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Thermoelectric coolers (TECs) for potential air-conditioning applications in buildings

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ABSTRACT

Refrigeration and air-conditioning systems consume about 15% of global electricity, and 46% of energy used in household and commercial buildings belongs to heating, ventilation and air-conditioning (HVAC) systems. Vapor-compression technologies dominate the HVAC market, and the refrigerants used in these systems have hazardous effects on the global environment. In this respect, alternative cooling technologies are needed to be developed toward latest low/zero carbon building targets. Thermoelectric coolers (TECs) are promising alternative systems for building space cooling applications compared to conventional vapour compression refrigeration (VCR) systems, as TECs do not use any refrigerant and they provide noiseless operation with their compact design. However their current coeeficient of performance (COP) ranges and cooling capacities are lower than those of conventional cooling systems. In this study, a systematic review of TECs is presented in terms of several aspects such as material type, design, thermal modelling, thermodynamic performance, building applications and environmental effects.

1. INTRODUCTION

Especially in the 21st century, due to large industrial developments and economic growth, fossil fuels which are not renewable and polluting have been consumed in large quantities [1]. For this reason, there has been a great interest in finding new alternative and renewable energy technologies in the last two decades. Thermoelectric devices are considered to be a good alternative because, they have no moving parts, long life span, fast thermal response, and they do not include any hazardous gas emissions [2]. Thermoelectric devices work according to seebeck and peltier effect. When there is a current in the cycle made of two different conductive materials, temperature difference occurs at opposite ends relative to the direction of the current. This is called as peltier effect [3].

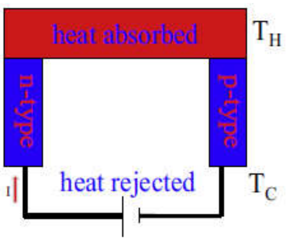

Fig.1: The schematic diagram of thermoelectric cooler.[3]

A typical thermoelectric cooler consists of P-type and N-type element pairs, which are electrically connected in series and thermally parallel between the two ceramic plates [4]. Thermoelectric cooling has several advantages compared to traditional cooling technologies. The main advantages are compact size, lightweightness, high reliability, no mechanical moving parts and thus no noise as well as not including working fluid [5]. In spite of inadequate ranges of coefficient of performance (COP) for high temperatures, thermoelectric coolers have a lot of usage areas like microelectronic systems, telecommunications, laser diodes, superconductor systems, aerospace industry, medical devices, food industry and building cooling[6].

2. Performance Parameter

There are three main parameters to evaluate the efficiency of thermoelectric coolers. The first performance parameter is given by a dimensionless quantity as follows:

$$ZT = \frac{\alpha^2}{p_e k} T$$

In the said equation; α, T, p_e, k are the Seebeck coefficient, temperature (usually the room temperature), electrical resistivity and thermal conductivity, respectively. The TEC's efficiency increases by the increase in ZT values.

The second performance parameter is the cooling power and is expressed by the following equation:

$$Q_c=(|\alpha_n|+|\alpha_p|)\,T_c I - \frac{1}{2}I^2(R_e+R_t) - k(T_h-T_c)$$

The third performance parameter is the cooling capacity gain per power consumption, and expressed by the following equation [7]:

$$COP=\frac{Q_c}{P_e}$$

3. Thermoelectric Materials

The efficiency of a thermoelectric device is highly dependent on the ZT value (figure of merit) of the materials considered. For this reason, an appropriate thermoelectric material is expected to have a good combination of high power factor and low thermal conductivity. Since it is difficult to keep the optimum values at the same time for these parameters, researchers attempt to optimize these parameters to increase TEC performance [8]. From the 1960s to the 1990s, cast-alloy materials such as Bi_2Te_3, PbTe, SiGe and $CoSb_3$ (the most commonly used species of Bi_2Te_3) were used as thermoelectric materials. Nevertheless, a significant improvement in ZT values for the mentioned period could not be achieved, but could be enhanced in certain quantities by various manufacturing methods. After 1990s, there has been a significant increase in ZT values with the use of nanostructured materials. Especially in the last two decades, reseachers conduct various researches to enhance the thermoelectric coolers' performance with new generation materials [9].

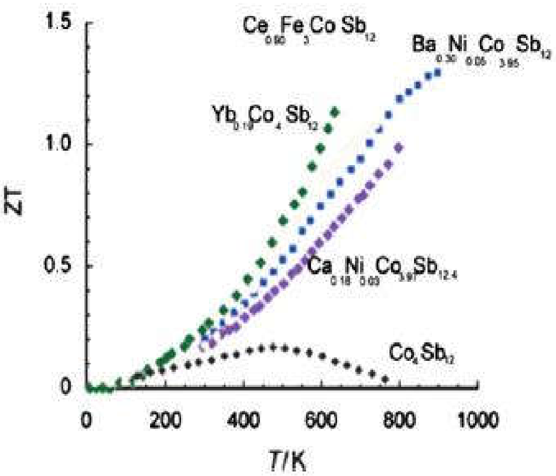

Fig 2: ZT as a function of temperature for skutterudites [9]

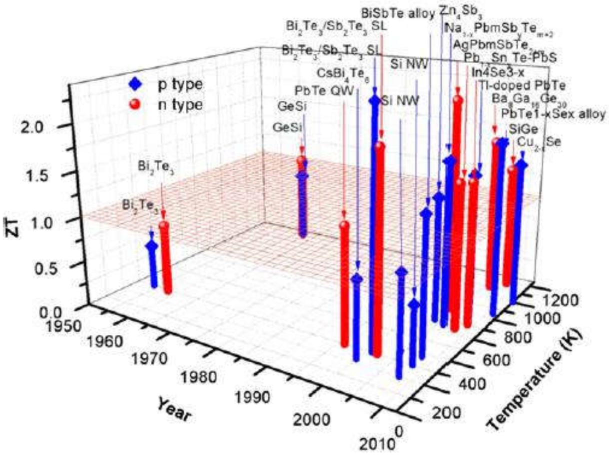

Fig.3: ZT as a function of temperature and year revealing the important development of thermoelectric materials[9].

4. TEC MODELİNG

There are four main models used for thermoelectric coolers:

Single-Stage TEC:

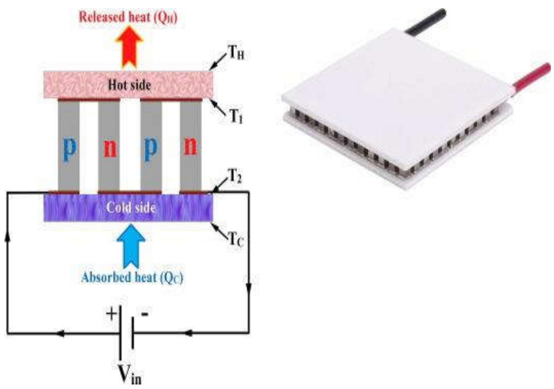

Fig.4: Schematic diagram of a single-stage thermoelectric device.[10]

Multi-Stage TEC:

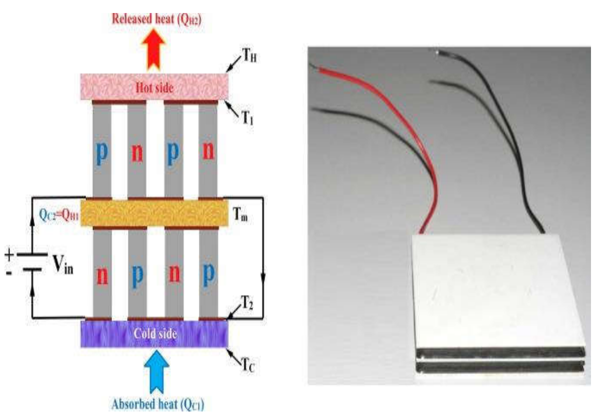

Fig.5: Schematic diagram of a two-stage thermoelectric device[10]

Trapezoid-Type TEC:

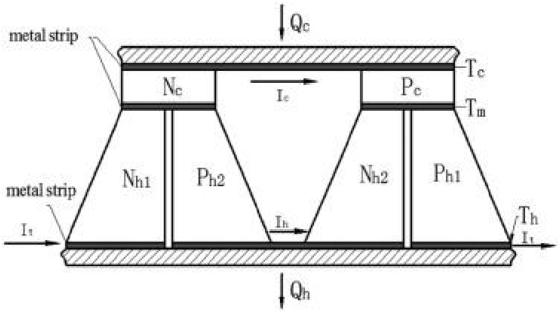

Fig.6: Schematic diagram of a TTPC model [11].

Annular-Type TEC:

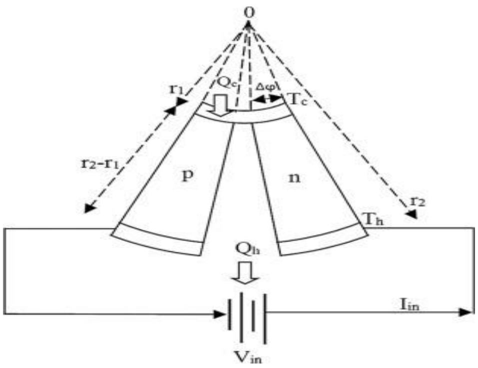

Fig.7: Annular thermoelectric cooler [12]

Though the trapezoid type TEC is more efficient than the annular TEC, their efficiency is lower than planar surface[12]. The highest efficiency values are achieved in multistage thermoelectric coolers. However, when the number of stages is too much increased, the ZT values start to decrease again [10].

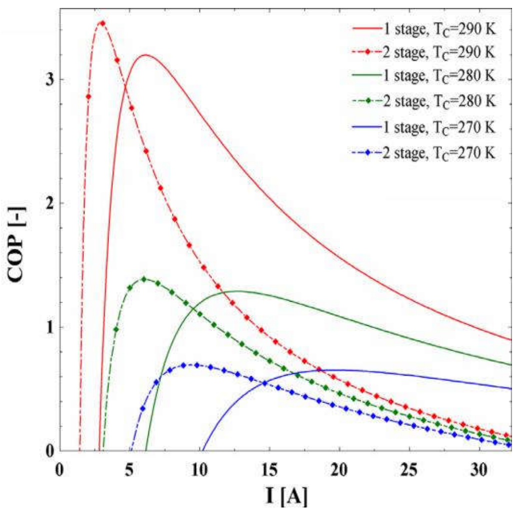

Fig.8: COP of single- and two-stage thermoelectric cooler versus current in different values of TC [10].

5. TEC Building Applications

One of the main problems of the 21st century is the global warming. The construction sector plays an important role by about 40% of global energy consumption. In addition, ventilation and heating systems constitute 60% of the energy consumed in buildings. For this reason, the effect of cooling systems on energy saving cannot be ignored [13]. For this purpose, Irshad et al. [14] conduct an experimental study to investigate the thermal comfort and economic performance of a thermoelectric-air duct system for a test room with space conditioning system.

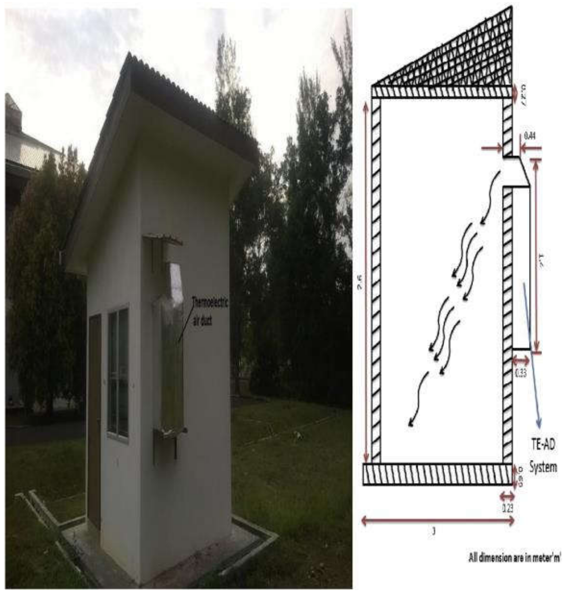

Fig.9: Test room equipped with TE-AD system [14]

They reveal that when the system operates at input supply of 6 A and 5 V, appropriate air quality and humidity levels are achieved. If the input current supply increases above 6 A, cooling performance of TE-AD system decreases. The payback period of the TE-AD system is found to be 6.4 years. Shen et al. [15] design a novel thermoelectric radiant air-conditioning (TE-RAC) system. In this system the thermoelectric modules operate like radiant panels instead of conventional hydronic panels and they have various advantages such as being freon free, convenient installation, no complex water distribution pipes, quiet and reliable operation, etc. The maximum COP is observed to be 1.77 when the applied current is 1.2 A and the cold side temperature is 20 ◦C. Nevertheless the conventional air conditioning systems are reported to be more efficient than the TE-RAC systems.

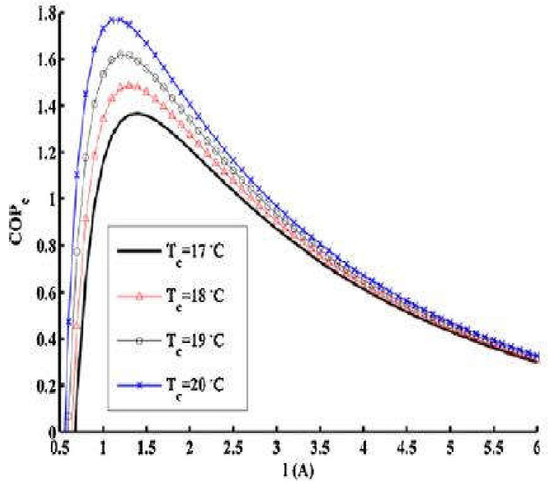

Fig. 10: Relationship between COPc and electrical current[15]

Manikandan et al. [16] design a modified pulse operation of the thermoelectric cooler (TEC) for building space cooling application. They study with different pulse width, pulse current, different pulse cooling power conditions and with different pulse shapes. The results reveal that the cooling power and COP are improved with the modified pulse operation by 23.3% and 2.12% respectively. For the modified pulse operation of the thermoelectric cooler, the optimum pulse current ratio and the optimum pulse width are 2 and 5 respectively. Additionally, the pulse shape is a crucial factor in terms of cooling performance and COP. The square shaped pulse have the highest cooling power and COP when compared to the ramp and exponential pulses.

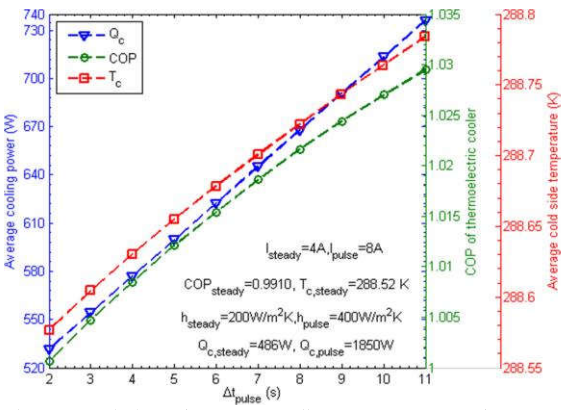

Fig. 11: Variation of average cooling power, COP and average cold side temperature with different pulse width [16].

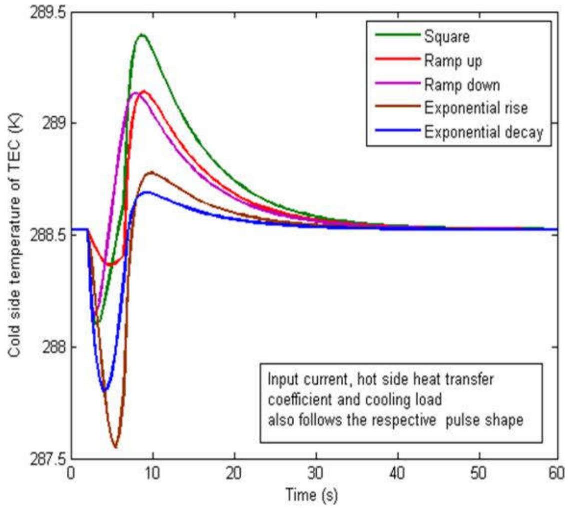

Fig. 12: Cold side temperature of TEC for different pulse shapes [16]

Gillott et al. [17] investigate the thermoelectric cooling devices for small-scale space conditioning applications in buildings. They also carry out a thermo-economical analysis for the said system. The theoretical study shows that when the temperatures on the hot and cold sides are stable, cooling capacity is only dependent on the number of thermoelectric modules. As the current input rises, the hot side temperature increases. The maximum COP can be obtained with low current input but this stuation causes low cooling capacity. The results of thermo-economic analyses reveal that if the PV panel costs decrease to lower than £1.25 per Watt, the system with PV panel can be competitive with conventional TEC applications.

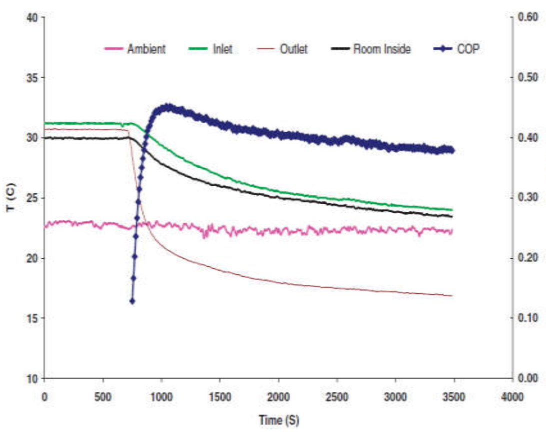

Fig.13: Temperature and COP variations for model room testing[17].

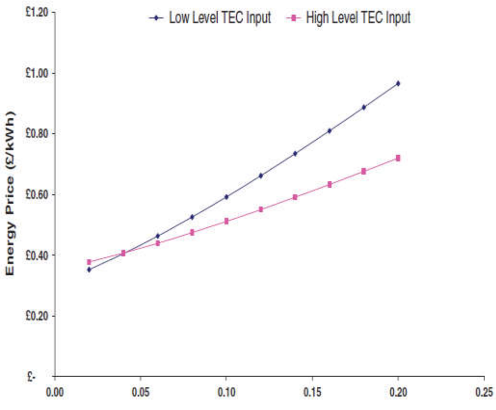

Fig.14: Average cooling energy price against interest rate[17].

Tan and Zhao [18] develop a thermoelectric cooling system integrated with phase change material (PCM) for the purpose of space cooling. PCM increases the system's performance efficiency by using the cold thermal energy which stored in the nights to reduce the warm side temperatures of the thermoelectric modules at runtime.

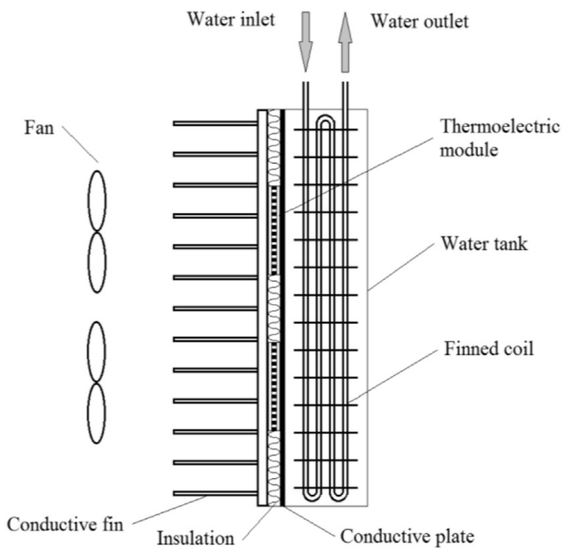

Fig.15: Schematic diagram of the thermoelectric cooling unit[18].

The empirical studies indicate that the average COP increase by 56% (from 0.5 to 0.78) for the lab scale thermoelectric cooling system with the integration of PCM. The local weather conditions should also be taken into account to ensure that the PCM is completely emptied at night.

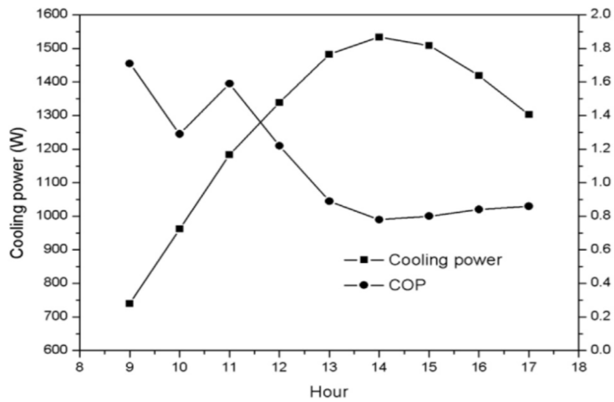

Fig. 16: Thermoelectric system's cooling performance during the cooling period [18].

Han et al. [19] conduct an experimental study of a thermoelectric ventilator. Firstly, they propose a mathematical model to develop an integrated design method and then conduct a series of experiment to test the ventilator’s performance under different weather conditions in summer and winter in Changsha, China. Maximum coefficient of performance (COP) is determined to be 4.78 in summer mode and 4.16 in winter mode. Because of the thermoelectric ventilator works more efficiently with lower fresh air temperatures in summer mode and higher fresh air temperatures in winter mode, the thermoelectric ventilator is more suitable for the mild weather conditions.

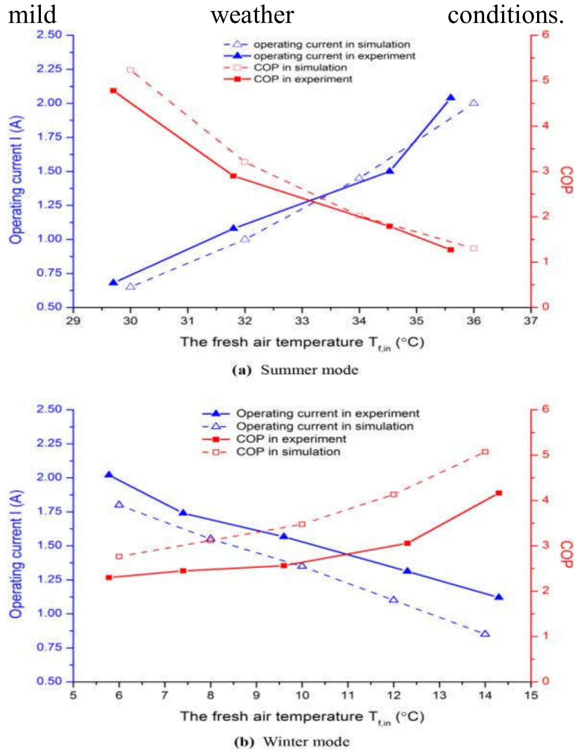

Fig.17: Operating current and COP under different fresh air temperatures[19].

Dizaji et al. [20] carry out an experimental study to determine cooling feasibility of air flow via a novel air-water based TEC system (as an alternative air cooling unit) for different climatic conditions. Differently, they adjust hot side temperature by a low constant water flow rate (not by an air fan) which significantly increases the cold side temperature of TEM. They also demonstrate that, cold side performance of TEC can be enhanced with the control of hot side temperature adjustment by a water flow rate.

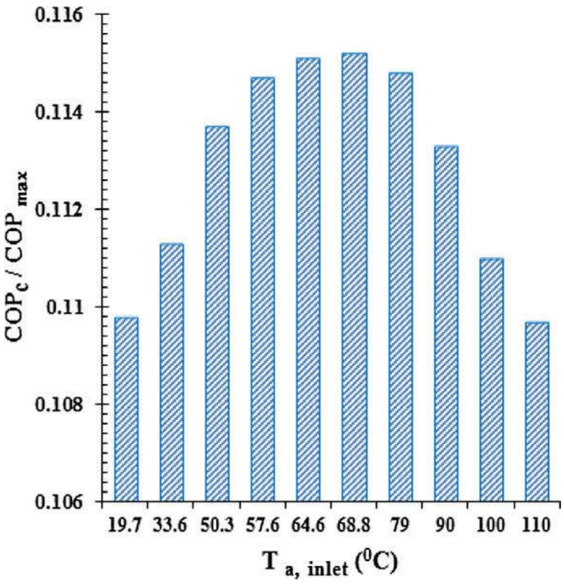

Fig. 18: The effect air inlet temperature on COPc/COPmax.[20]

6. Advantages and Disadvantages

The advantages of thermoelectric coolers can be listed as follows:

- Ideal for small volume cooling applications.
- It works quietly and without vibration.
- It does not contain any refrigerant and so eco-friendly.
- Ideal for applications where temperature control is important, very precise temperature control can be done.
- It requires very little maintenance as there is no moving part.
- They can work in all kinds of vertical, horizontal, gravity free environments.

Disadvantages:

- Cooling performance coefficients are low.
- They are not suitable for high cooling loads.
- Their costs are high.

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