

Survey of Thermal Storage for Parabolic Trough Power Plants

**Period of Performance:
September 13, 1999–June 12, 2000**

Pilkington Solar International GmbH
Cologne, Germany



NREL

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

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List of Acronyms

ETDE	Energy Technology Data Exchange
EU	European Union
h	hour
HTF	heat transfer fluid
IEA	International Energy Agency
ISCCS	integrated solar combined cycle systems
kWh	kilowatt-hours
kWh _e	kilowatt-hours electric
kWh _t	kilowatt-hour thermal
MUSD	million U.S. dollar
MWe	megawatts electric
MW	megawatt
MWh	megawatt-hour
MWh _t	megawatt-hours thermal
NREL	National Renewable Energy Laboratory
PCM	phase change material
PNL	Pacific Northwest Laboratory
PNNL	Pacific Northwest National Laboratory
PSA	Plataforma Solar Almería
PV	photovoltaics
RTR	reversible thermochemical reaction
SEGS	solar electric generating system
SERI	Solar Energy Research Institute
TES	thermal energy storage
ZSW	Center for Solar Energy and Hydrogen Research, Stuttgart, Germany

1.0 Introduction

The electrical output of a solar thermal electric plant is inherently in a state of change, being dictated by both predictable and unpredictable variations—the influences of time and weather. In either event, utility system needs may require a fully functional storage system to mitigate the changes in solar radiation or to meet demand peaks.

A distinct advantage of solar thermal power plants compared with other renewable energies, such as photovoltaics (PV) and wind, is the possibility of using relatively cheap storage systems. That is, storing the thermal energy itself. Storing electricity is much more expensive.

A thermal energy storage (TES) option can collect energy in order to shift its delivery to a later time, or to smooth out the plant output during intermittently cloudy weather conditions. Hence, the operation of a solar thermal power plant can be extended beyond periods of no solar radiation without the need to burn fossil fuel. Times of mismatch between energy supply by the sun and energy demand can be reduced.

When used with Integrated Solar Combined Cycle Systems (ISCCS), energy storage could provide another important advantage. If the plant operates at baseload, it will operate at full load only when enough solar energy is available. At part load, the turbine efficiency can decrease considerably. If fossil energy is used to augment turbine load (through the use of duct firing, a heat transfer fluid [HTF] heater, or a backup boiler) when solar is not available, the plant converts that fossil fuel at a substantially lower efficiency than if it had been used directly in the combined cycle. Using thermal energy storage instead of a fossil burner can help to overcome this problem.

Economic thermal storage is a key technological issue for the future success of solar thermal technologies.

1.1 Scope of this Report

The purpose of this report is to identify and selectively review previous work done on the evaluation and use of thermal energy storage systems applied to parabolic trough power plants. Appropriate storage concepts and technical options are first discussed, followed by a review of previous work. This review is divided into two parts: work done before 1990 and work done after that date. This division was chosen because much of the work currently cited in this field was carried out and reported prior to 1990, and a key objective of the review was to highlight more recent results though they are less plentiful. Finally, observations and conclusions on the status of TES systems for trough plants are put forward, based on the body of literature covered.

1.2 Storage Concepts for Solar Thermal Systems

The principle options for using TES in a solar thermal system highly depend on the daily and yearly variation of radiation and on the electricity demand profile. As noted above, the main options are:

- Buffering
- Delivery period displacement

- Delivery period extension
- Yearly averaging

The goal of a buffer is to smooth out transients in the solar input caused by passing clouds, which can significantly affect operation of a solar electric generating system (SEGS) plant. The efficiency of electrical production will degrade with intermittent insolation, largely because the turbine-generator will frequently operate at partial load and in a transient mode. If regular and substantial cloudiness occurs over a short period, turbine steam conditions and/or flow can degrade enough to force turbine trips if there is no supplementary thermal source to "ride through" the disturbance. Buffer TES systems would typically require small storage capacities (maximum 1 hour full load).

Delivery period displacement requires the use of a larger storage capacity. The storage shifts some or all of the energy collected during periods with sunshine to a later period with higher electricity demand or tariffs (electricity tariffs can be a function of hour of the day, day of the week, and the season). This type of TES does not necessarily increase either the solar fraction or the required collection area. The typical size ranges from 3 to 6 hours of full load operation.

The size of a TES for delivery period extension will be of similar size (3 to 12 hours of full load). However, the purpose is to extend the period of power plant operation with solar energy. This TES increases the solar fraction and requires larger solar fields than a system without storage.

Yearly averaging of electricity production requires much larger TES and solar fields. In general, these are very expensive systems and have not been given serious consideration in the literature, nor will they be considered here.

Definitive selection of storage capacity is site- and system-dependent. Therefore, detailed statistical analysis of system electrical demand and weather patterns at a given site, along with a comprehensive economic tradeoff analysis, are desirable in a feasibility study to select the best storage capacity for a specific application.

1.3 Design Criteria

A key issue in the design of a thermal energy storage system is its thermal capacity - the amount of energy that it can store and provide. However selection of the appropriate system depends on many cost-benefit considerations.

The cost of a TES system mainly depends on the following items:

- The storage material itself
- The heat exchanger for charging and discharging the system
- The cost for the space and/or enclosure for the TES

From the technical point of view, the crucial requirements are:

- High energy density (per-unit mass or per-unit volume) in the storage material
- Good heat transfer between heat transfer fluid (HTF) and the storage medium

- Mechanical and chemical stability of storage material
- Compatibility between HTF, heat exchanger and/or storage medium
- Complete reversibility for a large number of charging/discharging cycles
- Thermal losses
- Ease of control

The most important design criteria are:

- Nominal temperature and specific enthalpy drop in load
- Maximum load
- Operational strategy
- Integration into the power plant

All these facts have to be considered when deciding on the type and the design of thermal storage. This review focuses on thermal energy storage for parabolic trough power plants, which operate under certain temperature limits. TES capacities up to 8 hours full load will be considered, which could significantly increase the solar share of a hybrid power plant, such as an ISCCS.

2.0 Technical Storage Options

Thermal energy storage can be classified by storage mechanism (sensible, latent, chemical) and by storage concept (active or passive).

2.1 Storage Media

Thermal storage can utilize sensible or latent heat mechanisms or heat coming from chemical reactions.

Sensible heat is the means of storing energy by increasing the temperature of a solid or liquid. Latent heat, on the other hand, is the means of storing energy via the heat of transition from a solid to liquid state. For example, molten salt has more energy per unit mass than solid salt.

Table 1 shows the characteristics of candidate solid and liquid sensible heat storage materials and potential phase change (latent) heat storage media for a SEGS plant.

For each material, the low and high temperature limits are given these limits, combined with the average mass density and heat capacity, lead to a volume-specific heat capacity in kWh_t per cubic meter. The table also presents the approximate costs of the storage media in dollars per kilogram, finally arriving at unit costs in $\$/\text{kWh}_t$.

The average thermal (heat) conductivity given in the table has a strong influence on the heat transfer design and heat transfer surface requirements of the storage system, particularly for solid media (high conductivity is preferable). High volumetric heat capacity is desirable because it leads to lower storage system size, reducing external

pipng and structural costs. Low unit costs obviously mean lower overall costs for a given thermal capacity.

2.1.1 Sensible Heat Storage

Thermal energy can be stored in the sensible heat (temperature change) of substances that experience a change in internal energy. The stored energy is calculated by the product of its mass, the average specific heat, and the temperature change. Besides the density and the specific heat of the storage material, other properties are important for sensible heat storage: operational temperatures, thermal conductivity and diffusivity, vapor pressure, compatibility among materials, stability, heat loss coefficient as a function of the surface areas to volume ratio, and cost.

Table 1. Candidate Storage Media for SEGS Plants (Geyer 1991)

Storage Medium	Temperature		Average density (kg/m ³)	Average heat conductivity (W/mK)	Average heat capacity (kJ/kgK)	Volume specific heat capacity (kWh _t /m ³)	Media costs per kg (\$/kg)	Media costs per kWh _t (\$/kWh _t)
	Cold (°C)	Hot (°C)						
Solid media								
Sand-rock-mineral oil	200	300	1,700	1.0	1.30	60	0.15	4.2
Reinforced concrete	200	400	2,200	1.5	0.85	100	0.05	1.0
NaCl (solid)	200	500	2,160	7.0	0.85	150	0.15	1.5
Cast iron	200	400	7,200	37.0	0.56	160	1.00	32.0
Cast steel	200	700	7,800	40.0	0.60	450	5.00	60.0
Silica fire bricks	200	700	1,820	1.5	1.00	150	1.00	7.0
Magnesia fire bricks	200	1,200	3,000	5.0	1.15	600	2.00	6.0
Liquid media								
Mineral oil	200	300	770	0.12	2.6	55	0.30	4.2
Synthetic oil	250	350	900	0.11	2.3	57	3.00	43.0
Silicone oil	300	400	900	0.10	2.1	52	5.00	80.0
Nitrite salts	250	450	1,825	0.57	1.5	152	1.00	12.0
Nitrate salts	265	565	1,870	0.52	1.6	250	0.70	5.2
Carbonate salts	450	850	2,100	2.0	1.8	430	2.40	11.0
Liquid sodium	270	530	850	71.0	1.3	80	2.00	21.0
Phase change media								
NaNO ₃	308		2,257	0.5	200	125	0.20	3.6
KNO ₃	333		2,110	0.5	267	156	0.30	4.1
KOH	380		2,044	0.5	150	85	1.00	24.0
Salt-ceramics (NaCO ₃ -BaCO ₃ /MgO)	500-850		2,600	5.0	420	300	2.00	17.0
NaCl	802		2,160	5.0	520	280	0.15	1.2
Na ₂ CO ₃	854		2,533	2.0	276	194	0.20	2.6
K ₂ CO ₃	897		2,290	2.0	236	150	0.60	9.1

2.1.1.1 Solid Media

For thermal storage, solid media usually are used in packed beds, requiring a fluid to exchange heat. When the fluid heat capacity is very low (e.g., when using air) the solid is the only storage material; but when the fluid is a liquid, its capacity is not negligible, and the system is called a dual storage system. Packed beds favor thermal stratification, which has advantages. Stored energy can easily be extracted from the warmer strata, and cold fluid can be taken from the colder strata and fed into the collector field.

An advantage of a dual system is the use of inexpensive solids such as rock, sand, or concrete for storage materials in conjunction with more expensive heat transfer fluids like thermal oil. However, pressure drop and, thus, parasitic energy consumption may be high in a dual system. This has to be considered in the storage design.

The cold-to-hot temperature limits of some solid media in Table 2 are greater than could be utilized in a SEGS plant because parabolic trough solar fields are limited to maximum outlet temperatures of about 400°C. Table 2 shows the effect on solid media by imposing this temperature limit on the storage medium temperature range, the unit heat capacities, and media costs.

Table 2. Solid Storage Media for SEGS Plants

Storage Medium	Heat Capacity kWh _t /m ³	Media Cost \$/kWh _t
Reinforced concrete	100	1
NaCl (solid)	100	2
Cast iron	160	32
Cast steel	180	150
Silica fire bricks	60	18
Magnesia fire bricks	120	30

Using these values and judging the options against the guidelines discussed above, the sand-rock-oil combination is eliminated because it is limited to 300°C. Reinforced concrete and salt have low cost and acceptable heat capacity but very low thermal conductivity. Silica and magnesia fire bricks, usually identified with high temperature thermal storage, offer no advantages over concrete and salt at these lower temperatures. Cast steel is too expensive, but cast iron offers a very high heat capacity and thermal conductivity at moderate cost.

2.1.1.2 Liquid Media

Liquid media maintain natural thermal stratification because of density differences between hot and cold fluid. To use this characteristic requires that the hot fluid be supplied to the upper part of a storage system during charging and the cold fluid be extracted from the bottom part during discharging, or using another mechanism to ensure that the fluid enters the storage at the appropriate level in accordance with its temperature (density) in order to avoid mixing. This can be done by some stratification devices (floating entry, mantle heat exchange, etc.).

The heat transfer fluid in a SEGS plant operates between the temperatures of 300°C and 400°C, approximately. Applying these limitations on temperature, and dropping mineral oil because it cannot operate at the upper temperature requirement gives the results shown in Table 3.

Table 3. Liquid Storage Media for SEGS Plants

Storage Medium	Heat Capacity kWh _t /m ³	Media Cost \$/kWh _t
Synthetic oil	57	43
Silicone oil	52	80
Nitrite salts	76	24
Nitrate salts	83	16
Carbonate salts	108	44
Liquid sodium	31	55

Both the oils and salts are feasible. The salts, however, generally have a higher melting point and parasitic heating is required to keep them liquid at night, during low insolation periods, or during plant shutdowns. Silicone oil is quite expensive, though it does have environmental benefits because it is a non-hazardous material, whereas synthetic oils may be classified as hazardous materials. Nitrites in salts present potential corrosion problems, though these are probably acceptable at the temperatures required here. (The U.S. Solar Two project has selected a eutectic of nitrate salts because of the corrosivity of nitrite salts at central receiver system temperature levels.)

2.1.2 Latent Heat Storage

Thermal energy can be stored nearly isothermally in some substances as the latent heat of phase change, that is, as heat of fusion (solid-liquid transition), heat of vaporization (liquid-vapor), or heat of solid-solid crystalline phase transformation. All substances with these characteristics are called phase change materials (PCMs). Because the latent heat of fusion between the liquid and solid states of materials is rather high compared to the sensible heat, storage systems utilizing PCMs can be reduced in size compared to single-phase sensible heating systems. However, heat transfer design and media selection are more difficult, and experience with low-temperature salts has shown that the performance of the materials can degrade after a moderate number of freeze-melt cycles. LUZ International Ltd. proposed evaluation of an innovative phase-change salt concept to the solar community that used a series of salts in a "cascade" design (to be discussed later).

Table 1 showed, for a number of potential salts, the temperature at which the phase change takes place as well as the heat capacity (heat of fusion). Data for the salts shown in that table that are applicable to SEGS plants are shown in Table 4 below. It can be seen that the heat capacities, at least for the nitrites, are high and unit costs are comparatively low.

Table 4. Latent Heat Storage Media for SEGS Plants

Storage Medium	Heat Capacity kWh_t/m³	Media Cost \$/kWh_t
NaNO ₃	125	4
KNO ₃	156	4
KOH	85	24

2.1.3 Chemical Storage

A third storage mechanism is by means of chemical reactions. For this type of storage it is necessary that the chemical reactions involved are completely reversible. The heat produced by the solar receiver is used to excite an endothermic chemical reaction. If this reaction is completely reversible the heat can be recovered completely by the reversed reaction. Often catalysts are necessary to release the heat. This is even more advantageous as the reaction can then be controlled by the catalyst.

Commonly cited advantages of TES in a reversible thermochemical reaction (RTR) are high storage energy densities, indefinitely long storage duration at near ambient temperature, and heat-pumping capability. Drawbacks may include complexity, uncertainties in the thermodynamic properties of the reaction components and of the reaction's kinetics under the wide range of operating conditions, high cost, toxicity, and flammability.

Although RTRs have several advantages concerning their thermodynamic characteristics, development is at a very early stage. To date, no viable prototype plant has been built.

2.2 Storage Concepts

Storage concepts can be classified as active or passive systems. Active storage is mainly characterized by forced convection heat transfer into the storage material. The storage medium itself circulates through a heat exchanger. This heat exchanger can also be a solar receiver or a steam generator.

The main characteristic of a passive system is that a heat transfer medium passes through storage only for charging and discharging. The heat transfer medium itself does not circulate.

2.2.1 Active Thermal Energy Storage

Active thermal systems typically utilize tank storage. They can be designed as one tank or two tank systems.

Active storage is again subdivided into direct and indirect systems. In a direct system the heat transfer fluid, which collects the solar heat, serves also as the storage medium, while in an indirect system, a second medium is used for storing the heat.

Two prominent examples of two-tank systems for solar electric applications are the storage systems of the SEGS I (Kroizer 1984) and Solar Two plants (Kelly and Lessly 1994, Pacheco and Gilbert 1999, and Valenti 1995). Figure 1 shows a schematic flow

diagram of SEGS I. An initial experience with a small-scale two-tank molten salt system has already been described (Chinen et al. 1983).

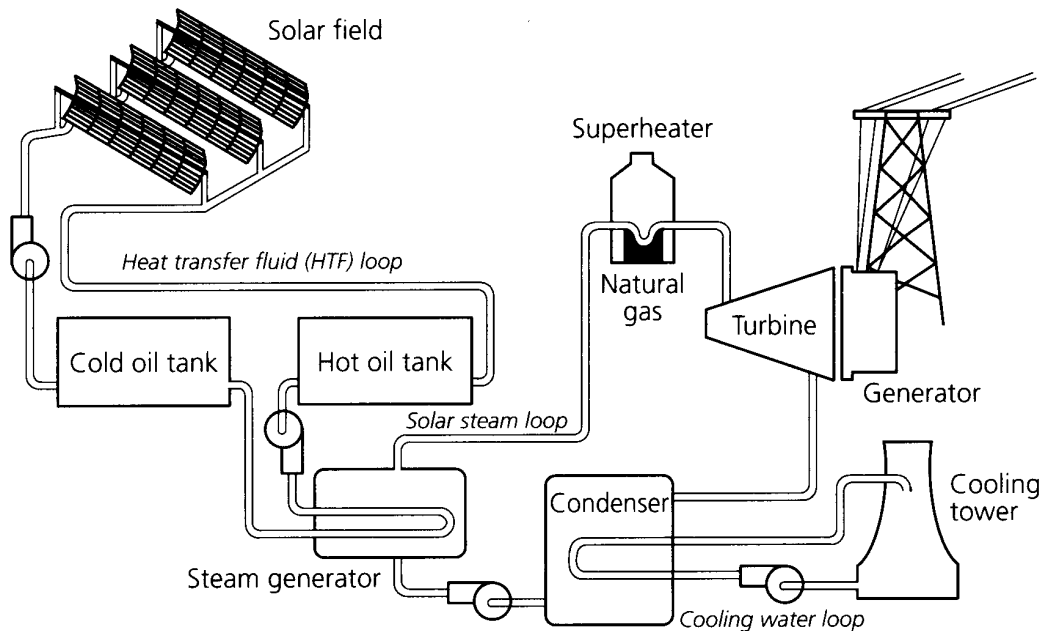


Figure 1. Schematic flow diagram of SEGS I plant

A two-tank system uses one tank for cold HTF coming from the steam generator and one tank for the hot HTF coming directly out of the solar receiver before it is fed to the steam generator. The advantage of this system is that cold and hot HTF are stored separately. The main disadvantage is the need for a second tank. In this type of system, the storage tanks are directly coupled to the HTF pressure levels (which is not necessarily a disadvantage).

The single-tank system reduces storage volume and cost by eliminating a second tank. However, in a single-tank system it is more difficult to separate the hot and cold HTF. Because of the density difference between hot and cold fluid, the HTF naturally stratifies in the tank, from coolest layers at the bottom to warmest layers at the top. These systems are called thermocline storage. Experience with thermocline storage was described by Castro et al. 1992, Dinter et al. 1990, Dugan 1980, and Kandari 1990. Maintaining the thermal stratification requires a controlled charging and discharging procedure, and appropriate methods or devices to avoid mixing. Filling the storage tank with a second solid storage material (rock, iron, sand etc.) can help to achieve the stratification.

2.2.2 Passive Thermal Energy Storage

Passive systems are generally dual medium storage systems. The HTF carries energy received from the energy source to the storage medium during charging and receives energy from the storage material when discharging. These systems are also called regenerators.

The storage medium can be a solid, liquid, or PCM. In general, a chemical storage system employs at least two media.

The main disadvantage of regenerators is that the HTF temperature decreases during discharging as the storage material cools down. Another problem is the internal heat transfer. Especially for solid materials, the heat transfer is rather low, and there is usually no direct contact between the HTF and the storage material as the heat is transferred via a heat exchanger.

3.0 State of the Art

3.1 Existing TES Systems in Solar Thermal Plants

Of eight installed thermal energy storage systems in solar thermal electric plants, seven have been of an experimental or prototype nature and one has been a commercial unit. Table 5 gives the characteristics of the existing units. All have been sensible heat storage systems: two single-tank oil thermocline systems, four single medium two-tank systems (one with oil and three with salt) and two dual medium single-tank systems. To put the size of these systems in perspective, a 30-MWe SEGS plant with a plant efficiency of 35% would require about 260 MWh_t for a 3-hour storage capability. This is considerably larger than any other solar thermal electric storage system built up to now.

All of these systems were successful to varying degrees, recognizing that most were development units that were expected to reveal design flaws or issues as a basis for future design improvements.

Two important characterizations of storage systems are the "round-trip efficiency" and the cost per unit of thermal energy delivery (\$/kW_t). The round-trip efficiency is, simply, the ratio of the useful energy recovered from the storage system to the amount of energy initially extracted from the heat source. This efficiency is affected by the laws of thermodynamics and by heat losses in the tanks, piping, and heat exchangers in the system; electric parasitic losses needed to circulate storage system fluids constitute additional losses.

Efficiency and cost experience from existing systems are informative but of limited relevancy to commercial plants because most of the existing facilities were one-of-a-kind development projects. Nevertheless, round-trip efficiencies of more than 90% were measured in many of the systems listed in Table 5, though some systems were as low as 70%. Both the oil systems and molten salt systems were shown to be technically feasible. While various problems arose due to mistakes in design, construction or operation, no fundamental issues surfaced for these approaches.

The SEGS I storage system cost \$25/kW_t in 1984 dollars, with the oil representing 42% of the investment cost. The oil used in the later SEGS plants for operation up to 400°C costs approximately eight times more than the SEGS I oil. This was reason enough that a storage system similar to the SEGS I storage concept was not repeated in later SEGS plants. However, there were other important considerations, such as total system investment, very large tank size requirements, and inflexibility compared to a back-up system.

Table 5. Existing TES Systems

Project	Type	Storage Medium	Cooling Loop	Nominal Temperature		Storage Concept	Tank Volume (m ³)	Thermal Capacity (MWh _t)
				Cold (°C)	Hot (°C)			
Irrigation pump Coolidge, AZ, USA	Parabolic Trough	Oil	Oil	200	228	1 Tank Thermocline	114	3
IEA-SSPS Almería, Spain	Parabolic Trough	Oil	Oil	225	295	1 Tank Thermocline	200	5
SEGS I Daggett, CA, USA	Parabolic Trough	Oil	Oil	240	307	Cold-Tank Hot-Tank	4160 4540	120
IEA-SSPS Almería, Spain	Parabolic Trough	Oil Cast Iron	Oil	225	295	1 Dual Medium Tank	100	4
Solar One Barstow, CA, USA	Central Receiver	Oil/Sand/Rock	Steam	224	304	1 Dual Medium Tank	3460	182
CESA-1 Almería, Spain	Central Receiver	Liquid Salt	Steam	220	340	Cold-Tank Hot-Tank	200 200	12
THEMIS Targassonne, France	Central Receiver	Liquid Salt	Liquid Salt	250	450	Cold-Tank Hot-Tank	310 310	40
Solar Two Barstow, CA, USA	Central Receiver	Liquid Salt	Liquid Salt	275	565	Cold-Tank Hot-Tank	875 875	110

3.2 Summary of Work Performed Before 1990

This section reviews the most relevant investigations and evaluations carried out prior to about 1990. Selected literature from this period has been listed in the References, but only selected works are explicitly discussed here. A valuable overview of the applicability of thermal storage to solar power plants was provided by Geyer 1991. Table 6 shows the storage systems initially considered there, though of these only a few were investigated in detail. The final systems are listed in the following paragraphs.

Dual medium sensible heat systems

Two single-tank alternatives were analyzed, one in which HTF oil flows through a storage medium of concrete and another in which the storage medium is solid salt. Cast iron and cast steel were eliminated as storage media due to high cost, even though they offered thermodynamic advantages.

Table 6. Candidate Storage Concepts for SEGS Plants

TES Concepts	Storage Type	Status*	Assessment
Sensible Active	Two-Tank Oil	T	Basic concept, state-of-the-art
	HITEC	T	2 variants analyzed based on existing PSA/THEMIS designs
	Thermocline	T	Proved on pilot scale, no advantages over basic two tank system
Sensible DMS	Oil/Cast Iron	T	Proved on pilot scale, no advantages over basic two tank system
	Oil/Steel	LR	Used in chipboard presses
	Oil/Concrete	MR	Several variants analyzed
	Oil/Solid Salt	MR	Several variants analyzed
PCM	Oil/PC Salts	HR	Several cascade arrangements analyzed
Chemical	Oil/Metal Hybrids	HR	Early state of development, no lead concepts, no cost data
* Nomenclature: T : Tested / LR : Low Risk / MR : Medium Risk / HR : High Risk			

Sensible heat molten salt system

A two-tank system (similar to SEGS I) utilizing the HITEC salt was chosen. HITEC is a eutectic mixture of 40% NaNO₂, 7% NaNO₃ and 53% KNO₃ with a 142°C melt-freeze point.

Phase-change systems

These higher-risk systems were judged to have high uncertainty in technical feasibility and cost, but were evaluated for their potential in this application. Three different phase-change concepts were evaluated. The first was a LUZ design using five PCMs in a series, or cascade, design (SERI 1989); the second was a design by the Spanish company INITEC, which also used five PCMs but in a different heat exchanger configuration; the third design originated with the German companies Siempelkamp and Gertec (SGR) and used three commercially available PCMs along with concrete for the higher temperatures.

3.2.1 Overview of Results

Storage system designs for the SEGS conditions based on these five concepts were developed in Dinter et al. 1990. Summary results are presented here giving overall system volume, thermal storage capacity and utilization, and specific costs in \$/kWh_t of capacity.

The utilization measure is an interesting aspect of storage systems. Earlier discussion described some of the aspects of temperature differences within the HTF fluid and between the HTF and a solid storage medium. Another aspect of storage design is the temperature difference within the medium itself. In a two-tank liquid system, for example, the entire fluid is heated to a charged temperature and hence the entire storage medium is utilized. PCM systems theoretically also have very high utilization factors. In a solid system, however, temperature gradients required for thermal conduction through the media itself prevent full utilization of the material. In this case, 100% utilization would be achieved if the entire solid medium were heated to the full

charging temperature. Hence, the “potential” storage capacity might be two or three times higher than the practical storage capacity. Detailed heat transfer calculations on specific designs provide this type of information.

Figure 2 gives results on the total volume, storage capacity and utilization, and specific cost of the six candidate systems analyzed for SEGS plants. For comparison purposes, we will select the INITEC PCM design as representative of the PCM class, with the qualifier that there is much more uncertainty and technical risk in the PCM results than in the sensible heat oil-solid systems or in the sensible heat HITEC molten salt system.

With regard to volume, the concrete and salt media fill about 6,900 and 5,200 m³ of space, respectively, whereas the molten salt and PCM system need 2,600 m³. If the cross-sectional area perpendicular to the flow measured 13m by 13m, the length of the concrete system would be 41 m compared to a 15-m length for the PCM system. A major reason for the larger sizes of the concrete and solid salt systems is the poor volume utilization. The concrete system, for example, is utilized at 36% of its full potential capacity. The molten salt and PCM systems, on the other hand, have utilization factors up to 100%. The concrete system does, however, have cost advantages due to the very low cost of concrete, which results in a low system cost even though there is more structure required for this larger volume system.

Generally, the storage costs developed in this assessment vary from \$25–\$50/kWh_t (on the order of \$65–\$130/kWh_e). At the low end, TES units of 270 and 450 MWh_t capacity would have a capital cost of 6.8 MUSD and 11.3 MUSD, respectively.

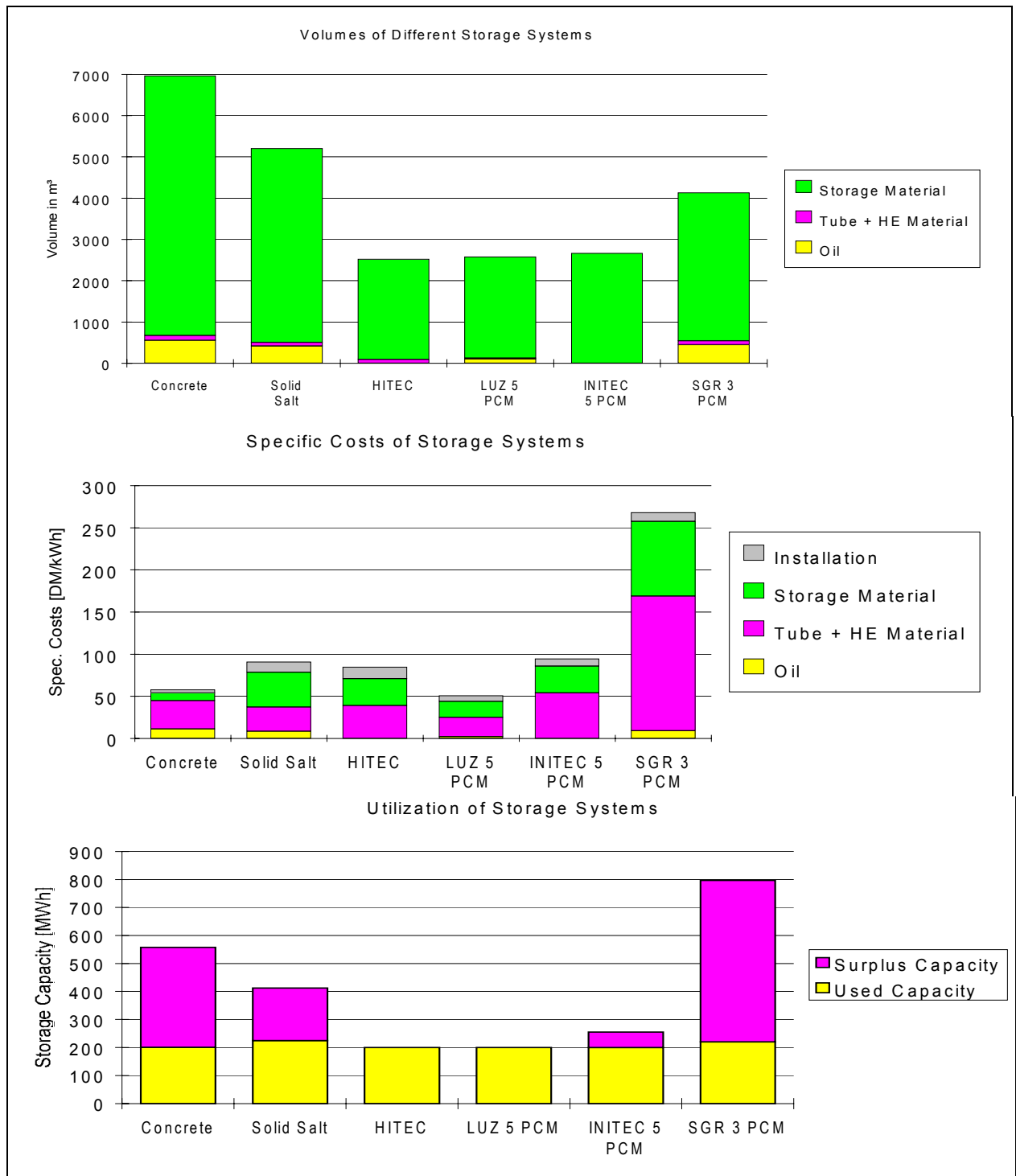


Figure 2. Results of TES evaluations for reference SEGS plant (Dinter et al. 1990)

3.2.2 SEGS TES Workshop

A symposium workshop (SERI 1989) on TES systems for SEGS plants, held in 1989 and sponsored by the Solar Energy Research Institute (SERI—now the National Renewable Energy Laboratory—NREL), discussed several of the options presented

above. While the workshop focused on phase-change material concepts, both sensible heat storage and chemical storage were also included in the agenda. The more detailed evaluations reported in Dinter et al. 1990 were completed subsequent to the workshop.

With respect to sensible heat storage, the workshop concluded that this approach could result in a cost-effective system. While no new research would be required, thorough and careful engineering development and small-scale testing would be necessary. Issues such as thermal expansion, potential leakage, heat transfer configuration, and heat exchange optimization require more detailed design within the context of a design concept.

Latent heat (or phase-change) storage was considered to be in a more primitive state of development. While the concept is promising, considerable research, system development, and proof-of-concept testing would be required. Concerns on heat transfer characteristics and heat exchange configuration were expressed. Of several possible configurations, it was concluded that both shell-and-tube heat exchangers and a system of encapsulated particles of phase-change salts were worthy of exploration, with the latter approach having both more potential for cost-effectiveness and a lower probability of success.

3.3 Experience and Research on TES since 1990

To analyze the work that has been done since 1990 on thermal storage for troughs, a thorough literature review was carried out. This review included a computerized literature search in the Energy Technology Data Exchange (ETDE) Energy database.

The ETDE Energy Database contains more than 3.8 million bibliographic records with abstracts for energy research and technology information from around the world. The EDTE, a multilateral information exchange program, was established in 1987 under the auspices of the International Energy Agency (IEA). Member countries share their energy research and technology information through the Energy Database. The database covers journal articles, research reports, conference papers, books, dissertations, computer software, and other miscellaneous types. Of all the records, 7.1% are devoted to energy storage and conservation.

Appendix A gives the report of the database search including the keywords used to identify the records of interest.

Sixty-five references that met the criteria defined through the keywords were identified. After evaluating the 65 abstracts, a lesser number (21) were applicable to TES systems in parabolic trough technology, and this group was added to the reference list given in Chapter 5. The abstracts for this group are included in Appendix B.

Table 7, summarizing the literature analysis, lists all identified works that may help in the selection of a candidate storage concept. The main results for the most promising options are discussed below.

Table 7. Results from Literature Review (after 1999)

Author	Year	Storage Concept	Type of Work*	Temperature Range	Capacity
M. Mitzel et al.	1990	Hydrid/Magnesium Thermochemical Storage	TH	?	-
Brown et al.	1991	Oxide/Hydroxide chemical storage	TH	300°C–400°C	-
D.Steiner, M. Groll	1995	MgH ₂ /Mg Chemical Storage	EX-LS	280°C–480°C	14 kWh
K. Lovegrove A. Luzzi et al.	1999	Ammonia Based Thermochemical Storage	EX-LS	450°C–650°C	?
B.Beine, F. Dinter, R. Ratzesberger et al.	1992	Concrete	EX-LS	290°C–400°C	50 kWh
J. Pacheco, D.B. Kelly et al.	1999	Molten-Salt 2-Tank	EX-FS	290°C–566°C	114 MWh
H. Michels, E. Hahne	1996	Cascaded PCM	EX-LS	250°C–450°C	8.5 kWh

* TH theoretical work
EX-LS experimental work in lab scale
EX-FS experimental work in full scale

In addition to the experimental works listed in Table 7, more theoretical works on TES were performed by Brower 1992, Lund 1994, Meier and Winkler 1993, Steel and Wen 1981, and Steinfeld et al. 1991.

3.3.1 Overview of Progress

3.3.1.1 Experience at Solar Two

The most significant recent work on molten salt storage comes from the experience in the Solar Two Project. This prototype facility, decommissioned in 1999, was a 10-MW power tower system using a nitrate eutectic molten salt as the HTF. A schematic of the system is shown in Figure 3. Molten salt is pumped from the cold storage tank through the tower receiver and then to the hot storage tank. When dictated by the operation, the hot salt is pumped through the steam generation system and then back to the cold tank. Solar Two is capable of producing 10 MWe net electricity. A number of lessons on the equipment design, material selection, and operation of molten salt systems were learned during the 1-1/2 years of testing and evaluation.

Solar Two used an efficient, molten nitrate-salt thermal-storage system (Pacheco and Gilbert 1999). It consisted of an 11.6-m-diameter by 7.8-m-high cold-salt storage tank, a 4.3-m-diameter by 3.4-m-high cold-salt receiver sump, an 11.6-m-diameter by 8.4-m-

high hot-salt storage tank, and a 4.3-m-diameter by 2.4-m-high hot-salt steam generator sump. The design thermal storage capacity of the Solar Two molten salt system was 105 MWh_t—enough to run the turbine at full output for 3 hours. The measured gross conversion efficiency of the 12-MWe (10-MWe-net) Solar Two turbine was 33%. Actual thermal storage capacity based on the mass of salt in the tanks, accounting for (subtracting) the 3-foot heels in each tank, and with design temperatures—1050°F hot salt, 550°F cold salt—was 114 MWh_t.

The system contained 1.5 million kilograms of nitrate salt composed of a mixture of 60% NaNO₃ and 40% KNO₃, provided by Chilean Nitrate Corporation (New York). This salt melted at 220°C and was thermally stable to about 600°C.

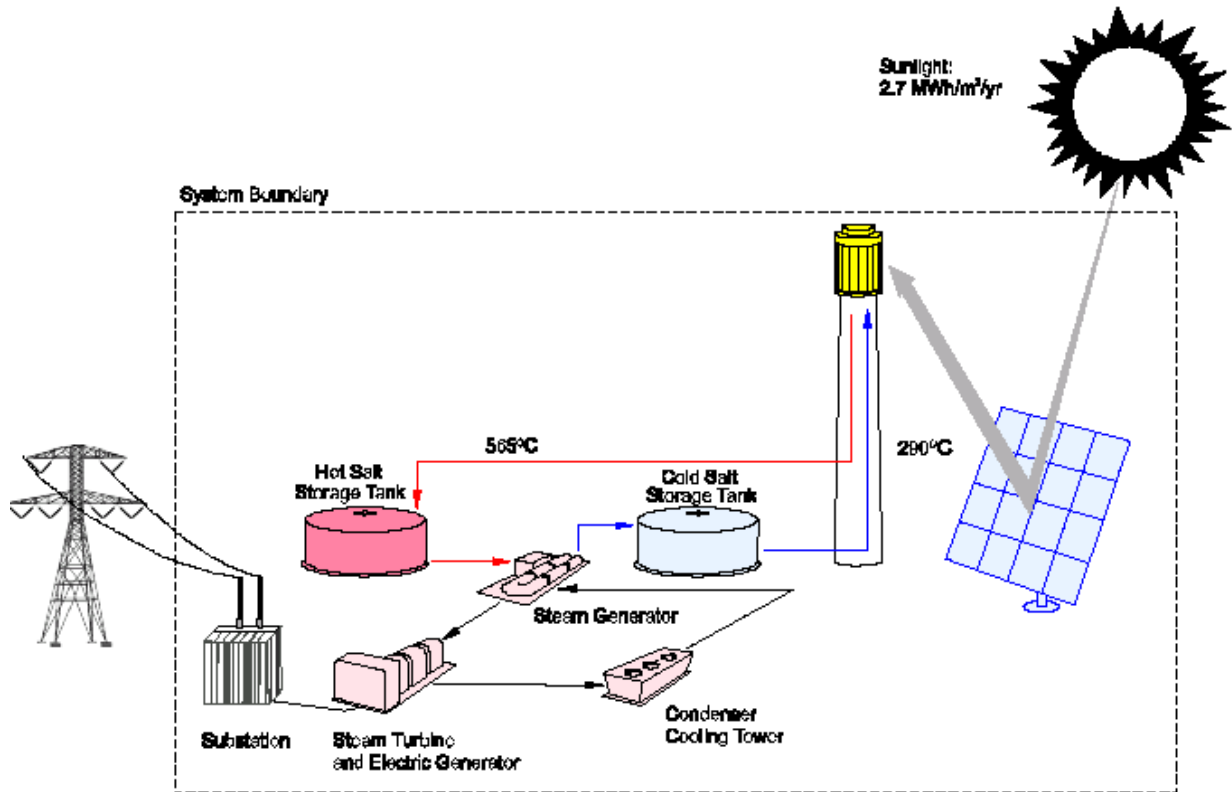


Figure 3. Molten salt power tower system schematic

Heat Losses

Several tests were conducted to quantify the thermal losses of major pieces of equipment throughout the plant and to compare the values to calculated estimates. The major pieces of equipment evaluated were the hot tank, cold tank, steam generator sump, and receiver sump. There were two methods of measuring the thermal losses in the tanks and sumps. One method was to turn off all auxiliary heaters and track the rate of decay of the average tank or sump temperature. By knowing the salt level, and thus the volume of salt in the vessel, an estimate of the heat loss could be made. Another method was to have the heaters energized and regulate the inventory at a set temperature. Once the vessel was at steady state, the power consumption of the

heaters was measured over a long period of time. The electrical power consumption was assumed to be equal to the heat loss rate.

A summary of the measured and calculated thermal losses is shown in Table 8. The thermal losses for the tanks and sumps were equal to the calculated values within experimental error, except for the steam generator sump heat loss rate. The losses for the steam generator sump were higher than predicted, possibly because the insulation may have degraded significantly since it was installed. Salt had leaked out of the sump through flanges and into the insulation, which adversely affected its insulating properties. Based on the measured heat loss rates, the total energy lost to the environment over the course of a typical operating year corresponds to a 98% annual thermal efficiency.

Table 8. Measured and Actual Thermal Losses of Major Equipment

Major Equipment	Calculated Thermal Loss, kW	Measured Thermal Loss, kW
Hot Tank	98	102
Cold Tank	45	44
Steam Generator Sump	14	29
Receiver Sump	13	9.5

Operating Experience¹

The capacity of the system is a function of the hot and cold salt temperatures. Hot salt temperatures at the bottom of the downcomer were typically only 1025°F because some of the isolation ball valves between the riser and downcomer leaked, attenuating the salt coming out of the receiver (which typically exited at 1050°F). The lower salt temperature derated the capacity of the thermal storage system by 5% to 108 MWht.

The fractional amount of the energy sent to thermal storage that was later discharged to the steam generator to make electricity is nearly 1, but is a function of the availability. The thermal losses are basically a fixed loss to the environment. When the plant availability is high, the collected energy increases and the losses are a smaller fraction of the total energy sent to storage. For example, on Dec. 2, 1997, on a sunny winter day, the receiver collected 217 MWh, which was sent to the steam generator system to make electricity. Based on a constant thermal loss of 185 kW from the hot and cold tanks, and the receiver and steam generator sumps, the total energy lost to the environment that day was 185kW x 24 h = 4.43 MWh or 2.0% of the collected energy. In contrast, on a sunny summer day—June 18, 1998—the receiver collected 334 MWht

¹ Comments provided by James Pacheco, Sandia National Laboratories Albuquerque, December 15, 1999.

and the thermal losses were 1.3% of the collected energy. Even with the very prototypical nature of Solar Two (i.e., poor availability, frequent outages, first year operation, etc.), over several months the fractional amount lost to the environment was only 6% of collected energy. If the plant ran with higher availability, i.e., typical mature operation, the fractional amount of stored energy lost to the environment would only be about 2% of collected energy.

There were no major operational problems with the thermal storage system and, in general terms, the system ran satisfactorily. Typically, the plant started using the stored energy within an hour or two after the receiver began collecting energy. Scenarios were also run, however, to demonstrate dispatching energy several times or to demonstrate the production of a constant output of electricity at night and through clouds. A number of practical lessons were learned, and no barriers to future implementation were evident.

3.3.1.2 Concrete

Limited prototype testing has been done on the concrete-steel thermal storage concept. Between 1991 and 1994, two concrete storage modules were tested at the storage test facility at the Center for Solar Energy and Hydrogen Research (ZSW) in Stuttgart, Germany (Ratzesberger et al. 1994). Figure 4 shows the prototype concrete module installed in the center's laboratory.

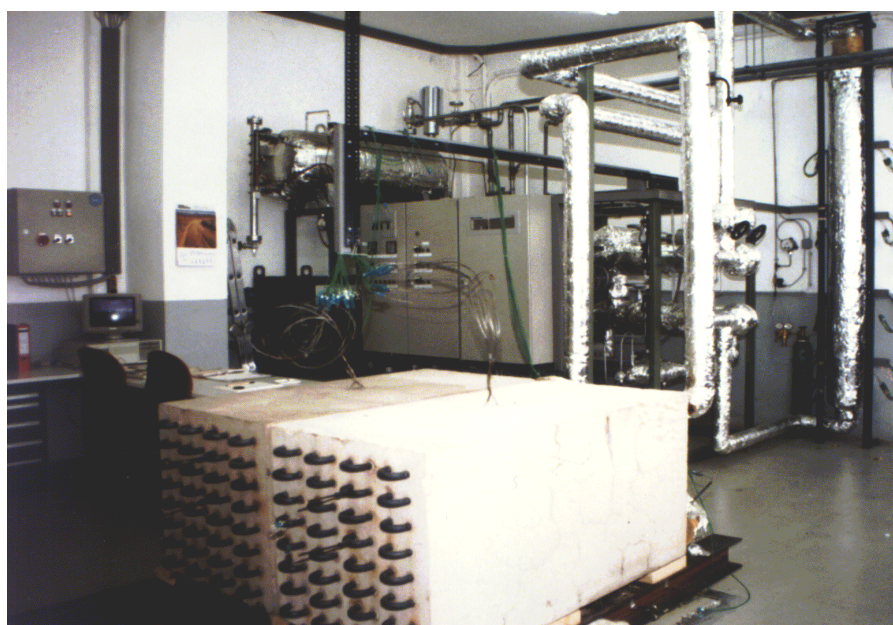


Figure 4. Test Facility for TES with two concrete storage modules at ZSW

The test results gained at ZSW in principle confirm the performance predictions given by Baddrudin, Dinter et al. 1992. Based on these tests, a numerical calculation model for concrete storage was developed by Ratzesberger 1995. He also proposed a slightly different design that results in the same performance but with considerably lower pressure loss in the storage module. According to his results, the pressure loss in a

200-MWh module can be reduced from 4.3 to 1.9 bar. The integration of a sensible heat storage system like concrete storage into a SEGS plant is depicted in Figure 5.

Ratzesberger recalculated the cost for storage and obtained a price of \$40/kWh in 1994 U.S. dollars. This is slightly higher than the number given by Dinter. As a next step in the development of concrete storage, a project has recently been proposed to the EU (European Union) by a European team (CONTEST 1999). The proposed project consists of a prototype module with a capacity of 1–2 MWh to be erected at the PSA and connected to a parabolic trough solar field. The project, if funded, will be led by the German company Siempelkamp Giesserei GmbH & CO KG. In the company's proposal, it is projected that storage costs of \$26/MWh in commercial scale can be realized.

Summarizing the work performed on concrete storage up to now, it can be concluded that this concept presents a relatively cheap option of thermal storage. The feasibility has already been proven in laboratory tests. The highest uncertainty still remains in the long-term stability of the concrete material itself after thousands of charging cycles. Special tests in a climatic chamber dedicated to investigation of this potential problem are included in the aforementioned EU proposal.

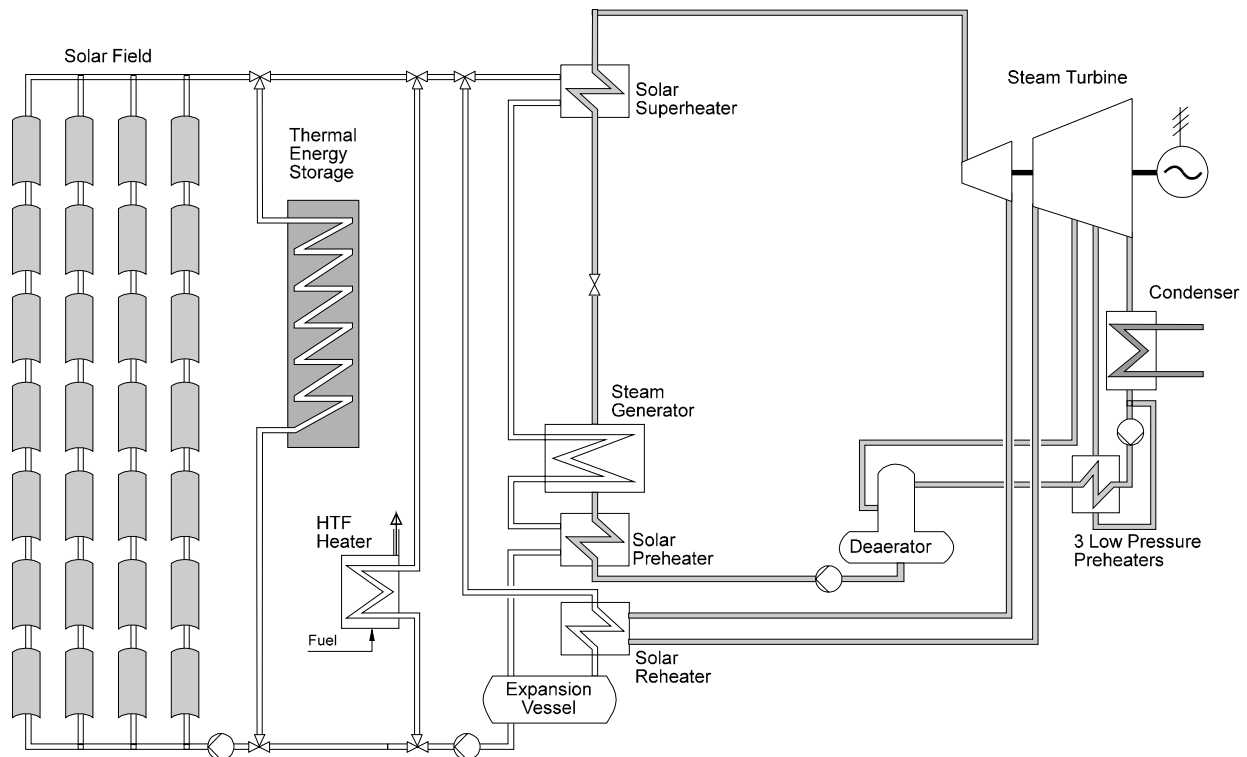


Figure 5. Schematic diagram of a SEGS plant with TES

3.3.1.3 Phase Change Material

Following the recommendations of the SERI workshop held in 1988 (SERI 1989), the ZSW, Germany, started to investigate storage using PCM. It was found by Dinter et al.

1990 that PCM storage has a relatively high heat capacity per volume and offers the lowest cost of all concepts investigated in this study (see also Figure 2).

A storage test facility has been set up in ZSW's laboratory allowing the investigation of various storage concepts independent from the sun. Electrical heating is the heat source, and a cooling tower is the heat sink. Figure 6 shows the flow diagram of the test loop with three PCM modules connected to the system. The modules can be charged by the HTF flow separately or connected to each other in series or in parallel.

A major objective was to investigate the heat transfer mechanism of different PCM salts during phase change and of liquid salts (Hunold et al. 1994, 1992, 1992, and 1994). In the work of Hunold, only one storage module filled with one salt was investigated in each case. Hunold showed that phase change storage is technically feasible and proposed a storage design built out of a shell and tube heat exchanger in a vertical orientation. By adjusting the vertical orientation of the tubes, natural convection and heat transfer can be improved. He selected the nitrate NaNO_3 , with a melting point at 305°C , as appropriate storage material for the SEGS-type power plants.

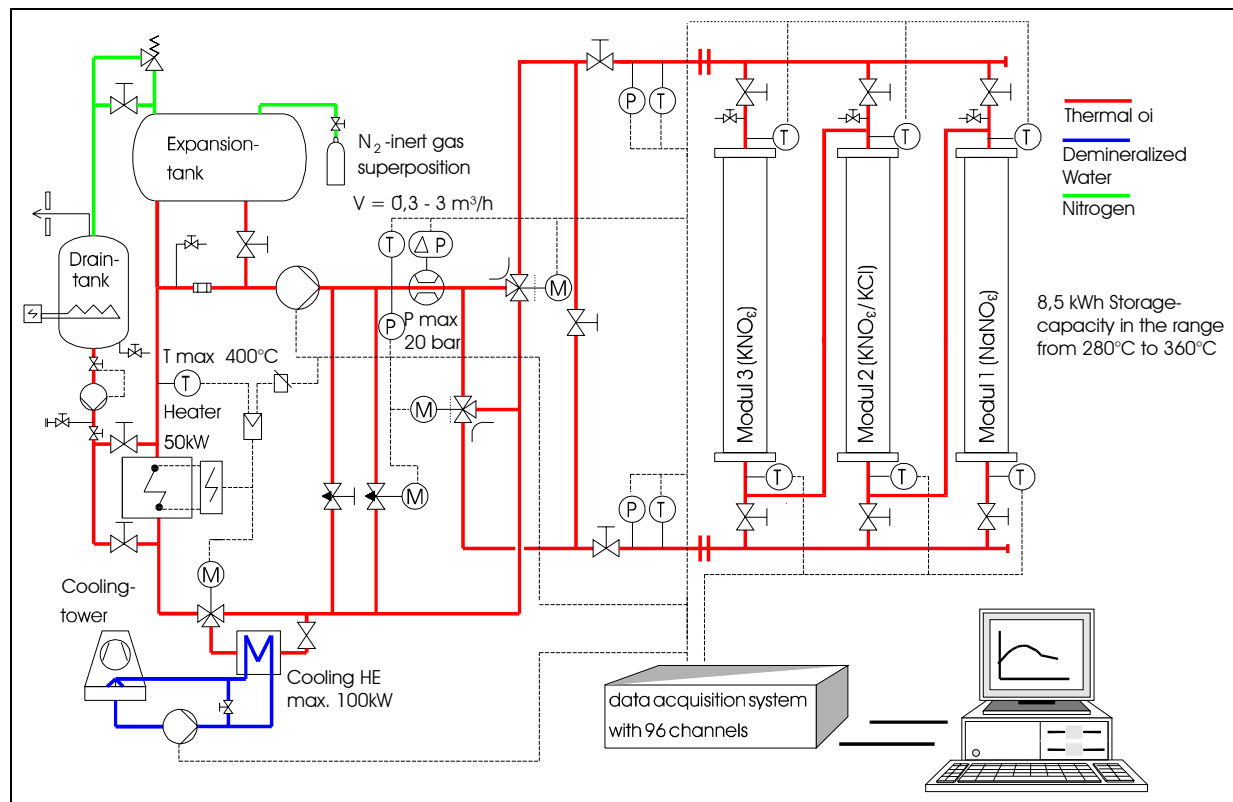


Figure 6. Flow diagram of storage test loop at ZSW (Michels and Hahne 1996)

However, one can only take full advantage of PCM storage by connecting several modules with different salts and different melting points in series as shown in Figure 7. Michels 1996 explained, by means of Figure 8, the reason for this. The left diagram shows the HTF temperature at the end of charging and discharging and the melting temperature of a single-stage salt storage as investigated by Hunold. During discharging the HTF temperature in the biggest part of the storage module is higher than the melting temperature of the salt. This means that a major portion of the salt

would not freeze during discharging and the high latent portion of the stored heat can not be extracted from the storage. Consequently, the utilization factor of the system would be relatively low.

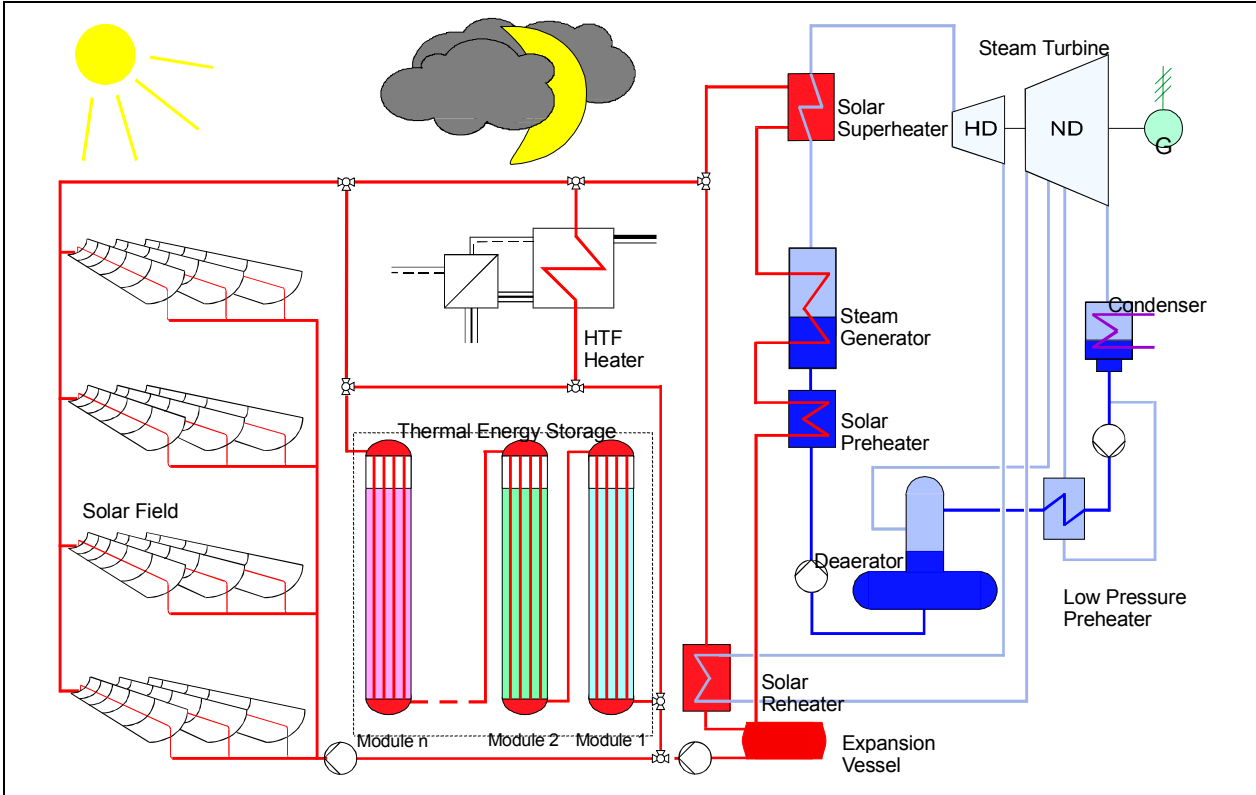


Figure 7. Possible process scheme of a SEGS with integrated PCM-TES (Michels and Hahne 1996)

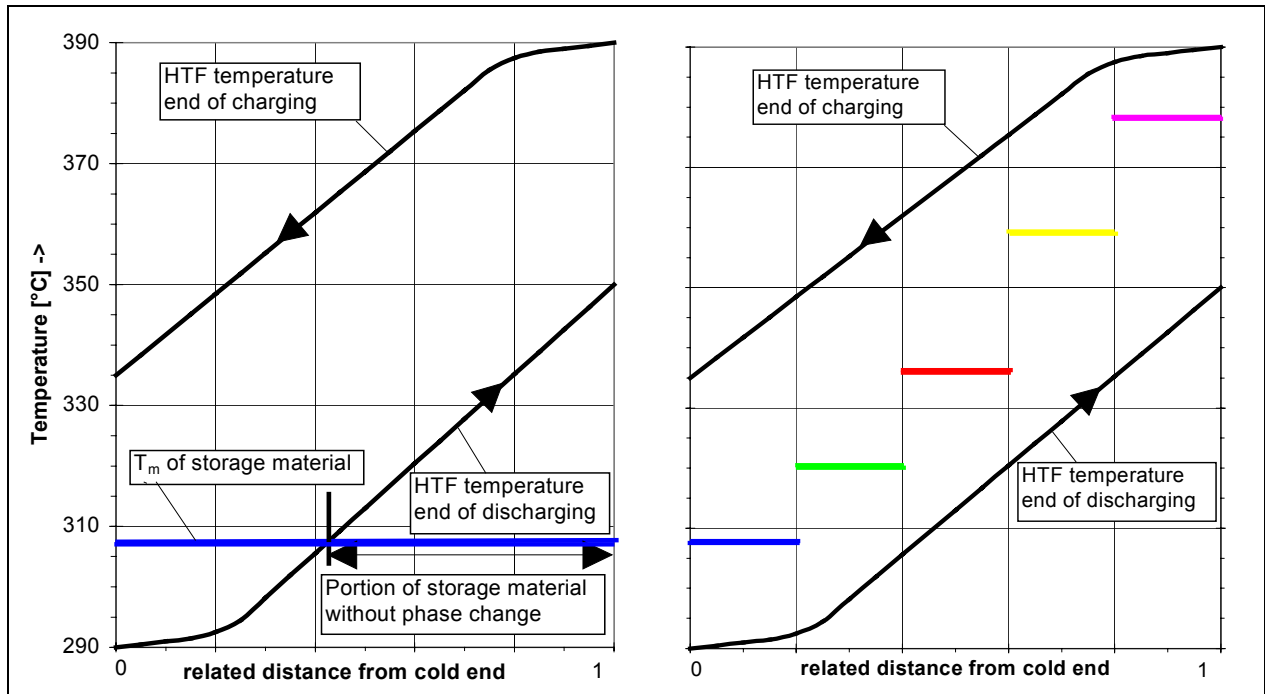


Figure 8. Theoretical temperature distribution in a PCM-TES for SEGS

The latent heat can only be used completely if, during charging, the temperature of the HTF is always higher than the melting point of the storage medium and, during discharging, always lower. This is shown in the right-hand diagram of Figure 8. According to Michels, five different PCMs have to be used for an optimized storage operating in the temperature range of a SEGS plant.

Michels experimentally investigated a configuration of three different modules connected in series (Michels and Hahne 1996). He used the nitrates KNO_3 , KNO_3/KCl and NaNO_3 . Figure 9 shows the measured temperature distribution in the test modules during charging.

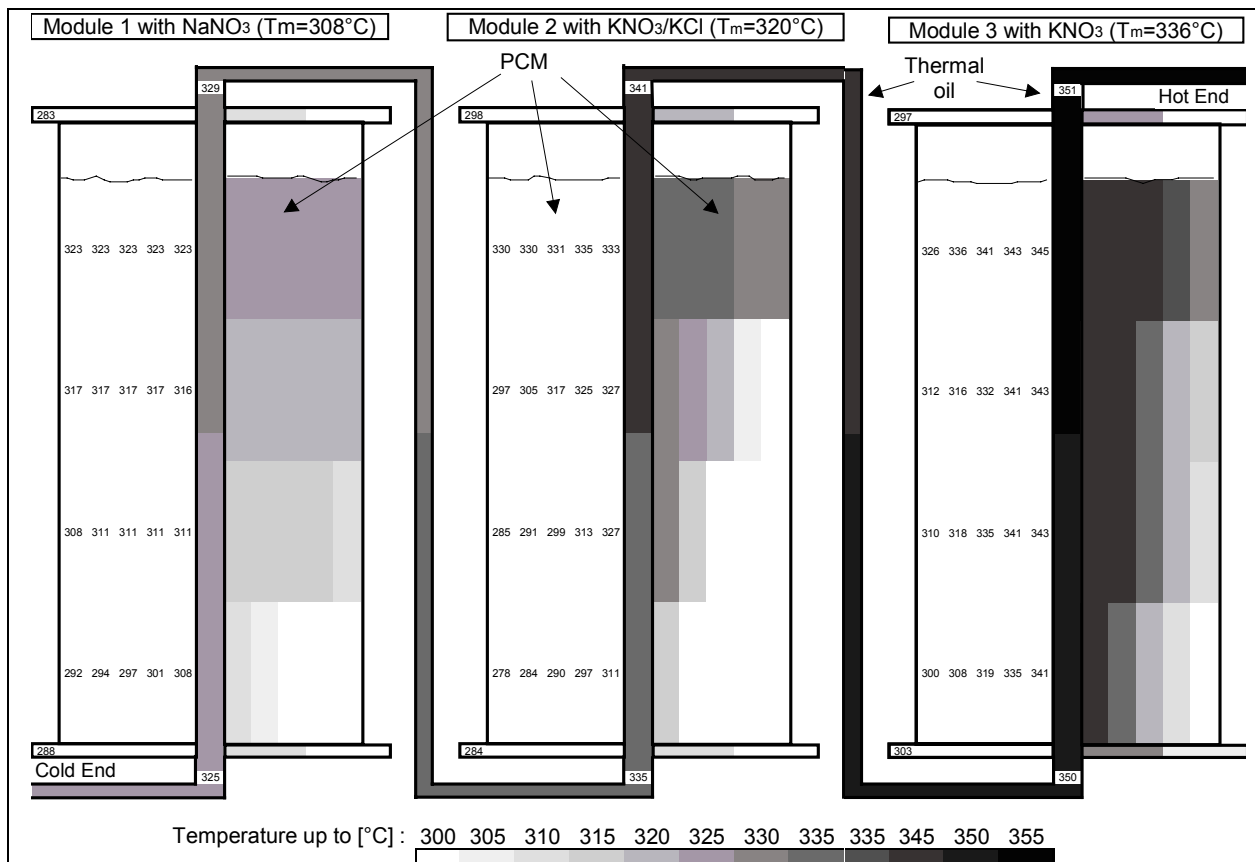


Figure 9. Temperature distribution inside the cascaded PCM test modules during charging

In his experiments, Michels proved the high utilization factor of a cascaded PCM storage. However additional experiments are required to verify the feasibility of a five-stage cascaded storage. Also additional design studies have to be performed to optimize the sizes of each stage, to select the appropriate material for the storage tank for each salt and to evaluate the cost.

Further works are concerned with PCM as storage material for parabolic troughs with Direct Steam Generation (Solomon 1991) and with the development of special measurement devices to observe the phase-change (Jaworske 1991).

A combined configuration of one sensible heat storage module, like concrete, and of two PCM modules at each end as proposed by Ratzesberger et al. (1994) seems to be a reasonable approach as a next step in the development of PCM storage.

3.3.1.4 Chemical Energy Storage

In the SERI workshop it was concluded that chemical energy storage is an attractive option in longer term and may offer relatively low cost. Based on a preliminary cost assessment the hydroxide/oxide reaction between CaO and H₂O was mentioned as one possibility (NASA 1979).

Subsequently, the Pacific Northwest Laboratory (PNL—now the Pacific Northwest National Laboratory—PNNL) conducted a study funded by the U.S. Department of

Energy to investigate the potential feasibility for a chemical energy storage based on this reaction. The report (Brown et al. 1991) concluded that this type of storage is, in principle, applicable under the SEGS temperature conditions. However, the study was based only on theoretical analysis and basic experimental investigations, and information was somewhat limited due to proprietary restrictions. The authors could not determine if the dynamics of the reaction fit to the requirements of storage for solar power plants, and also concluded that the question of proper integration into the solar power system remained unsolved. Costs were roughly estimated to be about \$45/kWh. No further development of this type of storage could be identified through the literature review, and it appears that considerable work is required to develop a chemical energy storage system with hydroxide/oxide reaction for commercial application.

Development of another type of chemical storage seems to be much advanced, namely the solar ammonia energy storage developed by the Australian National University (Kreetz and Lovegrove 1999, Lovegrove et al. 1999, and Luzzi et al.). In this system, liquid ammonia is dissociated in a solar reactor into hydrogen and nitrogen. The energy is recovered in an ammonia synthesis reactor. The ammonia system was developed for use with parabolic dishes, but theoretically can also be used in the temperature range of parabolic trough collectors.

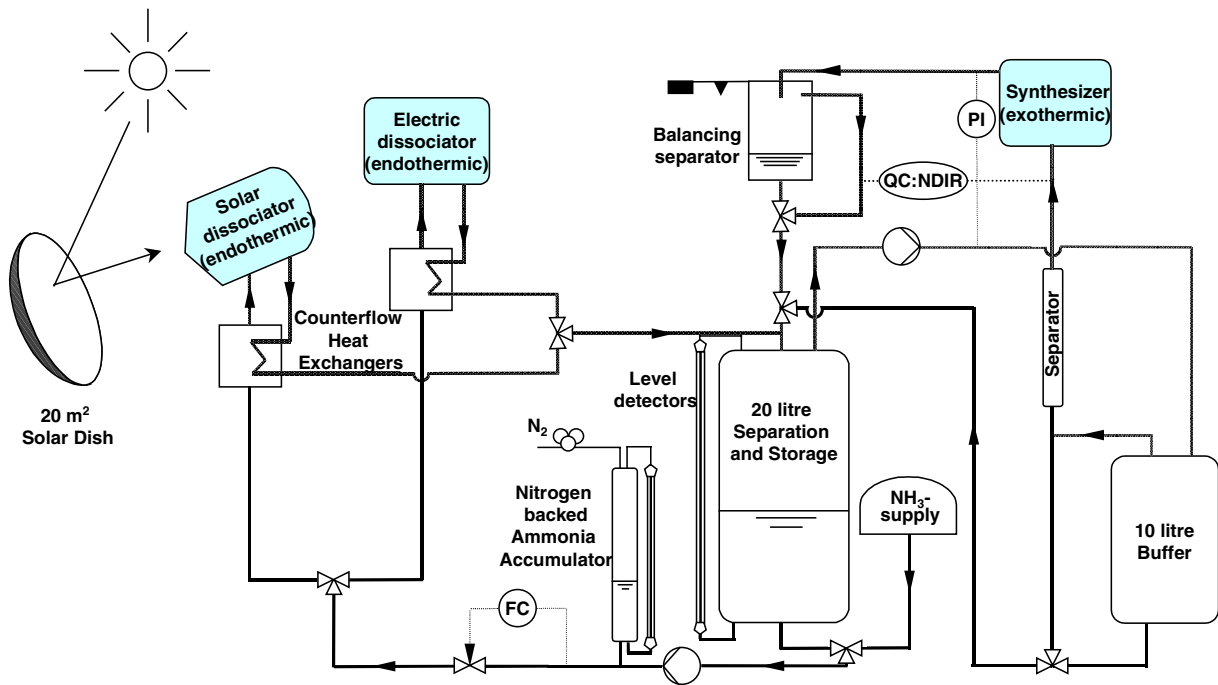


Figure 10. Test loop set up for solar ammonia energy storage (Lovegrove et al. 1999)

The first small-scale solar test facility was set up and has been operating for more than a year. Figure 10 shows the flow diagram of the test installation. The nominal solar input into the system is 1 kW. At this scale, it is clear that potential scale-up to a multi-megawatt system would be a significant undertaking.

Current estimates are that a 10-MW plant built largely from industry standard or proven components will cost about \$100 million (U.S. 1999) (Luzzi et al.).

4.0 Observations and Recommendations

Based on the body of literature examined in this survey, we come to the following observations:

- There have been no *major* bold developments in the field of thermal energy storage systems for trough power plants in the 1990s compared to prior work. However, there have been important contributions furthering work on candidate systems previously identified.
- Within the context of the Solar Two project, a prototype two-tank molten salt system containing a nitrate salt eutectic was successfully tested over a 11/2 year testing period.
- Molten salt systems with lower melting points should be explored for trough applications. The two-tank system as implemented at Solar Two is a relatively low-risk approach. A one-tank thermocline system is riskier with respect to performance, but offers the promise of important cost reductions.
- Useful laboratory-scale testing on several PCM modules was carried out by ZSW. The results substantiate the prior conclusion that these systems offer promise, and further work appears warranted.
- A proposal for prototype construction and testing of 1–2-MWh prototype concrete-steel storage system was submitted to the European Union in the summer of 1999. Present indications at the issuance of this report are that funding for this project will not be granted in the current round of accepted projects, and resubmission in early 2000 is anticipated.
- We found no evidence that the design and development of chemical storage for parabolic trough applications has been *significantly* advanced in the last decade, though some further useful evaluations have been carried out.

These observations lead us to the following recommendations:

1. On the basis of current progress and cost estimates, molten salts and concrete systems merit priority as candidates for near-term deployment. PCM systems are the additional system of choice for longer-term development.
2. The focus of near-term research should be prototype system development and field implementation to refine designs and provide the bases for valid performance and cost estimates.

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APPENDIX A:
Report of Database Search

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ENERGY FILE SEARCH STATISTICS - P337407K 03 DEC 1999 15:03:04 PAGE 2

THERM. ENERGIESPEICHERUNG

26 ANSWERS PRINTED IN FORMAT 'ALL'

IN FILE 'ENERGY'

USING QUERY:

L1 6747 SEA FILE=ENERGY THERMAL ENERGY STORAGE EQUIPMENT/CT
L2 4627 SEA FILE=ENERGY 1427/CC
L3 1873 SEA FILE=ENERGY L1 AND L2
L4 166176 SEA FILE=ENERGY ("POWER PLANTS"/CT OR "DUAL-PURPOSE POWER
PLANTS"/CT OR "FUEL CELL POWER PLANTS"/CT OR "GAS TURBINE
POWER PLANTS"/CT OR "HYDROELECTRIC POWER PLANTS"/CT OR
"HIGH-HEAD HYDROELECTRIC POWER PLANTS"/CT OR "LOW-HEAD
HYDROELECTRIC POWER PLANTS"/CT OR "MEDIUM-HEAD HYDROELECTRIC
POWER PLANTS"/CT OR "MICRO-SCALE HYDROELECTRIC POWER
PLANTS"/CT
OR "PUMPED STORAGE POWER PLANTS"/CT OR "SMALL-SCALE
HYDROELECTRIC POWER PLANTS"/CT OR "MHD POWER PLANTS"/CT OR "MHD
GENERATOR
ETF"/CT OR "PEAKING POWER PLANTS"/CT OR "COMPRESSED AIR
STORAGE POWER PLANTS"/CT OR "PUMPED STORAGE POWER
PLANTS"/CT
OR "SOLAR POWER PLANTS"/CT OR "OCEAN THERMAL POWER
PLANTS"/CT
OR "ORBITAL SOLAR POWER PLANTS"/CT OR "PHOTOVOLTAIC POWER
PLANTS"/CT OR "SALINITY GRADIENT POWER PLANTS"/CT OR "SOLAR
THERMAL POWER PLANTS"/CT OR "DISTRIBUTED COLLECTOR POWER
PLANTS"/CT OR "TOWER FOCUS POWER PLANTS"/CT OR "BARSTOW
SOLAR
PILOT PLANT"/CT OR "THERMAL POWER PLANTS"/CT OR
"COMBINED-CYCLE
POWER PLANTS"/CT OR "MHD GENERATOR ETF"/CT OR "FOSSIL-FUEL
POWER PLANTS"/CT OR "KINGSTON STEAM PLANT"/CT OR "PARADISE
STEAM PLANT"/CT OR "SHAWNEE STEAM PLANT"/CT OR "WIDOWS
CREEK
STEAM PLANT"/CT OR "GEOHERMAL POWER PLANTS"/CT OR "NUCLEAR
POWER PLANTS"/CT OR "BOPSSAR STANDARD PLANT"/CT OR "EBASCO
STANDARD PLANT"/CT OR "GIBBSAR STANDARD PLANT"/CT OR
"OFFSHORE
NUCLEAR POWER PLANTS"/CT OR "SWESSAR STANDARD PLANT"/CT
OR

STN INTERNATIONAL®

ENERGY FILE SEARCH STATISTICS - P337407K 03 DEC 1999 15:03:04 PAGE 3

"UNDERGROUND NUCLEAR STATIONS"/CT OR "OCEAN THERMAL POWER
PLANTS"/CT OR "REFUSE-FUELED POWER PLANTS"/CT OR "SOLAR
THERMAL POWER PLANTS"/CT OR "DISTRIBUTED COLLECTOR POWER
PLANTS"/CT OR "TOWER FOCUS POWER PLANTS"/CT OR "BARSTOW
SOLAR
PILOT PLANT"/CT OR "WOOD-FUEL POWER PLANTS"/CT OR
"THERMONUCLEA
R POWER PLANTS"/CT OR "TIDAL POWER PLANTS"/CT OR
"KISLOGUBSK
POWER PLANT"/CT OR "PASSAMAQUODDY POWER PLANT"/CT OR
"RANCE
POWER PLANT"/CT OR "WIND POWER PLANTS"/CT OR "EFD WIND
GENERATORS"/CT)
L5 245 SEA FILE=ENERGY L3 AND L4
L7 26 SEA FILE=ENERGY L5 AND PY>=1990

APPENDIX B:
Abstracts of Selected References



L7 ANSWER 2 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
AN 1996(3):15026 ENERGY
TI Development and investigation of thermal energy storage systems for the medium temperature range.
AU Steiner, D.; Groll, M. (Univ. Stuttgart (Germany). Inst. fuer Kernenergetik und Energiesysteme);
Wierse, M. (Forschungsinstitut fuer Kerntechnik und Energiewandlung e.V., Stuttgart (Germany))
NR CONF-950729-
SO Proceedings of the 30. intersociety energy conversion engineering conference. Volume 2. Editor(s): Goswami, D.Y. (Univ. of Florida, Gainesville, FL (United States)); Kannberg, L.D.; Somasundaram, S. (Pacific Northwest Lab., Richland, WA (United States)); Mancini, T.R. (Sandia National Labs., Albuquerque, NM (United States))
New York, NY: American Society of Mechanical Engineers. 1995. p. 193-198 of 658 p.
American Society of Mechanical Engineers, United Engineering Center, 345 East 47th Street, New York, NY 10017 (United States).
Conference: 30. Intersociety energy conversion conference, Orlando, FL (United States), 30 Jul - 5 Aug 1995
DT Book Article; Conference
CY United States
LA English
FA AB
AB Within the frame of two projects funded by the German Federal Ministry for Research and Technology (BMFR) a thermochemical energy storage system for solar application and a sensible/latent hybrid storage system for industrial application were investigated. The thermochemical energy storage system utilizes the heat of reaction of the reversible reaction of magnesium and hydrogen. The operation temperature range is between 280 C and 480 C.
The storage capacity amounts to about 54 MJ. The combination of the MgH₂/Mg system with an appropriate low-temperature alloy/hydride offers the option of producing cold below 0 C in the heat retrieval cycle. The hybrid storage system uses a salt/ceramic which consists of a micro-porous MgO matrix, the pores of which are filled with a salt (85 wt% NaNO₃, 15 wt% NaNO₂). The sensible heat of both the ceramic and the salt and the phase change enthalpy of the salt in the temperature range 250 C to 290 C can be utilized. The experimental storage bed was operated in the temperature range of 150 C to 450 C, the storage capacity was about 400 MJ. Air was used as the heating and cooling heat transfer medium
CC *250600; 142000
CT DESIGN; LATENT HEAT STORAGE; MAGNESIUM HYDRIDES; MAGNESIUM OXIDES; NITRITES;
PERFORMANCE; SENSIBLE HEAT STORAGE; SODIUM COMPOUNDS; SODIUM NITRATES;
SOLAR
THERMAL POWER PLANTS; THERMAL ENERGY STORAGE EQUIPMENT;
THERMOCHEMICAL HEAT
STORAGE; WASTE HEAT UTILIZATION
*THERMAL ENERGY STORAGE EQUIPMENT: -DESIGN; -THERMAL ENERGY STORAGE EQUIPMENT: -PERFORMANCE; -SOLAR THERMAL POWER PLANTS: -THERMOCHEMICAL
HEAT
L7 ANSWER 2 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
STORAGE
BT ALKALI METAL COMPOUNDS; ALKALINE EARTH METAL COMPOUNDS; CHALCOGENIDES; ENERGY STORAGE; ENERGY STORAGE SYSTEMS; ENERGY SYSTEMS; EQUIPMENT;
HEAT
STORAGE; HYDRIDES; HYDROGEN COMPOUNDS; MAGNESIUM COMPOUNDS; NITRATES;
NITROGEN
COMPOUNDS; OXIDES; OXYGEN COMPOUNDS; POWER PLANTS; SODIUM COMPOUNDS;
SOLAR

L7 ANSWER 4 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
AN 1995(16):102317 ENERGY
TI Storing solar energy in salt.
AU Valenti, M.
SO Mechanical Engineering (United States) (Jun 1995) v. 117(6) p. 72-75.
CODEN: MEENAH ISSN: 0025-6501
DT Journal
CY United States
LA English
FA AB
AB This article describes the world's largest power tower incorporating one of the newest commercial solar energy systems and being build in California's Mojave Desert. The project — sponsored by the Department of Energy (DOE) and a consortium of western utilities, municipalities, and associations — is called Solar Two, and it will use molten salt to absorb solar energy and store that energy until it is needed to generate electricity. Construction will be completed on Solar Two in September. Solar thermal systems convert the sun's rays into electricity by using a thousand or more dual-axis, sun-tracking mirrors, called heliostats, to focus optimum sunlight on the solar receiver of a power tower containing a working fluid. The fluid is heated to a desired temperature and sent to a storage facility. During periods of peak demand, the fluid is circulating through heat exchangers to generate steam used to drive a turbine
CC *142000; 140702
CT CENTRAL RECEIVERS; HYBRID SYSTEMS; MOLTEN SALTS; PHYSICAL PROPERTIES; THERMAL ENERGY STORAGE EQUIPMENT; TOWER FOCUS POWER PLANTS
•TOWER FOCUS POWER PLANTS: -THERMAL ENERGY STORAGE EQUIPMENT; "MOLTEN SALTS: -PHYSICAL PROPERTIES
BT ENERGY STORAGE SYSTEMS; ENERGY SYSTEMS; EQUIPMENT; POWER PLANTS; SALTS; SOLAR POWER PLANTS; SOLAR RECEIVERS; SOLAR THERMAL POWER PLANTS; THERMAL POWER PLANTS

L7 ANSWER 5 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
AN 1995(8>:50639 ENERGY
TI Investigation of commercial central receiver thermal storage and steam generator issues.
AU Kelly, B.O.; Lessley, R.L. (Bechtel Corp., San Francisco, CA (United States))
NR CONF-940326-
SO Solar engineering 1994.
Editor(s): Klett, D.E.; Hogan, R.E.; Tanaka, Tadayoshi
New York, NY: American Society of Mechanical Engineers. 1994. p. 611-616 of 670 p.
American Society of Mechanical Engineers, United Engineering Center, 345 East 47th Street,
New York, 10017 (United States).
Conference: ASME/JSME/JSES international solar energy conference, San Francisco, CA (United
States), 27-30 Mar 1994
ISBN: 0-7918-1192-1
DT Book Article; Conference
CY United States
LA English
FA AB
AB Conceptual designs, cost estimates, and warranty provisions were developed for nitrate salt
steam generators and thermal storage system hot salt tanks in the initial 100 MWe
commercial central receiver power plants. All of the steam generator designs, including the
U-tube/U-shell, straight tube/straight shell, and U-tube/kettle boiler, offered comparable steady
state and transient performance and competitive cost estimates. The hot salt tank designs
included <1) a stainless steel tank with external insulation and (2) a carbon steel tank
with
internal refractory insulation and a corrugated Incoloy liner to isolate the salt from the
refractory. The stainless steel tank designs had both lower heat losses and lower capital
costs
CC *140702; 142000; 360104
CT COMMERCIALIZATION; COMPARATIVE EVALUATIONS; FEASIBILITY STUDIES; HEAT LOSSES;
MATERIALS TESTING; PERFORMANCE; STEAM GENERATORS; THERMAL ANALYSIS; THERMAL
ENERGY STORAGE EQUIPMENT; TOWER FOCUS POWER PLANTS
*TOWER FOCUS POWER PLANTS: COMMERCIALIZATION; *STEAM GENERATORS:
•FEASIBILITY STUDIES; -THERMAL ENERGY STORAGE EQUIPMENT: -FEASIBILITY STUDIES
BT BOILERS; ENERGY LOSSES; ENERGY STORAGE SYSTEMS; ENERGY SYSTEMS; EQUIPMENT;
EVALUATION; LOSSES; POWER PLANTS; SOLAR POWER PLANTS; SOLAR THERMAL POWER
PLANTS; TESTING; THERMAL POWER PLANTS; VAPOR GENERATORS
ET U

- L7 ANSWER 6 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
- AN 1995(8):50627 ENERGY
- TI Attenuation thermal energy storage in sensible-heat solar-dynamic receivers.
- AU Lund, K.O. (Univ. of California. La Jolla, CA (United States). Center for Energy and Combustion Research)
- NR CONF-940326-
- SO Solar engineering 1994.
Editors): Klett, D.E.; Hogan, R.E.; Tanaka, Tadayoshi
New York, NY: American Society of Mechanical Engineers. 1994. p. 273-281 of 670 p.
American Society of Mechanical Engineers, United Engineering Center, 345 East 47th Street, New York, 10017 (United States).
Conference: ASME/JSME/JSES international solar energy conference, San Francisco, CA (United States), 27-30 Mar 1994
ISBN: 0-7918-1192-1
- DT Book Article; Conference
- CY United States
- LA English
- FA AB
- AB Solar dynamic receiver designs are investigated and evaluated for possible use with sensible energy storage in single-phase materials. The designs are similar to previous receivers having axial distribution of concentrated solar input flux, but differ in utilizing axial conduction in the storage material for attenuation of the solar flux "signal", and in having convective beat removal at the base of the receiver. One-dimensional, time-dependent heat transfer equations are formulated for the storage material temperature field, including radiative losses to the environment, and a general heat exchange effectiveness boundary condition at the base. The orbital periodic input solar flux is represented as the sum of steady and oscillating components, with the steady component solved numerically subject to specified receiver thermal efficiency. For the oscillating components the Fast Fourier Transform algorithm (FFT) is applied, and the complex transfer function of the receiver is obtained and evaluated as a filter for the input flux spectrum. Inverse transformation, result in the amplitudes and mode shapes of the oscillating temperatures. By adjustment of design parameters, the amplitude of the oscillating component of the outlet gas temperature is limited to an acceptable magnitude. The overall result of the investigation is the dependence of the receiver $M\cdot c$ product (mass times specific heat) on the conduction transfer units, which leads to lower weight designs than comparable previous single and two phase designs, when all constraints are included. As these designs also offer improvements in cost reduction and reliability they warrant further detailed investigation
- CC *140700; 142000
- CT DESIGN; MATHEMATICAL MODELS; PERFORMANCE; SENSIBLE HEAT STORAGE; SOLAR RECEIVERS; SOLAR THERMAL POWER PLANTS; SPACECRAFT POWER SUPPLIES; THERMAL ENERGY STORAGE EQUIPMENT
- L7 ANSWER 6 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
*SOLAR RECEIVERS: -DESIGN; *SOLAR RECEIVERS: -SENSIBLE HEAT STORAGE; *SOLAR THERMAL POWER PLANTS: -DESIGN; -SPACECRAFT POWER SUPPLIES: -DESIGN
- BT ELECTRONIC EQUIPMENT; ENERGY STORAGE; ENERGY STORAGE SYSTEMS; ENERGY SYSTEMS;
EQUIPMENT; HEAT STORAGE; POWER PLANTS; POWER SUPPLIES; SOLAR POWER PLANTS; STORAGE; THERMAL POWER PLANTS

L7 ANSWER 7 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
 AN 1995(7):41657 ENERGY
 TI Thermal energy storage at medium and high temperatures for solar power plants.
 Thermische Energiespeicherung bei mittleren und hohen Temperaturen fuer Solarkraftwerke.
 AU Hunold, D. (Geschaeftsbereich Solarthermische Energietechnik des Zentrums fuer Sonnenenergie-
 und Wasserstoff-Forschung Baden-Wuerttemberg (ZSW), Stuttgart (Germany)); Tamme, R.
 (Fachgruppe Thermische und Chemische Speicher in der Deutschen Forschungsanstalt fuer
 Luft-
 und Raumfahrt (DLR), Stuttgart (Germany))
 SO Forschungsverbund Sonnenenergie. Topics 93/94. Solar thermal power. Thermal uses of solar
 energy.
 Forschungsverbund Sonnenenergie. Themen 93/94. Solarthermie. Thermische Nutzung der
 Solarenergie.
 Compiler: Hertlein, H.P.
 Forschungsverbund Sonnenenergie, Koein (Germany) (9204591)
 Fob 1994. p. 75-82 of 98 p. Available from FIZ Karlsruhe.
 ISBN: 0939-7582
 DT Miscellaneous; Availability Note
 CY Germany, Federal Republic of
 LA German
 FA AB; ABDE
 AB The current R and D activities in the field of medium and high temperature storage are
 presented and the storage test facilities of ZSW and DLR briefly described. The R and D
 activities include studies on heat transfer processes in alkali metal nitrates used as
 phase-change storage material for the medium temperature range with different geometries
 of the heat exchanger, as well as investigations of different salt ceramic hybrid materials
 for high temperature applications. The state of development of medium and high
 temperature
 storage systems is shown, possible constructions of storage systems are presented, and an
 outlook on further studies is provided, (orig.)
 CC *142000; 140700
 CT COMPARATIVE EVALUATIONS; DESIGN; ECONOMICS; ENERGY STORAGE; FLOWSHEETS;
 FORECASTING; HEAT EXCHANGERS; HEAT TRANSFER; PHASE CHANGE MATERIALS;
 SOLAR
 POWER PLANTS; TECHNOLOGY UTILIZATION; THERMAL ENERGY STORAGE EQUIPMENT;
 WORKING FLUIDS
 -ENERGY STORAGE: -SOLAR POWER PLANTS
 BT DIAGRAMS; ENERGY STORAGE SYSTEMS; ENERGY SYSTEMS; ENERGY TRANSFER;
 EQUIPMENT;
 EVALUATION; FLUIDS; MATERIALS; POWER PLANTS; STORAGE
 ET D; Es

L7 ANSWER 10 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
 AN 1994(2):12158 ENERGY
 TI Storage of solar high temperature heat.
 Speicherung solarer Hochtemperaturwaerme.
 AU Meier, A.; Winkler, C. (Paul Scherrer Inst. (PSI), Villigen (Switzerland))
 CS Paul Scherrer Inst. (PSI), Villigen (Switzerland) (5107100)
 NR PSI-93-07
 SO Dee 1993. 62 p. OSTI as DE94726403; NTIS.
 ISBN: 1019-0643
 DT Report; Numerical Data
 CY Switzerland
 LA German
 FA AB
 AB Based on a mathematical-physical model for the description of sensible heat storage in packed beds, the simulation program PACKBED has been developed, which is intended to serve as a decision base for the assessment of packed bed storage systems used in solar high temperature applications. For the validation of the theoretical model, the thermodynamic behaviour of packed beds consisting of sensible heat storage material has been investigated in the experimental store ARIANE. using air as heat transfer medium. Different material tests in the temperature range up to 800oC have been carried out. The short-time storage in large scale solar thermal power plants has been simulated under real operating conditions, as they are expected for the planned 30 MWe PHOEBUS solar tower power plant. For the same storage, it has been shown that the pressure drop, and therefore the required pumping power of the fan, can be reduced significantly by introducing an air bypass system. For the characterization of the storage performance, a storage quality factor has been introduced, which allows to compare different sensible heat storage systems and to describe the degradation of such storage systems during consecutive charging/discharging cycles. In the field of latent heat storage, a thorough literature research has been performed. With a new simulation program for large scale latent heat storage systems, parameter studies have been performed in order to clarify the suitability of latent storage material for storing solar high temperature heat in packed beds. (author) 22 figs., 7 tabs., 88 refs.

CC *142000; 140702
 CT COMPUTERIZED SIMULATION; EXPERIMENTAL DATA; LATENT HEAT STORAGE;
 MATHEMATICAL MODELS; P CODES; PACKED BEDS; PARAMETRIC ANALYSIS; SENSIBLE HEAT STORAGE; SOLAR ENERGY; TEMPERATURE RANGE 0273-0400 K; TEMPERATURE RANGE 0400-1000 K; THEORETICAL DATA; THERMAL ENERGY STORAGE EQUIPMENT; TOWER FOCUS POWER PLANTS; VALIDATION
 *SOLAR ENERGY: -SENSIBLE HEAT STORAGE; -THERMAL ENERGY STORAGE EQUIPMENT:
 *PACKED BEDS
 BT COMPUTER CODES; DATA; ENERGY; ENERGY SOURCES; ENERGY STORAGE; EQUIPMENT; HEAT STORAGE; INFORMATION; NUMERICAL DATA; POWER PLANTS; RENEWABLE ENERGY SOURCES; SIMULATION; SOLAR POWER PLANTS; SOLAR THERMAL POWER PLANTS; STORAGE; TEMPERATURE RANGE; TESTING; THERMAL POWER PLANTS

L7 ANSWER 13 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
 AN 1992(21):156481 ENERGY
 TI A solar energy-based direct steam generation method using latent heat thermal energy storage.
 AU Solomon, A.D. (Univ. of Tennessee, Knoxville (United States))
 NR CONF-910277—
 SO WATTec '91. The technical professional: Staying current/staying competitive.
 Anon.
 Oak Ridge, TN: Sun Graphics Inc. 1991. p. 67-68 of 80 p. Sun Graphics Inc., 101 East Tyrone Rd., Oak Ridge, TN 37830 (United States).
 Conference: 18. annual WATTec interdisciplinary technical conference and exhibition, Knoxville, TN (United States), 19-22 Feb 1991
 DT Book Article; Conference
 CY United States
 LA English
 FA AB
 AB The heart of a solar-energy based electricity generation approach is a direct steam generation (DSG) unit consisting of tube banks, embedded in a phase changing material (PCM). During times of high solar energy availability steam is pumped through the tubes, releasing heat to the PCM which takes it up as the latent heat of melting and undergoes a phase change to its liquid phase. This period is referred to as the charging period. The discharge period is marked by water being pumped through the tubes; now heat is transferred from the PCM to the water which, under appropriate conditions, will boil and emerge as steam. The process of heat exchange between the water or steam in the tube (during charge and discharge) and the PCM is a complex one governed by a variety of factors including tube size, pressure drops, quality of the two phase flow region, extent of this region, and flow rates. In order to examine the performance of such a DSG unit a computer code simulating two phase flow, heat exchange between tube and PCM, and heat transfer and phase change in the PCM has been prepared. The code permits the user to vary all major geometric and thermophysical parameters; options include variable tube diameter, angle of inclination and different flow directions during charge and discharge. In this paper the author describes the above code, examining its underlying assumptions and algorithms. Among points raised are the role of natural convection in the melt. Results shown include sample runs and simple analytical approximations for key performance factors. In addition he describes preliminary experimental work being done to verify the computer model.
 CC *140700; 142000
 CT COMPUTERIZED SIMULATION; HEAT TRANSFER; PERFORMANCE; PHASE CHANGE MATERIALS; PHASE TRANSFORMATIONS; SOLAR THERMAL POWER PLANTS; THERMAL ENERGY STORAGE EQUIPMENT
 *SOLAR THERMAL POWER PLANTS: -THERMAL ENERGY STORAGE EQUIPMENT; -THERMAL ENERGY STORAGE EQUIPMENT: -COMPUTERIZED SIMULATION
 BT ENERGY TRANSFER; EQUIPMENT; MATERIALS; POWER PLANTS; SIMULATION; SOLAR POWER PLANTS; THERMAL POWER PLANTS

L7 ANSWER 14 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
 AN 1992(20):149792 ENERGY
 TI Energy storage.
 AU Anon.
 SO Cool energy. Renewal solutions to environmental problems.
 Brower, M.
 Cambridge, MA: Massachusetts Inst. of Tech. Press. 1992. p. 155-172 of 225 p. MIT Press,
 Massachusetts Institute of Technology, Cambridge, MA 02142 (United States).
 Book Article
 CY United States
 LA English
 FA AB
 AB This chapter discusses the role that energy storage may have on the energy future of the
 US. The topics discussed in the chapter include historical aspects of energy storage,
 thermal
 energy storage including sensible heat storage, latent heat storage, thermochemical heat
 storage, and seasonal heat storage, electricity storage including batteries, pumped
 hydroelectric
 storage, compressed air energy storage, and superconducting magnetic energy storage, and
 production and combustion of hydrogen as an energy storage option.
 CC *250000; 142000; 290301; 299000; C5700
 CT COMPRESSED AIR ENERGY STORAGE EQUIPMENT; COMPRESSED AIR STORAGE POWER
 PLANTS; ECONOMICS; ELECTRIC BATTERIES; ELECTRIC-POWERED VEHICLES; ENERGY
 STORAGE;
 ENERGY STORAGE SYSTEMS; ENVIRONMENTAL IMPACTS; HYDROGEN FUEL CELLS; HYDROGEN
 PRODUCTION; HYDROGEN STORAGE; LEAD-ACID BATTERIES; MAGNETIC ENERGY STORAGE
 EQUIPMENT; OFF-PEAK ENERGY STORAGE; PEAKING POWER PLANTS; SUPERCONDUCTING
 COILS; SUPERCONDUCTING MAGNETS; TECHNOLOGY ASSESSMENT; THERMAL ENERGY
 STORAGE
 EQUIPMENT; UNDERGROUND STORAGE
 *ENERGY STORAGE SYSTEMS: -ECONOMICS; -ENERGY STORAGE SYSTEMS: -ENVIRONMENTAL
 IMPACTS; -ENERGY STORAGE SYSTEMS: -TECHNOLOGY ASSESSMENT
 BT DIRECT ENERGY CONVERTERS; ELECTRIC BATTERIES; ELECTRICAL EQUIPMENT;
 ELECTROCHEMICAL CELLS; ELECTROMAGNETS; ENERGY STORAGE; EQUIPMENT; FUEL CELLS;
 MAGNETS; PEAKING POWER PLANTS; POWER PLANTS; STORAGE; SUPERCONDUCTING
 DEVICES; VEHICLES

L7 ANSWER 17 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
 AN 1992(10):67921 ENERGY
 TI Observations of the freeze/thaw performance of lithium fluoride by motion picture
 photography.
 AU Jaworske, D.A. (National Aeronautics and Space Administration, Cleveland, OH (United States).
 Lewis Research Center); Perry, W.D. (Auburn Univ., AL (United States). Dept. of Chemistry)
 NR CONF-910801—
 SO Proceedings of the 26th intersociety energy conversion engineering conference. Volume 4.
 Anon.
 La Grange Park, IL: American Nuclear Society. 1991. p. 151-154 of 575 p. American Nuclear
 Society, 555 North Kensington Ave., La Grange Park, IL 60525 (United States).
 Conference: 26. intersociety energy conversion engineering (IECE) conference, Boston, MA
 (United States), 3-9 Aug 1991
 ISBN: 0-89448-163 ~ \

DT Book Article; Conference
 CY United States
 LA English
 FA AB
 AB Molten salts are attractive candidates for thermal energy storage in solar dynamic power
 systems owing to their high latent heat of fusion. This paper reports that, to gain direct
 observation of the molten salt phase change, a novel containerless technique was developed
 where the high surface tension of lithium fluoride was used to suspend a bead of the
 molten salt inside a specially designed wire cage. By varying the current passing through
 the wire, the cage also served as a variable heat source. In this way, the freeze/thaw
 performance of the lithium fluoride could be photographed by motion picture photography
 without the influence of container walls. The motion picture photography of the lithium
 fluoride sample revealed several zones during the phase change, a solid zone and a liquid
 zone. as expected, and a slush zone that was predicted by thermal analysis modeling.
 «250600; 142000; 140700; 360204
 FUSION HEAT; LATENT HEAT STORAGE; LITHIUM FLUORIDES; MATERIALS TESTING; MOLTEN
 SALTS; PERFORMANCE TESTING; PHASE CHANGE MATERIALS; SOLAR THERMAL POWER
 PLANTS; THERMAL ANALYSIS; THERMAL ENERGY STORAGE EQUIPMENT
 •LATENT HEAT STORAGE: -THERMAL ENERGY STORAGE EQUIPMENT; -MOLTEN SALTS:
 -FUSION HEAT; -LITHIUM FLUORIDES: -THERMAL ANALYSIS; -LITHIUM FLUORIDES:
 -PERFORMANCE TESTING
 ALKALI METAL COMPOUNDS; ENERGY STORAGE; ENTHALPY; EQUIPMENT; FLUORIDES;
 FLUORINE COMPOUNDS; HALIDES; HALOGEN COMPOUNDS; HEAT STORAGE; LITHIUM
 COMPOUNDS; LITHIUM HALIDES; MATERIALS; PHYSICAL PROPERTIES; POWER PLANTS;
 SALTS; SOLAR POWER PLANTS; STORAGE; TESTING; THERMAL POWER PLANTS;
 THERMODYNAMIC PROPERTIES; TRANSITION HEAT

L7 ANSWER 20 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
 AN 1992(5):26741 ENERGY
 TI C.R.S. receiver and storage systems evaluation.
 AU Castro, M.; Presa, J.L.; Diaz, J.; Peire, J. (Univ. Politecnica de Madrid (Spain)); Faas, S.E.;
 SO Radosevich, L.G.; Skinrood, A.C. (Sandia National Labs. Livermore, CA (United States))
 Solar Energy (Journal of Solar Energy Science and Engineering) (United States) (1991)
 v. 47(3) p. 197-207.
 CODEN: SRENA4 ISSN: 0038-092X
 DT Journal
 CY United States
 LA English
 FA AB
 AB This article describes a comparison and evaluation of the Solar One and CESA-I receiver
 and thermal storage systems. The evaluation is based on operating data from Solar One,
 the MWe experimental solar central receiver plant located near Barstow, California, USA and
 CESA-I, the 1.2 MWe experimental solar central receiver plant located near Almeria, Spain.
 This study was sponsored by the US-Spain Joint Committee for Scientific and Technological
 Cooperation. Significant differences exist in the design and operation of the receiver and
 thermal storage systems for the two experimental plants. An evaluation of their
 performance has increased our understanding of the plant design variables and provides useful
 information to improve the designs of future central receiver plants.
 *140702; 142000
 CALIFORNIA; CENTRAL RECEIVERS; COMPARATIVE EVALUATIONS; DESIGN; EVALUATION;
 INTERNATIONAL COOPERATION; PERFORMANCE; SPAIN; THERMAL ENERGY STORAGE
 EQUIPMENT; TOWER FOCUS POWER PLANTS
 *TOWER FOCUS POWER PLANTS: *EVALUATION
 COOPERATION; DEVELOPED COUNTRIES; DEVELOPING COUNTRIES; EQUIPMENT; EUROPE;
 EVALUATION; NORTH AMERICA; POWER PLANTS; SOLAR POWER PLANTS; SOLAR
 RECEIVERS; SOLAR THERMAL POWER PLANTS; THERMAL POWER PLANTS; USA
 ET I

L7 ANSWER 21 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
 AN 1991(20>:132341 ENERGY
 TI Large energy storage facilities (200 mWh th) for medium-temperature-range solar power stations.
 Grosse Energiespeicher (200 MWh th) fuer Solarkraftwerke im Mitteltemperaturbereich.
 AU Beine, B. (Siempelkamp Giesserei GmbH und Co., Krefeld (Germany, F.R.))
 NR CONF-901033—
 SO 7th international solar energy forum. Energy-use efficiency and harnessing of renewable energy sources at the regional and municipal levels. What can be their contribution towards averting the threat to the climate? Conference report. Vol. 3.
 7. Internationales Sonnenforum. Rationelle Energieverwendung und Nutzung erneuerbarer Energiequellen im regionalen und kommunalen Bereich. Welchen Beitrag koennen sie zur Abwehr der Klimabedrohung leisten? Tagungsbericht. Bd. 3.
 Deutsche Gesellschaft fuer Sonnenenergie e.V. (DGS), Muenchen (Germany) (9201294)
 Muenchen: DGS-Sonnenenergie Verlags-GmbH. 1990. p. 1680-1685 of 769 p.
 Conference: 7. international solar forum: rational use of energy a"d "se of renewable resources of energy in regional and municipal domains. 7. Internationales Sonnenforum: Rationelle Energieverwendung und Nutzung Erneuerbarer Energiequellen im Regionalen und Kommunalen Bereich - Welchen Beitrag Koennen Sie zur Abwehr der Klimabedrohung Leisten, Frankfurt am Main (Germany), 9-12 Oct 1990

DT Book Article; Conference
 CY Germany.Federal Republic of
 LA German
 FA AB; ABDE
 AB The objective of the study was to find a thermal energy storage unit for a medium-temperature solar power station in the temperature range between 200deg C and 400deg C requiring investment cost of less than 25 US Dollar/kWh of exploitable thermal energy. The following storage types were compared: Hot-tank and cold-tank liquid salt storage unit with pumps and heat exchangers; thermal oil storage unit; concrete storage unit with cast-in pipes; solid salt slab storage unit with cast-in pipes, and liquid salt storage unit in cascade connection. A concrete storage unit will have to be preferred none the least for reasons of technical risks and fast erectibility. (BWI).

CC *142000; 140700
 CT BOILERS; COMPARATIVE EVALUATIONS; CONCRETE BLOCKS; DESIGN; INVESTMENT; MEASURING METHODS; OPERATION; SOLAR THERMAL POWER PLANTS; THERMAL ENERGY STORAGE EQUIPMENT
 *SOLAR THERMAL POWER PLANTS: -THERMAL ENERGY STORAGE EQUIPMENT; -THERMAL ENERGY STORAGE EQUIPMENT: -INVESTMENT; -THERMAL ENERGY STORAGE EQUIPMENT: -COMPARATIVE EVALUATIONS

BT BUILDING MATERIALS; EQUIPMENT; EVALUATION; MATERIALS; POWER PLANTS; SOLAR POWER PLANTS; THERMAL POWER PLANTS
 ET Es

L7 ANSWER 22 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
 AN 1991(20):132340 ENERGY
 TI Solar power plant with thermo-chemical storage - progress in development.
 Solarkraftwerk mit thermochemischem Speicher - Fortschritte in der Entwicklung.
 AU Mitzel, M. (Bomin-Solar GmbH, Loerrach (Germany, F.R.)); Bogdanovic, B. (Max-Planck-Institut
 fuer Kohleforschung, Muelheim an der Ruhr (Germany, F.R.). Inst. fuer Kerntechnik und
 Energiewandlung e.V.); Ritter, A. (Max-Planck-Institut fuer Strahlenchemie, Muelheim an der
 Ruhr (Germany, F.R.))
 NR CONF-901033—
 SO 7th international solar energy forum. Energy-use efficiency a"nd harnessing of renewable
 energy sources at the regional and municipal levels. What can be their contribution towards
 averting the threat to the climate? Conference report. Vol. 3.
 7. Internationales Sonnenforum. Rationelle Energieverwendung und Nutzung erneuerbarer
 Energiequellen im regionalen und kommunalen Bereich. Welchen Beitrag koennen sie zur
 Abwehr der Klimabedrohung leisten? Tagungsbericht. Bd. 3.
 Deutsche Gesellschaft fuer Sonnenenergie e.V. (DGS), Muenchen (Germany) (9201294)
 Muenchen: DGS-Sonnenenergie Verlags-GmbH. 1990. p. 1674-1679 of 769 p.
 Conference: 7. international solar forum: rational use of energy and use of renewable
 resources of energy in regional and municipal domains. 7. Internationales Sonnenforum:
 Rationelle Energieverwendung und Nutzung Erneuerbarer Energiequellen im Regionalen und
 Kommunalen Bereich - Welchen Beitrag Koennen Sie zur Abwehr der Klimabedrohung Leisten,
 Frankfurt am Main (Germany). 9-12 Oct 1990
 DT Book Article; Conference
 CY Germany.Federal Republic of
 LA German
 FA AB; ABDE
 AB This papers describes the functional mode of a solar energy station using thermochemical
 storage based on magnesium hydride/magnesium which is being developed currently on
 commission by the Federal Minister for Research and Technology by a study group
 comprising Bomin Solar GmbH and Co. KG, Loerrach, Max-Planck Institut fuer
 Kohleforschung,
 Muelheim a.d. Ruhr, Institut fuer Kerntechnik u. Energiewandlung e.V., Max-Planck-Institut fuer
 Strahlenchemie, Muelheim a.d. Ruhr. (orig.).
 CC *142000; 140700
 CT DESIGN; DIAGRAMS; ELECTRIC POWER; HYBRID SYSTEMS; HYDRIDES; OPERATION;
 PROCESS
 HEAT; SOLAR CONCENTRATORS; SOLAR POWER PLANTS; TEMPERATURE
 DEPENDENCE;
 THERMAL ENERGY STORAGE EQUIPMENT; THERMOCHEMICAL HEAT STORAGE
 *SOLAR POWER PLANTS: THERMOCHEMICAL HEAT STORAGE
 BT ENERGY; ENERGY STORAGE; EQUIPMENT; HEAT; HEAT STORAGE; HYDROGEN
 COMPOUNDS;
 POWER; POWER PLANTS; SOLAR EQUIPMENT; STORAGE
 ET Co

ANSWER 26 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
1990(14):100530 ENERGY

Thermal stratification in hot storage-tanks.

Kandari, A.M. (Kuwait Inst. for Scientific Research, Safat (KW). Energy Div.)

Applied Energy <UK> (1990) v. 35(4) p. 299-315.

CODEN: APENDX ISSN: 0306-2619

Journal

United Kingdom

English

AB

This experimental investigation was conducted as a support activity for the development at Sulaibiyah, which has a 22 m³ stratified tank to act as a buffer reservoir between the paraboloid-dish solar collector and the toluence turbine energy-conversion device. The results show that the disturbed zone is 1500 mm thick (i.e. nearly 30% of the usable tank height).

Based on these results, an experimental model (1/25th scale by volume) was constructed to study the effect of using improved distributor header geometry and a settling mesh for reducing the buffer-zone thickness. Using the new header configuration, extraction efficiencies of 85% could be achieved, (author).

*142000

EFFICIENCY; SCALE MODELS; SOLAR THERMAL POWER PLANTS; STRATIFICATION; THERMAL ENERGY STORAGE EQUIPMENT

-THERMAL ENERGY STORAGE EQUIPMENT: -STRATIFICATION; -THERMAL ENERGY STORAGE EQUIPMENT: -SOLAR THERMAL POWER PLANTS

EQUIPMENT; POWER PLANTS; SOLAR POWER PLANTS; STRUCTURAL MODELS; THERMAL POWER PLANTS

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L4 ANSWER 1 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
AN 1996(20):141769 ENERGY
TI Regenerators in parabolic dish solar power stations.
Regeneratoren in Parabolrinnen-Solarkraftwerken.
AU Ratzesberger, R.
CS Deutsche Forschungsanstalt fuer Luft- und Raumfahrt e.V. <DLR>. Koein (Germany) (2143700)
Funding Organisation: Bundesministerium fuer Forschung und Technologie, Bonn (Germany)
(9200321)
SO Thesis. Duesseldorf: VDI-Verl. 1995. 131 p.
Ser. Title: Fortschritt-Berichte VDI. Reihe 6, Energietechnik, v. 330.
ISBN: 3-18-333006-7 ISSN: 0178-9414
DT Book; Dissertation
CY Germany, Federal Republic of
LA German
FA AB; ABDE
AB For the parabolic dish solar powerstations of the solar electric generating system (SEGS)
type, regenerators are designed which use the thermal oil used for solar collectors as heat
carrier. Alternative concepts with concrete and/or phase change material as storage material
are compared. The design for a compound regenerator with a capacity of 200 MWhth is
discussed. Using quasi steady state thermodynamic process calculations, the interaction
between the regenerator and powerstation operation is measured and the use of the store
is thus quantified. From annual energy balances, the effect of solar field size and store
capacity on the duration of annual powerstation operation is determined. Finally, from an
economy calculation, one can prove that the additional investment in an enlarged solar field
and a thermal energy store reduces the electricity generating costs of the plant, (orig.)
CC *140703
CT CALCULATION METHODS; HEAT STORAGE; OPERATION; REGENERATORS; SIMULATION; SOLAR
COLLECTORS; SOLAR POWER PLANTS; THERMAL ENERGY STORAGE EQUIPMENT
•SOLAR POWER PLANTS: *SOLAR COLLECTORS
BT ENERGY STORAGE; ENERGY STORAGE SYSTEMS; ENERGY SYSTEMS; EQUIPMENT; POWER
PLANTS; SOLAR EQUIPMENT; STORAGE

L4 ANSWER 2 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
AN 1994(0);99103 ENERGY
TI Design of a C02-CH4 reformer for a 100 Kw parabolic dish solar concentrator.
AU Steinfeld, A.; Segal, A.; Levy, M. (Weizmann Inst. of Science, Rehovoth (Israel))
CS Weizmann Inst. of Science, Rehovoth (Israel) (6860000)
NC 90-05 25/90-1-85
NR INIS-mf-13968
SO Jan 1991. 6 p. OSTI as DE94628358; NTIS (US Sales Only); INIS.
DT Report; Progress Report
CY Israel
LA English
FA AB
AB Design of a C02-CH4 reformer. A schematic diagram of the system components is shown.
(authors). 1 fig.
CC *140300; F1522
CT CARBON DIOXIDE; CATALYTIC CONVERTERS; CHEMICAL REACTION KINETICS; CHEMICAL
REACTION YIELD; COMPUTER CODES; COMPUTERIZED SIMULATION; DESIGN; PARABOLIC DISH
COLLECTORS; PROGRESS REPORT; SOLAR ENERGY CONVERSION; SPECIFICATIONS;
THERMOCHEMICAL HEAT STORAGE
-PARABOLIC DISH COLLECTORS: *THERMOCHEMICAL HEAT STORAGE; *THERMOCHEMICAL
HEAT STORAGE: *CATALYTIC CONVERTERS; "THERMOCHEMICAL HEAT STORAGE:
•COMPUTERIZED SIMULATION
CARBON COMPOUNDS; CARBON OXIDES; CHALCOGENIDES; CONCENTRATING COLLECTORS;
CONVERSION; DOCUMENT TYPES; ENERGY CONVERSION; ENERGY STORAGE; EQUIPMENT;
HEAT
STORAGE; KINETICS; OXIDES; OXYGEN COMPOUNDS; PARABOLIC COLLECTORS; POLLUTION
CONTROL EQUIPMENT; REACTION KINETICS; SIMULATION; SOLAR COLLECTORS; SOLAR
EQUIPMENT; STORAGE; YIELDS
ET C*H*0; C02; C cp; cp; 0 cp; CH4; H cp; C02-CH4

PLANTS; STORAGE; THERMAL POWER PLANTS

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ENERGY FILE SEARCH RESULTS - P330399K 26 NOV 1999 15:02:41 PAGE 9

L4 ANSWER 7 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
AN 1986(1):1691 ENERGY
TI Design of a 13 MWe parabolic trough plant at Daggett. California.
AU Kroizer, 1. (Luz Engineering, Encino, CA) [United States]
CS Solar Energy Research Inst, Golden, CO (USA) (9506687)
NR SERI/SP—271-2664; CONF-8406111—; DE85002949
SO Design and performance of large solar thermal collector arrays.
Mar 1985. pp. 534-536 Availability: NTIS, PC A24/MF A01; 1.
Conference: International Energy Agency workshop on the design and performance of large
solar thermal collectors, San Diego, CA. USA, 11 Jun 1984
DT Report Article; Conference
CY United States
LA English
DN ERA-11:005107
AB The solar power plant design characteristics and system description at Daggett California are
presented. The solar collector assembly (SCA) is the primary building block of this modular
system. A single SCA consists of a row of eight parabolic trough collectors, a single drive
motor, and a local microprocessor control unit. The basic components of the parabolic trough
collector are a mirrored glass reflector, a unique and high-efficiency heat collection element,
and a positioning system. The heat collection element includes a stainless steel absorber
tube coated with a black chrome selective surface, which is contained within a unique and
high-efficiency evacuated cylindrical glass envelope. The SCA is designed to have an
operating efficiency of 67% at 265 deg C under a direct normal insolation of 3500 kJ/m².
The operation of the system is discussed.
CC *140700
CT *SOLAR THERMAL POWER PLANTS: -OPERATION; *SOLAR THERMAL POWER PLANTS:
•PERFORMANCE; PARABOLIC TROUGH COLLECTORS; POWER GENERATION; SENSIBLE HEAT
STORAGE
BT CONCENTRATING COLLECTORS; ENERGY STORAGE; EQUIPMENT; HEAT STORAGE; PARABOLIC
COLLECTORS; POWER PLANTS; SOLAR COLLECTORS; SOLAR EQUIPMENT; SOLAR POWER

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ENERGY FILE SEARCH RESULTS - P330399K 26 NOV 1999 15:02:41 PAGE 12

L4 ANSWER 10 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
 AN 1985(7):44992 ENERGY
 TI Performance characteristics of solar thermal power generation system with flat plate mirror and parabolic mirror.
 AU Chinen, M.; Anzai, S.; Sasaki, S.; Sato, S.; Sumida, 1.; Taki, T.; Tsukamoto, M. (Energy Research Laboratory, Hitachi Ltd., Hitachi) [Japan]
 NR CONF-830839-
 SO Solar world congress. Vol. 3.
 Szokolay, S.V.
 Oxford, England: Pergamon Press. 1983. pp. 1581-1585
 Conference: Solar world congress, Perth, Australia, 15 Aug 1983
 DT Book Article; Conference
 CY United Kingdom
 LA English
 AB The IMWe solar thermal power generation pilot plant featuring plane-parabolic type concentrators and molten salt heat storages succeeded to generate IMWe power and operated about 2 years. Thermal simulation of the plant predicted the plant operation well and confirmed designed performance of the heat storage system. Optical performance of concentrator was evaluated and led to the following results. 1. The optical performance of the evaporator was satisfactory, and the measured error of parabolic mirror and collecting pipe bending had negligible effect on evaporator concentrator. 2. The bending of collecting pipe produced slight leakage in superheater concentrator, that is about 3%. 3. Adjustment were needed to some sun tracking mechanism due to the friction in sliding parts of it after about 2 years operation.
 CC *140700; 141000
 CT *SOLAR THERMAL POWER PLANTS; «MIRRORS; *SOLAR THERMAL POWER PLANTS: •PARABOLIC REFLECTORS; 'PARABOLIC REFLECTORS: -PERFORMANCE; *SOLAR THERMAL POWER PLANTS: -PERFORMANCE; -MIRRORS: -PERFORMANCE; COMPUTERIZED SIMULATION; OPTICAL PROPERTIES; POWER RANGE 1-10 MW
 BT EQUIPMENT; PHYSICAL PROPERTIES; POWER PLANTS; SIMULATION; SOLAR CONCENTRATORS;

ANSWER 14 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE

1982(17):122788 ENERGY

Comparison of electrochemical and thermal storage for hybrid parabolic dish solar power plants.

Steele, HI.; Wen, L. (JPL, Pasadena, Calif, USA) [United States]

Am. Soc. Mech. Eng., [Pap.] (1981) (81-WA/Sol-27) vp

CODEN: ASMSA4

Journal

United States

English

ERA-07:049782

The cost of storage systems which can compete with the use of fuel in hybrid parabolic dish solar power plants is identified for one set of specific assumptions. The hybrid plants burn fuel to increase the hours of usage each day. The cost and performance characteristics of concentrators, receivers and power conversion units are based on estimates by the contractors developing this hardware under the direction of the Department of Energy and the Jet Propulsion Laboratory (JPL). Thermal storage systems are not yet designed and only the cost goal which would make them competitive is known. 12 refs.

«140703; 142000; 250904; 141000

•DISTRIBUTED COLLECTOR POWER PLANTS; -ENERGY STORAGE; -DISTRIBUTED COLLECTOR POWER PLANTS; *HEAT STORAGE; -DISTRIBUTED COLLECTOR POWER PLANTS; -PARABOLIC DISH COLLECTORS; COST; ELECTRIC BATTERIES; HYBRID SYSTEMS; PERFORMANCE; POWER RANGE 1-10 MW; VERY HIGH TEMPERATURE CONCENTRATING COLLECTORS; ELECTROCHEMICAL CELLS; ENERGY STORAGE; EQUIPMENT; PARABOLIC COLLECTORS; POWER PLANTS; SOLAR COLLECTORS; SOLAR EQUIPMENT; SOLAR POWER PLANTS; SOLAR THERMAL POWER PLANTS; STORAGE; THERMAL POWER

L4 ANSWER 15 OF 26 ENERGY COPYRIGHT 1999 USDOE/IEA-ETDE
AN 1982(17):122775 ENERGY
TI Parabolic trough development: lessons learned at Willard and Gila Bend.
AU Dugan, V.L. (Sandia National Labs., Albuquerque, NM) [United States]
NR CONF-801203-; DE81015033
SO National conference on renewable energy technologies.
1980. pp. 6.3-6.4 Availability: NTIS, PC A99/MF A01.
DT Conference: National conference on renewable energy technologies, Honolulu, HI, USA, 7 Dec
1980
CY Report Article; Conference
LA United States
DN English
ERA-07:049745
AB Two irrigation projects, one at Willard, New Mexico, and the other at Gila Bend, Arizona,
are briefly described, and lessons learned from three years of operating experience relative
to collectors, energy transport, engines, and thermocline storage are outlined. (LEW)
CC *140703
CT •PARABOLIC TROUGH COLLECTORS; -IRRIGATION; ARIZONA; NEW MEXICO; RANKINE CYCLE
ENGINES; SENSIBLE HEAT STORAGE; SOLAR HEAT ENGINES
BT CONCENTRATING COLLECTORS; ENERGY STORAGE; ENGINES; EQUIPMENT; FEDERAL REGION IX;
FEDERAL REGION VI; HEAT ENGINES; HEAT STORAGE; NORTH AMERICA; PARABOLIC
COLLECTORS; SOLAR COLLECTORS; SOLAR EQUIPMENT; STORAGE; USA

L3 ANSWER 22 OF 39 ENTEC COPYRIGHT 1999 FIZ Karlsruhe
AN 1995:0116924 ENTEC
TI Regeneratoren mit Beton und Phasenwechselmaterial als Speichermasse.
Regenerators with concrete and phase change material as storage mass.
AU Ratzesberger, R.; Hahne, E.; Beine, B.
SO Energiespeicher fuer Strom, Waerme und Kaelte.
Energy storage for electric power, heat and refrigeration.
Verein Deutscher Ingenieure (VDI) - Gesellschaft Energietechnik, Duesseldorf (DE)
Duesseldorf: VDI-Verl. 1994. p. 467-481. of 481 p.
Serientitel: VDI-Berichte. v. 1168.
Konferenz: VDI-GET conference: Electric power and thermal energy storage for electric
power, heat and refrigeration, VDI-GET-Tagung: Energiespeicher fuer Strom, Waerme und
Kaelte, Leipzig (DE). 6-7 Dee 1994
ISBN: 3-18-091168-9
DT Kapitel der Monographic; Konferenz
CY Deutschland, Bundesrepublik
LA Deutsch
FA AB; ABDE
IP FIZ Karlsruhe
ABDE Die Firma Siempelkamp. Krefeld. hat in einern BrnFT-Vorhaben einen Regenerator mit
temperaturbestaendigem Beton als Speichermaterial entwickelt. Als Waermetraeger dient das
synthetische Thermooel aus dem Solarfeldkreislauf mit 400 C und einern Betriebsdruck von
16 bar. Dieser Beton-Regenerator wurde von Dinter F. (1992) in einer urnfassenden technischen
und oekonomischen Berechnung als das guenstigste Speicherkonzept fuer die bestehenden
Parabolrinnen-Solkraftwerke ermittelt. Am ZSW wurden im Rahmen des BmFT-Vorhaben zwei
Testmodule mit zusammen 50 kWlh_Leistungsaufnahme eingehend untersucht. (orig./HW)

L3 ANSWER 23 OF 39 ENTEC COPYRIGHT 1999 FIZ Karlsruhe
AN 1995:0112684 ENTEC
TI Zur Alistegung und Konstruktion von thermischen Energiespeichern mit einern fest/fluessig
Phasenwechsel des Speichermaterials fuer Parabolrinnen-Solarkraftwerke.
Design and construction of thermal energy storage systems with a solid-to-liquid change of
phase of the storage material for parabolic trough solar power plants.
AU Hunold. D.
CS Technische Hochschule Aachen (DE)
SO Duesseldorf: VDI-Verl. 1994. 139 p.
Diss.
Serientitel: Fortschritt-Berichte VDI. Reihe 6, Energietechnik. v. 308.
ISBN: 3-18-330806-1
DT Monographic; Hochschulschrift
CY Deutschland, Bundesrepublik
LA Deutsch
FA AB; ABDE
IP FIZ Karlsruhe
ABDE In dieser Arbeit werden Speicherkonzepte fuer Parabolrinnen-Solarkraftwerke sowohl hinsichtlich
der Waermeuebertrager-Konstruktion als auch der moeglichen Speichermaterialien betrachtet.
Dabei wird eine Konstruktion fuer einen Phasenwechsel-Speicher erarbeitet, der sich als ein
senkrecht stehender Rohrregister-Waermeuebetrager ergibt, in dessen Mantelraum das
Phasenwechselmaterial aufgeschmolzen und erstarrt wird. - Die massgeblichen Einflussgroessen
auf den Waermeuebergang werden an 2,5 m hohen zylindrischen Doppelrohr-Modulen und durch
vergleichende Messungen an einern Rohrregister-Speicher im Temperaturbereich von 250-400
C untersucht. Die erzielten Ergebnisse werden in Form von dimensionslosen
Kennzahl-Korrelationen angegeben. - Nachfolgend werden weitere Schritte zur Realisierung
groesserer Phasenwechsel-Speicher, auch im Hinblick auf Wasser/Dampf anstelle von
Thermaloeel als Waermetraegerfluid, abgeleitet und entsprechende weiterfuehrende Experimente
vorgestellt. Anhand eines Entwurfs fuer einen modular aufgebauten Phasenwechsel-Speicher mit
einer Kapazitaet von 200 MWhth_wird abschliessend eine unter waerme- und
fertigungstechnischen Aspekten optimierte Konstruktion fuer einen Speicher im Pilot-Massstab
vorgestellt. (orig.)

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (<i>Maximum 200 words</i>) The purpose of this report is to identify and selectively review previous work done on the evaluation and use of thermal energy storage systems applied to parabolic trough power plants. Appropriate storage concepts and technical options are first discussed, followed by a review of previous work.				
14. SUBJECT TERMS solar thermal systems; electric plants; renewable energy; power plants; parabolic trough; Pilkington Solar; PilKSolar; solar electric generating systems; SEGs; thermal energy storage; TES; concentrating solar power; CSP			15. NUMBER OF PAGES	
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