Optimisation and Cost Analysis of a Lithium Bromide Absorption Solar Cooling System

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SUMMARY

This paper presents the optimisation of the various components of a lithium bromide (LiBr) absorption solar cooling system such as the type, slope and area of solar collector and storage tank size. The collector types considered are the flat plate, compound parabolic and evacuated tube collectors. The optimisation is based on an energy benefit analysis, i.e., the amount of useful energy collected against the life cycle cost of the solar system. The above analysis considers the current prices for fuel and equipment costs, which have increased greatly during the last 5 years. A solar absorption system consisting of a lithium bromide-water unit, a solar collector and a storage tank is modelled with the TRNSYS computer program using a typical meteorological year (TMY) for a hot climate (Nicosia, Cyprus). For this analysis a typical house is modelled for a full year. The solar system can be used during summer to provide part of the heat required by the absorption unit and during winter to provide part of the heating load. The results indicate that due to the present high cost of fuel a large part of the building load can be covered with solar energy.

INTRODUCTION

Solar energy is in abundance in Cyprus. In summer, mean monthly temperatures for Nicosia at 14.00 hours in July, are 35.4°C with the temperature sometimes reaching 43°C. Therefore, there is a need to lower the indoor temperature considerably in order to be able to provide comfort. Solar cooling of buildings seems to be one of the most attractive solutions. This is an application in which the demand for cooling energy closely matches the availability of solar energy, not only to the seasonal but also to the daily variation.

Many researchers have developed solar assisted absorption refrigeration systems. Most of them have been produced as experimental units and computer codes were written to simulate the systems. Relevant studies are shown in [1-4].

The objective of this paper is to model a complete system, consisting of a number of solar collectors, storage tank, a boiler and a LiBr-water absorption refrigerator, which will cover a typical house load during the whole year. Conclusions are drawn by comparing the economics of the system between the years 2001 and 2007 when there was a dramatic change in the fuel price.

For this analysis the typical house indicated in Fig. 1 is considered. The house thermal load is minimised by considering an insulated roof, insulated walls, double glazed windows, internal shading and night ventilation (3 ach) in summer. The above factors were studied and found to be economically viable [5]. The double-walls are made of 0.10 m hollow brick and 0.02m plaster on each side and a layer of 0.05 m insulation in between. The roof is constructed from fair-faced 0.15 m heavy concrete, 0.05 m polystyrene insulation, 0.07 m screed and 0.004 m asphalt, covered with aluminum paint of 0.55 solar absorptivity. The above construction requires an annual cooling load at 25°C of 17,600 kWh with a peak load of 10.3 kW and an annual heating load at 21°C of 3,530 kWh with a peak load of 5.5 kW.

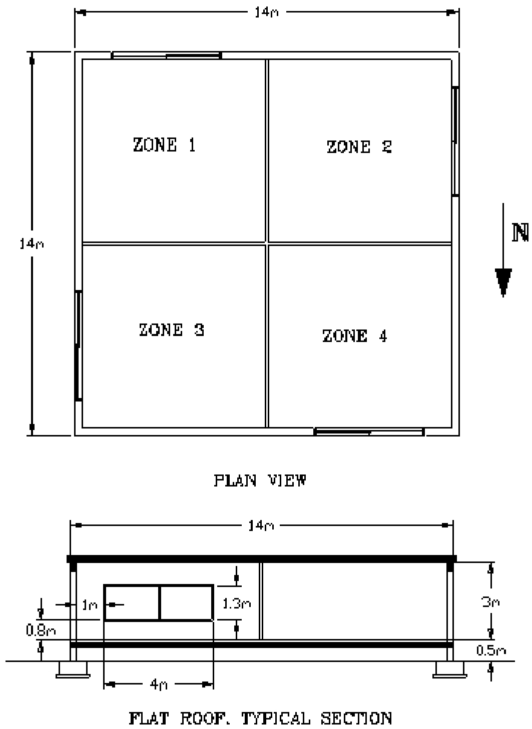

Fig. 1 Model house

The TRNSYS program is used to model the complete system (house load estimation with solar powered heating and absorption cooling), together with the weather values of a typical meteorological year (TMY) file for Nicosia, Cyprus.

The solar powered system consists of an array of solar collectors, boiler, storage tank, 11 kW absorption cooling unit, pumps and thermostats.

Using this approach a system optimisation is performed in order to select the right equipment, i.e., the collector type, the storage tank volume and the collector slope angle and area. The collector area is decided by performing an economic analysis of the system. Also the long-term integrated system performance and the dynamic system behaviour is evaluated and an economic comparison is made between the years 2001 and 2007.

CHARACTERISTICS OF AN 11 KW WATER-LIBR ABSORPTION CHILLER

The characteristics needed in TRNSYS deck file are the generator load, the mass flow of the heating water to the generator heat exchanger and its input and output temperatures. Referring to previous work [6] the calculated 11 kW unit characteristics are as shown in Table 1. Also other parameters needed for the TRNSYS input file were calculated based on this previous work.

Table 1 Water-LiBr absorption refrigeration system calculations based on a generator temperature of 75°C and a solution heat exchanger exit temperature of 55°C

Point	H (kJ/kg)	$\dot{m}$ (Kg/s)	P (kPa)	T (°C)	%LiBr (X)	Remarks
1	83	0.05691	0.93	34.9	**55**	
2	83	0.05691	4.82	34.9	55	
3	124.7	0.05691	4.82	**55**	55	Sub-cooled liquid
4	183.2	0.05217	4.82	**75**	**60**	
5	137.8	0.05217	4.82	51.5	60	
6	137.8	0.05217	0.93	44.5	60	
7	2612	0.00474	4.82	**70**	0	Superheated Steam
8	131.0	0.00474	4.82	31.5	0	Saturated liquid
9	131.0	0.00474	0.93	6	0	
10	2511.8	0.00463	0.93	6	0	Saturated vapour
11	23.45	0.00011	0.93	6	0	Saturated liquid

Description	Symbol	kW
Capacity (evaporator output power)	$\dot{Q}_e$	**11.0**
Absorber heat, rejected to the environment	$\dot{Q}_a$	14.1
Heat input to the generator	$\dot{Q}_g$	14.9
Condenser heat, rejected to the environment	$\dot{Q}_c$	11.8
Coefficient of performance	COP	0.74

THE COMPLETE SYSTEM CHARACTERISTICS

The complete system besides the absorption refrigerator consists of a number of solar collectors, a thermally insulated vertical storage tank, a conventional boiler and interconnecting piping. A schematic of the system showing also the simulation program information flow is shown in Fig. 2.

The system was modelled with the TRNSYS simulation program. The program consists of many subroutines that model subsystem components. The type number of every TRNSYS subroutine used to model each component is also shown in Fig. 2.

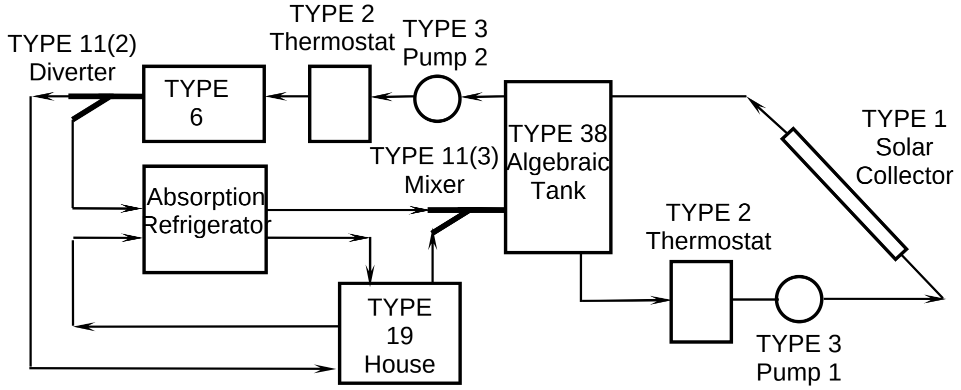

Fig. 2 Circuit diagram and TRNSYS types used for modelling the system.

The construction and type of the solar collectors is important and relevant to the operation and efficiency of the whole system. Three types of solar collectors, modelled with TRNSYS Type 1, are evaluated in this study as follows:

Flat Plate Collectors: These are predominantly used for domestic hot water production. The external casing of the collectors considered in this study, which are manufactured locally, is made of high corrosion resistant galvanised steel sheet, sprayed with aluzinc paint. The casing is covered with a 4 mm thick single glass and sealed with a rubber gasket. The absorber plate is made of copper. High radiation absorption is achieved by the use of black fine matt finish on the copper surface, which has a high absorption coefficient. The underside of the absorber plate and the side casing are well insulated to reduce conduction losses with 50 mm and 30 mm fibreglass insulation respectively. Each flat plate collector consist of 12 evenly spaced parallel copper pipes, 15 mm in diameter, embossed by semi-circular grooves formed in the flat plate absorber.

Conventional flat plate collectors are developed for use in sunny and warm climates. During cold, cloudy and windy days their performance is greatly reduced. Furthermore, condensation and moisture can cause early deterioration of internal materials resulting in reduced performance and system failure.

Compound Parabolic Concentrating Collectors (CPC): These collectors use curved reflecting surfaces to concentrate sunlight onto a small absorber area. CPC's are used for higher water temperature applications than the flat plate collectors. Such a focusing collector performs very well in direct sunlight but, depending on the concentration ratio, does not perform well under cloudy or hazy skies because only a few rays are captured and reflected onto the absorber. A compound parabolic collector system can work either as a stationary system, or it can track the sun. In stationary systems, much of the sunlight that hits the concentrator's reflector often misses the absorber. Tracking devices allow the collector to follow the sun's movement across the sky. This ensures that the concentrator always faces toward the sun. Such systems are usually employed for higher temperature applications. Since residential applications only require medium temperatures, stationary systems are usually employed. Stationary systems are also less expensive and are easier to install and maintain. Concentrating collectors work best in climates with a high amount of direct solar radiation as in Cyprus.

Evacuated Tube Collectors: These collectors are highly efficient, made of an absorber pipe enclosed within a larger glass tube. The absorber pipe may also be attached to a black copper fin that fills the tube (absorber plate). The space between the glass and the absorber is evacuated. Only radiant heat is transmitted from the absorber pipe to the outside of the collector and in this way the efficiency of the collector is substantially increased.

The tubes are usually mounted into a manifold and the heated liquid is either used directly or circulates through a heat exchanger and gives off its heat to water. The coated surface of the absorber pipe has high absorption (> 92 %) of solar radiation and low emittance (< 6 %) for the infrared heat radiation. The absorber coating also has high resistance to long-term vapour condensation and high operating temperature.

The performance of the system employing these three types of collectors is investigated in order to select the most suitable for the present application. The final selection is made by considering the financial viability of the system.

Hot water is stored in a TRNSYS Type 38 tank. The vertical cylinder construction is made of copper and is thermally insulated with polyurethane. Also the tank is protected by a galvanised outer shell 0.6 mm thick.

The backup boiler (TRNSYS Type 6) is assumed to have a maximum heating rate of 18 kW and a set upper temperature of 93°C.

A number of thermostats (TRNSYS Type 2) are also used in order to control:

a. The flow to the solar panels, allowing the fluid to circulate only when the temperature of the fluid returning from the collectors to the storage tank is higher than that of the fluid delivered to the load; and

b. The operation of the boiler, allowing the boiler to operate only when the temperature of the fluid delivered to the load is below an optimum value. In this case the boiler will keep the water temperature delivered to the absorption cooler always above 85°C.

SYSTEM OPTIMISATION AND ENERGY FLOWS

A number of simulations were carried out in order to optimise the various factors affecting the performance of the system. The parameters considered are as follows:

The collector slope angle: The solar heat gain from the system for various collector slope angles was examined. The optimum angle in the Cyprus environment is:

i. 25°-30° for the flat plate collector
ii. 30° for the compound parabolic collector, and
iii. 30° for the evacuated tube solar collector

This is due to the solar altitude angle, which for the latitude of Cyprus (35°) can reach to 78° during noon in June. Also, because of the load characteristics, with the total cooling loads being about 6 times bigger than the heating loads, the optimum angle should be such that the collectors are absorbing greater heat during summer.

Storage tank size: This factor also plays a role in the optimisation of the system. Simulations show that for all three types of collectors, a smaller tank size results in slightly less energy consumption by the boiler and slightly less energy collected by the solar collectors.

The storage tank size is therefore decided only from the length of time intervals between firing the boiler. Between these intervals the tank should be able to supply the system with the needed water mass flow at the correct temperature in the summer. As it results, when the storage tank size is small the temperature in the cylinder cannot be kept above 85°C for long periods of time.

Assuming that the boiler is firing every 12 minutes, which may be a reasonable interval, the optimum storage tank size needed for the system would be:

i. 0.8 m^3 for the flat plate collector
ii. 0.6 m^3 for the compound parabolic collector and
iii. 0.6 m^3 for the evacuated tube solar collector

Finally the effect of the collector area is evaluated against the boiler heat required. As it is expected the greater the collector area the less the boiler heat needed as indicated in Fig. 3 and the more the collected heat as indicated in Fig. 4.

To determine the optimum collector area the cost of the solar system must be compared against the fuel saved due to its use. The cost of the various types of collectors is shown in Table 2.

Table 2 Cost of solar collectors

Collector type	2001 Cost (€/ m^2)	2007 Cost (€/ m^2)
Flat plate collector	186	220
Compound parabolic collector	305	370
Evacuated tube collector	425	460

The economic method used, is the life cycle analysis [7]. For solar systems the following equation can be used:

System annual cost = Extra mortgage payment + Maintenance cost – Extra fuel savings

– Extra electricity savings – Extra tax savings (1)

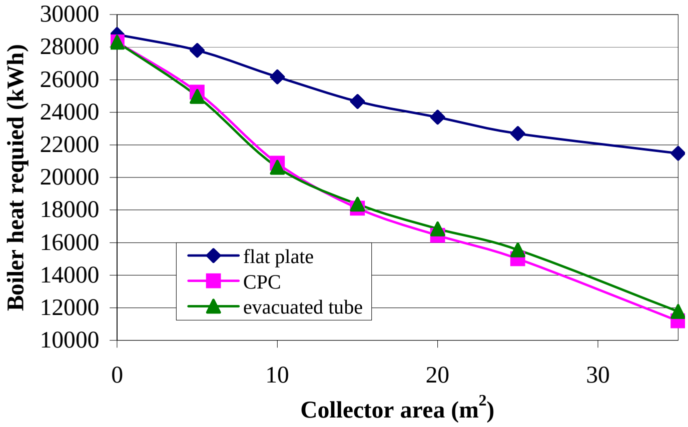

Fig. 3 Effect of the collector area on the boiler heat required by the system

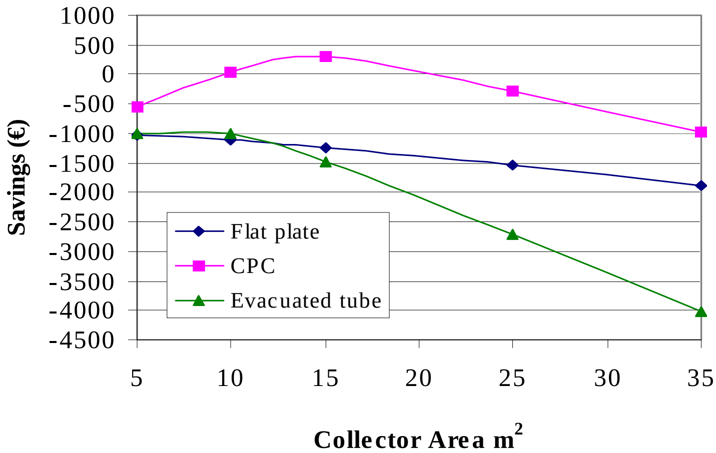

Fig. 4 Effect of the collector area on the collector heat gain

The scenario considered is that 30% of the initial cost of the system is paid at the beginning and the rest is paid in equal instalments in the next 10 years. The evaluation is based on the price of the diesel in 2001, which was € 0.29 per lt and the current price which is € 0.73 per lt.

The results of the economic analysis are presented in Fig. 5. As it is observed the only economically viable solution in 2001 was to use the CPC with a collector area of 15 m^2. The flat plate collector and the evacuated tube collector were not suitable for this application then due to the low price of fuel.

Now, in 2007, the situation has changed and CPC and evacuated tube collectors can be used economically as indicated in Fig. 6.

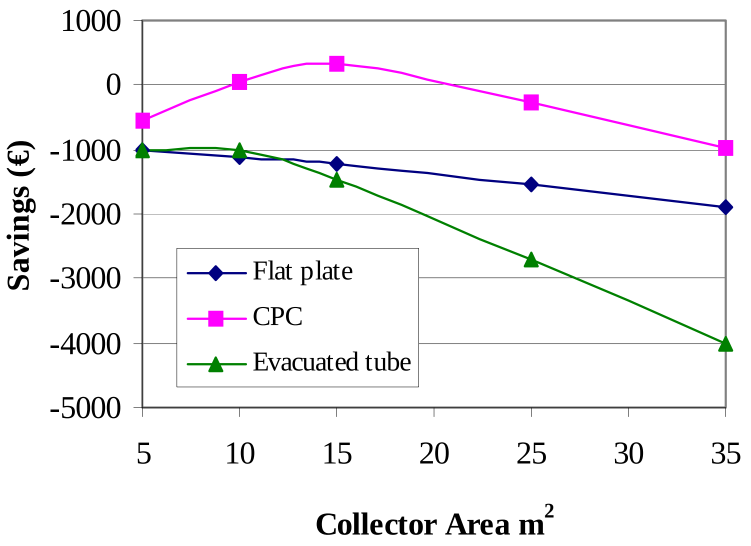

Fig. 5 Collector area against life cycle savings in € for a fuel price of €0.29 per lt and a 20 year period.

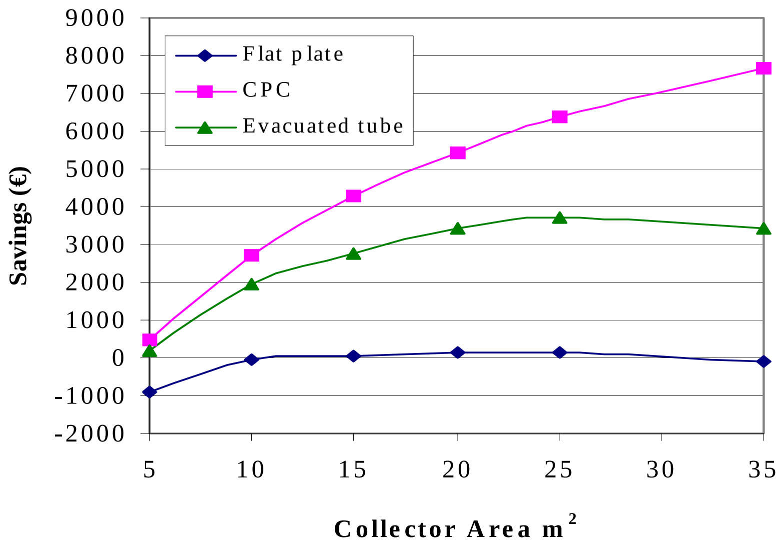

Fig. 6 Collector area against life cycle savings in € for a fuel price of €0.73 per lt and a 20-year period.

SYSTEM LONG-TERM PERFORMANCE AND ECONOMIC ANALYSIS

The specifications of the final system obtained from the optimisation study are shown in Table 3.

The energy flows of the system are shown in Figs. 7 and 8 for the years 2001 and 2007 respectively. The cooling load of the building reaches a maximum monthly value of 4200 kWh (in July), whereas the maximum monthly heating load occurs during January and is equal to 1250 kWh. The heat required from the conventional boiler is also shown in the above figures. The maximum monthly load supplied by the solar system is 1500 kWh and as can be seen from the difference of the curves for the cooling load and boiler heat, nearly all collector heat can be utilised for cooling or heating purposes.

Table 3 The final optimum system in 2001 and 2007

Item	Year 2001	Year 2007
Collector type	CPC	CPC
Collector area	15 m^2	35 m^2
Collector slope	30°	30°
Storage tank size	600 lt	600 lt

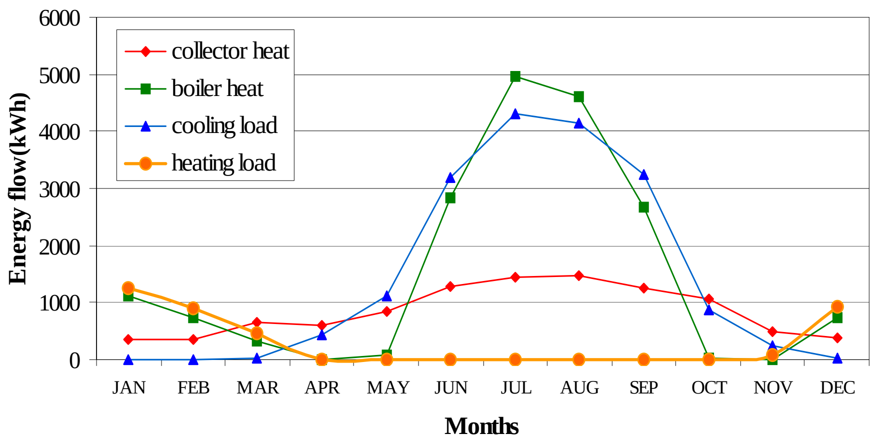

Fig. 7 System energy flows for 2001

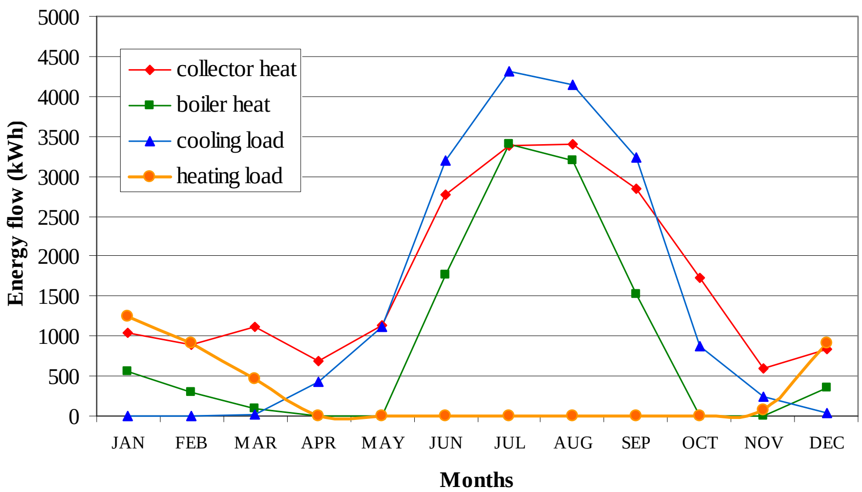

Fig. 8 System energy flows for 2007

The annual cooling load of 17,600 kWh is covered with a total supply of 15,220 kWh of boiler heat, supplemented by 8500 kWh of solar heat, offered by the solar system. The annual heating load of 3530 kWh is covered with a total supply of 2880 kWh of boiler heat and 1500 kWh of solar heat.

In 2001, the total life cycle cost of a complete system comprising the collector and the absorption unit, for a 20-year period was €22,700 with an estimated price for the absorption unit together with its accessories equal to € 8,140. In order to have the same total life cycle cost the price of the absorption unit together with its accessories should not be higher than € 3,400. This could be possible only when absorption units were mass-produced.

Today (in 2007) the final optimum system, as obtained from the complete system simulations, consists of 35 m^2 compound parabolic collectors. The only limitation is the available area on the house roof, which cannot be completely blocked. The price of diesel in 2007, which is € 0.73 per lt indicates that it is economical to replace about 20,000 kWh with solar energy collected with 35 m^2 of CPC and the life cycle savings of such a system are € 7,700. The total life cycle cost of a complete system comprising the collector and the absorption unit, for a 20-year period is € 38,200.

CONCLUSIONS

The final optimum system for 2007 as obtained from the complete system simulations, consisted of 35 m^2 compound parabolic collector tilted at 30° from horizontal and 600 liters hot water storage tank. The typical insulated house considered, requires an annual cooling load at 25°C of 17,600 kWh with a peak load of 10.3 kW and an annual heating load at 21°C of 3,530 kWh with a peak load of 5.5 kW. This annual load could be met by using about 28,100 kWh of boiler heat. The price of diesel in 2001, which was € 0.29 per lt indicated that it was economical to replace about 10,000 kWh with solar energy collected with 15 m^2 of CPC and the life cycle savings of such a system were € 320. The life cycle savings for the present system and 2007 fuel price (€ 0.73 per lt) give life cycle savings of € 7,700. The increase of the cost of fuel compels consumers to move to other energy forms in order to meet their needs. So gradually renewable energy forms can economically replace part of the fuel energy as the fuel price increases.

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