ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

IJESRT

INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

DESIGN AND CONSTRUCTION OF SOLAR WATER HEATER FOR THE HOTEL, CATERING AND INSTITUTIONAL MANAGEMENT DEPARTMENT OF BOLGATANGA POLYTECHNIC

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DOI: 10.5281/zenodo.1184431

ABSTRACT

Solar water heating system consists of a collector plate to collect solar energy and an insulated storage tank to store hot water which can be used for domestic, industrial and small institutional purposes. This paper presents a systematic design and construction of solar water heater for use in the Hotel, Catering and Institutional Management (H.C.I.M) Department of the Bolgatanga Polytechnic in the Upper East Region of Ghana. The solar water heater was well constructed using locally available materials. A plain glass was used as a collector plate and an aluminium sheet metal obtained from a scrap yard painted black was used as an absorber plate. In addition, copper pipes attached to the absorber plate as fluid carrying tubes were also designed. The solar energy incident on the coated absorber plate transfers the heat to the fluid carrying pipes underneath the absorber plate placed in an insulated casing with a transparent glass cover having a cold and a hot water tank integrated in the system. The water passing through the pipes gets heated and flows into a storage tank by the principle of thermosyphon system. When tested, a maximum fluid output temperature of 80ºC was observed at a maximum collector temperature of 55ºC with ambient temperature of 37°C, and solar radiation 4.61 kWh/m^2/day on a good sunny day. A total amount of 50 litres of hot water was harnessed which was in excess of hot water needed in the Department. This solar water heating system which is a renewable energy resource will continue to serve the heating needs of the Department and the Polytechnic at large since the area has abundant and consistent solar radiation.

KEYWORDS: Design and construction; solar water heaters; solar energy, collector plate, natural circulation.

I. INTRODUCTION

Renewable energy is one of the energy resources whose replenishment rate is shorter than the rate at which it is used. The sun which is a good example of renewable energy resource is produced by means of nuclear fusion from hydrogen into helium, whose rate of depletion is about 4.8 x 106 tons per second [1]. It is estimated that only a small amount of the sun's energy reaching the earth is good enough to meet the earth's energy requirement since the earth's population for now will need about 16 terawatts of energy whereas the total amount of solar radiation that reaches the earth on daily basis amount to 122,000 terawatts [2]. Ever since the world experienced oil crisis about 36 years ago, there has been a new way of energy thinking that has led to the development of alternative energy that is renewable and environmentally friendly. Also, issues with the use of hydrocarbon as a source of heat energy which includes air pollution, health hazards and the depletion of oil reserves as well as global climate change and oil demand have led to the use of alternative energy resources that will help to overcome these effects. Currently, renewable energy resources such as solar is being used for various applications which include power generation, space heating as well as water heating system for domestic and industrial use [3]. The sun's energy is transmitted by means of electromagnetic radiation from the sun to the earth but will have to be changed into heat energy by means of a device before it can be used for heating. Solar water heating (SWH) process involves the use of the sun's energy to heat water using thermal collector. It involves various technologies that are used in the whole wide world [4]. The solar water heating systems are used to produce hot water for most periods of the year but in the raining season where there may not be enough sunshine to produce the desired heat for hot water, a gas or electric booster is incorporated to heat up the water [5]. Solar water heaters which are suitable for hot climate are simpler and cheaper to design and are considered a suitable technology for these places. Heating of water makes use of a greater part of the energy in many residential and commercial homes as it is estimated that about

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

18% of energy is used in heating water in residential homes and 4% in commercial buildings. Using solar energy to heat water instead of electricity or gas can meet up to 75% of the hot water needed at homes without any environmental pollution[6, 7]. Solar water heaters for residential and small institutional purposes can be grouped into two types namely passive which sometimes refers to as "compact" and active which also refers to as "pumped" system [8]. These two types of heaters can include an auxiliary energy source such as electric heating element or gas which is brought into use when the water temperature in the tank falls below a minimum temperature level, which ensures that there is always hot water available all year round. Also, the use of wood-stove chimney as a backup heat for solar water heating system can also enable hot water system to operate throughout the year including cooler regions without the use of electricity [1, 9]. Solar water heaters are also classified as thermosyphon Systems and integrated collector storage (ICS) [10, 11]. The thermosyphon system operates on the principle of natural convection which is caused by variation in water density and hence does not use a pump. The heated water expands, which leads to decrease in density. When it cools down, its volume decreases and hence density increases. These changes in density set up convection currents which allow circulation of water to take place. These systems are very efficient especially in areas which have a high level of solar radiation such as in the Northern, Upper East and West Regions of Ghana [4, 12]. Integrated Collector Storage (ICS) also referred to as the batch beater system has a tank which acts as a solar collector and at the same time as a storage tank. These types of heaters are normally made from a thin tank with the side containing the glass facing the sun during the day. Batch heaters are very simple and less expensive to produce but they sometimes need extra reinforcement if they are installed on top of a building because they are very heavy when filled with water. The integrated collector storage has the disadvantage that there is a lot of heat loss at night because the side facing the sun is not insulated. This type of heater is suitable for moderate climates[13]. Solar energy is diffused before it reaches the earth, the device that is used to convert it into heat energy which is the solar collector ought to be large. The solar collector usually is a plain glass that is able to absorb solar radiation efficiently and then convert this absorbed radiation into heat energy which raises the temperature of the absorbing fluid. There are basically three types of collectors flat-plate, evacuated and concentrating [14]. The simplest form and the most commonly used type is the flat plate solar collector, which normally works with a fluid to fluid heat exchanger and has a very high heat transfer rate [4]. The thermodynamic process that involves energy transfer is the process that is used for solar water heating to raise the temperature of water [7, 15]. The uses of hot water for domestic activities include washing, bathing, cleaning and cooking in addition to many other uses of hot water for industrial applications .The total amount of heat energy that a solar water heater can deliver depends on the amount of solar radiation produced by the sun in a given day. In areas around the equator the amount of heat energy delivered by the sun is relatively high, about 7 kWh/m^2/day[4]. Also the average amount of solar radiation can vary from location to location even in the same latitude due to difference in weather patterns. In order to estimate the amount of solar radiation at a given site, a useful instrument with the Joint Research Laboratory of the European Commission and the American National Renewable Energy Laboratory is what was used. Table 1 below indicates an amount of heat energy to be expected from a 2m^2 absorber area with two evacuated tubes and three flat plate solar collectors from a domestic solar water heating system. The two rows at the bottom of the Table 1 give the daily energy production in kWh/day for both temperate and tropical regions and are for heating water to a temperature of 85^{o}C. The heat energy output for most solar water heating systems are linear with the surface area of the absorber plate and therefore it is important to note that a collector with less absorber area will result in lesser heat output[16].

Table 1 Energy production (kWh) on daily bases of five types of solar collectors

Technology	Flat plate	Flat plate	Flat plate	Evac. tube	Evac. tube
Configuration	Direct active	Thermosyphon	Indirect active	Indirect active	Direct active
Overall size(m^2)	2.47	1.88	1.92	2.85	2.97
Absorber size(m^2)	2.23	2.21	1.82	2.85	2.96
Max. Efficiency	0.66	0.76	0.64	0.57	0.46
Energy Prod.(kW.h/day)	5.5	4.1	3.5	4.8	4.0
Radiation 6.5 kWh/day (tropical)	11.4	7.8	7.4	9.9	8.4

Source: Energysavingtrust [16]

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Many researchers continue to work on solar water heater but the performance efficiency and universal standard solar heater system remain unanswered [13, 17-19]. Because of these problems, Dehariya and Jaurker (2013) [20] did some comprehensive reviews on the current status for various solar water heater related studies and indicates the need for future research to improve on the current solar water heater system. Also in Ghana, Asamoah et al. (2012) [21] designed a solar water heater for a bungalow with five occupants using plain glass and plastic container from U.K and installed it at the KNUST campus. Their design couldn't produce the required water temperature of 50°C and also fell short of the quantity of hot water needed for occupants of the bungalow even though they recorded main collector temperature of 40°C. In addition, Aziafor Jonas (2009) [22], design a batch water heating system at the KNUST campus and they couldn't obtain a hot water temperature of 40°C even though they used plastic container which was an imported product. In view to improve on these designs and reduce the exorbitant gas and electricity bills incurred in the HCIM Department for heating water, it was intended to design and construct a solar water heater for the HCIM Department of Bolgatanga Polytechnic in the Upper East Region which has the same climatic condition as in China, Europe, Japan and India by using appropriate technology and locally produced materials to produce 50 liters of hot water at a temperature of 75°C as a viable project.

II. MATERIALS AND METHODS

The project started with an overview of various types of solar water heating systems and a simple feasibility study to gather information on the amount of solar radiation energy that is available in the Upper East Region using RET Screen. It was also to observe the total area or space that will be used for the installation and to access the economic viability of the entire project. A design procedure for the solar water heating systems was prepared and updated in the course of the design of the solar water heating system for the Hotel Catering and Institutional Management Department of Bolgatanga Polytechnic in the Upper East Region of Ghana until the correct method was achieved. Collector and absorber areas of 1m^2 and 1.25 m^2 with a ground space of 2 m^2 were assessed. A south facing collector at an angle of 15° was selected because a tilt at that angle will receive a great amount of solar radiation in Ghana due to Ghana's location in the northern hemisphere [23]. Also, solar water heater components were assessed with information from various manufacturers of which the one with the most cost-effective was selected. Table 2 below shows some design parameters used in the design of the water heating system.

Table 2 Summary of basic design parameters used for the design of the solar water heating System

Average horizontal irradiation (daily basis)	**5.51 kWh /m2 /day**
Collector Area	1m^2
Collector orientation	South facing
Absorber size	1.45 m x 0.86 m
Angle of inclination of collector	15 °C

Weather data are collated by gathering quantitative data about the current state of the atmosphere in a given location and then using scientific understanding of atmospheric processes to project how the atmosphere will change [24]. A daily solar radiation on a horizontal surface in Bolgatanga from RET Screen is as shown in Table 3.

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Table 3 Daily solar radiation on horizontal surface. Source: [25]

MONTH	DAILY SOLAR RADIATION ($kWh/m^2/day$)
January	5.72
February	5.96
March	6.11
April	6.06
May	5.82
June	5.32
July	4.88
August	4.61
September	4.95
October	5.58
November	5.56
December	5.59
Average	5.51

The best amount of radiation on a horizontal surface in Bolgatanga according to RET Screen is 6.11KWh /m^2/day, for the month of March as shown in Table 3 above. From the Table, the average solar radiation on the horizontal surface is 5.51kWh/m^2/day, therefore for a collector sizing, and the determination of the peak sun hours, this average value was used. It has been observed that the more the peak sun hours (PSH) available, the more the heat is produced by the solar collector. An estimated period of 10 hours of peak sun hours per day was used (from 7 am to 5 pm).

III. DESIGN CALCULATIONS AND PARAMETERS

The amount of energy (E) produced by the sun during this peak sun hours was determined by the formula;

$$E = \text{Solar radiation} \times \text{Collector Area} \times \text{P.S.H} / 24 \quad (1)$$

The amount of energy needed for the solar heater is equal to the amount of hot water in demand. The solar heating system heats up the cold water (from the water company, from 20°C to 75°C),

The analysis of the design is based on the following calculations and formulas.

The amount of heat (Q), required to raise the temperature of a given substance is given as;

$$Q = M \times C \times \Delta T \quad (2)$$

where Q is the amount of heat energy needed (J), C is the heat capacity (J/kgk), M is the mass (kg), and ΔT is the temperature difference (K).

Sizing of collector Area (A_c) is very essential in achieving efficient performance of the solar heater water. The area of a collector (A_c) is defined as the ratio of the amount of heat energy Q_w needed to raise water temperature from its initial temperature (T_{in}) to its final temperature (T_{out}) to the amount of heat energy absorbed by the solar collector over a given time period .

$$\text{Collector Area } A_c = \frac{Qw}{\eta I} = \frac{Mw\ Cw\ \Delta T}{\eta\ I} \quad (3)$$

where

Q_w = Useful energy absorbed by the water

η = collector efficiency,

I = Solar insolation

Therefore:

$$Q_w = M_w C_w(T_{out} - T_{in}) = \rho v\, C_w(T_{out} - T_{in})$$

Quantity of water on the Absorber plate is given by

$$V = \frac{\pi d^2}{4} h \quad (4)$$

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where V is the volume of water obtained after 56 seconds, d is the diameter of pipe and h is the circulating pipe length on the absorber plate.

The desired volume of water to be obtained from the system is 50 litres, therefore useful energy absorbed by the water for 56 seconds

$=\frac{Q_W}{t}=\frac{\rho V\, C_W}{56}$x $(T_{out} - T_{in})$ (5)

$$= \frac{1000\text{kg/m}^3 \text{ x } 0.05 \text{ m}^3 \text{ x } 4200 \text{ Jkg}^{-1}\text{oC}^{-1} \text{ x } (87 - 35)}{56}$$

$= 1.950$ kJ

I =Solar insolation $= 4.61$ kWh /m^2,

Average efficiency for flat-plate collector (η) = 40%.

Area of collector $(A_c) = \frac{Qw}{I\,\eta} = \frac{1.950}{4.61 \ x\, 0.4} = 1.06$ m^2

The proper sizing of the piping system is needed for proper rate of heat transfer for the design to be obtained. Ogie et al (2013) used these relations for pipe sizing [1].

Figure 1 Pipe Spacing

From Fig. 1, above $x = L/7$ where x is the spacing between pipes. Width of 2.5 m was chosen, therefore, $W_c = 2.5\ m$ and pipe spacing is 0.10 m. Then the number of equal "center to center" pipes (N_s) is given as;

$N_s = \frac{W_c}{0.10} = 25$ (6)

Therefore, twenty-five parallel pipes with equal center spacing were used.

The total number of pipes used for the construction is 25 which include two headers and twenty-three risers of diameter 12.7 mm.

The pipe has a circulating length of 750 mm, whiles the distance between the pipe and the cold water tank is 57mm. Overall length of pipe is 1040 mm,

The cold water storage tank is a plastic bucket with a capacity of 50 litres and a height of 500mm.

Since 1000 litres = 1 m^3

50 litres =50× 10^{-3}m^3= 0.05m^3, = 0.05 x 10^6 mm

Volume (V) = Area (A) × Height (H).

But A= $\frac{\pi d^2}{4}$, where d is the diameter of the tank

V= $\frac{\pi d^2}{4}\ x$ H where H is the height of the tank and is 500mm

d = $\sqrt{\frac{4\,V}{H\,\pi}} = \sqrt{\frac{4\ x\ 0.05\ x\ 10^9}{500\ x\ 3.142}} =$ 356.8 mm = 0.3568 m

Diameter of the cold water tank (d) is 0.357m.

Also the pressure (P_c) inside the cold water storage tank when full is given by

$$P_c = \rho_w g H_c \quad (7)$$

Where P_C is the pressure at the outlet of the cold water storage tank

g is the acceleration due to gravity (m/s^2)

ρ_w is density of cold water (kg/m^3)

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H_c = height of coldwater tank

P_c= 1,000× 9.81 × 0.5 = 4905 N/m^2

It means that as the height of the cold tank increases, the pressure also increases. This increase in pressure inside the tank leads to an increase in the rate of flow of water in the collector and this leads to an improved efficiency. The transfer of the entrapped heat in the collector to the water inside the pipe will move faster, thereby minimizing convection and other losses from the collector.

Mass flow rate (m_f)-The rate of flow of water within the collector plate area is given by

$$m_f = \frac{Mass}{Time} \quad (8)$$

and was determined to have a value of 0.54 kg / s.

In all, a total time of 56 sec was used to drain 50 litres of water within the collector at a temperature of 87^{o}C.

Heat transfer through the collector plate (q): The combined heat transfer through the collector plate is given by;

$$q = \frac{T_i - T_e}{\frac{1}{hA} + \frac{\Delta x}{kA}} \quad (9)$$

where q is the amount of heat transfer in W/m^2, k is the material's conductivity in W/(mK), h is the heat transfer coefficient in W/(m^{2}K), $T_i - T_e$ is the temperature difference between the internal and external surfaces, A is the area of the plate in m^2, and Δx is the thickness of the plate in (m).

Conduction heat transfer through the absorber plate

From Fourier's law

$$q = \frac{kA(T_e - T_i)}{\Delta x} \quad (10)$$

where the symbols have their usual meaning

IV. CONSTRUCTION

The collector plate-A transparent cover or the solar collector is needed to help provide the "greenhouse" effect necessary to heat up the water. Glass was used as the collector plate because of its high transmittance to visible light and low transmittance to infrared radiation. It also has the ability to reduce heat loss by convection at the top of the plate. With the designed area of 1.06 m^2, the minimum dimensions of the flat-plate collector are 1.25 m x 0.85 m x 0.05 m for the transparent glass cover and this was acquired from the Sawaba scrap depot in Bolgatanga and used for the construction. The main disadvantage of this class cover is its low resistance to shatter. The collector housing is made of wood, and the glass front cover is sealed to reduce heat loss and also to prevent dirt, insects or humidity from getting into the collector itself. The collector houses the absorber plate and it takes the solar radiation and converts it into heat. The collector housing is highly insulated at the back and sides, to reduce the amount of heat loss within the collector housing.

The absorber plate-The absorber is made of aluminum because it is relatively cheap, has adequate mechanical properties, has good means of attachment to the fluid flowing pipes and other materials, and has good thermal conductivity and good resistance to corrosion. It is also painted black as shown in Fig 2 since black materials absorb heat very well and are able to retain the heat for a very long time.

Figure 2 The constructed Absorber plate

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Collector and Absorber insulation-Insulation is done to reduce the amount of heat loss in the collector plate and the hot water tank so as to increase the efficiency of the solar water heater. The insulation is done to reduce heat loss by conduction and convection, from the bottom and sides of the collector housing unit. Insulation materials such as sawdust and Styrofoam were used because they have very low thermal conductivity, are relatively cheap and readily available.

Pipe system (including risers and headers): Plastic pipes such as P.V.C were used for the piping system because of its rigidity and it's resistant to corrosion; this is very important because it can hold the water and keep it clean to be used domestically. Fig. 3 shows the attachment of pipe tubes to the absorber plate.

Figure 3 Attached fluid pipe onto the absorber plate

In constructing and assembling the solar water heater, the system was divided into the following components: cold water storage tank, absorber plate, collector plate, insulation materials, fluid passage pipes and hot water outlet tap as shown in Fig 4. In order to produce the needed hot water, using solar energy, the collector was mounted on the ground in an inclined position across the path of the sun and was made to face south in order to receive maximum energy from the sun. The working fluid is water which is made to flow through the fluid tubes by natural convection which is also known as passive system. The collector used for the construction is glass-topped with a flat metal sheet which is painted black as an absorber and the whole assembly is attached to the tubes as shown in Fig 4. As the sun hits the collector surface the heat energy is transferred into the tube by means of the absorber plate and as the water heats up the lighter portion rises and the colder and the heavier one moves in to take their place by natural convection.

Figure 4 The prototype of solar water heater for the HCIM Department of Bolgatanga Polytechnic

V. DISCUSSION OF TEST RESULTS

The cold water tank was filled with water after proper filtration. The valve was opened to allow the water to flow into the circulating pipes, which consist of riser and header pipes, through the inlet pipe. The water was heated by the heat supplied by the absorber plate to the tubes underneath the absorber plate, by means of the density

ISSN: 2277-9655
Impact Factor: 5.164
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difference between the cold water and hot water. A flow is initiated by means of natural convection. The hot water moves up to the top of the circulation pipes which have a valve to allow for tapping when needed for use. Table 4 and Figure 5 give the test results of the system on a normal sunny day, 25th March, 2015.

Table 4 Temperature results on solar water heating system at the Bolgatanga on 25th March, 2015

Time (h)	Ambient temp(°C)	Inlet water Temp (°C)	Outlet water Temp. (°C)	Absorber Temp. (°C)
7 : 00	33	35	40	44
8 : 00	35	36	42	46
9 : 00	35	36	44	48
10 : 00	35	36	70	77
11 : 00	37	40	78	86
12 : 00	37	43	82	90
13 : 00	39	44	88	97
14 : 00	40	45	90	99
15 : 00	36	43	86	95
16 : 00	36	43	75	83
17 : 00	35	40	65	72

From Table 4, ambient temperature varied between 33°C and 40°C. Maximum water output temperature and the absorber temperature were obtained between 11 am and 3:00 pm using laboratory thermometer. This instrument was used because it can record very high temperatures. It can also be seen from the graph that the temperature increases from a low value of 35°C at 7: 00 am, got to a peak around 2: 00 pm and then fell back to a low value of 35°C again.

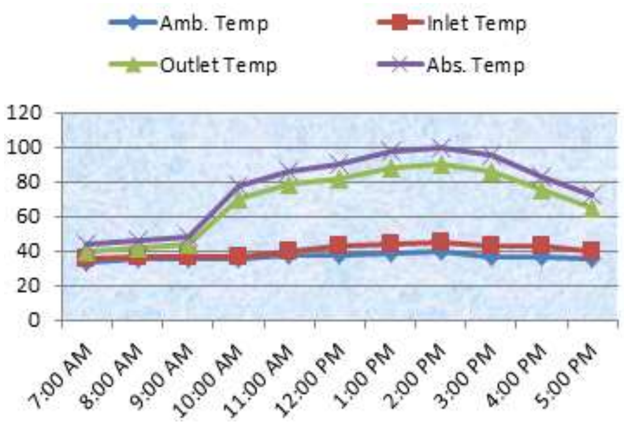

Figure 5 System temperature variation for 25th March, 2015 (Normal sunny day on the Bolgatanga Polytechnic Campus)

VI. CONCLUSION

A solar water heater has been designed and constructed for the Hotel Catering and Institutional Management (H.C.I.M) Department of the Bolgatanga Polytechnic in the Bolgatanga Municipality of Upper East Region of Ghana. A collector and absorber areas of 1 m^2 and 1.25 m^2 was used to produce 50 litres of hot water at a temperature of 78°C. An inlet water temperature of 35 degrees Celsius was able to get to 80 degrees Celsius within seven hours in a day signifying that the period of sunshine in the area is good for the design of solar water heaters. Daily solar radiation of 4.61 KWh/m^2/day for the month of August being the least throughout the year was used as a reference for the collector sizing. The test results of the design show that the design was well constructed and works satisfactorily and will satisfy the heating needs of the people in the Department. It is also affordable since most of the materials used are relatively cheap and can be obtained in the local market. The design also ascertained the right amount of solar radiation in the Bolgatanga Polytechnic campus that would be enough to heat up 50 litres of water to a temperature of 75 degree Celsius. The design also selected the correct type and size of solar collector that produced the required hot water. Test results also showed that 50 litres of hot water at a temperature of 87°C was obtained measurements were conducted on the system. The outcome and performance of the design also showed that these technologies have enormous potential and with the vast variety of solar technologies present in the market these days, it is, therefore, possible to design a large water heater that can operate on solar energy to help minimize cost of using electricity in the whole institution. In addition to saving in energy, this design is environmentally friendly and cost-effective since it reduces the emission of carbon gases when compared with other methods of heating such as electricity, wood and gas and therefore its use should be encouraged.

VII. RECOMMENDATIONS

In order to improve the operational performance of the solar water heater, the following recommendations should be considered.

- A better and very good insulation material should be used as there was heat loss from the material used.
- Since there are almost 30% energy losses to surrounding, the system needs better insulation performance. The price of insulation materials is relatively inexpensive, therefore doubling the thickness of insulation material is recommended.
- As a matter of our economic situation, the government of Ghana and cooperate organizations should partner in order to install this type of heater in the Polytechnics and Technical Universities across the country as well as in our hospitals especially the maternity wards where a lot of hot water is used to help reduce the cost of heating water.
- In August, which is mostly the raining season in Bolgatanga, there is almost no direct solar radiation most times of the day, and the heater cannot heat up to the expected temperature, there is, therefore, the need to supplement the heater with other forms of energy during this period.

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