Final report of Subtask C
"Phase Change Materials"
The overview

A Report of IEA Solar Heating and Cooling programme - Task 32

Advanced storage concepts for solar and low energy buildings

Report C7 of Subtask C

March 2008

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Final report of Subtask C
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by

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Final report of Subtask C

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Executive Summary

This report is the final report of a Subtask of the Task 32 “Advanced Storage Concepts for solar and low energy buildings” of the Solar Heating and Cooling Programme of the International Energy Agency.

As a final report of a Subtask it has two aims:

1. it summarizes all the work conducted in the Subtask during the period of the Task (June 2003 – December 2007) highlighting some important results that the participants in the Subtask reached and it refers to all the detailed documents that have been produced by the Subtask and Task 32,
2. it presents some hints on the management of an IEA Subtask in order to improve future collaborative works within this framework.

In Subtask C, major achievements have been:

1. Documentation of State of the Art in PCM storage in the Task 32 Handbook [1].
2. Development of various heat store laboratory prototypes including PCM either in containers located in a more or less common water store, or with PCM as the storage fluid with an immersed heat exchanger for charging and discharging. While normally subcooling of the PCM is tried to be avoided, one application makes actively use of this feature in order to achieve long term heat storage.
3. Experimental testing of these stores in the laboratories under various conditions and PCM contents in order to characterize energy content, heat transfer, heat losses etc.
4. Development of four simulation models for the TRNSYS simulation environment. Two models deal with macroencapsulated PCM in containers of various shapes with a number of different heat exchangers and in- and outlets available. One store-model simulates a store filled with PCM with an immersed finned tube heat exchanger. The last model deals with the subcooling long term heat storage.
5. Finally seasonal simulations were performed from 4 groups by integrating these PCM store models in complete systems for various applications. The applications were mainly related to the reference conditions developed in Subtask A for solar combisystems (and are therefore comparable to results from other subtasks) but also for conventional systems using the PCM store to reduce the cycling operation for conventional boilers.
6. Unfortunately most of the applications could not show a significant improvement of PCM stores compared to conventional water stores. Only the long term heat storage with subcooled liquid PCM shows the possibility to achieve 100 % solar fraction with PCM store volumes of about 10 m³ for a 135 m² floor area passive houses (15 kWh/(m²a) space heating demand). Water stores have to be far bigger to achieve the 100 % solar fraction. 80 – 90 % solar fraction can be achieved also with water stores of 5 - 10 m³.
7. Input for the storage part of the strategic research agenda of the European Solar Thermal Technology Platform, further refining the compact heat storage R&D questions that should be tackled on an international level.

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

IEA Solar Heating and Cooling Programme

The *International Energy Agency* (IEA) is an autonomous body within the framework of the Organization for Economic Co-operation and Development (OECD) based in Paris. Established in 1974 after the first "oil shock," the IEA is committed to carrying out a comprehensive program of energy cooperation among its members and the Commission of the European Communities.

The IEA provides a legal framework, through IEA Implementing Agreements such as the *Solar Heating and Cooling Agreement*, for international collaboration in energy technology research and development (R&D) and deployment. This IEA experience has proved that such collaboration contributes significantly to faster technological progress, while reducing costs; to eliminating technological risks and duplication of efforts; and to creating numerous other benefits, such as swifter expansion of the knowledge base and easier harmonization of standards.

The *Solar Heating and Cooling Programme* was one of the first IEA Implementing Agreements to be established. Since 1977, its members have been collaborating to advance active solar and passive solar and their application in buildings and other areas, such as agriculture and industry. Current members are:

Australia	Finland	Portugal
Austria	France	Spain
Belgium	Italy	Sweden
Canada	Mexico	Switzerland
Denmark	Netherlands	United States
European Commission	New Zealand	
Germany	Norway	

A total of 39 Tasks have been initiated, 30 of which have been completed. Each Task is managed by an Operating Agent from one of the participating countries. Overall control of the program rests with an Executive Committee comprised of one representative from each contracting party to the Implementing Agreement. In addition to the Task work, a number of special activities—Memorandum of Understanding with solar thermal trade organizations, statistics collection and analysis, conferences and workshops—have been undertaken.

The Tasks of the IEA Solar Heating and Cooling Programme, both underway and completed are as follows:

Current Tasks:

Task 32	*Advanced Storage Concepts for Solar and Low Energy Buildings*
Task 33	*Solar Heat for Industrial Processes*
Task 34	*Testing and Validation of Building Energy Simulation Tools*
Task 35	*PV/Thermal Solar Systems*
Task 36	*Solar Resource Knowledge Management*
Task 37	*Advanced Housing Renovation with Solar & Conservation*
Task 38	*Solar Assisted Cooling Systems*
Task 39	*Polymeric Materials for Solar Thermal Applications*

Completed Tasks:

Task 1	*Investigation of the Performance of Solar Heating and Cooling Systems*
Task 2	*Coordination of Solar Heating and Cooling R&D*
Task 3	*Performance Testing of Solar Collectors*
Task 4	*Development of an Insolation Handbook and Instrument Package*
Task 5	*Use of Existing Meteorological Information for Solar Energy Application*
Task 6	*Performance of Solar Systems Using Evacuated Collectors*
Task 7	*Central Solar Heating Plants with Seasonal Storage*
Task 8	*Passive and Hybrid Solar Low Energy Buildings*
Task 9	*Solar Radiation and Pyranometry Studies*
Task 10	*Solar Materials R&D*
Task 11	*Passive and Hybrid Solar Commercial Buildings*
Task 12	*Building Energy Analysis and Design Tools for Solar Applications*
Task 13	*Advance Solar Low Energy Buildings*
Task 14	*Advance Active Solar Energy Systems*
Task 16	*Photovoltaics in Buildings*
Task 17	*Measuring and Modeling Spectral Radiation*
Task 18	*Advanced Glazing and Associated Materials for Solar and Building Applications*
Task 19	*Solar Air Systems*
Task 20	*Solar Energy in Building Renovation*
Task 21	*Daylight in Buildings*
Task 23	*Optimization of Solar Energy Use in Large Buildings*
Task 22	*Building Energy Analysis Tools*
Task 24	*Solar Procurement*
Task 25	*Solar Assisted Air Conditioning of Buildings*
Task 26	*Solar Combisystems*
Task 28	*Solar Sustainable Housing*
Task 27	*Performance of Solar Facade Components*
Task 29	*Solar Crop Drying*
Task 31	*Daylighting Buildings in the 21st Century*

Completed Working Groups:
CSHPSS, ISOLDE, Materials in Solar Thermal Collectors, and the Evaluation of Task 13 Houses

To find Solar Heating and Cooling Programme publications and learn more about the Programme visit **www.iea-shc.org** or contact the SHC Executive Secretary, Pamela Murphy, e-mail: pmurphy@MorseAssociatesInc.com

September 2007

What is IEA SHC Task 32
"Advanced Storage Concepts for solar and low energy buildings" ?

The main goal of this Task is to investigate new or advanced solutions for storing heat in systems providing heating or cooling for low energy buildings.

- The first objective is to contribute to the development of advanced storage solutions in thermal solar systems for buildings that lead to high solar fraction up to 100% in a typical 45N latitude climate.

- The second objective is to propose advanced storage solutions for other heating or cooling technologies than solar, for example systems based on current compression and absorption heat pumps or new heat pumps based on the storage material itself.

Applications that are included in the scope of this task include:

- new buildings designed for low energy consumption
- buildings retrofitted for low energy consumption.

The ambition of the Task is not to develop new storage systems independent of a system application. The focus is on the integration of advanced storage concepts in a thermal system for low energy housing. This provides both a framework and a goal to develop new technologies.

The Subtasks are:

- Subtask A: Evaluation and Dissemination
- Subtask B: Chemical and Sorption
- Subtask C: Phase Change Materials
- Subtask D: Water tank solutions

Duration

July 2003 - December 2007.

www.iea-shc.org look for Task32

IEA SHC Task 32 Subtask C
"Phase Change Materials"

This report is part of Subtask C of the Task 32 of the Solar Heating and Cooling Programme of the International Energy Agency dealing with solutions for storage based on Phase Change Materials (PCM).

It is the final subtask report that presents the major achievements within a Subtask and the remaining open questions. It presents a summary of the results and not the details to be found in other Subtask reports, which are listed in the reference chapter, and that can be found on the IEA web site www.iea-shc.org, when the report was classified as public by the IEA SHC Executive Committee.

The storage density of PCMs compared to water is theoretically by a factor of 1.2 to 5 higher, depending on the temperature range of comparison. Small temperature differences will favour PCM solutions, whereas larger temperature ranges, 30 to 60 K and more will probably favour sensible storage in water.

The application of PCM for solar energy storage is not completely new, but the way Task 32 has handled it is new. From material to system and simulation, the process was application oriented: a solar combisystem has a target.

PCM could also be used to reduce the cycling of boilers in a small volume tank. This new idea was also investigated in Task 32 in a project bringing more insight on the usefulness of PCMs in storing heat and power.

The report does not cover all aspects of the topic, since the rule of an IEA SHC Task is, that participating countries share information on projects they decide to bring in the Task.

Projects presented in this report reflect the knowledge of the participating body presenting the project.

The Operating Agent would like to thank the participants of all Subtasks within Task 32 for their implication in the search of future storage solutions for solar thermal energy, the key to a solar future for the heating and cooling of our buildings.

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Description of scope of Subtask C

This Subtask focuses on solutions for storing heat or "cold" using Phase Change Materials (PCM).

The scope, in terms of general system aspects, for Subtask C was the same as that for the whole of Task 32, namely solar heating and cooling systems for residential buildings, principally detached houses for one up to a few families. Buildings with a larger specific heat load (>100 kWh/(m^2a) for Zurich climate) are not considered. The main focus was to find storage solutions sized to achieve a significant solar fraction but also for other applications in the heat storage field for domestic housing, especially to reduce the cycling rate of conventional boilers.

All solutions with PCM stores were compared to pure water stores.

Some solutions using such materials have already been tested in full scale pilot plants and some durable commercial products are already on the market for special applications (Cristopia, Rubitherm among others).

Detailed activities include

- the selection of suitable materials,
- the development of storage prototypes and
- the optimization of existing solutions in an integrated system such as the reference combisystem defined by Subtask A.

Figure *1* shows a classification of processes for PCM storage of heat, in Subtask C only the paraffins (analytical grade) and hydrated salts have been addressed.

In terms of temperature, the storage solutions have been limited to temperatures < 85°C, because the maximum needed temperature for the domestic applications with low temperature heating systems is the DHW demand with around 50°C. The phase change temperature of the materials chosen (mainly sodium acetate trihydrate, partly embedded in a graphite matrix to increase the thermal conductivity) is at about 58°C. For some other tests additional PCM with a lower phase change temperature was chosen (paraffin).

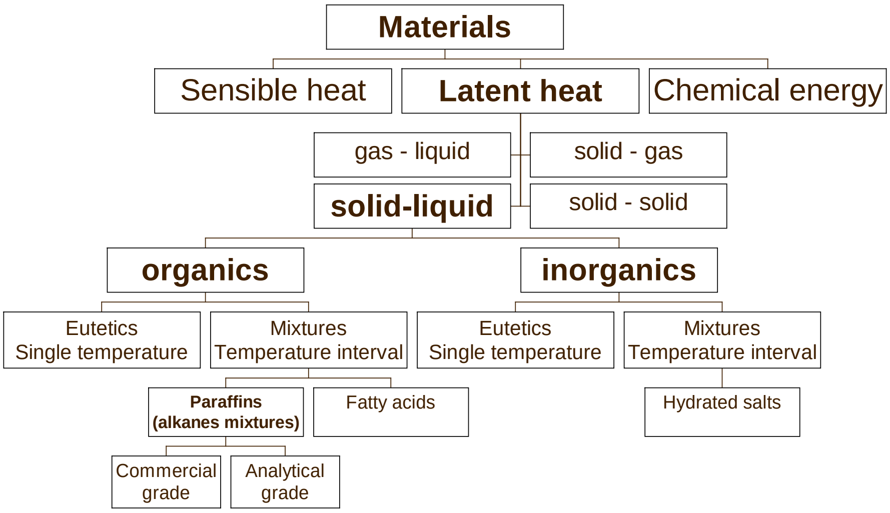


Figure 1: Classification of energy storage materials [2].

Simulation models of the PCM storage component were developed for different types of PCM heat store philosophies, as no validated models were available for the simulation software TRNSYS. These models were validated before being integrated into a system model within TRNSYS. Each Subtask was responsible to develop an appropriate tool, in order to enable an estimation of the performance of a system with the proposed storage concept.

1 Projects within Subtask C

There are five PCM related projects included in Task 32. A summary of these projects is given in

Table 1.

Three projects dealt with macro-encapsulated PCM containers in water stores. All of these projects include the development of TRNSYS models for the PCM stores:

- At Lleida University, Spain, bottles and filled up heat exchangers of PCM material with graphite matrix for the enhancement of the heat conduction and increase of power input/output were tested. Applications are free-cooling and DHW tanks.
- At the University of Applied Sciences Western Switzerland in Yverdon-les-Bains/Switzerland a parametric study for the use of PCM in heat stores embedded in aluminium bottles for solar combisystems was carried out.
- The Institute of Thermal Engineering at Graz University of Technology performed tests and simulations with different PCM materials encapsulated in plastic tubes and steel containers for stores for conventional boilers to reduce the number of start-stop cycles of the burner.

The two other projects are slightly different:

- At the Department of Civil Engineering, Technical University of Denmark the use of super cooling of PCM materials for long-term heat storage was investigated with simulations. This project showed that a 10 m^3 only PCM seasonal storage using the supercooling effect is theoretically possible. Experimental setup assessed some assumptions on heat transfer in a bulk PCM tank
- The Institute of Thermal Engineering at Graz University of Technology performed tests and simulations with PCM-slurries of microencapsulated paraffins for stores for conventional boilers to reduce the number of start-stop cycles.

The above project is also dealing with heat exchangers immersed in PCM material

- The Institute of Thermal Engineering at Graz University of Technology performed tests and simulations with a bulk PCM tank with an immersed water-to-air heat exchanger for stores for conventional boilers to reduce the number of start-stop cycles of the burner.

A summary of these projects is given in

Table 1, and the main results are given in the following chapter.

Table 1: Summary of prototype storage units studied in Subtask C.

Type of Technology	Material	Stage of Development	Investigating Institute
PCM seasonal storage using subcooling	$Na(CH_3COO)\cdot 3\ H_2O$	Lab prototype; Simulation model for store developed and seasonal simulations of the system were performed	Technical University of Denmark (DTI), Denmark
Macroencapsulated PCM in storage tank	$Na(CH_3COO)\cdot 3\ H_2O$ + graphite	Lab prototype; Seasonal simulations of the system were performed, using the model developed by the Institute of Thermal Engineering, Graz Unviersity of Technology	University of Lleida, Spain
Macroencapsulated PCM in storage tank with integrated burner	$Na(CH_3COO)\cdot 3\ H_2O$ + graphite	Lab prototypes; Simulation model for store developeda and validated; Seasonal simulations of the system were performed according to the reference conditions from Subtask A	University of Applied Sciences Western Switzerland (HEIG-VD), Switzerland
Microencapsluated PCM slurry	Paraffine,	Lab prototypes, Development of simulation models for a store filled with slurry with various internal heat exchangers and flow/return pipes and an external heat exchanger with PCM slurry on one or both sides.	Graz University of Technology, (IWT-TU Graz), Austria
Macroencapsulated PCM in storage tank	Paraffine, $Na(CH_3COO)\cdot 3\ H_2O$ with/without graphite	Simulation model for store developed and validated; Seasonal simulations of the system were performed for various hydraulic schemes for heating systems in order to analyze the reduction of the boiler cycling rate compared to water stores.	Graz University of Technology, (IWT-TU Graz), Austria
Immersed heat exchanger in PCM	$Na(CH_3COO)\cdot 3\ H_2O$ without graphite	Simulation model for store developed and validated; Seasonal simulations of the system were performed for various hydraulic schemes for heating systems in order to analyze the reduction of the boiler cycling rate compared to water stores.	Graz University of Technology, (IWT-TU Graz), Austria

2 Main results of Subtask C

2.1 Results of the laboratory measurements (Reports C3, C4)

All storage solutions dealt with in Subtask C were only laboratory prototypes. The results of the store systems are shown in Table 2.

Measured results and projected heat storage densities for units of 70 and 1000 kWh storage for single family houses are reported. The prototypes use either paraffins or sodium acetate trihydrate, but all of them have a phase change at about 58°C in order to provide space heating and domestic hot water. The system from HEIG-VD additionally uses a PCM with phase change at 27°C in the preheating zone of the buffer store.

The prototypes are intended for different applications. While the stores from HEIG-VD, Switzerland and University of Lleida, Spain are short term heat storages for solar combi-systems, the store from the Technical University of Denmark is used as seasonal storage by making use of the subcooling effect in hydrated salts. The work of Graz University of Technology is dealing with very short term storage for boilers, to reduce start-stop cycles and emissions. For small short term storages one decisive factor is to deliver enough thermal power for the domestic hot water demand (26 kW e.g. for a single family residential building). This means high specific power and therefore either high thermal conductivity of the solid PCM and/or small distances for the heat transfer from PCM to the heat carrier. For larger stores this problem is far smaller due to the lower necessary specific power. The projects are financed partly from national and partly from European Union projects.

The storage density compared to water is strongly dependent on the temperature lift in the storage tank. For small temperature differences (50 – 70 °C) and a bulk PCM tank with immersed heat exchanger (like the store used at the Institute of Thermal Engineering, Graz University of Technology), the store can be sized about 1/3 of the volume compared to water, if sodium acetate trihydrate is used as PCM. With this layout additionally the about 20 kW thermal power can be delivered for the DHW production. For the same PCM-material but macro-encapsulated and for a temperature lift from 25 to 85°C or 20 to 70°C in solar combisystems the store has the same size as a water store. For such cases there is only little benefit from PCM with respect to the store size.

For PCM store used for seasonal storage the comparison to water stores is not as simple, because there are no heat losses of the subcooled PCM store. Compared to the theoretical heat storage of water without heat losses the volume of the PCM store can be reduced by about 30 %.

Table 2 Comparison of the stores with PCM material

Parameter	**DTU**	**Lleida**	**HEIG-VD**	**TU Graz**	**TU Graz**
Type of technology	Seasonal storage with subcooled	Macroencapsu-lated PCM in solar combistore	Macroencapsulated PCM in solar combistore	Macroencapsulated PCM in store for boiler	Immersed heat exchanger in PCM store
Cost of material					
Storage materials weight: in kg	$Na(CH_3COO)\cdot 3\ H_2O$: 60	$Na(CH_3COO)\cdot 3\ H_2O$ + graphite: 4.2 Water: 140	$Na(CH_3COO)\cdot 3\ H_2O$ +graphite: 90 water: 710 paraffin RT27: 43	$Na(CH_3COO)\cdot 3\ H_2O$ + graphite: 13.7 water :20.8	$Na(CH_3COO)\cdot 3\ H_2O$: 45 Water: 0
Temperature difference in tank	35/70°C	20/70°C	25/85	50/70°C	50/70°C
Floor space required for prototype	1.3 m^2	0.25 m^2	1.8 m^2	0.4 m^2	0.2 m^2
Energy density of material (NRJ4.1) in kWh/m³ (ratio to water)	128 (3.2)	56 0.97)	Water 69,7 SAT 81.2 (1.16) Paraffin RT27 58.3 (0.84)	85 (3.7)	103 (4.44)
Energy density of prototype - heat (NRJ4.2) in kWh/m³ (ratio to water)	10.9 (0.3)	57 (0.98)	70 (1.0)	40 (1.7)	76 (3.3)
Energy density of material in kWh/m³ (ratio to water, 15/35°C)			Water 23.2 Paraffin RT27 57 (2.45)		
Energy density of material in kWh/m³ (NRJ4.2) (ratio to water, 50/70°C)			Water 23.2 SAT 51.4 (2.21)		
Charge rate in kW	N/A		Auxiliary 20	0.5-1	5-20
Discharge rate in kW	N/A		DHW around 30	0.5-1	5-20
Estimated size for 70 kWh in m³ (energy density ratio to water)	2.8 (0.6)	1.2 (1)	1 (1)	1.75 (1.7)	0.92 (3.0)
Estimated size for 1000 kWh in m³ (energy density ratio to water)	17 (1.4)	17.5 (1)	14.3 (1)	25 (1.7)	13 (3.3)

SAT = sodium acetate trihydrate

In terms of material cost, all materials are expensive compared to water, ranging from pure sodium acetate with about 1€/kg, paraffin with about 2 €/kg (including nucleation enhancer) to sodium acetate trihydrate with graphite and nucleation enhancers with about 3 - 4 €/kg. The cost for the whole storage system has not been estimated here.

The work at **BYG DTU, Department of Civil Engineering, Denmark** measurements dealt in the first phase of the laboratory tests on melting approximately 70 kg of sodium acetate trihydrate and afterwards let it supercool in the large melting tank. The melting was performed by circulation of 85 °C hot water through the mantle of the melting container. The melting process required about 2 days before stationary temperatures in the melted salt was obtained. The tube pump was started after one day to obtain a good mixing in the melted salt and avoid sediments of undissolved salt hydrates.
In the second phase experiments have been carried out with filling of laminated plastic bags with melted sodium acetate trihydrate both as warm salt (80 °C) and as supercooled salt at room temperature. The experiments with warm melted salt solution worked well, while the experiments with the supercooled salt solution failed due to immediate solidification when the supercooled salt was exposed to the surrounding air. The conclusions from the filling experiments are that it is possible to fill the bags with warm melted sodium acetate trihydrate. It might also be possible to fill the bags with supercooled salt solution, but in this case the filling system should be sealed to avoid any water evaporation
In the third phase the activation of the solidification of the supercooled sodium acetate trihydrate by a microprocessor controller was tried out. Several different experiments of ways to activate the solidification of a supercooled salt solution have been tested, e.g. ultrasound, local heating and mechanical by a piston injected into the salt by an electromagnet. The latter seems to be the most feasible solution resulting in activation of the solidification. The reason could either be the mechanical impact itself or the fact that the piston when withdrawn from the salt solution will hold some crystals that are injected next time the piston is activated.
Finally a very small test prototype storage, which is just large enough to investigate the control system, activation mechanism and the supercooling and to get an idea of the heat transfer possibilities, was developed. The prototype design is not at all optimised for maximum storage capacity per volume unit and therefore the achieved figures are not at all representative for the expected final storage design

At **Lleida University, Spain** the same store with three different fillings was used:

- pure water,
- aluminium bottles filled with sodium acetate trihydrate with graphite and
- the coil of the heat exchanger in the middle of the tank with additional three bottles filled with sodium acetate trihydrate with graphite.

The amount of PCM placed in the each cylindrical bottle was 1150 g, which means that the 8 modules configuration had 9200 g (4.18% of the water volume). In the coil/modules configuration, the coil had 4900 g of PCM and the 3 modules 1050 g each one, meaning 8050 g in total (4.92% of the water volume – see that the PCM included in the coil does not take volume to the water). The amount of PCM placed into the coil results in an experimental density of 0.5 kg/L, significantly lower than the value provided by the manufacturer (1.3 kg/L).

The experimental work consisted of charging and discharging tests. The discharging experiments were performed introducing cold water (24ºC) at the bottom part of the tank, and extracting hot water (65ºC) from the top. The flow rate was regulated using a valve. The system worked in a closed loop, cooling the water going out of the top part of the tank. The cooling was done using tap water at public drinking water system supply temperature passing through a plate heat exchanger. In these experiments the inlet with stratifier was used

In the charging tests, hot water (65ºC) was introduced at the top part of the tank, and cold water (24ºC) was extracted from the bottom. The flow rate was regulated using a valve. The heating system was an electrical resistance of 5 kW of nominal power, ensuring an inlet temperature of 65ºC. The temperature control was done with a PID control system used in the test ring installation. The system worked in a closed loop, heating the water going out of the bottom port of the tank.

The main conclusions from the experiments are:

1. Cooling down experiments
   - Sodium acetate trihydrate cools down slower than sodium acetate trihydrate + graphite due to its worse heat transfer
   - There is a big dependence from the ambient temperature in long term storage (i.e. cool down test)
2. Charging experiments
   - When only sodium acetate trihydrate is used, the PCM temperature is the same as the water temperature, no melting is observed.
   - On the other hand, a clear melting process is observed when using graphite mixed with the sodium acetate trihydrate
3. Discharging experiments
   - All at 20ºC → water or PCM?
     - If high flow rate → PCM is not fully solidified and a reheating process is observed
     - If low flow rate → No reheating is observed, PCM is fully solidified
   - There was no influence of the ambient temperature due to the short time of the test, therefore comparison of the graphics was possible
4. Cycles experiments
   - The five-minutes shower does only affected the bottom of the tank

Different discharge flow rates were performed (2, 3, 4 and 5 L/min). There was no significant increase of the energy content of the three tanks, but as the maximum theoretical increase was only 2 % this was expected. The main focus of theses experiments was laid on the level of stratification within the tanks. It could be shown, that the stratification was not disturbed by the (little amount) of PCM in the store.

In the project at **HEIG-VD, Switzerland** , PCM bottles of about 1l volume were placed in the water tank. The bottles are made of aluminium and the caps are made of polypropylene. The latter have been modified in order to resist pressure variation between the water tank and the PCM in the bottle. The modification consists in an aluminium disk and a rubber disk. The system has been tested in a special tank in which the pressure could be modified. The bottle has resisted to a relative pressure between minus one bar to three bars.

A set of 102 bottles filled with paraffin (40%) and sodium acetate trihydrate (60%) are plunged in the water tank. The occupied volume represents approximately 15% percent of the tank volume. This low ratio of PCM is due to various problems:

- The two heat exchangers

- The extra-heating system
- The bottles are not filled to the top to allow for PCM expansion.

Nevertheless, these tests with a rather low PCM ratio were undertaken. The results are compared to the simulation results, in order to validate the model developed for TRNSYS (See Report C5).

A 7 day heating test with two different winter periods of the Zürich climate, for a single family house with a 140m^2 floor area and a heat demand of 30 [kWh/(m^2.a)] were performed. The DHW demand is 7.5 [kWh/day]. The first weather sequence is a medium sunny winter and the second one is a high sunny winter. Additonal DHW tests over 24 hour with a large ad a small draw off were performed.

The measured stores were filled either with pure water and in comparison with water and 102 bottles of PCM (12 % PCM, 60 bottles of sodium acetate with graphite in the upper part of the tank and 42 bottles of paraffin RT27 in the lower part)

For the heating tests there was no significant difference between the pure water tank and the one filled with PCM bottles. For the DHW test it could be seen, that the burner had to switch on more often with the PCM store due to the lower water content and the low heat transfer from PCM to water.

At **the Institute of Thermal Engineering, Graz University of Technology, Austria,** different approaches of integrating PCMs into thermal storage tanks were studied:

- macro-encapsulation (store volume 34 litres)
- PCM tank with an immersed heat exchanger (store volume 45 litres)
- microencapsulated PCM slurry

4 different experimental tanks have been built and tested in the laboratory. The goal of the work was to find a simple and efficient way of PCM integration, that allows both high energy densities and high charge and discharge powers. Besides a measurement method for the determination of the enthalpy as a function of temperature of PCM materials was applied.
The results of the experimental work were also used to validate a PCM storage simulation model that has been developed at the Institute [3].

For the tests with macroencaspulated PCM the evolution of the discharge power with time for different PCM materials inside of the cylindrical PCM modules was measured. At the beginning of the experiment the discharge powers are relatively high, which is a result of the hot water being pushed out of the tank by the cold water entering at the bottom. After that the heat is discharged only from the PCM modules. With the paraffin as well as with sodium acetate trihydrate the discharge power is quite low (about 0.2 kW), due to the low thermal conductivity of these materials. This results in a very long discharge time and a limitation concerning the possible applications. When the sodium acetate trihydrate graphite compound is used inside the modules, the achievable discharge power is much higher (0.6 kW), due to the enhancement of the thermal conductivity. For sodium acetate trihydrate (with and without graphite) a subcooling effect can be observed, resulting in a local minimum of the discharge power.

Another approach was a tank with a volume of 45 litres filled with Sodium Acetate Trihydrate and an immersed water-to-air heat exchanger (PCM volume fraction ~ 80%). Due to the large heat exchanger surface a discharge power of up to 20-30 kW can be achieved with an acceptable temperature loss (outlet temperatures of 45 to 50°C at a melting temperature of 58°C) during the phase change of the PCM material.

The stores with microencapsulated PCM did not show an advantage compared to water stores, because the PCM is paraffin (which has a relatively low heat of fusion per volume), not a fixed temperature but a melting temperature range (at technical grade) and at maximum a mass fraction of 35 % PCM in water in order to be pumpable. Additionally the heat transfer rate decreases strongly with the concentration of microcapsules in water and the pumping power increases significantly due to higher viscosity of the fluid.

2.2 Simulation modules developed (Report C5)

In the beginning of the Task 32 no simulation models for PCM stores were available. Therefore three groups started to develop numerical models for PCM stores.

- At **HEIG-VD in Yverdon-les-Bains, Switzerland** a PCM model using the TRNSYS standard type 60 as basis, was developed for different shapes (plates, cylinders and spheres) and numbers of PCM modules in the tank (Type 860). Additionally subcooling, hysteresis and convection of the liquid part of the PCM in the modules was modelled. The type of PCM is modelled by 5 points of the temperature-enthalpy curve.
- At the **Institute of Thermal Engineering (IWT), Graz University of Technology, Austria** a new type for a heat storage including pure water, PCM slurries, PCM modules (plates, cylinders and spheres), subcooling and hysteresis was developed (Type 840). The PCM type is given by an ASCII-Input file that is read by the module. Instead of water a PCM slurry can be used as the storage medium.
- Another store model for an immersed heat exchanger (finned air to water type) in a PCM filled tank was developed at IWT for the simulation of applications with high requirements concerning the charging and discharging power with little temperature loss (Type 841).
- **At BYG DTU, Department of Civil Engineering, Denmark** a store model for long term storage of subcooled PCM in different compartments was developed and validated against laboratory measurements (Type 185).

All models were validated by experiments and are suitable for the TRNSYS simulation environment. Nevertheless the authors do NOT take any responsibility for the results of the models.

All models were used for yearly system simulations including PCM storage.

With these models there is now the opportunity to develop optimized systems with various PCM store, hydraulic and control configurations and to compare PCM heat store systems with water heat store systems.

The use of the models for the public is decided by the author of the model individually.

All models are described in Report C5 in detail

2.3 Results of System simulations (Report C6)

Four simulation studies were performed in Subtask C. Three of them were using more or less the reference conditions defined in Subtask A (Report A2). One of them dealt with a complete different application to reduce boiler cycling by introducing a PCM store.

The simulation results from **HEIG-VD in Yverdon-les-Bains, Switzerland** concerning the advantage of makroencapsulated PCM in solar combisystems are shown in Figure 2. It should be reminded that the proposed system has been analysed only from the simulation side, where a water tank storage filled only with water or filled with water + PCM (paraffin RT35) is compared.

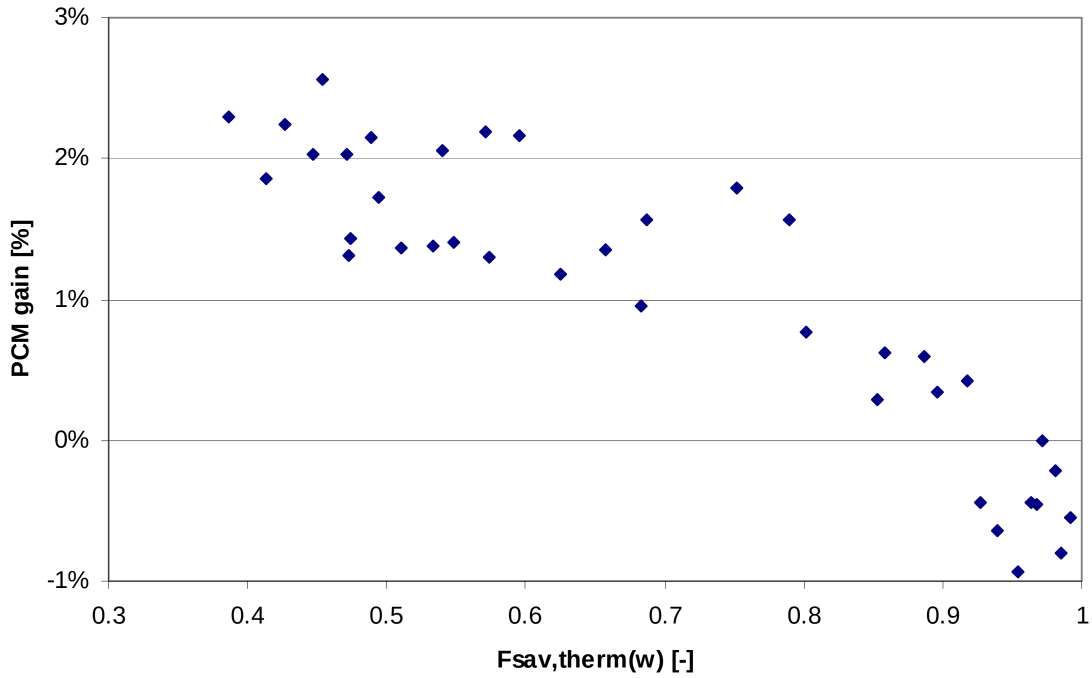


Figure 2: Difference between pure water and water + PCM system. The PCM gain = $F_{sav,therm(W+PCM)}/F_{sav,therm(W)}$ - 1

To evaluate the impact of the PCM on the performances, it is possible to define the energy gain between the $F_{sav,therm}$ for the tank with PCM ($F_{sav,therm(W+PCM)}$) and only with water ($F_{sav,therm(W)}$). If this gain is higher than 0, then the PCM brings an advantage. As it can be seen in Figure, the gain due to using PCM is low. A decrease of the RATIO according to the increase of the $F_{sav,therm}$ can also be noticed. But it should be remembered, that when the $F_{sav,therm}$ is high, the solar installation is oversized. As it can be seen, adding a PCM becomes less interesting when the solar system is oversized. This is due to the fact, that when oversized, the storage of heating is less relevant.

According to the additional cost of adding the PCM and the environmental impacts results described in Report C3, this system with PCM does not show a substantial benefit compare to a storage tank filled only with water.

Only the long term heat storage with subcooled liquid PCM (**BYG DTU, Department of Civil Engineering, Denmark,** Figure 3) shows the possibility to achieve 100 % solar fraction with PCM store volumes of about 10 m³ a 135 m² floor area passive houses (15 kWh/m²a space heating energy demand). Water stores have to be far bigger to achieve the 100 % solar fraction. 80 – 90 % solar fraction can be achieved also with water stores of 5 - 10 m³. Taking into account the long term heat losses of water stores the size reduction is far bigger.

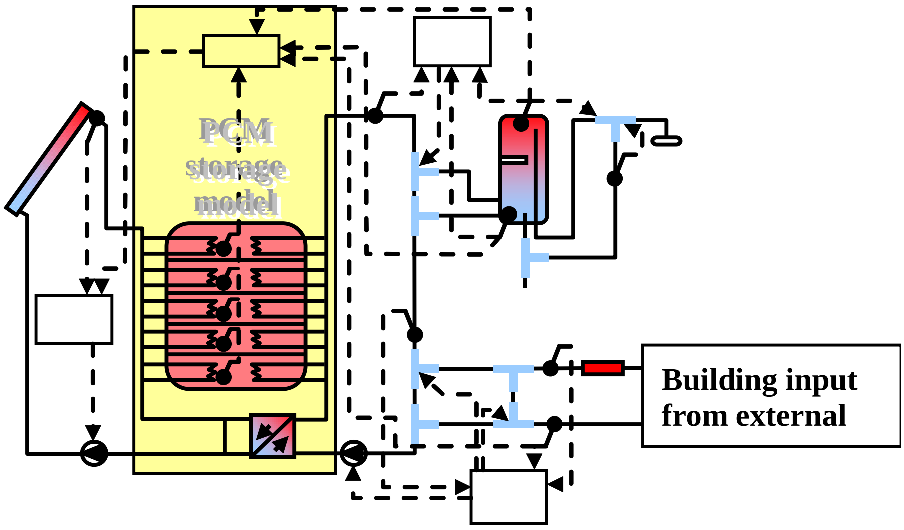


Figure 3: Simulation model of BYG DTU, Department of Civil Engineering, Denmark

At the **Institute of Thermal Engineering (IWT), Graz University of Technology, Austria** different hydraulic systems were investigated in terms of their ability to reduce boiler cycling operation. In the following a description of the hydraulic systems, which are used in the simulations, is given. Table 3 shows a summary of all simulated concepts.

The results for the system with a water storage (G2a) and for systems with a water storage with integrated PCM modules (G2b) are shown in Figure 4 for different storage volumes In comparison to the systems without buffer storage the number of start-stop cycles is reduced strongly. Even with the smallest volume of only 25 litres a reduction of about 70 % (set temp. 50°C) or 90 % (set temp. 65°C) can be achieved. With increasing storage volumes the number of cycles decreases, whereby the potential for a further reduction is low for volumes above 200 litres. Because of the lower utilized temperature difference the number of cycles is higher with a boiler temperature of 50°C in comparison to 65°C. On the other hand the higher temperatures decrease the annual efficiencies of the condensing boiler by 2-3 %.
The integration of PCM modules (boiler set temp. 65°C in all cases) allows an enhancement of the storage capacity, resulting in a further decrease of the number of start-stop cycles especially with small storage volumes. There are only minor differences between the PCM volume fractions of 50 and 75 %. The integration of PCM modules hardly influences the annual efficiencies of the boiler and the system.

Table 3: Summary of all simulated system concepts

system	type of boiler	type of buffer storage	type of DHW preparation	hydraulic integration and control of the boiler
System Category 1: no buffer storage, DHW tank				
G1a	gas	no storage	DHW tank	boiler temperature controlled as a function of the ambient temperature, throttle control
G1b	gas	no storage	DHW tank	constant boiler temp., flow temperature control via mixing valve
G1c	gas	no storage	DHW tank	constant boiler temp., flow temperature control via mixing valve, hydraulic switch
P1	pellets	no storage	DHW tank	constant boiler temp., flow temperature control via mixing valve, hydraulic switch, return temperature control
System Category 2: buffer storage, DHW tank				
G2a	gas	water storage	DHW tank	constant boiler temp., flow temperature control via mixing valve, buffer storage
G2b	gas	water storage + PCM modules	DHW tank	constant boiler temp., flow temperature control via mixing valve, buffer storage
P2a	pellets	water storage	DHW tank	constant boiler temp., flow temperature control via mixing valve, buffer storage, return temperature control
P2b	pellets	water storage + PCM modules	DHW tank	constant boiler temp., flow temperature control via mixing valve, buffer storage, return temperature control
System Category 3: buffer storage, instantaneous preparation of DHW				
G3a	gas	water storage	instantaneous preparation of DHW	constant boiler temp., flow temperature control via mixing valve, buffer storage
G3b	gas	bulk PCM tank	instantaneous preparation of DHW	constant boiler temp., flow temperature control via mixing valve, buffer storage

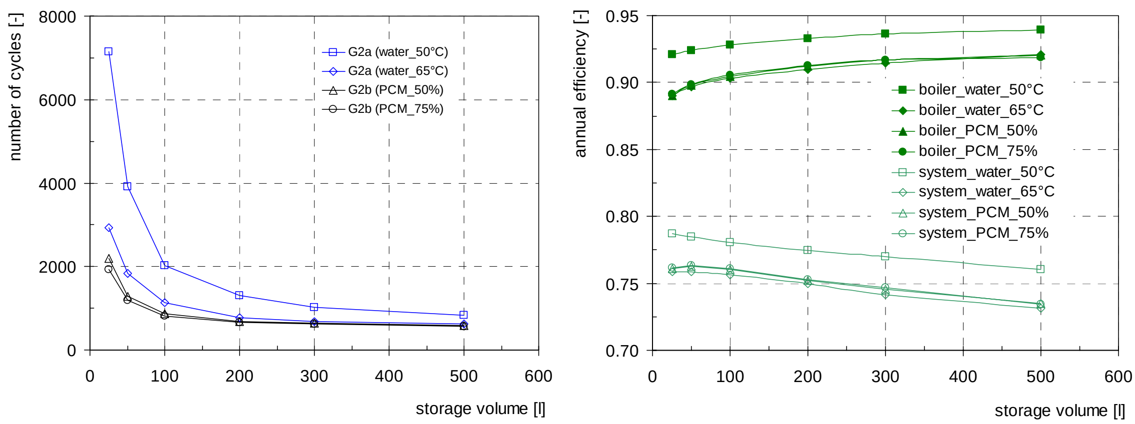
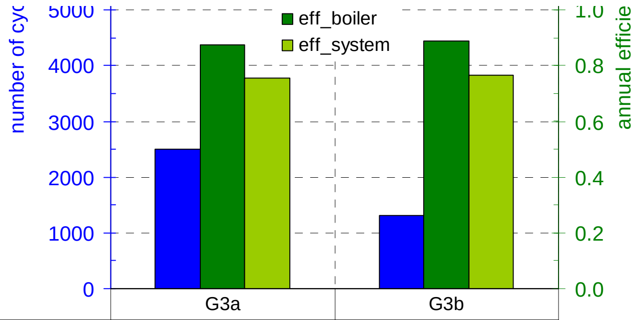


Figure 4: Gas boiler: annual number of start-stop cycles (left) and annual efficiencies (right) for different storage volumes for systems with water storage (G2a) and for systems with water storage with integrated PCM modules (G2b)

Figure 5 shows the number of start-stop cycles and the annual efficiencies for the system G3a (water storage) and the system G3b (bulk PCM storage). Due to the higher storage capacity of the PCM storage (assuming the same volume of 45 liters) in system G3b the number of cycles can be reduced by 50 % compared to system G3a. The annual efficiency of the boiler is also slightly higher, which is a result of the lower amount of heat produced in start-stop operation due to the higher storage capacity.



	G3a	G3b
n_cycles	2503	1307
Reihe4		
Reihe3		
Reihe5		
eff_boiler	0.87	0.89
eff_system	0.76	0.77

Figure 5: Annual number of start-stop cycles and annual efficiency for the systems G3a (water storage) and G3b (bulk PCM storage)

2.4 Final conclusions of the scientific work

Phase change materials as heat storage offer an advantage compared to water stores on the one hand, when the cycling temperature is close around the phase change temperature and the phase change can be used quite often. The other possible application is the use of the subcooling effect for seasonal storage. The investigations reported here showed only little advantages for macro-encapsulated PCM modules in combistores and for PCM slurries for heat stores in solar combisystems.

3 Future work on the Subtask C topic

Current situation

The results of Subtask C showed, that the improvement of using PCM in heat stores are very limited compared to water stores for most of the applications looked at. The only application that, in theory, can achieve significant improvement is the long term storage using subcooling for 100 % solar heated lowest energy buildings. But this system is probably very complicated due to the need of several storages insulated against each other and a reliable mechanism to activate crystallization. Additionally such a seasonal storage is only used once (or a slightly higher number of times).Therefore the investment cost should be not too high.

Therefore the following future work should be performed in the field of PCM:

1. Screening for better PCM materials with higher heat of fusion. Laboratory results on these materials and their suitability for solar storage in low energy buildings

2. Improvement of store concepts with PCM to get a high PCM fraction and a high heat transfer rate between the heat carrier and the PCM in order to fulfill the user demand (about 26 kW for filling a bath tube) without high temperature loss in the heat exchanger or in the heat conduction in the solid PCM. Laboratory prototypes of storage units. These concepts include also embedded PCM in the building structure.

3. Development of simulation models of such store units based on selected materials and technology, and programmed as a TRNSYS "type"

4. Screening for better suited applications where the heat store is used very often over the temperature range of the phase change.

5. Development of hydraulic layouts and control of solar systems including the user demands optimized for the specifications of PCM stores.

6. Test of storage units in a real or laboratory solar combi-systems installation

7. TRNSYS (or equivalent) simulations of an ideal design or a possible prototype of a system (according to Subtask A specifications) with an advanced storage unit

8. if succeeded, new storage units ready for industrialization

9. Proposals for future work and demonstration installations

10. A limited selection of candidates (maximum three to four, depending on the number of research teams and industries participating) for advanced storage solutions based on phase change material, readily available or available within the time frame of the Task, with or without a collaboration of the Subtask participants

4 Management aspects of Subtask C

Subtask C was organized this way:

- The general aims of the Subtask were defined in the Task definition.
- In practice, all groups that wanted to participate and whose projects were within the scope of the Subtask were welcomed into it. Except one all groups started from the beginning. One group started about 1 year late.
- Subtask C meetings were held in the plenary sessions of the Task 32 experts meetings. At the first meetings, the majority of the time was devoted to presentations of recent studies, but towards the end more emphasis was put into discussions on inter-comparison and contents of reports.
- There was one additional meeting for the development of the simulation tools.
- The subtask leader visited several of the groups in order to gain a better understanding of their work.
- The members of the Subtask have had the opportunity of visiting most of the labs used in the studies during the course of the Task meetings.

What was efficient was the open exchange of information between groups. The presentations have led to productive formal and informal discussions. The people involved in the Subtask have a large number of years of experience and have been able to give constructive criticism and advice to one another. The quality of the work has been high. The fact that the whole Task has had a common goal and framework for simulations and inter-comparison has been appreciated by all. The discussions have been more focussed and it has been easier to put one’s own work into perspective.

Short term has been the focus of most of the work in Subtask C. Most of Subatsk B were dealing with seasonal storage, which fits nicely in the strategy of the Subtask C project using supercooling of phase change materials and added another dimension to the inter-comparison of possible technologies.

The Subtask has resulted in a deeper direct collaboration or interchange of staff or resources between the participants. There was e.g. a three month visit of a member of the Lleida group in Graz and a separate meeting on simulation modules. Not that much effort has been possible to devote within the individual projects for the inter-comparison work due to the fact that they have been funded nationally. Also a member of Lleida visited HEIG-VD, and a member of HEIG-VD visited Lleida for 1 week. Finally, three members of Lleida assisted a course on water store at DTU for 1 week.

The nature of IEA-SHC is such that this picture is likely to be repeated, with the majority of the benefit being interchange of information between mostly independent projects with the possibility of inter-comparison based on common boundary conditions. However, the depth of these inter-comparisons is dependent on the individual funding of each project. It is suggested that common funding is applied for that will finance the central aspects of future Tasks, such as definition of boundary conditions, the exchange of experts between parts of a Task and the inter-comparison work.

It should also finance the work required of a number of participants to produce the Task specific results from their ongoing individual projects.

EC funded projects could provide a partial basis for the common funding of parts of a Task, but this contribution would probably be restricted to participants from EU countries. National counter-financing for non-EU countries is then a prerequisite to a balanced funding model. This touches the core of the present IEA model for Implementing Agreements. This model should be revisited on a higher level, taking account of the increasing importance of international collaboration in energy R&D and the decreasing future number of scientists available.

5 References

Subtask reports (available on: www.iea-shc.org**)**

1. Report A2 "The Reference Heating System, the Template Solar System"
2. Report C3 "Laboratory Prototypes of PCM Storage Units"
3. Report C4 "Laboratory Prototypes of PCM Storage Units (Improvements since Report C3)"
4. Report C5 "Simulation Models of PCM Storage Units"
5. Report C6 "Simulation Report of PCM Storage Units" and 4 companion reports (C6.1, C6.2, C6.3, C6.4)

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Other reports

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Articles in Conferences related to Subtask C developments

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6 Heinz, A., Streicher, W., (2005), *Experimental testing of a storage tank filled with microencapsulated PCM slurries, Phase Change Material and Slurry*: Scientific Conference and Business Forum, 15.-17. Juni 2005, Yverdon les Bains, Schweiz, S. 67 – 76

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8 Heinz, A., Streicher, W., (2006) *Neue Entwicklungen bei Wärmespeichern unter Ausnützung der Phase Change Materials – PCM*, Conference Innovative Solar-Speichertechnologien, Wirtschaftskammer Wien, 17.3.2006, Seite 8/1 – 8/10.

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14 Ibáñez, M., Cabeza, L.F., Solé, C., Roca, J., Nogués, M., (2006), *Modelization of a water tank including a PCM module*. Applied Thermal Engineering, 26, 1328-1333.

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