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HIGH TEMPERATURE THERMAL ENERGY STORAGE SYSTEM APPLICATIONS

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ABSTRACT

Thermal energy storage (TES) includes a number of different technologies. Thermal energy can be stored at temperatures from -40°C to more than 400°C as sensible heat, latent heat and chemical energy (i.e. thermo-chemical energy storage) using chemical reactions. Thermal energy storage in the form of sensible heat is based on the specific heat of a storage medium, which is usually kept in storage tanks with high thermal insulation. The most popular and commercial heat storage medium is water, which has a number of residential and industrial applications. Underground storage of sensible heat in both liquid and solid media is also used for typically large-scale applications. However, TES systems based on sensible heat storage offer a storage capacity that is limited by the specific heat of the storage medium. Phase change materials (PCMs) can offer a higher storage capacity that is associated with the latent heat of the phase change. PCMs also enable a target-oriented discharging temperature that is set by the constant temperature of the phase change. Thermo-chemical storage (TCS) can offer even higher storage capacities. Thermo-chemical reactions (e.g. adsorption or the adhesion of a substance to the surface of another solid or liquid) can be used to accumulate and discharge heat and cold on demand (also regulating humidity) in a variety of applications using different chemical reactants. At present, TES systems based on sensible heat are commercially available while TCS and PCM-based storage systems are mostly under development and demonstration The storage of thermal energy (typically from renewable energy sources, waste heat or surplus energy production) can replace heat and cold production from fossil fuels, reduce CO2 emissions and lower the need for costly peak power and heat production capacity. In Europe, it has been estimated that around 1.4 million GWh per year could be saved— and 400 million tonnes of CO2 emissions avoided—in the building and industrial sectors by more extensive use of heat and cold storage. However, TES technologies face some barriers to market entry. In most cases, cost is a major issue. Storage systems based on TCS and PCM also need improvements in the stability of storage performance, which is associated with material properties.

INTRODUCTION

Process and Technology Status

Energy storage systems are designed to accumulate energy when production exceeds demand and to make it available at the user's request. They can help match energy supply and demand, exploit the variable production of renewable energy sources (e.g. solar and wind), increase the overall efficiency of the energy system and reduce CO2 emissions.

This brief deals primarily with heat storage systems or thermal energy storage (TES). An energy storage system can be described in terms of the following properties:

● Capacity: defines the energy stored in the system and depends on the storage process, the medium and the size of the system;

● Power: defines how fast the energy stored in the system can be discharged (and charged);

● Efficiency: is the ratio of the energy provided to the user to the energy needed to charge the storage system. It accounts for the energy loss during the storage period and the charging/discharging cycle;

● Storage period: defines how long the energy is stored and lasts hours to months (i.e. hours, days, weeks and months for seasonal storage);

● Charge and discharge time: defines how much time is needed to charge/ discharge the system; and

● Cost: refers to either capacity (€/kWh) or power (€/kW) of the storage system and depends on the capital and operation costs of the storage equipment and its lifetime (i.e. the number of cycles). Capacity, power and discharge time are interdependent variables and in some storage systems, capacity and power can also depend on each other. For example, in TES systems, high power means enhanced heat transfer (e.g. additional fins in the heat exchanger), which, for a given volume, reduce the amount of active storage material and thereby the capacity. Thermal energy (i.e. heat and cold) can be stored as sensible heat in heat storage media, as latent heat associated with phase change materials (PCMs) or as thermo-chemical energy associated with chemical reactions (i.e. thermo-chemical storage) at operation temperatures ranging from -40°C to above 400°C.

Sensible Thermal Energy Storage –

The use of hot water tanks is a well-known technology for thermal energy storage [2]. Hot water tanks serve the purpose of energy saving in water heating systems based on solar energy and in co-generation (i.e. heat and power) energy supply systems. State-of the -art projects [3] have shown that water tank storage is a cost-effective storage option and that its efficiency can be further improved by ensuring an optimal water stratify cation in the tank and highly effective thermal insulation. Today's R&D activities focus, for example, on evacuated super-insulation with a thermal loss rate of = 0,01 W/mK at 90°C and 0,1 mbar and on optimised system integration. Hot water storage systems used as a buff er storage for domestic hot water (DHW) supply are usually in the range of 500l to several m3. This technology is also used in solar thermal installations for DHW combined with building heating systems (Solar-Combi-Systems). Large hot water tanks are used for seasonal storage of solar thermal heat in combination with small district heating systems. These systems can have a volume up to several thousand cubic meters (m3). Charging temperatures are in the range of 80-90°C. The usable temperature diff erence can be enhanced by the use of heat pumps for discharging (down to temperatures around 10 °C). For example (Figure 1), the solar district heating "Am Ackermann-bogen" (Munich, Germany)

Figure 1 – Large Hot Water Storage (construction and final state) combined with Solar Thermal District Heating "Am Ackermann-bogen" in Munich, Germany

Supplies solar energy for space heating and domestic hot water for about 320 apartments in 12 multi-story dwellings with about 30,400 m2 of living area. The system is designed to cover more than 50% of the annual heat demand (i.e. about 2,000 MWh/a) using solar energy collected by 2,761 m2 of fl at-plate collectors. The heat collected is used either directly or stored in a 6,000 m3 underground seasonal hot water storage. Supplementary heating is provided by an absorption heat pump driven by the city district heating system using the seasonal storage as a low temperature heat reservoir. This allows for a wide operation temperature range of the storage (i.e. between 10-90°C). Direct connection of the district system and heating installations in the houses avoids typical temperature drops at heat exchangers and increases the temperature spread. The district system is operated at a supply temperature of 60°C with a return temperature of 30°C, which is properly monitored. The solar energy fraction in the second year of operation was 45% and could reach values above 50% after further optimisation [4].

Underground Thermal Energy Storage (UTES) –

UTES is also a widely used storage technology, which makes use of the underground as a storage medium for both heat and cold storage. UTES technologies include borehole storage, aquifer storage, cavern storage and pit storage. Which of these technologies is selected strongly depends on the local geological conditions. Borehole storage is based on vertical heat exchangers installed underground, which ensure the transfer of thermal energy to and from the ground layers (e.g. clay, sand, rock). Many projects aim for seasonal storage of solar heat in summer to heat houses or offices in winter. Ground heat exchangers are also frequently used in combination with heat pumps where the ground heat exchanger extracts low-temperature heat from the soil. Aquifer storage uses a natural underground water-permeable layer as a storage medium. The transfer of thermal energy is achieved by mass transfer (i.e. extracting/re-injecting water from/into the underground layer). Most – Typical Parameters of Thermal Energy Storage Systems [1] TES System Capacity (kWh/t) Power MW) Effi ciency (%) Storage period (h, d, m) Cost (€/kWh) Sensible (hot water) 10-50 0.001-10 50-90 d/m 0.1-10 PCM 50-150 0.001-1 75-90 h/m 10-50 Chemical reactions 120-250 0.01-1 75-100 h/d 8-100 Figure 1 – Large Hot Water Storage (construction and final state) combined with Solar Thermal District Heating “Am Ackermann-bogen” in Munich, Germany 12-30705_Thermal Energy Storage_ Inhalt.indd 7 21.12.12 15:04 8 Thermal Energy Storage | Technology Brief applications deal with the storage of winter cold to be used for the cooling of large office buildings and industrial processes in the summer (Figure 2).

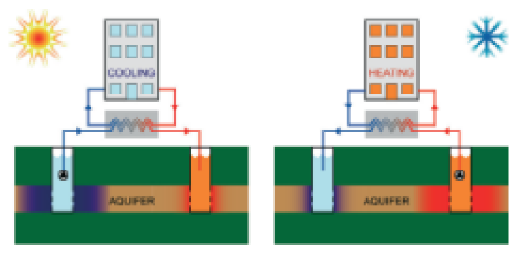

Figure 2 – Layout Scheme of an Aquifer Storage System

A major prerequisite for this technology is the availability of suitable geological formations. Cavern storage and pit storage are based on large underground water reservoirs created in the subsoil to serve as thermal energy storage systems. These storage options are technically feasible, but applications are limited because of the high investment costs. For high-temperature (i.e. above 100 °C) sensible heat storage, the technology of choice is based on the use of liquids (e.g. oil or molten salts, the latter for temperatures up to 550°C. See ETSAP E10). For very high temperatures, solid materials (e.g. ceramics, concrete) are also taken into consideration. However, most of such high-temperature-sensible TES options are still under development or demonstration.

Phase Change Materials for TES –

Sensible heat storage is relatively inexpensive, but its drawbacks are its low energy density and its variable discharging temperature [2]. These issues can be overcome by phase change materials (PCM)-based TES, which enables higher storage capacities and target oriented discharging temperatures. The change of phase could be either a solid/liquid or a solid/solid process. Melting processes involve energy densities on the order of 100 kWh/m3 (e.g. ice) compared to a typical 25 kWh/m3 for sensible heat storage options. Figure 3 compares the achievable storage capacity at a given temperature diff erence for a storage medium with and without phase change. Phase change materials can be used for both short-term (daily) and long-term (seasonal) energy storage, using a variety of techniques and materials.

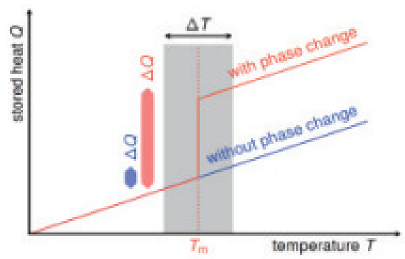

Figure 3 – Stored Heat vs. Temperature for Sensible (without phase change) and Latent TES

Thermal Energy Storage via Chemical Reactions –

High energy density (i.e. 300 kWh/m3) TES systems can be achieved using chemical reactions (e.g. thermo-chemical storage, TCS) [2]. Thermo-chemical reactions, such as adsorption (i.e. adhesion of a substance to the surface of another solid or liquid), can be used to store heat and cold, as well as to control humidity. Typical applications involve adsorption of water vapour to silica-gel or zeolites (i.e. micro-porous crystalline alumino-silicates). Of special importance for use in hot/humid climates or confined spaces with high humidity are open sorption systems based on lithium-chloride to cool water and on zeolites to control humidity. Figure 5 shows an example of thermal energy storage by an adsorption process (e.g. water vapour on zeolite): during charging, water molecules are desorbed from the inner surface of the adsorbent. The TES remains in this state until water molecules can be absorbed by the adsorbent and the TES is discharged again.. Interesting filds of application include waste heat utilisation. In this context, TCSs are able to store thermal energy with high effi ciency and to convert heat into cold (i.e. desiccant cooling) at the same time, which makes these systems very attractive. The high storage capacity of sorption processes also allows thermal energy transportation. Figure 6 shows a schematic view of such a system. For example, an ongoing demonstration project utilises waste heat from an incineration plant to be used at an industrial drying process. The sorption TES (using zeolite/water) is charged at 150°C, transported over seven kilometers and discharged at 180°C. Dry and hot air during discharging are directly integrated into the drying process. The higher discharging temperature is made possible because the enthalpy of the humid air from drying is converted into a temperature lift by the adsorption of water vapour. A pilot storage in a standard freight container containing 13 tonnes of zeolite, with a storage capacity of up to three MWh and a charging power of 500 kW, is currently on the road. The economic analysis shows that applications of mobile storage systems with more than 200 storage cycles per year allow the system to run with a final cost of delivered heat of about €55/MWh. Of course, the distance between energy source and demand site, investment costs and energy capacity have a strong influence on the energy price [9]. 12-30705_Thermal Energy Storage_Inhalt.indd 10 21.12.12 15:04 Thermal Energy Storage | Technology Brief 11. While sorption storages can only work up to temperatures of about 350°C, chemical reactions can go much higher. Figure 7 shows the different TES technologies: sensible heat (i.e. water as an example); latent heat (i.e. different materials); and thermo-chemical (i.e. sorption and chemical reactions).

APPLICATIONS

Important fields of application for TES systems are in the building sector (e.g. domestic hot water, space heating, air-conditioning) and in the industrial sector (e.g. process heat and cold). TES systems can be installed as either centralised plants or distributed devices. Centralised plants are designed to store waste heat from large industrial processes, conventional power plants, combined heat and power plants and from renewable power plants, such as concentrated solar power (CSP). Their power capacity ranges typically from hundreds of kW to several MW (i.e. thermal power).
Distributed devices are usually buff r storage systems to accumulate solar heat to be used for domestic and commercial buildings (e.g. hot water, heating, appliances). Distributed systems are mostly in the range of a few to tens of kW. TES systems – either centralised or distributed - improve the energy effi ciency of industrial processes, residential energy uses and power plants by storing waste or by-product heat or renewable heat when it is available and supplying it upon demand. Thermo-chemical storage systems can also convert waste heat into higher temperature heat or into cold. A number of energy-intensive industrial sectors and processes (e.g. cement, iron and steel, glass) benefit from TES systems. Manufacturing industry (e.g. automobile industry) can also benefit significantly from TES. Most importantly, TES can help integrate variable solar heat into the energy system. This applies either to short-term storage based on daily heat buffers for domestic hot-water production or to long-term heat storage for residential and industrial heating purposes, based on large central storage systems and district heating networks. TES systems can also help integrate renewable electricity from PV and wind. For example, the efficiency of a (mechanical) compressed air energy storage (CAES) can be improved from about 50% to more than 70% by storing heat during compression and discharging it to support expansion (see ETSAP E18). Charging a cold storage system using renewable electricity during high solar irradiation periods or wind peaks and delivering cold to consumers on demand is a further potential TES application. Along with their contribution to energy efficiency or to the integration of renewable energy
Cool storage can potentially reduce the on-peak energy consumption, peak demand, and most importantly, average cost of energy consumed. While most building space cooling applications are potentially attractive candidates, the prospects will be especially attractive if one or more of the following conditions exists.

- Electric rate structures with high demand charges, ratcheted demand charges, or large variation in hourly energy charges (peak/off-peak or time-of-use rates).
- Buildings where off-peak cooling load is less than the peak-cooling load.
- Climates with higher temperature gradient from day to night.
- Expansion of an existing cooling system, replacement of older cooling equipment, or building expansion / new construction.
- Available physical space to house the storage medium and associated equipment.

With the above criteria in mind, it can be seen that certain building types in the Federal sector are attractive for TES. In general, office buildings, schools, and certain laboratory / R&D facilities are prime candidates for TES because on-peak demand can easily be shifted to unoccupied, off-peak hours. To a lesser extent, hospitals and other round-the-clock facilities may apply if there is a significant drop in off-peak loads and electric rates are favourable. Using TES also depends on the type of cooling available in the facilities. TES is not generally applicable to buildings cooled by smaller residential or small commercial-style heat pumps, packaged air-conditioning units, or swamp coolers. The exception is when smaller "roof-top" air-conditioning units are converted to act as air-handlers for a chilled water loop served by a chiller/TES system. TES can be used in a district cooling system where multiple buildings are cooled by a chilled water loop provided by a central chiller plant. In this scenario, buildings of various sizes and use types typically not attractive to TES might also benefit from aggregating building loads. Another important factor for TES application is the availability of space for a storage tank and associated pumps and heat exchangers. Many Federal facilities benefit from a campus-like setting, providing ample room for the storage medium. If large enough, the large chilled water storage tanks are able to take advantage of economies of scale to reduce the cost per shifted ton of refrigeration. Where space is a factor, one TES system consists of 190 ton-hr storage modules that can be joined together through a manifold. The modules can be added as needed, stacked, even stored in several rooms, indoors or out and even buried in the ground. The affect of the Environmental Protection Agency's ban on chlorofluorocarbons (CFCs) in chillers provides another opportunity for TES. As aging chillers are replaced, sites should consider downsizing to smaller, more efficient chillers combined with a TES system.

LITERATURE REVIEW

System analysis and test loop design for the CellFlux storage concept

W.D. Steinmann, C.Odenthal and M.Eck* license

Systems using air at ambient pressure as a working fluid and solid media like natural stones or bricks as storage materials represent the most cost effective option to store sensible heat at medium and high temperatures. The application of this storage concept also for liquid working fluids like thermal oil or molten salts is the basic idea of the CellFlux storage concept. Here, an intermediate air cycle transfers thermal energy between a heat exchanger and a solid medium storage volume. The development of the CellFlux concept comprises various stages: in the initial phase, options for the main subcomponents are identified and evaluated. The integration concept of the CellFlux storage unit into the power plant is essential for the success of the concept. The size of the heat exchanger strongly depends on the average temperature difference between air and working fluid. The costs for the heat exchanger are power dependent and dominate the total capital costs of the CellFlux storage unit. In order to demonstrate the feasibility of the CellFlux, a storage unit with a storage volume of 30m³ for operation with thermal oil at up to 400 °C was designed.

Due to the option to use low cost storage materials the CellFlux concept is considered to offer a cost effective alternative for thermal energy storage for temperatures up to 550 °C. Since the costs of the heat exchanger are dominant, the minimization of these costs is essential for the success of the concept. These costs are strongly dependent on the effective temperature difference between air and HTF in the heat exchanger. Various options to increase the effective temperature difference are currently evaluated. The experimental results provided by a pilot scale test facility will help to validate the results of the simulation tools.

Simulation and testing of a latent heat thermal energy storage unit with metallic phase change material

J.*P. Kotzéa*, T.W. von Backströma and P.J. Erensa*

Latent heat thermal energy storage in metallic phase change materials offers a thermal energy storage concept that can store energy at higher temperatures than with sensible thermal energy storage. This may enable the use of high efficiency thermodynamic cycles in CSP applications, which may lead to a reduction in levelised cost of electricity. Eutectic aluminium silicon alloy, AlSi12, is an attractive phase change material because of its moderate melting temperature, high thermal conductivity, and high heat of fusion. A prototype thermal energy storage test rig has been built and tested as to better understand the behavior of latent heat thermal energy storage. A mathematical model was developed to predict the behavior of such a heat storage unit. The model was compared with the behavior of the test rig during discharge. The model proved to simulate the latent heat thermal energy storage with reasonable accuracy. It is recommended that more accurate material property data be obtained and that the thermal energy storage test rig be modified as to improve readings.

Latent heat thermal energy storage in metallic phase change materials offers high temperature, isothermal energy storage. The higher storage temperatures may lead to a reduction in LCOE through the use of higher efficiency power blocks. Kotze et al. [1] proposed the use of metallic phase change materials along with metallic heat transfer fluids as a storage concept and identified AlSi12 as a good candidate metallic PCM for research purposes. To prove the concept and to evaluate the heat transfer analysis, a prototype LHTES unit was built and tested. It has a unique construction enabling the measurement of the solidification front of the PCM through discharge. The data obtained from this test is presented and it shows that the test rig works well within designed parameters.

A heat transfer model of the moving boundary problem is presented. The model is solved using an enthalpy tracking method rather than a finite difference method. This model is used to predict the performance of a large thermal energy storage system [1], and has been implemented on a model representing the test setup for validation. The results show that trends could be matched to a reasonable degree; the results will be improved with better materials testing and model refinement.

Thermo chemical solar energy storage via redox oxides: materials and reactor/heat exchanger concepts

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Thermo chemical Storage of solar heat exploits the heat effects of reversible chemical reactions for the storage of solar energy. Among the possible reversible gas-solid chemical reactions, the utilization of a pair of redox reactions of multivalent solid oxides can be directly coupled to CSP plants employing air as the heat transfer fluid bypassing the need for a separate heat exchanger. The present work concerns the development of thermo chemical storage systems based on such oxide-based redox materials and in particular on cobalt oxide; in the one hand by tailoring their heat storage/release capability and on the other hand via their incorporation in proper reactor/heat exchanger devices. In this respect the first stage of the work involved parametric testing of cobalt oxide compositions via Thermo-Gravimetric Analysis to comparatively investigate the temperature range for cyclic oxidation-reduction and optimize the cycle conditions for maximum reduction and re-oxidation extent. Subsequently, two reactor concepts for the coupling of solar energy to the redox reactions have been implemented and tested. These reactor concepts include in one hand structured ceramic reactors/heat exchangers based on redox-oxide-coated honeycombs and on the other hand powder-fed, solar-heated, rotary kiln reactors. The two reactor concepts were tested within non-solar-aided lab-scale and solar-aided campaigns, respectively. The feasibility of both concepts was shown and good chemical conversions were achieved. The experiments pointed out the challenging points related to the manufacture of pilot-scale reactors/heat exchangers with enhanced heat storage capacity. A numerical model using commercial CFD software is developed to define optimal geometrical characteristics and operating conditions and refine the pilot scale design in order to achieve efficient, long-term off-sun operation.
Thermo chemical solar heat storage with redox oxides is a promising route for increasing the storage density of Solar Thermal Power Plants. However, a necessary condition for its large-scale implementation is the development of efficient, integrated thermo chemical reactors/heat exchangers, suitably incorporated within the plants' infrastructure. One option is redox-oxide-powders-fed rotary kiln receiver/reactors that can be directly solar-irradiated. Another option is redox-powder-coated honeycomb reactors. Direct solar heating of the latter via implementation of integrated receiver/reactors is rather complicated to be realized in large-scale due to limited available irradiated surface and material conductivity. For this reason the heating up of such reactors "indirectly" by using hot air produced in a separate solar receiver is considered the best option. This can be realized by placing the reactor inside an insulating housing where air passes through, transferring its heat to the solid material.

Combined Cooling Heating and Power System with Integration of Middle-and-low temperature Solar Thermal Energy and Methanol Decomposition
Da Xua,b, Qibin Liua,, Hongguang Jina The 6th International Conference on Applied Energy – ICAE2014*

In this paper, a novel distributed energy system, which contains the process of mid-and-low temperature solar energy thermo chemical hybridization with methanol is proposed. Through the solar energy receiver/reactor, solar thermal energy collected by a parabolic trough concentrator, at 250°C -300°C, drives the decomposition reaction of methanol into solar fuels of syngas, thus converts to chemical energy. The chemical energy of syngas releases in the combustion chamber of a micro gas turbine to drive the combined cooling heating and power systems. Extra produced solar fuel reserves a gas tank. Energy analysis and exergy analysis of the system are implemented, and the design and off-design performance of the system and the character of chemical energy storage under variable solar radiation are discussed. As a result, the primary energy ratio of the system is 76.40%, and the net solar-to-electricity rate reaches 22.56% much higher than the exited large-scale solar thermal power plant. As the solar thermo chemical energy storage contained in the system, the generating efficiency becomes insensitive to the solar radiation, and thus the efficient and stable utilization of solar thermal energy is achieved at all work condition. In this paper, a novel distributed energy combined cooling power and heat with mid-and-low temperature solar energy thermo chemical hybridization with methanol is proposed. The primary energy ratio of the system is 76.40%, the energy efficiency of the system is 48.81%, and the net solar-to-electricity rate reaches 22.56%. Owing to the fact that the solar thermo chemical energy storage is integrated to the system, the generating efficiency is insensitive to the solar direct radiation, and thus the efficient and stable utilization of solar thermal energy is achieved

POTENTIAL AND BARRIERS

TES technologies face some barriers to market entry and cost is a key issue. Other barriers relate to material properties and stability, in particular for TCS. Each storage application needs a specific TES design to fit specific boundary conditions and requirements. R&D activities focus on all TES technologies. Most of such R&D efforts deal with materials (i.e. storage media for different temperature ranges), containers and thermal insulation development. More complex systems (i.e. PCM, TCS) require R&D eff orts to improve reacting materials, as well as a better understanding of system integration and process parameters . TES market development and penetration varies considerably, depending on the application fields and regions. Penetration in the building sector is comparably slow in Europe where the construction of new buildings is around 1.3% per year and the renovation rate is around 1.5%; of course, the integration of TES systems is easier during construction. The estimate of the European potential is based on a 5% implementation rate of TES systems in buildings [16]. Penetration could be much higher in emerging economies with their high rates of new building construction. TES potential for co-generation and district heating in Europe is also associated with the building stock. The implementation rate of co-generation is 10.2% [17], while the implementation of TES in these systems is assumed to be 15%. As far as TES for power applications is concerned, a driving sector is the concentrating solar power (CSP) where almost all new power plants in operation or under construction are equipped with TES systems, mostly based on molten salt. This is perhaps the most important development fi led for large, centralised TES installations [18]. In the industrial sector, about 5% of the fi nal energy consumption is assumed to be used by TES installations. In particular, the use of industrial waste heat is expected to grow since the price of fossil fuels will rise and energy effi ciency will be the keyto competitiveness. Based on the University of Lleida study [16], the expansion of TES technologies is expected to be signify cant in Europe and Asia (particularly Japan) and somewhat lower (50%) in the United States. The global potential is estimated at approximately three times the European potential

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