salt at 220°C in cold tank

Figure 4. Reference middle temperature of the tanks



cmax = 99% salt in hot tank at 340°C ; c50 = 50% salt in hot tank at 340°C and 50% salt in cold tank at 220°C ; cmin = 1% salt in hot tank at 340°C and 99% salt in cold tank at 220°C

Figure [illegible] System losses at three filling ratios

3.3.4

Advanced Latent Heat Storage Concepts for Intermediate Temperature Applications (LUZ-Systems)

A: direct contact heat exchange

B: salt/ceramic hybrid materials

Rainer Tamme
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Pfaffenwaldring 38-40
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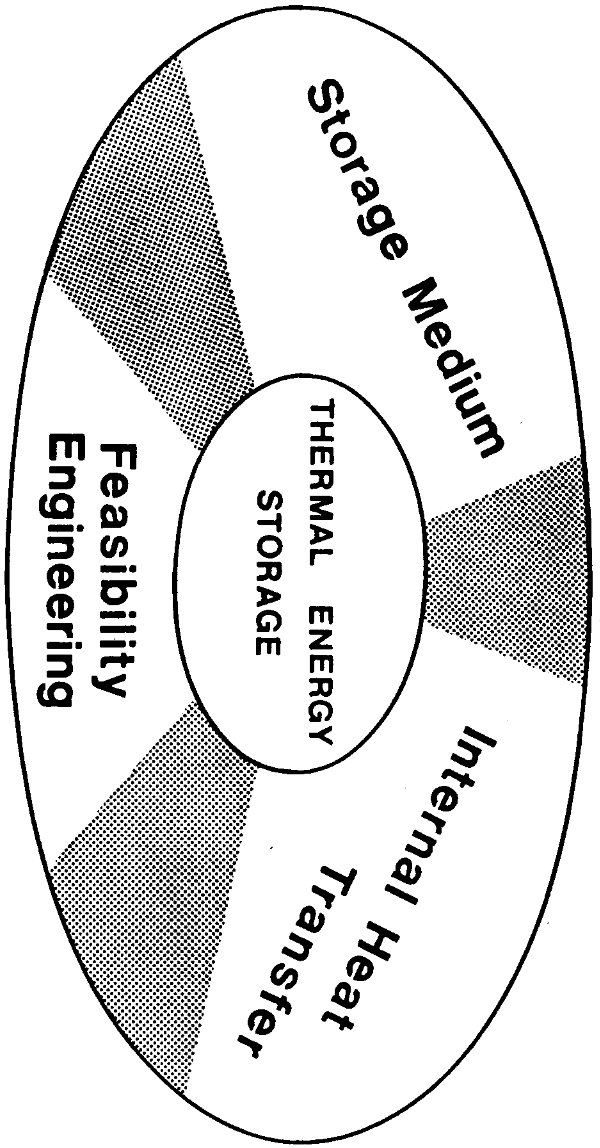
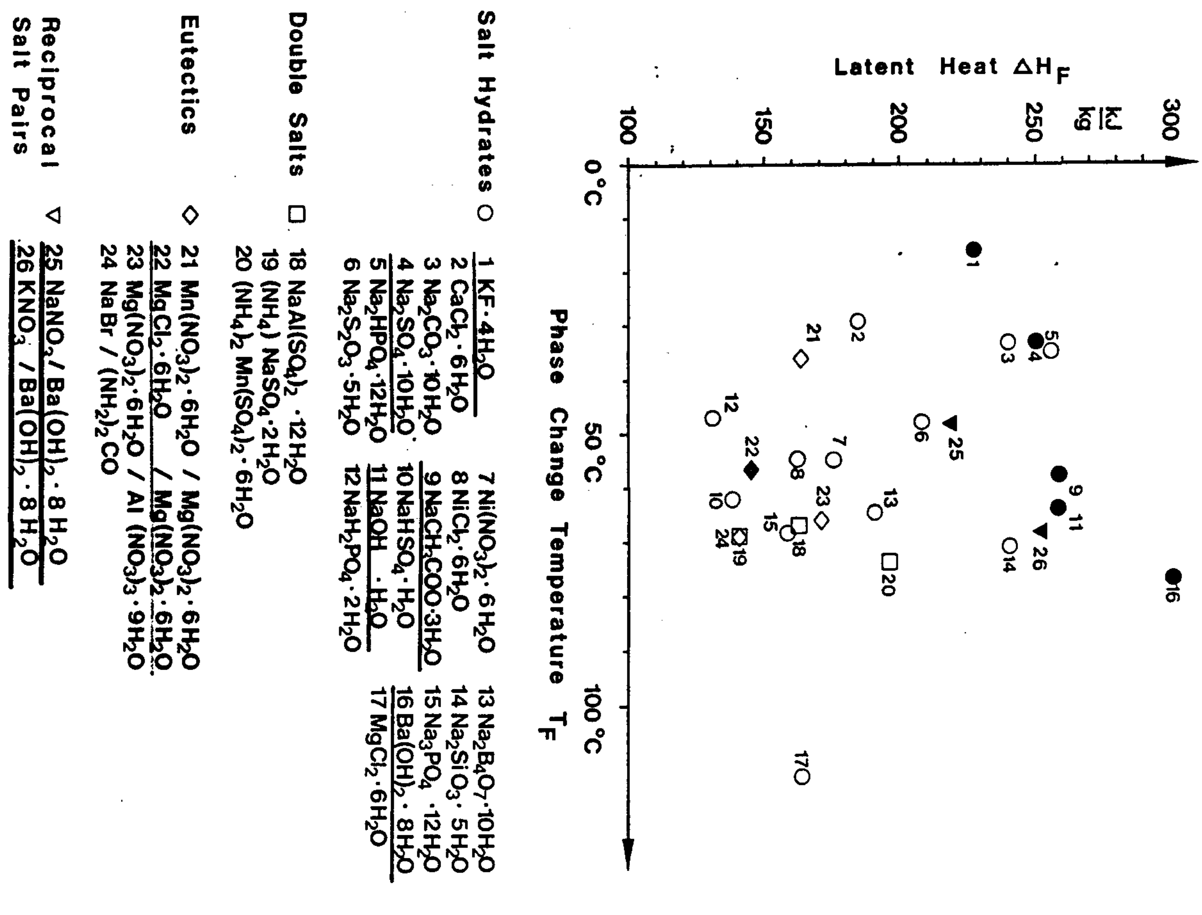


REQUIREMENTS

- Immiscibility of the storage medium and the heat transfer fluid
- Solidification in separate crystals
- Reversibility of the phase change process
- No interaction between salt and heat carrier oil

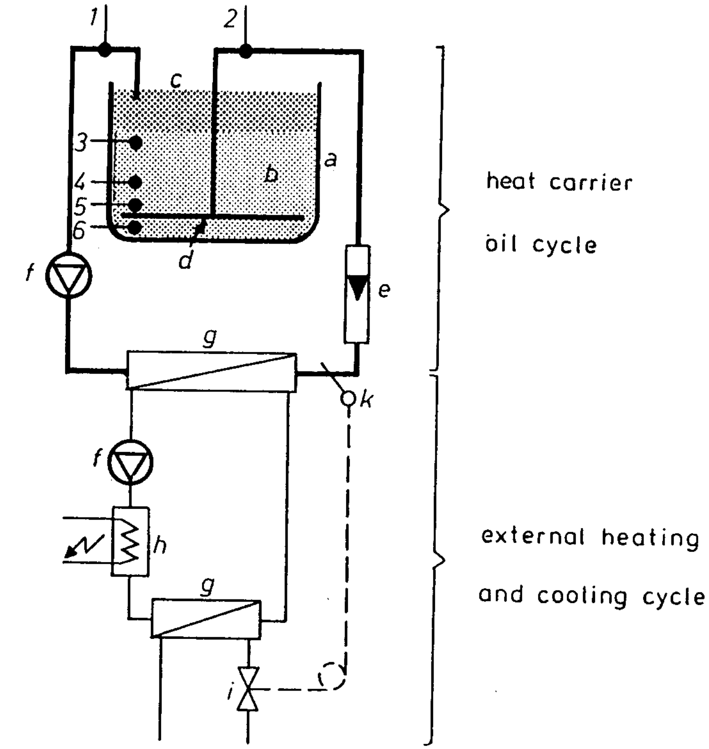


Salt Hydrate System*	Number of Tested Media Compositions	Heat Carrier Oil	Temperat. Range °C	Number of Discharge Tests
$MgCl_2 \cdot 6H_2O/Mg(NO_3)_2 \cdot 6H_2O/H_2O$	3	HVS 13	40 - 70	45
$NaOH$ / $NaOH \cdot H_2O$ / H_2O	3	HVS 13	50 - 70	66
$NaCH_3COO \cdot 3H_2O$ / H_2O / $NaOH$	3	HVS 13/WM 2	40 - 70	130
$Ba(OH)_2 \cdot 8H_2O$ / H_2O	4	HVS 13/WM 2	60 - 90	102
RSP I / H_2O / NaOH	4	HVS 13	30 - 50	37
RSP II / $H_2O/Ba(OH)_2 \cdot 8H_2O$	5	WM 2	50 - 70	61

* Main compound is underlined

KEY PROBLEMS OF LAB-SCALE TESTS

- Crystallizing and melting behaviour
- Stability of the salt system
- Reversibility of the phase change process
- Interaction between the salt and the heat carrier oil
- Appearance of detrimental salt carry-over



a: storage tank with storage medium (b) and heat carrier oil (c)

Properties of Used Heat Carrier Oils

Properties	HVS 13 at 60 °C	WM 2 at 80 °C
density, kg/ℓ	0.78	0.81
viscosity, c St	1.75	5.4
therm. conductivity, W/(mK)	0.12	0.13
specific heat, kJ/(kgK)	2.08	2.16

Conclusions

- Storage capacity of TES varies depending on the useful heat carrier exit temperature and on the useful discharge power

---

- 70 – 90 °C / [illegible] °F applications

  Barium Hydroxide Storage using DCHX

  $Ba(OH)_2 \cdot 8H_2O$; $T_F = 78\,°C / 172\,°F$

  $\Delta H_F = 300\ kJ/kg$

  300 l Model ; BH III

  5 – 12 h storage ; 110 – 120 kWh/m^3 $\left\{ \begin{array}{l} \sim 70\% \\ \sim 85\% \end{array} \right\}$

- 50 – 70 °C / 120 – 155 °F applications

  Sodium Acetate Storage using DCHX

  $CH_3COONa \cdot 3H_2O$; $T_F = 58\,°C / 137\,°F$

  $\Delta H_F = 260\ kJ/kg$

  1000 l Model ; NA II

  6 – 15 h storage ; 75 – 85 kWh/m^3 $\left\{ \begin{array}{l} \sim 85\% \\ \sim 100\% \end{array} \right\}$

MATERIALS AND PROCESS ENGINEERING
FOR HIGH TEMPERATURE STORAGE

REQUIREMENTS FOR NEW APPLICATIONS

→ Solar Thermal

→ Industrial Process Heat

- closed loop
- charge/discharge cycles up to 16 h
- cold blast temperatures up to 500 - 800 ^{o}C
- pressure above 10 bar

→ Conclusions

- new storage materials with higher energy density
- modified design and construction, new checker support systems

REQUIREMENTS

for
Solar Thermal Applications
and
Industrial Process Heat Storage

- closed loop
- charge/discharge cycles up to 16 h
- coldt blast temperatures up to 500 - 800 ^{o}C
- pressure above 10 bar

CONCLUSIONS

- new storage materials with higher energy density
- modified design and construction, new checker support systems

ADVANCED STORAGE MATERIALS

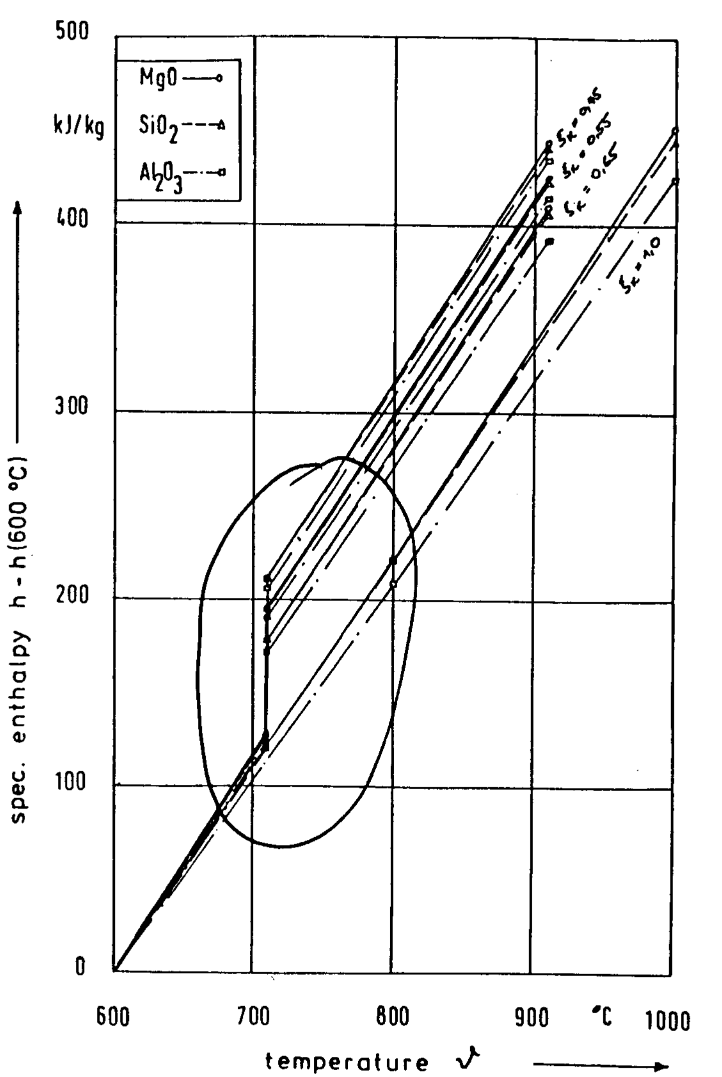
KEY PROBLEMS

- chemical stability of the system "salt-ceramic"
- thermal stability of the hybrid material
- strength of the solid structure above the melting point
- influence of thermal cycling
- compatibility with the heat carrier

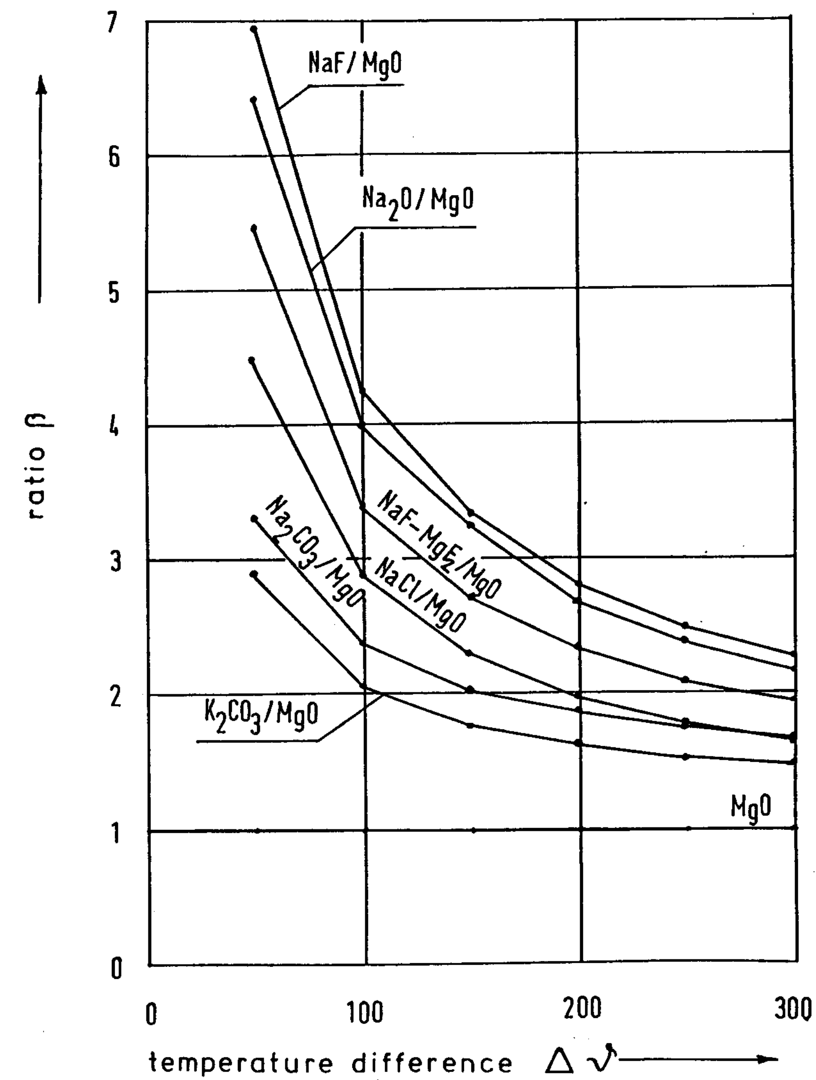
- transfer into a technical product
- demonstration of long term stability
- development of economic manufacturing processes

matrix \ phase change material	salt	metal
oxid ceramic	Na-Ba-CO_3/MgO Na-Mg-F /MgO IGT, USA ORNL, USA DFVLR, D	
metal		AlSi / Si Al / Ni ORNL, USA Ohio Univ., USA

formation by <u>microencapsulation</u>
<u>macroencapsulation</u>



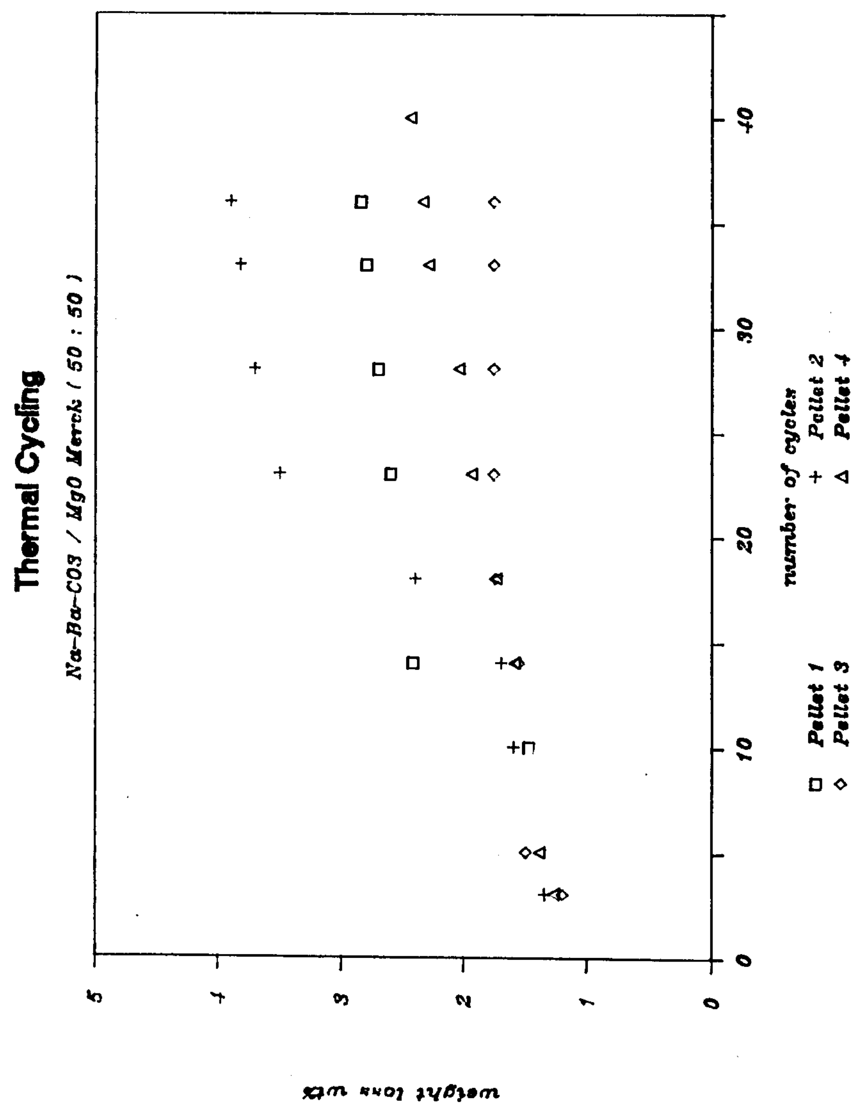
Temperature dependence of specific enthalpy of selected Na_2CO_3- $BaCO_3$/Ceramic hybrid materials



Ratio of specific storage capacities of selected Salt/MgO hybrid materials (45 % salt by weight) and specific capacity of pure MgO-ceramic for different temperatures

Investigated Salt/MgO - Hybridmaterials

salt	salt content wt. %	temperature range, °C	results
Li_2CO_3 Na_2CO_3 K_2CO_3	50	250 - 550	very good stability, no cracking, used for TA
Na_2CO_3	50; 60	700 - 1000	good stability, after 40 thermal cycles weight loss
Li_2CO_3	50	580 - 880	good stability, no cracking significant weight loss during thermyl cycling
KCl KF K_2CO_3	50	380 - 680	no stability, decomposition of the salt
NaF	40; 50	840 - 1140	low stability, formation of cracks, no molten salt retention
NaF CaF_2 MgF_2	40; 50	600 - 900	good stability, no molten salt retention
LiF KF	40; 50	340 - 640	low stability, cracking during thermal cycling
NaCl $NaNO_3$	50	150 - 450	good stability, no cracking
$LiNO_3$ KNO_3 $NaNO_3$	50	70 - 270	good stability, no cracking
$NaNO_3$ KNO_3	50	180 - 380	good stability, no cracking
$FeCl_3$ NaCl	50	100 - 250	low stability, no molten salt retention



Results of $NaF-MgF_2/MgO$

particle size salt µm	salt content wt. %	density g/cm³	compressive strength at 930 °C g/cm²
0 - 50	30	2,3	> 200
5 - 100	30	2,4	> 200
100 - 200	30	2,4	200
0 - 50	35	2,4	200
50 - 100	35	2,4	200
100 - 200	35	2,4	200
50 - 100	40	2,4	low
100 - 200	40	2,4	low

Presen Status of Lab-Scale Materials

$Na_2CO_3-BaCO_3/MgO$

45 wt.% salt hybrid material
50 wt.% salt sandwich

cold pressed pellets:
26 mm diameter ~ 20 g

$D = 2.6$ g/cm³, $T_F \sim 700$ °C

$Q_{\Delta T} = 300$ K ~ 420 kJ/kg

→ ~ 300 kWh/m³

Compressive strength =
1100 g/cm²
stacked arrangement of ~ 3 m

$NaF-MgF_2/MgO$

35 wt.% salt hybrid material

cold pressed pellets:
26 mm diameter - 18 g

$D = 2.4$ g/cm³, $T_F \sim 825$ °C

$Q_{\Delta T} = 300$ K ~ 580 kJ/kg

→ ~ 390 kWh/m³

Compressive strength ~
200 g/cm³
stacked arrangement of ~ 0,8 m

4. IEA - SSPS Task IV Status Meeting
Davos, August 27, 1990

4.1 Agenda

1. Adoption of Agenda

2. Present Status of Task IV (R. Tamme, DLR)

3. Status and 1989/90 Results of Subtask IV.2 "Development of Composite Salt/Ceramic Materials" (R. Tamme, A. Glück, DLR and C. Streuber, DIDIER-Werke AG)

4. Report on Storage Activities at Paul Scherrer Institute (A. Meier, PSI)

5. Report on further Storage Activities

   - Status of Storage Program at the Weizmann Institute of Science (as guest M. Epstein, WIS)

6. Miscellaneous

4. IEA - SSPS Task IV Status Meeting
Davos, August 27, 1990

4.2 Participants

Name	Institution
A. Roy	Ben Gurion University, Israel
H. Bastek	KfA-BEO Jülich, Germany
A. Meier	PSI, Würenlingen, Switzerland
J. Rheinländer	ZSW, Stuttgart, Germany
M. Epstein	WIS, Rehovot, Israel
A. Glück	Didier / DLR, Stuttgart, Germany
C. Streuber	Didier-Werke AG, Wiesbaden, Germany
A. Kogan	WIS, Rehovot, Israel
H.P. Boßmann	ABB, Heidelberg, Germany
U. Taut	Universität Stuttgart, Germany
R. Tamme	DLR EN-TT, Stuttgart, Germany
B. Gupta	SERI, Golden, Colorado, USA
W. Meinecke	DLR MD-ET, Cologne, Germany
M. Becker	DLR MD-ET, Cologne, DLR
P. Heinrich	Fichtner, Stuttgart, Germany
M. Sanchez	CIEMAT, Plataforma Solar, Spain
C. Winkler	PSI, Würenlingen, Switzerland
P. Delaquil	Bechtel, San Francisco, USA
H. Fricker	FCC, Richenbach, Switzerland

4. IEA - SSPS Task IV Status Meeting
Davos, August 27, 1990

4.3 Reports, Papers, Presentations

4.3.1 Investigation of High Temperature Storage Materials in a Technical Scale Test Facility (A. Glück, DLR)

4.3.2 Report on Activities at DIDIER-Werke AG (G. Streuber, DIDIER)

4.3.3 Sensible Heat Storage in Air/Rock Bed Systems (A. Meier, PSI)

4.3.1

SSPS Task IV Meeting, Davos, August 27, 1990

INVESTIGATION OF HIGH TEMPERATURE STORAGE MATERIALS IN A TECHNICAL SCALE TEST FACILITY

A. Glück

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ABSTRACT

For new industrial and solar applications of high temperature storage systems advanced storage materials with higher energy density than the existing refractory materials are required. For this, the 'composite salt/ceramic thermal energy storage concept' has been proposed. The paper presents a technical scale test facility, which has been built for investigating, among others, new developed hybrid materials in form of technical products, following this concept. It gives a survey of the planned tests, summarizes the main targets and describes the first checkerwork.

1. INTRODUCTION

Like conventional power plants, solar plants must cover the energy demand of the consumer. That means they have to guarantee a specified output. This requirement often does not correspond with the energy input of the solar plant that is limited by diurnal, seasonal and weather related insolation changes. In order to balance energy supply and demand, solar plants must be constructed with thermal energy storage (TES) and/or fossil fired backup systems [1]. Both have the functions to prolong operation times, to guarantee a defined output, and to shift energy output from low price off peak periods to peak periods.

TES systems could furthermore be used for pressure transforming between the heat source (receiver/burner) and the consumer (e.g. a Brayton cycle).In relation to solar power plants, the term 'high temperature' is commonly used for solar thermal central receiver (STCR) systems with air as the primary coolant and operating temperatures above 600°C as a result of progress made in receiver development (new design and materials). There are yet no existing plants, but the concept has shown to be feasible [2]. The STCR plant PHOEBUS, designed for electricity production, is planned to be built in Jordan within the next few years. Feasibility studies for PHOEBUS have shown that the use of refractory materials as storage media seems to be the straightforward solution. These refractory materials are state of the art in large scale industrial storage systems, commonly known as regenerators, recuperators and cowpers. They store sensible heat, and therefore, high temperature differences during charging and discharging and/or great checkerwork masses are necessary for adequate storage capacities. Moreover they are operated continuously at 12 to 24 charge/discharge cycles per day and optimized for efficient heat exchange. The specific costs of a solar TES system are characterized by the fact that only one complete charging and discharging per day is done. Therefore, storage materials with higher storage densities than the existing refractory materials and with comparable material and manufacturing costs are required. In addition new checkerwork and storage design, including improved grid technology, is necessary. The advanced 'composite salt/ceramic TES media concept' offers the potential of using phase change materials (PCM) via direct contact heat exchange, and therefore, the potential of significant cost improvement through elimination of heat exchanger materials, reduction of storage materials and containment size [3,4]. This salt/ceramic approach may be explained as microencapsulation of a PCM within the submicron pores of a ceramic matrix. The liquid salt is retained within the solid ceramic network by surface tension and capillary forces. Heat storage occurs as latent heat of the PCM and as sensible heat of the basic ceramic material and the PCM. Therefore, the use of salt/ceramic materials represents not a pure latent heat, but a latent/sensible hybrid storage concept.

2. THE HTWS-PROJECT

The HTWS project is promoted by the German Ministry of Research and Development (BMFT). Its main goals are the development and realization of new storage media and concepts to enable further industrial applications and to cover the existing requirements in the field of solar energy. For a list of project partners and their main activities within this joint venture, see table 1.

DLR (ITT)	DIDIER WERKE AG Entwicklung Anlagentechnik	Universität Stuttgart (ITW)
• development of hybrid materials • qualification of lab scale materials • long term stability tests with lab scale and technical scale materials	• process engineering and construction of new regenerators • manufactoring of new storage media • qualification of technical scale materials • development of a mathematical model for calculation of storage systems	• determination of thermophysical properties • development of a simulation code for a PCM storage
• investigations with the High Temperature Storage Test Facility		

Table 1: HTWS-project, participants and main activities

The project deals with the above mentioned salt/ceramic media concept. The special constellation of the project - co-operation of research and industry - shall guarantee that the results are technically feasible and that the materials can be manufactured under industrial conditions. Regarding this aspect a technical scale test facility has been built (see below). It is used to investigate the materials developed at DLR laboratories and produced under DIDIER manufacturing conditions.

3. HIGH TEMPERATURE STORAGE TEST FACILITY

The following chapter describes the test facility and the possible working conditions (tab.2). The plant has been built at DLR in Stuttgart (pic.1). It is operated automatically by a central control station, which also serves as data acquisition system. The desired data can be transferred to a PC by means of a transfer software. Data reduction and evaluation can be done on the PC or on a linked host computer.

The whole plant can be divided into an open, pressureless charging cycle and a closed discharging cycle, which can be put under the maximum pressure of 20 bar. Connecting part of both cycles is the storage. Its maximum dimensions can be described by a pillar with 0.5m in diameter and a height of 2m (usable storage volume 0.4m3). The axial and radial temperature profiles can be measured with 88 thermocouples distributed individually within the checkerwork during its erection. In order to enable quick and easy checkerwork exchange a lifting device is placed below the storage. The storage containment can be opened at the bottom and the checkerwork can be lowered.

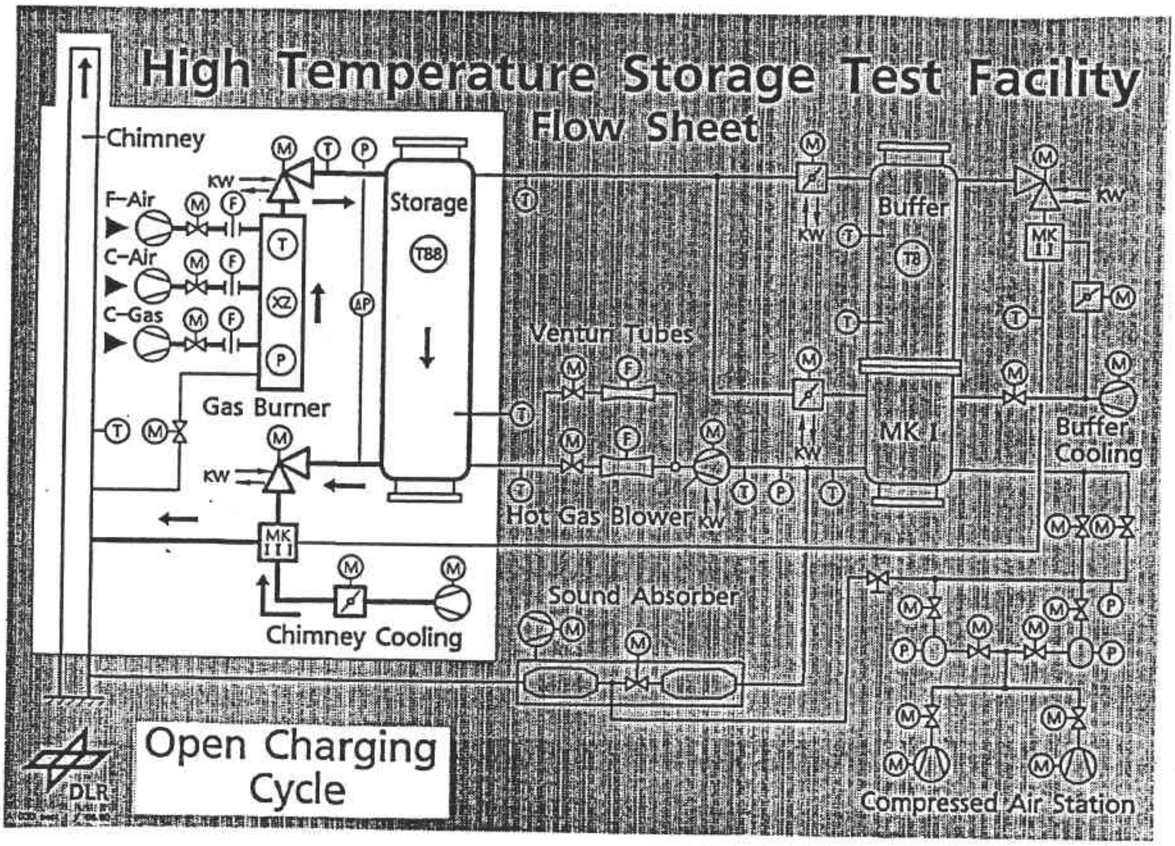
Charging of the storage is done with the flue gas of a 200kW-gas burner (pic.2). The adjustable temperature range is between 100 and 1300°C. The gas flow can be chosen between 100 and 1000m3i.N./h. In order to reach a clean and complete combustion, the air/gas proportion of the burner is fixed. Therefore a certain flue gas temperature would imply a certain flue gas flow and vice versa. The independent choice of both parameters is guaranteed by separate fresh air, added to the flue gas within the combustion chamber. Since gas flow measuring at temperatures up to 1300°C is very complicated, the mass flows in the three mains leading to the combustion chamber (natural gas, combustion air and fresh air) are measured with orifice plates. Addition of the three values yields the total charging gas mass flow. The gas enters the storage at the top with a max. temperature of 1300°C and leaves it at the bottom with max. 700°C. The limit at the outlet is due to the material used for the grid. If the now used metal grid will be replaced by a new developed ceramic one, this temperature could be increased up to 900°C. Before leaving the cycle cold air is added to the gas in order not to exceed the allowable chimney temperature of 250°C. There are two ways how to stop the charging mode. The condition with the minor priority is the lapse of the chosen charging time. The process is stopped before, if a certain outlet temperature is reached. This value is eligible between 100 and 700°C.

Discharging is done in a closed cycle with uncoupled buner (pic.3). It is designed for pressures up to 20bar. During charging two compressors fill two pressure vessels (total volume 5m3) with air up to 32bar. Before starting the discharge mode the cycle is set under the chosen pressure. The air is now circulated by a hot gas blower, which works at temperatures up to 700°C. The air enters the storage at the bottom and leaves it at the top (counterflow heat exchange, see above) with max. 1300°C. Since the air circulates in a closed cycle the absorbed heat must be transferred to a heat exchanger before it reenters the storage with the given inlet temperature. No conventional heat exchanger could be found working under the given conditions. Therefore the following solution has been realised: the hot air runs through the so-called buffer which is in fact a second storage with larger dimensions (0.7m diameter, 3.2m height). The checkerwork is made of conventional ceramics and won't be changed throughout the different experiments. Such a regenerative heat exchanger is not able to guarantee the required constant and eligible outlet temperature together with a given flow. Therefore a bypass has been built through which part of the air can go around the buffer. The two flows are controlled by flap valves. The temperature in the mixing chamber, where the flows are reunited, must correspond to the chosen storage inlet temperature. The longitudinal temperature profile of the buffer is measured with eight thermocouples. The buffer is cooled with ambient air by a so-called buffer cooling blower during the following charging cycle in order to have similar conditions at the beginning of the next discharging cycle. Measuring and controlling of the total circulated air flow is done by means of two venturi tubes of different size. Dependent on the chosen air flow the control system decides which venturi is used. Similar to the charging mode there are two limiting conditions for discharging. The first is once again the discharge time, the second occurs when the outlet temperature at the storage top falls beyond a given margin, that means when the 'consumer' cannot use the heat anymore. The pressure is now released and the air leaves the system through two sound absorbers.

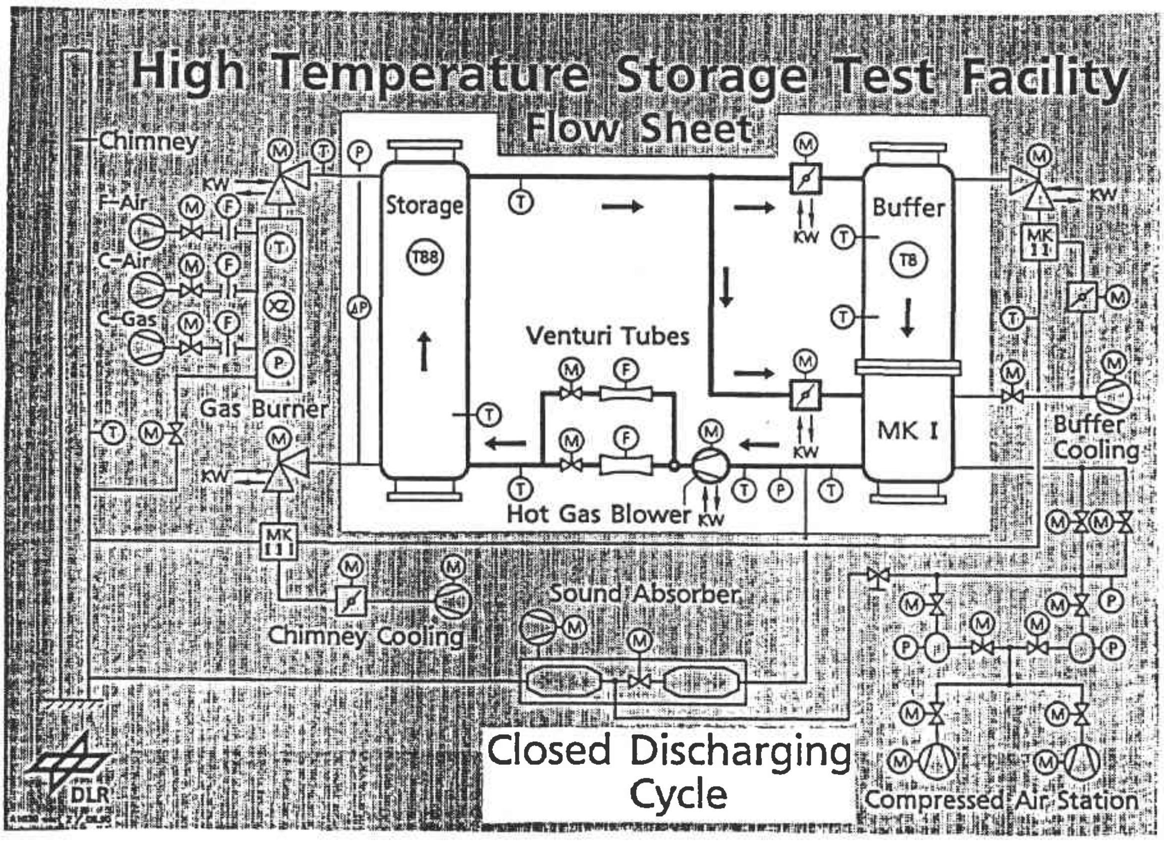
	charging mode	discharging mode
heat transfer medium	flue gas/air	air
max. temperature inlet storage [°C]	1300	700
max. temperature outlet storage [°C]	700 (900)	1300
max. pressure in cycle [bar]	1	21
heating power of burner [kW]	200	–
cooling power of buffer [kW]	–	200
general data		
height of storage pillar [m]	2	
diameter of storage pillar [m]	0.5	
volume flow [m^3i.N./h]	100...1000	
permissible cycle period [h]	0.1...15	
max. pressure loss in storage [mbar]	100	

Table 2: Data of High Temperature Storage Test Facility

Picture 1: High Temperature Storage Test Facility



Picture 2: Charging Mode



Picture 3: Discharging Mode

4. MAIN INTENTIONS OF THE TEST FACILITY

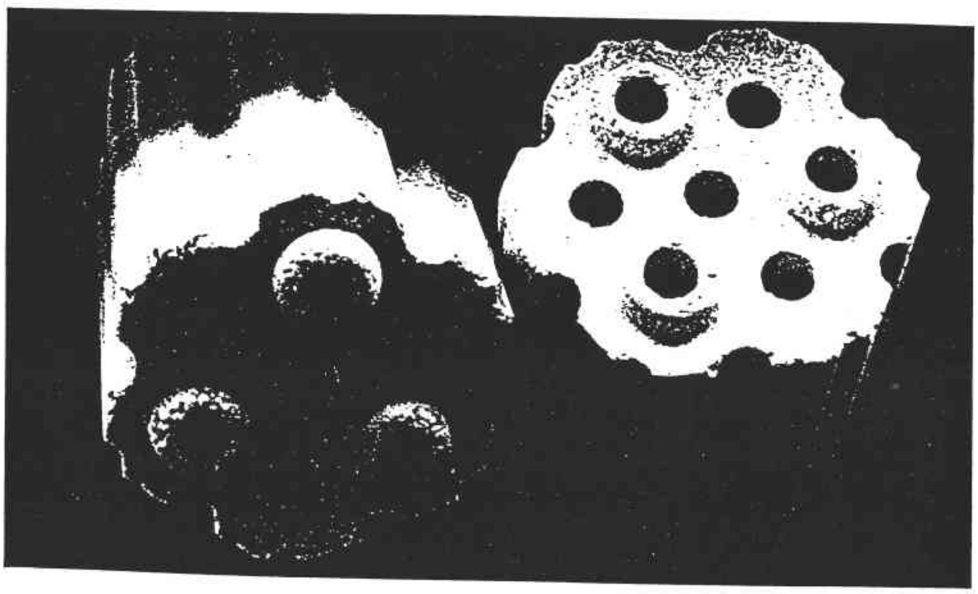
Primary goal of the test facility is to carry out material tests with new developed hybrid materials, proving their thermal, chemical and mechanical stability. These lifetime experiments serve to demonstrate the realization of the salt/ceramic concept and the transferability of the lab scale results to technical scale manufacturing. As described above a simulation code for the thermal behaviour of storage systems is to be developed at the ITW. The verification of this computer code will be done using experimental data of the test facility. Especially in the case of hybrid materials this point is very important, because another possibility for comparing simulation results with experimental data does not exist.After the verification of the simulation program the experiment continues to serve as a construction device for planned applications. Considering the laws of similarity, it can be used for model experiments, especially if the real checkerwork geometry differs significantly from the simplifications made in the computer program. The influence of checkerwork geometry - specific heating surface, specific free cross area, channel diameter, channel form - on the storage performance - cycle time, discharge power, temperature profiles - is also investigated. For future applications even higher temperatures at the 'cold' end will be desirable. Therefore it is planned to change the now used grid construction and material to show the technical feasibility of, for example, a ceramic grid.

5. FIRST CHECKER WORK AND PLANNED TESTS

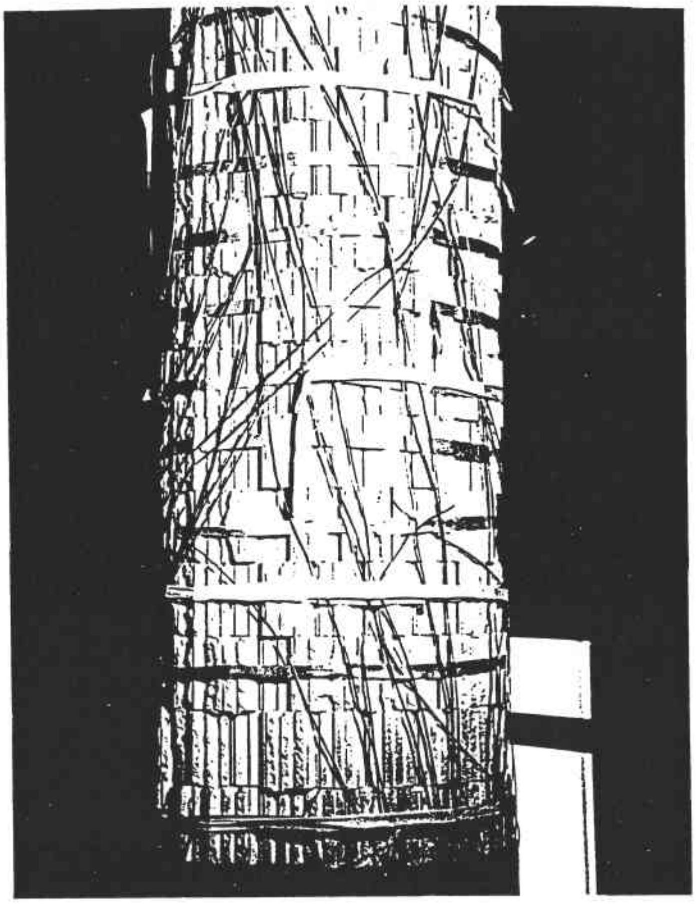
In the first test period - the plant has been put into operation in the middle of August 1990 - a checkerwork with the characte-ristic data of the proposed PHOEBUS storage system will be investigated. It is an almost conventional refractory material, storing only sensible heat with an optimized geometry for long cycles (for data see tab.3). Pic.4 shows a single checker brick and pic.5 the complete stacked arrange-ment before being lifted into the storage containment.

ITEM	VALUE	UNIT
height of single checker brick	100	mm
mass of single checker brick	688	g
free cross section area	22.7	%
specific wall thickness	8.5	mm
channel diameter	10	mm
bulk density	2400.0	kg/m^3
specific heat capacity	~ 1.2	kJ/kgK
thermal conductivity	~ 1.7	W/mK

Table 3: Data of 1st checkerwork bricks



Picture 4: Single checker brick



Picture 5: Test storage checkerwork

After the run-in period of the test facility, experiments with parameters corresponding to the PHOEBUS plant will be carried out. Tests corresponding to planned industrial applications will follow. With regard to the upcoming hybrid material tests, so-called reference tests under certain conditions are made with the PHOEBUS material to be able to work out the special influence of the latent phase. After removing the first checkerwork the facility is run with an empty testbed to determine plant influences, for example the storage capacity of the insulation or the pressure drop of the grid. These so-called 'base lines' have to be carried out, if possible, under the same conditions as the experiments which they refer to.It is planned that the following second checkerwork will be a new developed hybrid material. A decision about that will be made at the end of 1990, because this test period is planned to start during the second quarter of 1991.

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[1] M.Geyer, R.Tamme, H.Klaiß, High Temperature Thermal Storage in Solar Plants, Proc. ISES Solar World Congress, Hamburg, 1987

[2] PHOEBUS, Phase IB - Feasibility Study, March 1990

[3] R.Tamme, P.Allenspacher, M.Geyer, 'High Temperature Thermal Storage Using Salt/Ceramic Phase Change Materials',Proc. 21st IECEC, 1986

[4] R.Tamme, 'High Temperature TES Systems Using a Checker Work Array of Salt/Ceramic Materials', Proc. Diveral/Industrial TES Research Activities Receiver, Report Mississippi State University, 1988

4.3.2

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TXE-Dr.St

IEA - SSPS Task IV Status Meeting on
"High Temperature Thermal Storage"
Davos / Switzerland, September 5, 1990

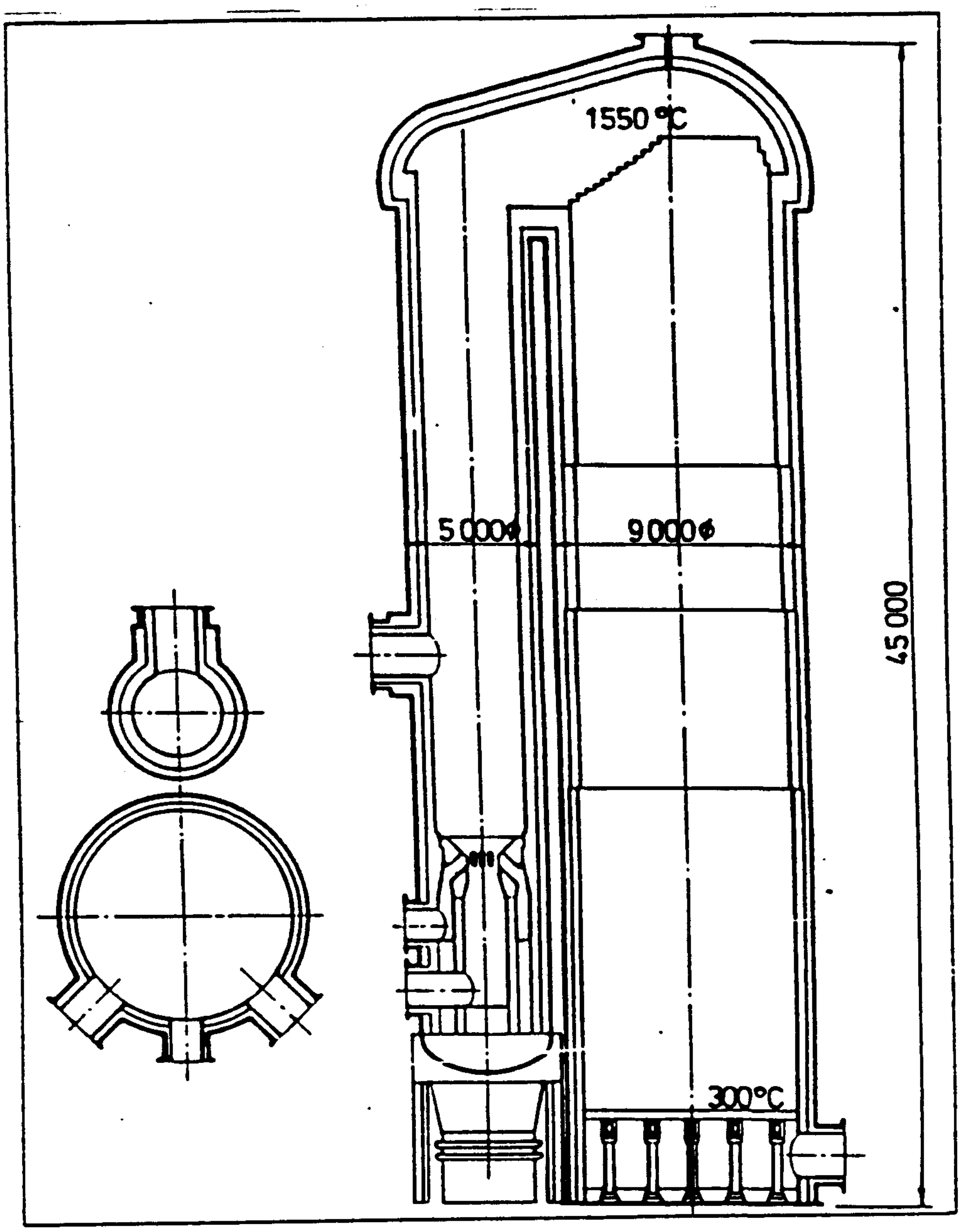
Report on Activities at DIDIER:

DIDIER Engineering Services, Wiesbaden
- Hot Blast Stoves
- Checkerwork and Checker Bricks

High Temperature Storage Development Project
- Partner and Tasks
- Hybrid Material
- Production Procedure
- Storage Brick (Channels D.I. 10 mm)

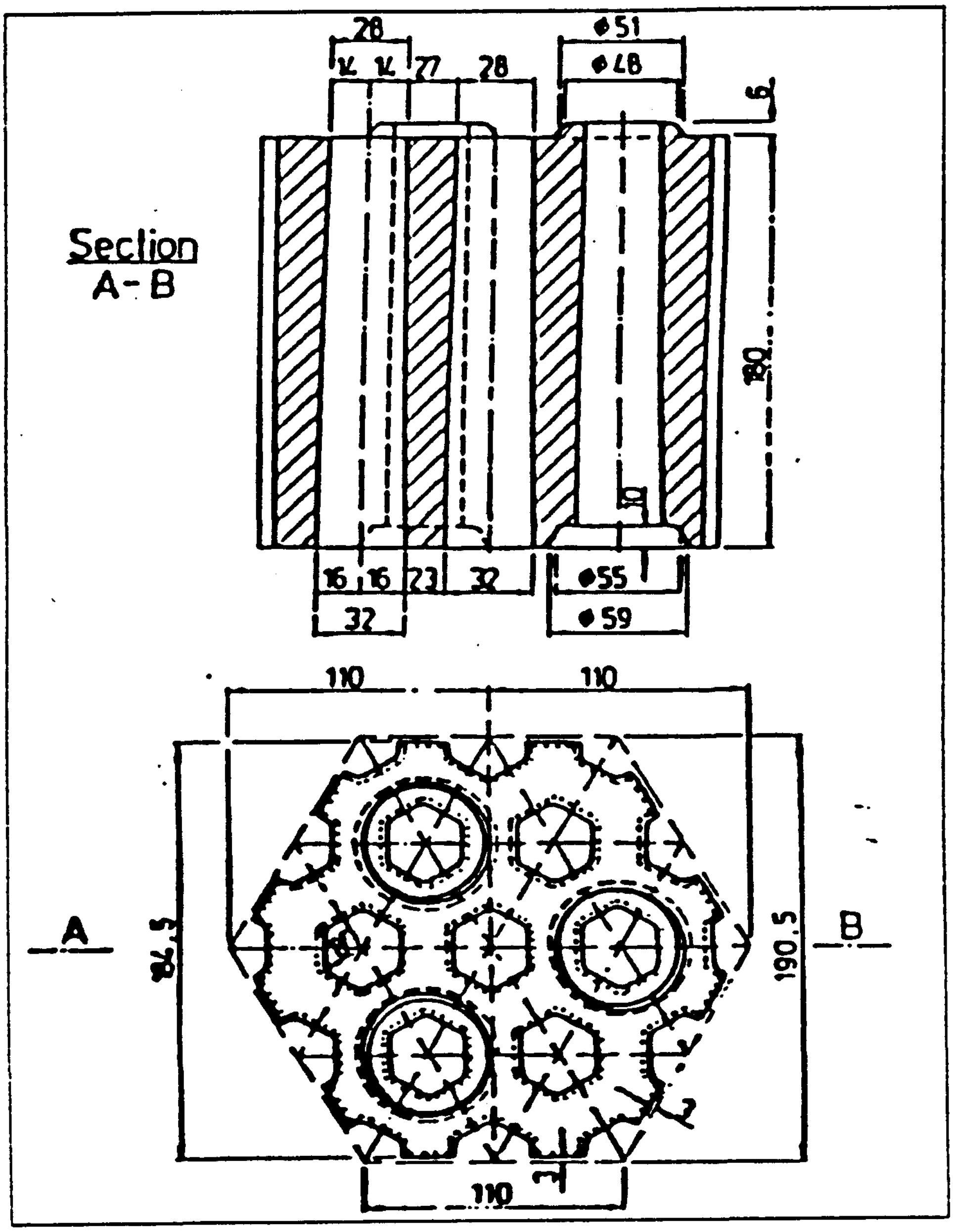
PHOEBUS Storage Design
- Data
- Sketch
- Temperatures in Checkerwork
- Temperature at Storage Outlet

TXE / Dr. Streuber



HOT BLAST STOVE WITH EXTERNAL COMBUSTION CHAMBER

DIDIER-WERKE AG		



DIDIER-WERKE AG	DIDIER CHECKER BRICK	

H T S - PROJECT

DLR	PELLETS
DIDIER	LABORATORY BRICKS
DIDIER	TEST PRODUCTION
DLR / DIDIER	TEST MATERIAL IN THE TESTFACILITY AT THE DLR IN STUTTGART

HYBRID MATERIALS

MgO + Salt

SiO_2 + Salt

DIDIER-WERKE AG

PROCEDURE

MIXING RAW MATERIAL

ADD BINDING AGENT

ADD SALT

MIXING

SIFTING

COMPRESSING

DRYING

BURNING

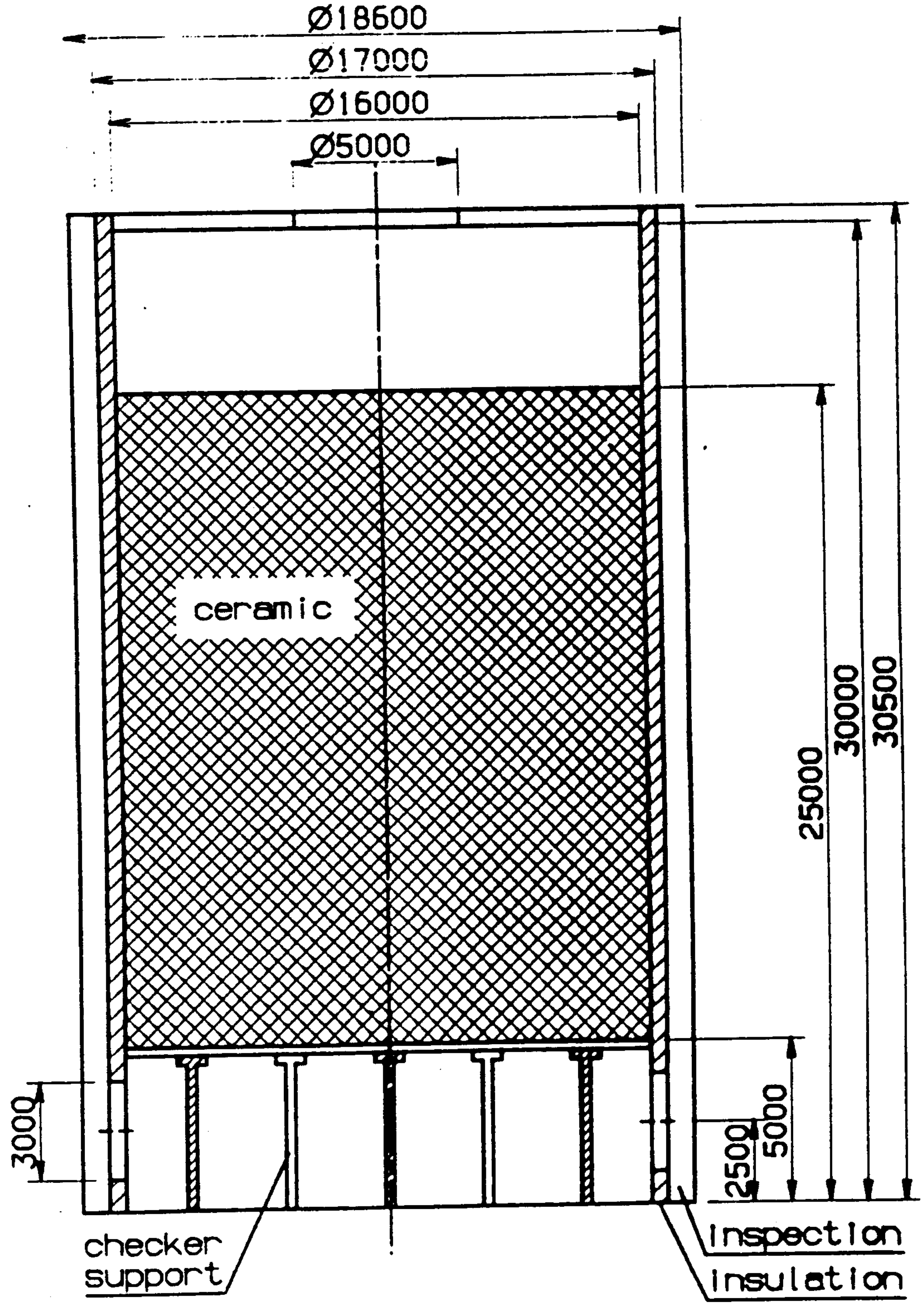
COOLING

DIDIER-WERKE AG		

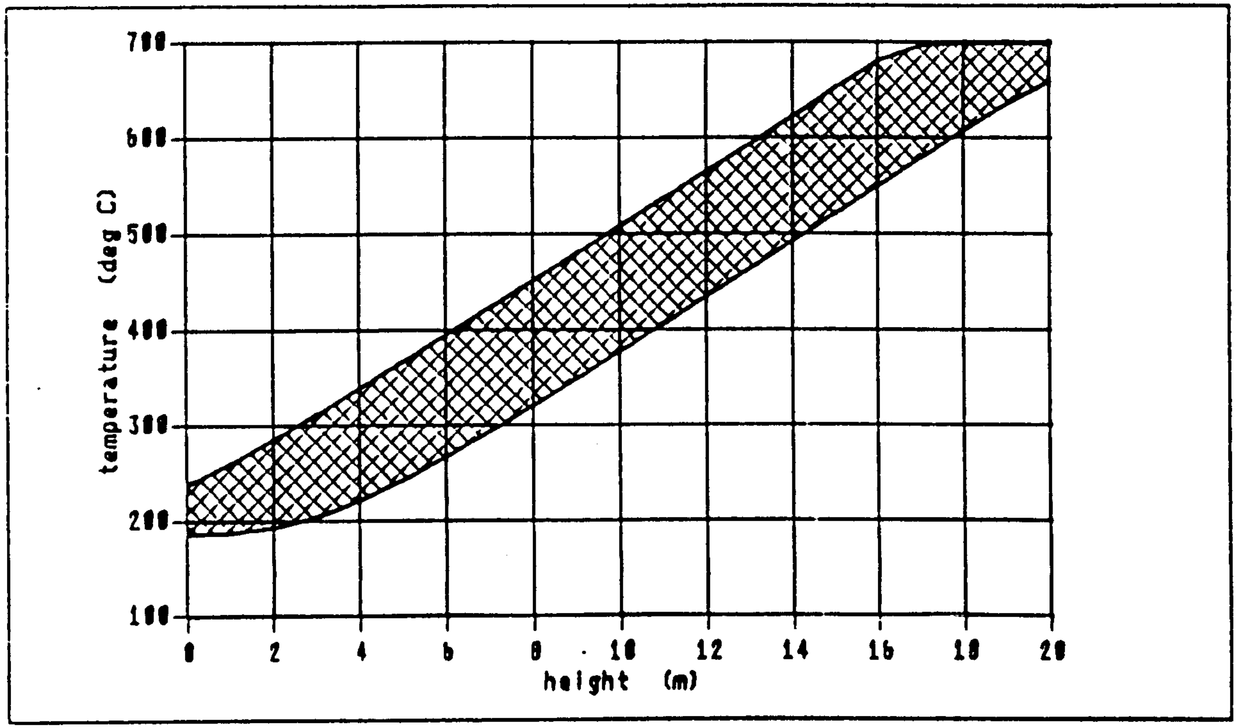
PHOEBUS STORAGE

ITEM	VALUE	UNIT
HEIGHT	20	m
DIAMETER CHECKER WORK	16	m
CHECKER AREA	200	m2
FREE CROSS SECTION	22,7	%
HYDRAULIC DIAMETER	10	mm
TOTAL WEIGHT	7400	t
DISCHARGING AIR FLOW	151	kg/s
DISCHARGING TEMP. HOT	700 ---> 640	deg C
DISCHARGING TEMP.COLD	185	deg C
DISCHARGING TIME	3	h

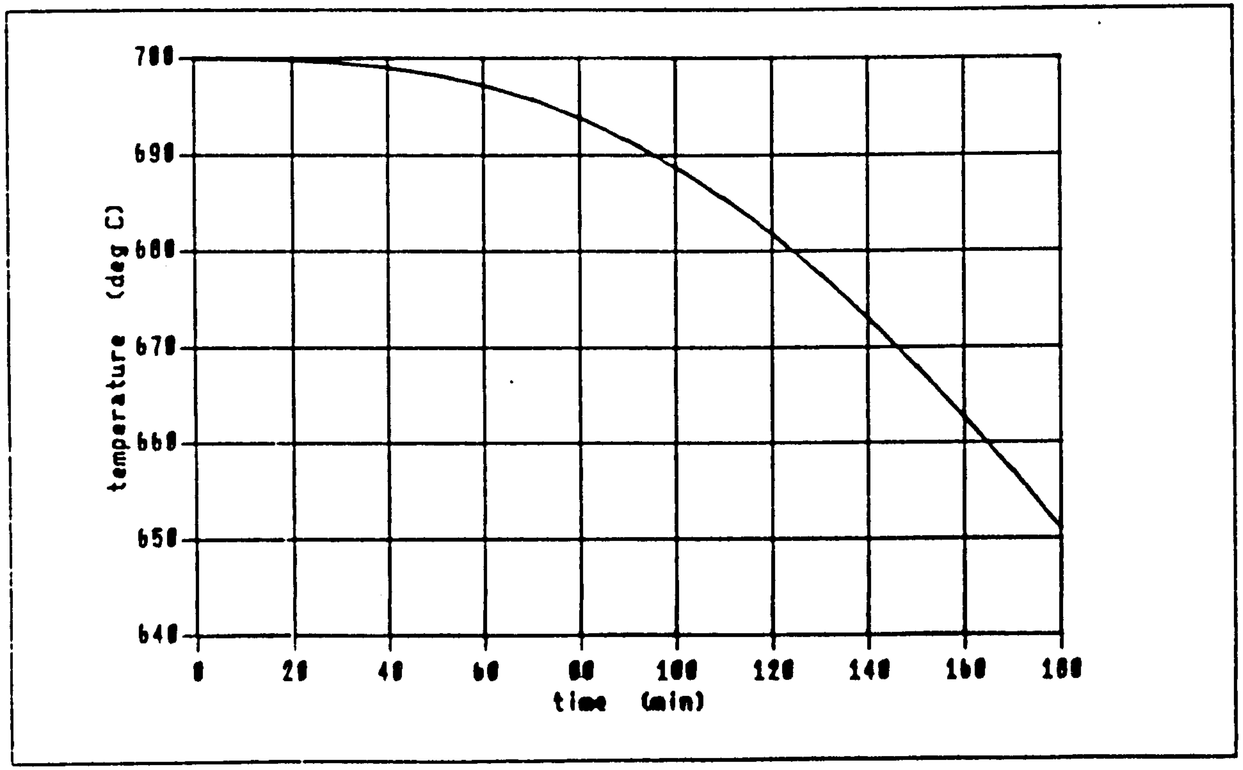
DIDIER-WERKE AG



DIDIER-WERKE AG	PHOEBUS STORAGE ARRANGEMENT	



DIDIER-WERKE AG	TEMPERATURE IN CHECKER WORK	



DIDIER-WERKE AG	DISCHARGING OUTLET TEMPERATURE	

4.3.3

SSPS Task IV Meeting, Davos, August 27, 1990

SENSIBLE HEAT STORAGE IN AIR/ROCK BED SYSTEMS

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Abstract

High temperature thermal storage in rock beds using air as a heat transfer medium is investigated both experimentally and theoretically in the High Temperature Solar Technology Division at Paul Scherrer Institute (PSI), Switzerland. With the experimental store called ARIANE, measurements of the transient behavior of the rock bed during the charging process were performed, which show a fairly well stratified temperature distribution. To simulate the thermal behavior of such a storage system, a computer code called PACKBEDA was developed [1]. It is based on a one-phase dynamic model solving analytically the one-dimensional linear nonhomogeneous boundary-value problem for the heat transfer between air and particles. Recently, this program has been improved and modified in order to include the temperature dependent thermophysical properties of air (density, viscosity, and thermal conductivity), as well as the heat losses through the insulated walls. Moreover, the program keeps track of the amount of pressure drop across the solid bed. The validation of the model with experimental data indicates that all features are well reproduced by the modified computer program PACKBEDA, which seems to be a reliable and useful tool for the analysis of large scale air/rock bed storage systems. Most of the remaining discrepancies can be explained by boundary effects near the wall (for details see [2]). These are mainly caused by the small ratio between vessel diameter and particle diameter. Further problems arise due to the somewhat unfavorable shape of the storage vessel with its high surface-to-volume ratio. Because of the small diameter of ARIANE, the insulation is quite bad, and therefore the heat losses through the wall are considerable. In order to solve these problems and to improve the agreement between measurements and model, it is suggested to build a bigger experimental store.

[1] W. Durisch, E. Frick, P. Kesselring, "Heat Storage in Solar Power Plants Using Solid Beds", Proc. Third Int. Workshop on Solar Thermal Central Receiver Systems, Konstanz (1986), 879

[2] A. Meier, C. Winkler, D. Wuillemin, "Experiment for Modeling High Temperature Rock Bed Storage", Proc. Fifth Symposium on Solar High Temperature Technologies, Davos (1990)

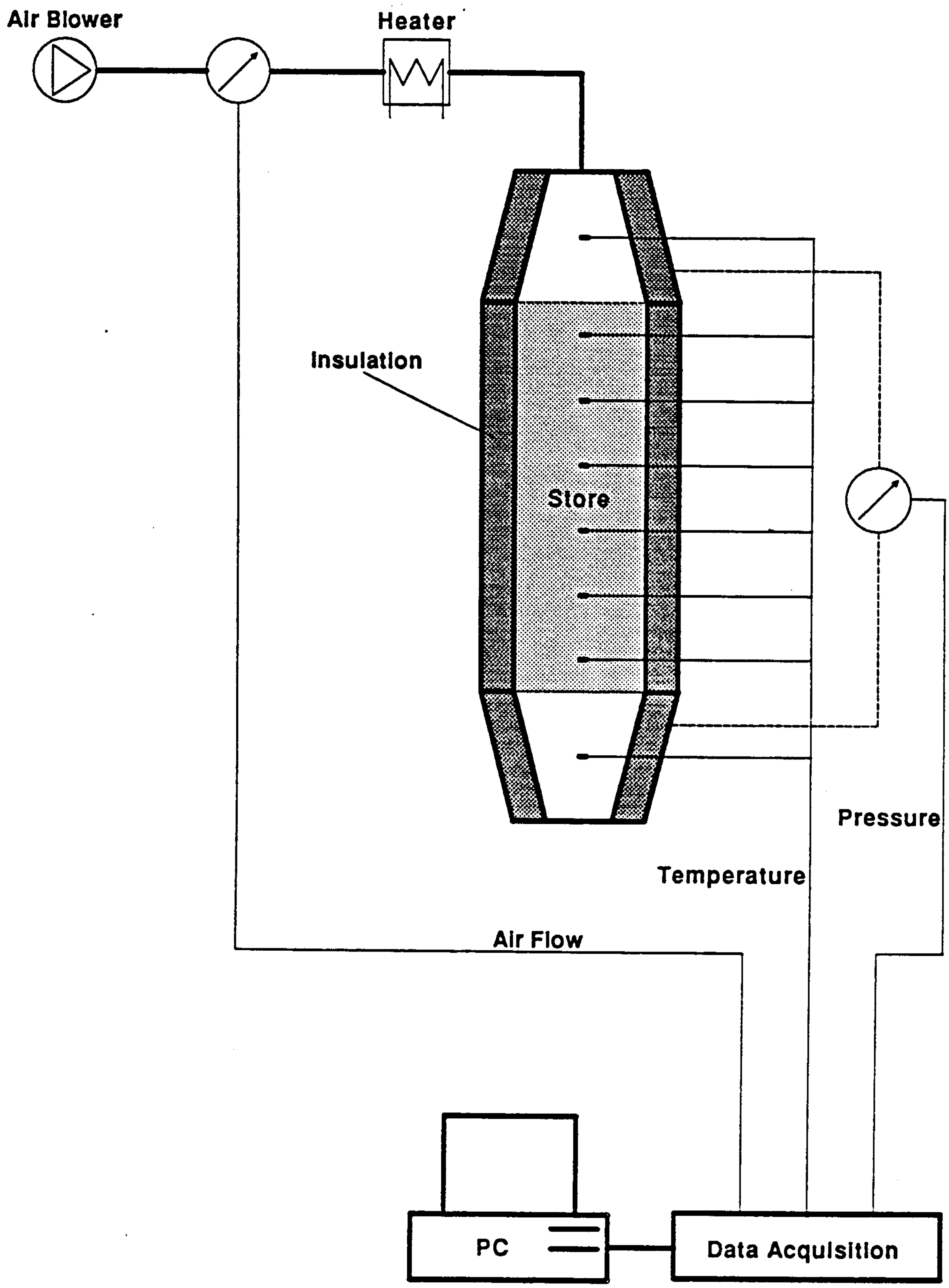
Task IV Meeting

Davos, 27-8-90

Report on activities at PSI

- Air/rock bed storage
- Experimental store ARIANE
- Model PACKBEDA
- Model Validation
- Problems

- Future activities



High Temperature Thermal Storage Experiment 'ARIANE' at PSI

MODEL

Reference

W. Durisch, E. Frick, P. Kesselring

Heat Storage in Solar Power Plants
Using Solid Beds

Proceedings of the
Third International Workshop
on Solar Central Receiver Systems
Konstanz, 1986

(PSI-TM-13-86-08)

Computer Program PACKBEDA

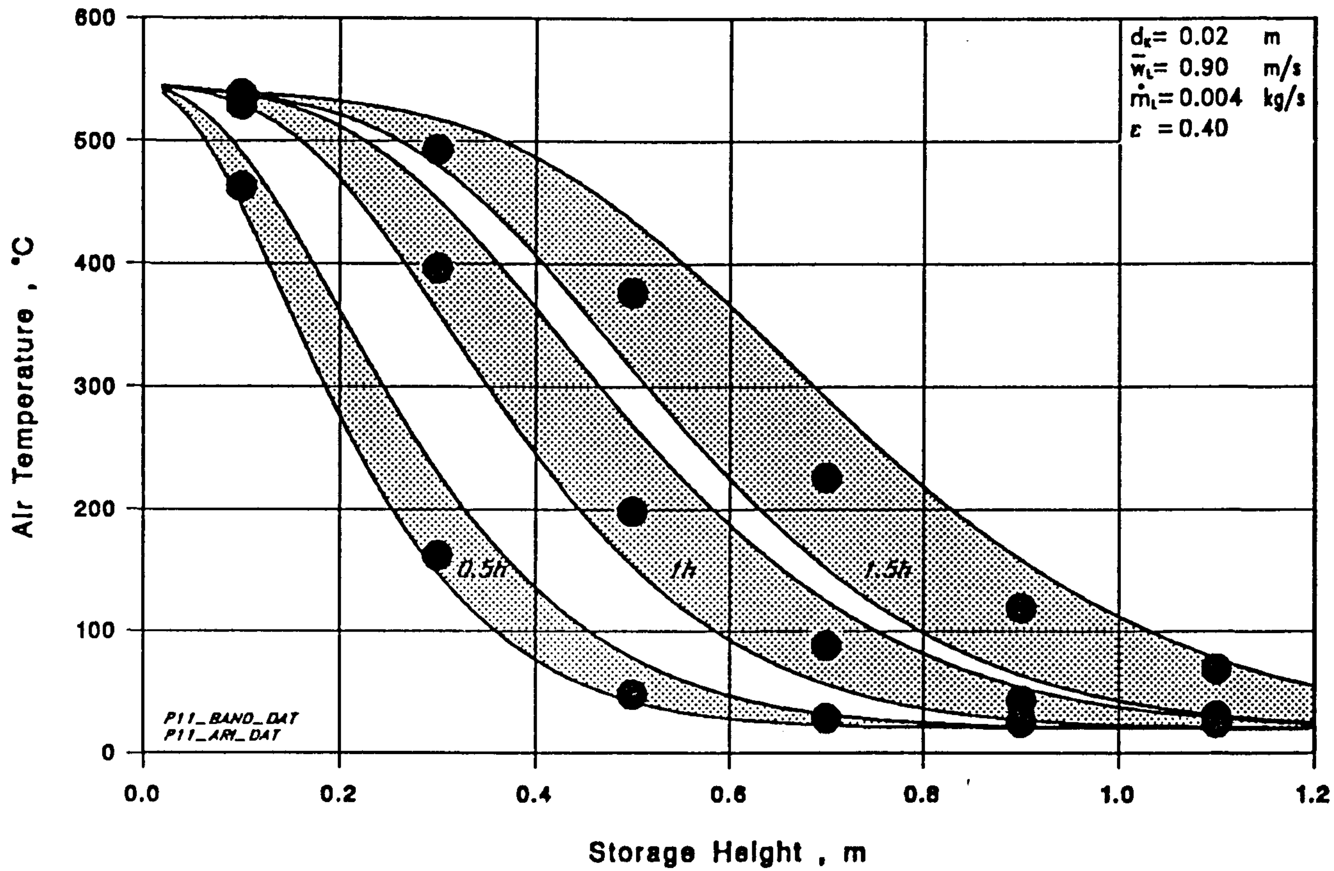
MODEL VALIDATION

Main Topics

- Investigate transient behaviour of rock bed during charging cycle
- Measure pressure drop
- Describe effects of parameter variations on stratification and pressure drop (sensitivity analysis)
- Validate model PACKBEDA with experimental data

HTTS Simulation Program PACKBEDA

Model Validation with ARIANE Data



Problems with ARIANE:

- unfavorable shape
  $H/D = 8$ → heat losses
  small radius → bad insulation
- $D/d_K = 7.5$ → boundary effects
  porosity $\varepsilon(r)$
  velocity $w_L(r)$
  temperature $T_L(r)$
- velocity w_L too high
  (limited by flow meter performance)

How can stratification be improved?

- reduce d_K → pressure drop ↑
  → fan power ↑
- reduce w_L → charging and discharging slowed down

⇒ build bigger experimental store

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