ASSESSING THE ENVIRONMENTAL IMPACTS OF USING SOLAR AIR HEATERS

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Abstract

Solar air heaters (SAH) are becoming increasingly popular in the food industry, agriculture, and especially in the building sector. The paper presents results of the assessment of the environmental effects resulting from the application of these devices for preheating ventilation air. In the first step it was determined energy efficiency of typical solar air heater based on results of experiments performed under the operating conditions. In the next step the potential annual energy savings for typical houses and potential reduction of the greenhouse gases (GHG) emissions were calculated.

Key words: *solar air heaters, ventilation air preheating, greenhouse gases, energy saving*

1. INTRODUCTION

Solar air heaters (SAH) are becoming more and more popular in many areas such as food industry, agriculture, and especially in the residential buildings sector. A general review of the construction of solar energy conversion devices were presented in (Saxena, Varun & El-Sebaii 2015) and (Zukowski 2013).

The authors characterized both the advantages and disadvantages of glazed, and unglazed, parallel-pass, and double-pass, and transpired solar air panels. As is generally known the air is not most effective working fluid with a view of optimization of heat exchangers. This negative feature is a direct result of the low value of thermal conductivity and specific heat. That is why, can also be applied various technical solutions in order to improve thermal performance of such devices. One of them is to increase surface of absorber plate.

Different types of rib configurations (discrete V-shaped, broken, transverse, and angled continuous) mounted in rectangular channels were investigated by Tanda (2011). Results of experiments showed that the rib-roughened absorber plates had a much better thermal performance than the reference flat plate.

Similar conclusions were also obtained by Kumar, Saini & Saini (2014) and Kumar (2015). The authors concluded that artificial roughness is the most effective and economic technique for improving the thermal efficiency.

Another thermal performance enhancement technique is use of porous packed bed materials. An extensive review of double air pas solar air heaters with packed bad was developed by Singh & Dhiman (2016).

Environmental impacts of all types of solar panels were presented by Aman et al. (2015). The authors considered this issue taking into account the manufacturing and demolition phases. It was concluded that due to content of toxic materials in their components, solar air and water panels can be environmental threats.

On the other hand solar passive and active systems provide significant environmental benefits during the operation phase.

Negative and positive environmental implications associated with the use of all kinds of solar energy techniques were reported by Tsoutsos, Frantzeskaki & Gekas (2005). The reduction of greenhouse gases (GHG) emissions and prevention of emission of toxic gases were listed by these author as a main environmental advantages.

2. METHOD FOR ESTIMATING THE REDUCTION OF THE GREENHOUSE GASES EMISSIONS

In order to determine the environmental impacts of using solar air heaters, in the first step should be to determine the reduction of energy consumption as a result of the operation of these devices.

2.1. Calculation of the ventilation air flow rate

The quantity of fresh air required for good indoor air quality was specified for a family of five people living in a detached house. The design outdoor air flow rate for ventilation system V_e can be determined based on the following formula:

$$V_e = n_p \cdot V_u, \quad (1)$$

where:

n_p – the number of persons [-],

V_u – minimum fresh air required per person (assuming V_u=0.00833) [m^3/s].

2.2. Energy required to heat the ventilation air

The total energy E_V required to heat incoming air is calculated using Eq. 2.

$$E_V = \sum_{i=1}^{n} (H_V \cdot \Delta t_i), \quad (2)$$

where:

n – number of time periods [-],

H_V – heat loss due to air change inside a building (Eq. 3) [W],

Δt_i – time period (assuming a constant outside air temperature during this time step) [s].

Heat loss by ventilation H_V can be expressed as:

$$H_V = V_e \cdot \rho_a \cdot c_p \cdot (T_i - T_e), \quad (3)$$

where:

ρ_a – air density [kg/m^3],

c_p – heat capacity of air [J/kg/K],

T_i – inside air temperature [^{o}C],

T_e – outside air temperature [^{o}C].

2.3. Reduction of energy consumption in the residential buildings

The use of solar energy for preheating ventilation air can reduce energy demand of the residential buildings. The reduction of energy consumption ΔE_V is the result of the increase the outside air temperature ΔT_{sol} by heating up the ventilation air inside the solar panels. Therefore, the value of ΔE_V can be estimated based on the following equation:

$$\Delta E_V = \sum_{i=1}^{n} \left[V_u \cdot \rho_a \cdot c_p \cdot (T_i - T_e - \Delta T_{sol}) \cdot \Delta t_i \right], \quad (4)$$

ΔE_V is equal to 0 when T_e+$\Delta T_{sol} \geq T_i$.

The temperature difference ΔT_{sol} between the inlet and outlet of the solar energy conversion device depends on the thermal performance. The next chapter describes the results of experimental studies, which allowed to determine ΔT_{sol} as a function of the intensity of solar radiation.

2.4. Calculation of greenhouse gases emissions

In this work, due to the complexity of environmental impacts of solar energy technologies, it shall be considered only one aspect occurring during the operation of solar air heaters. Precisely, this issue is

the reduction of the greenhouse gases emissions. The value of this reduction ΔP_{em} is directly related to the elimination of heat production from conventional energy sources ΔE_{fuel}.

$$\Delta E_{fuel} = \frac{\Delta E_V}{\eta_H}, \quad (5)$$

where:

$\eta_H = \eta_E \cdot \eta_D \cdot \eta_C \cdot \eta_B$ ·(Tchervilov, Grytsenko & Kaloyanov 2012),

η_E – emission efficiency [-],

η_D – distribution efficiency [-],

η_C – efficiency of the automatic control system [-],

η_B – boiler seasonal efficiency based on fuel, boiler age and type [-] (EN 15378 2009).

Reduction of annual air pollutant emission ΔP_{em} from combustion can be obtained by use of the following general equation (EMEP/EEA 2013):

$$\Delta P_{em} = \Delta E_{fuel} \cdot PF_{em}, \quad (6)$$

where:

PF_{em} – emission factor of air pollutant [kg/TJ].

Default emission factors of greenhouse gases (CO_2, CH_4, N_2O) for stationary combustion in the residential category were drawn up by Gomez et al. (2006). The values of PF_{em} coefficients for selected and most popular fuels are presented in Table 1.

Table 1. Emission factors in kg of greenhouse gas per TJ (Gomez et al. 2006)

Fuel	PF_{CO2}	PF_{CH4}	PF_{N2O}
Natural Gas	56100	5	0.1
Natural Gas Liquids	64200	10	0.6
Wood/Wood Waste	112000	300	4
Coal	94600	300	1.5
Oil	74100	10	0.6

3. THE RESULTS OF EXPERIMENTAL RESEARCH

This chapter presents the results of experimental tests of the SAH, which is a mass-producing solar energy conversion device.

3.1. General characteristic of the SAH under the test

Flat solar air heater under the test was made of an aluminum casing with the following dimensions: height – 2000mm, depth – 190mm (without the channel connections), length – 850mm (without handles). Top cover of the SAH was a solar glass with thickness of 3.2mm approved for use in solar collectors by the Institute für Solartechnik SPF in Switzerland in accordance with EN 9500. Mineral wool thermal insulation (thickness – 40mm, thermal conductivity λ =0.039W/m/K) was applied as a protection against heat loss. The most important part of the collector – absorber was made of aluminum sheet covered with a special coating ensures high absorption of solar radiation (ε =0.97). Inlet and outlet channels were made of ϕ125mm diameter aluminum Spiro pipes. The solar panel was equipped with a system to change the angle of inclination in the range of 30 to 60 degrees.

The main dimensions of the solar heater are as follows:

- Gross area (calculated as the height multiplied by length) – 1.7m^2,
- Absorber area (calculated as the exposed area of the absorber plate) – 3.4m^2,
- Aperture area (calculated as the area of the glazing exposed to the Sun's radiation) – 1.53m^2.

As shown in Fig. 1, solar air heater was placed on the roof of the building of Faculty of Civil Engineering and Environmental Engineering - Bialystok University of Technology (Poland).



Figure 1. Solar air heater tested experimentally under normal operating conditions

3.2. Experimental apparatus and procedures

The test stand is given in Fig. 2. The external air was sucked from the back shaded side of the collector by axial fan (1). The flow rate was maintained constantly at 152m^3/h±3m^3/h. The air temperature at the inlet (2) and outlet (3) from the solar heater (4) was measured with the use of PT100 TOPW-1 resistance sensors. A data scanner-recorder (5) was used to record and collect the results of the experiment with a time step equal to 10 seconds.

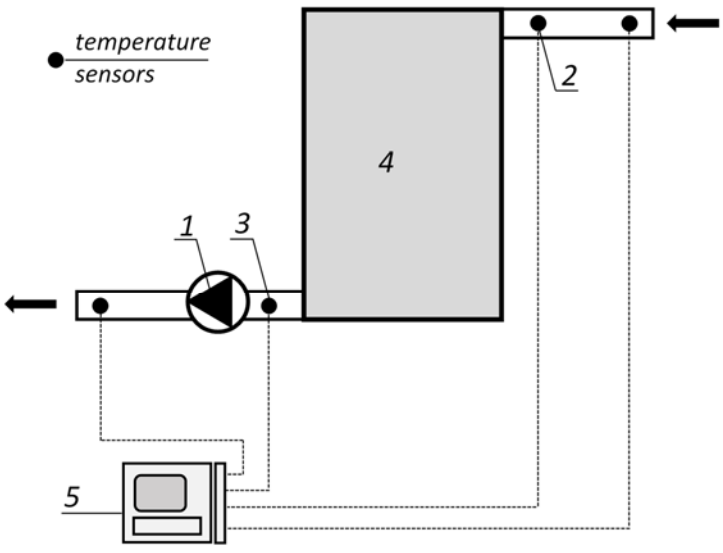


Figure 2. Diagram showing the measurement stand: 1 - axial fan; 2 - inlet temperature sensor, 3 - outlet temperature sensor, 4 – solar air heater, 5 - data logger.

For monitoring meteorological parameters it was applied automatic weather station integrated with another data logger. The station can measure environmental parameters such as outside air temperature, wind speed and direction, humidity, and solar radiation. Data logging runs every 5 seconds.

During the experimental tests performed in highly different weather conditions the temperature of ambient air was changed from -16.6ºC (3-01-2016 10:19) to 24,4ºC(4-10-2015 14:39).

The goal of these experiments was to obtain the efficiency of the SAH and decrease in the air temperature ΔT_{sol} inside the collector as a function of solar radiation intensity.

The thermal efficiency of the solar heater η_{SAH} is directly proportional to the air flow rate and ΔT_{sol} (so-called useful energy) and is inversely proportional to the solar radiation flux incident on surface of the absorber.

$$\eta_{SAH} = \frac{V_e \cdot \rho_a \cdot c_p \cdot \Delta T_{sol}}{I_{sol} \cdot A_A}, \quad (7)$$

where:

I_{sol} – solar radiation flux density [W/m^2],

A_A – surface area of a collector [m^2].

3.3. Summary of main experimental results

Selected results of 163 measurement series are presented in two graphs. Fig. 3 shows the relationship between the thermal efficiency related to gross area of the solar heater and flux density of solar radiation. The results of experiment can be approximated with a good accuracy (the square of the correlation coefficient R^2=0.8526) using the following linear relation:

$$\eta_{SAH} = 0.0005 \cdot I_{sol} + 0.13. \quad (8)$$

Analyzing the graph in Fig. 3, we can conclude that the efficiency of the collector is not too high but is at a comparable level to other similar devices. The maximum value is achieved at the highest intensity of solar radiation and is less than 60%.

The maximum uncertainty in the thermal efficiency of solar air collector was 3.5%.

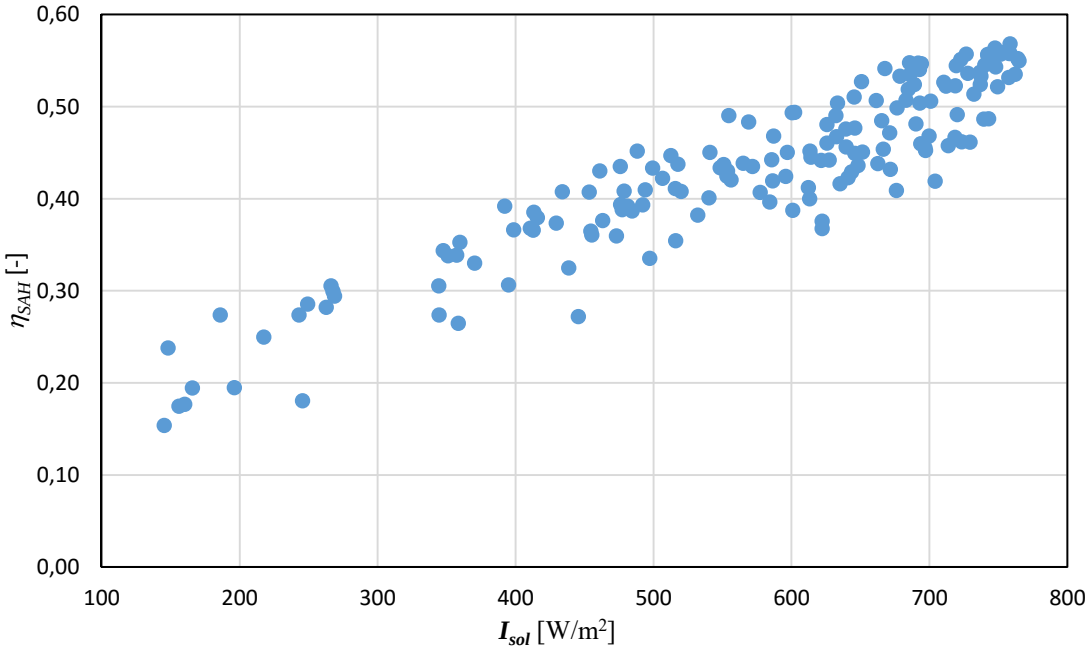


Figure 3. Dependence between SAH thermal efficiency and solar radiation flux density

The air temperature rise inside the solar panel as a function of solar radiation flux density is presented at the next graph (Fig. 4). Similarly to the previous case the measurement results is approximated (Eq. 9) with much greater accuracy (R^2=0.9307).

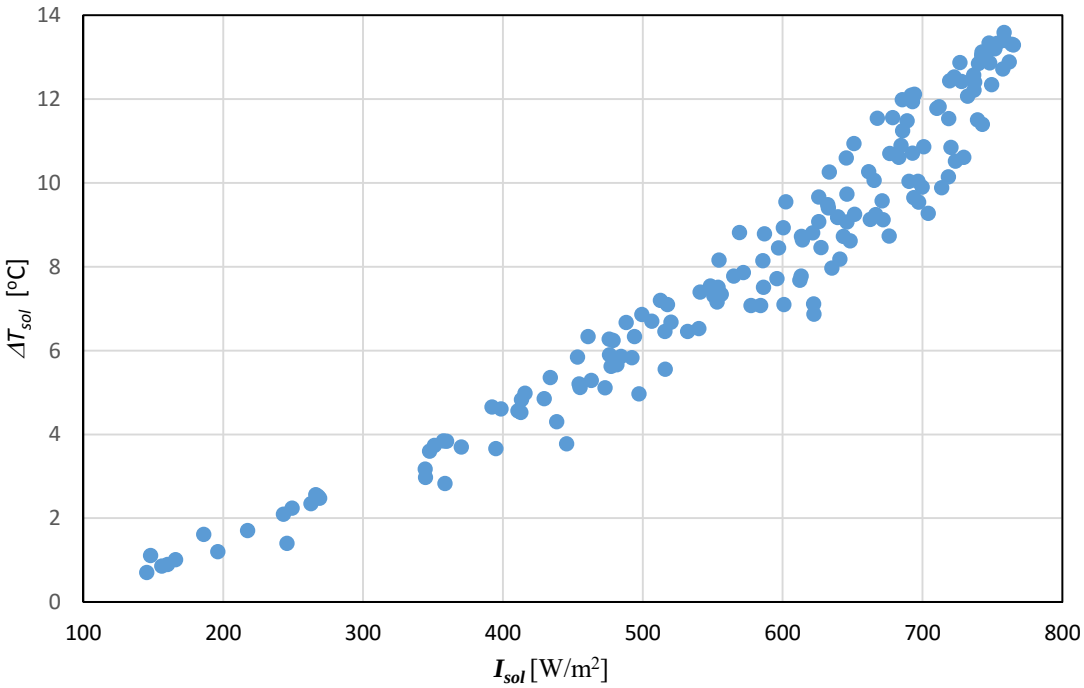


Figure 4. Dependence between air temperature rise ΔT_{sol} and solar radiation flux density

As a result of very precise calibration, the difference in temperature was measured with an accuracy of 0.1°C.

$$\Delta T_{sol} = 0.0207 \cdot I_{sol} - 3.6523. \quad (9)$$

The above relation was used to determine the reduction of energy consumption in the next chapter.

If we need to achieve higher value of temperature rise, we must reduce the flow rate. Previous studies (not yet published) have shown that at a volume flow rate equal to 35m^3/h ΔT_{sol} can even reach 34.8°C.

4. CALCULATION OF REDUCTION OF THE GREENHOUSE GASES EMISSIONS

In the calculations it was assumed:

- Typical year of meteorological data for the station Bialystok (Poland) (EnergyPlus Weather Data 2015),
- Time period with a constant meteorological parameters Δt_i=3600s,
- Number of time periods n=8760 (full year),
- Flow rate of ventilation air V_e=150m^3/h (5perons×0.00833=0.04167m^3/s),
- Seasonal efficiency of the heating system (gas boiler with automatic ignition and radiator system – η_H=0.67; oil boiler with radiator system – η_H=0.65; auto feed solid fuel with radiator system – η_H=0.56).

It was considered two cases. In the first case (*Case I*) it was assumed that external air is heated to design temperature inside a building T_i=20°C. In the second case (*Case II*), it was considered the maximum increase in the air temperature. For example, it becomes possible when we additionally use SAH and special heat exchanger for domestic hot water production and storage.

In the first step of the analysis, it was determined ΔE_V value using Eq. 4. The results are shown in Fig. 5 for *Case I* and Fig. 6 for *Case II*. Calculations were made for four inclination angles of solar panel due to the fact that sometimes it is not possible to apply optimal tilt angle (Zukowski & Radzajewska 2015).

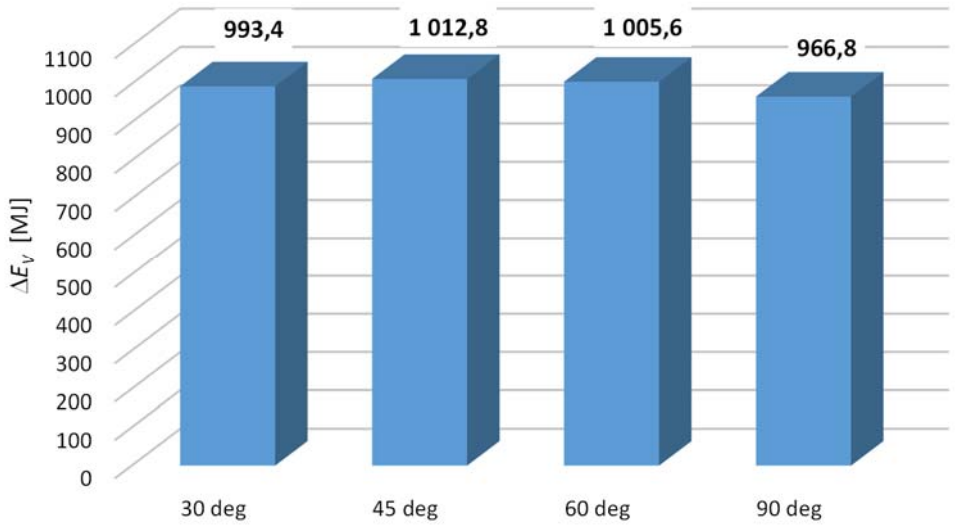


Figure 5. The reduction of energy consumption depending on the tilt angle of solar collector (*Case I*)

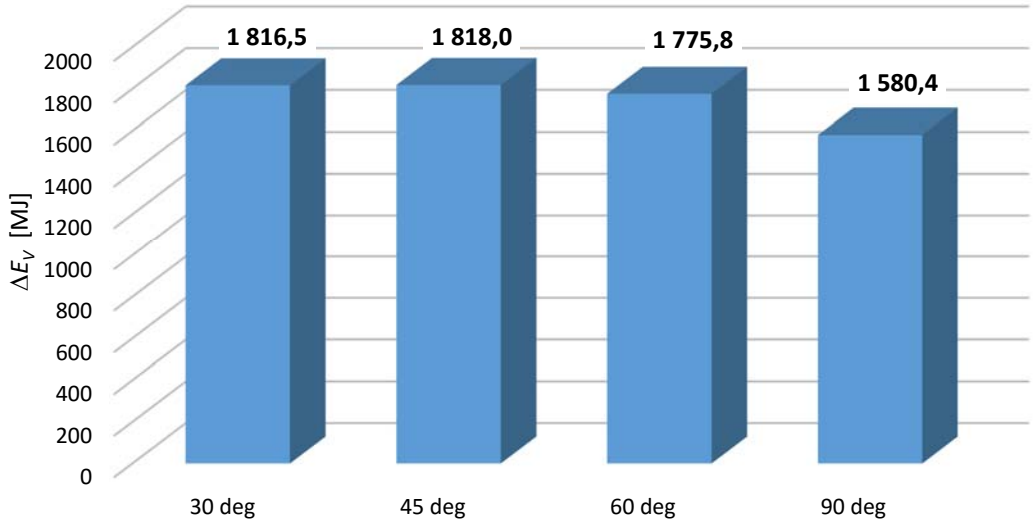


Figure 6. The reduction of energy consumption depending on the tilt angle of solar collector (*Case II*)

As the next step of the calculations, the reduction of annual air pollutant emission ΔP_{em} for selected and most popular fuels was determined using Eq. 5 and Eq. 6. Based on graphs in Fig. 5 and Fig. 6, we can conclude that the maximum energy gain occurred at the tilt angle 45°. For this selected parameter

the results of the calculations are presented below. Table 2 and Table 3 gives the final results of the analysis for *Case I* and *Case II*, respectively.

Table 2. Reduction of annual air pollutant emission ΔP_{em} (*Case I*)

	ΔE_{fuel} [TJ]	ΔP_{CO2} [kg]	$\Delta P_{CH4} \times 1000$ [kg]	$\Delta P_{N2O} \times 1000$ [kg]
Natural Gas	0.000151168	8.481	0.756	0.015
Natural Gas Liquids	0.000151168	9.705	1.512	0.091
Wood/Wood Waste	0.000180862	20.257	54.259	0.723
Coal	0.000180862	17.110	54.259	0.271
Oil	0.000155820	11.546	1.558	0.093

Table 3. Reduction of annual air pollutant emission ΔP_{em} (*Case II*)

	ΔE_{fuel} [TJ]	ΔP_{CO2} [kg]	$\Delta P_{CH4} \times 1000$ [kg]	$\Delta P_{N2O} \times 1000$ [kg]
Natural Gas	0.000271340	15.222	1.357	0.027
Natural Gas Liquids	0.000271340	17.420	2.713	0.163
Wood/Wood Waste	0.000324639	36.360	97.392	1.299
Coal	0.000324639	30.711	97.392	0.487
Oil	0.000279689	20.725	2.797	0.168

It should also be noted that the operation of the solar air collectors require energy to drive the fan, which was equal to 40.7MJ in *Case I* and 48.1MJ in *Case II*.

5. SUMMARY AND CONCLUSION

One of the most important environmental issues are global climate change and global warming. Amongst the causes of this phenomenon may be an excessive emission of greenhouse gases. This article presents one of the ways leading to the reduction of the GHG emission from stationary combustion of fossil fuels. The main goal of the current analysis was to determine the environmental impact which results from the operation of the solar air heaters. From the measurements, it was obtained the thermal performance of a typical device. As it was found out, the thermal efficiency of the collector is at an average level and does not exceed 60% in normal operating conditions. Also it was determined the air temperature rise inside the solar panel (Eq. 9) and based on this value it was calculated reduction of: heating energy demand for ventilation purposes, and finally greenhouse gases emission. The findings of the current study showed that the environmental effects resulting from the use of SAH for preheating ventilation air is not too significant - maximum to 36 kg of carbon dioxide for combustion of wood. However, it should be noted that the reduction of annual air pollutant emissions, shown in Table 2 and Table 3, were calculated only for one single family house. When considering this issue on the global scale we can obtain a significant effect.

There is an ongoing discussion in the scientific literature concerning the role of greenhouse gases in the Earth's radiation balance and global climate change. We can find radically different opinions on this topic. However, this issue should be considered from another point of view. By reducing the

consumption of fossil fuels through the use of technology that converts solar energy into heat can be achieved following effects: improving ambient air quality and increase of energy security at the local level.

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