Simulation for Energy Savings in AC Systems Equipped with Shaded Condensing Units

Dr. Maher Shehadi, Purdue Polytechnic Institute

Dr. Shehadi is an Assistant Professor of Mechanical Engineering Technology (MET) at Purdue University. His academic experiences have focused on learning and discovery in areas related to HVAC, indoor air quality, human thermal comfort, and energy conservation. While working with industry, he oversaw maintenance and management programs for various facilities including industrial plants, high rise residential and commercial buildings, energy audits and condition surveys for various mechanical and electrical and systems. He has conducted several projects to reduce carbon dioxide and other building emission impacts by evaluating and improving the energy practices through the integration of sustainable systems with existing systems. His current research focuses on engaging and educating students in sustainable and green buildings' design and energy conservation. He is currently investigating various ways to reduce energy consumption in office buildings.

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Abstract

Part of Purdue's University Mechanical Engineering Technology (MET) program is to educate its MET students on energy conservation in general and for buildings in specific. In this study, which was part of a project conducted for HVAC & Refrigeration class (MET 42100), the team decided to investigate ways to reduce energy or improve the coefficient of performance (COP) and efficiency of refrigeration cycles by looking into energy consumption in the condenser unit of the system. Sometimes overlooked and underappreciated, a power plant condenser can make or break the efficiency and power delivery goals. Understanding how important a role the condenser plays is a good step toward greater energy conservation awareness. The team conducted a parametric study to analytically investigate improvements in the COP of a refrigeration cycle when its condenser is shaded from the solar flux. Energy balance and heat transfer equations for heat exchangers were used to determine the shaded and unshaded condenser temperatures while keeping the split temperature difference constant. The simulation investigated improvement in COP for multiple chiller units having various cooling loads varying from 286-1300 kW. Multiple cases and scenarios were investigated keeping the evaporator temperature fixed while varying the outdoor temperature and vice versa. A base case with 5°C evaporator temperature and 35°C for the ambient air temperature was used. The improvement in the COP for the base case with shaded condenser ranged between 10-15% for various cooling loads. As the ambient air temperature increased, the COP decreased whereas when the evaporator temperature increased, the COP increased.

Students involved in the project were exposed to higher level of learning skills such as logical thinking, team work, problem solving and simulation. Many of these outcomes contribute towards ABET learning outcomes.

Introduction

Whatever type of refrigerating system is being used, it is fundamental to minimize the required heat extraction and to keep the difference between "T_c" (condenser unit temperature) and "T_e" (evaporator unit temperature) as small as possible [1].

Residential and commercial buildings compose 40% of the US primary energy of which 75% is electrical. Half this amount of energy consumed is by the ventilation and air-conditioning systems of the building [2]. The world equipment demand for heating, ventilation and air-conditioning (HVAC) has increased from 50 billion US dollars in 2004 to more than 90 billion US dollars in 2014 and for the US from almost 11 billion to 19 billion US dollars over the same period [3]. A reduction in the HVAC energy consumption load would reflect a significant reduction in the total energy consumed.

In this paper, the improvement in refrigeration efficiency and COP were analytically investigated by looking into a shaded condenser as compared to unshaded units. Thermodynamic equilibrium and energy conservation equations were used to estimate changes in the condenser temperatures.

Methodology

The study assumed that the difference in the rejected heat by a shaded and unshaded condenser is due to solar flux received by the condenser face area. Thus, to investigate the effects of a shaded condenser on the COP of the refrigeration cycle, solar flux was skipped for the correlating equations and compared to the normal case when solar flux is available.

The improvement in the COP of the cycle was defined as:

$$I = \frac{COP_s - COP_u}{COP_u} \qquad (1)$$

where the subscripts "s" and "u" stand for shaded and unshaded cases, respectively.

To evaluate the COP of each case, equations (2) and (3) were used for shaded and unshaded COP, respectively.

$$COP_s = \frac{T_e}{T_{c,s} - T_e} \qquad (2)$$

$$COP_u = \frac{T_e}{T_{c,u} - T_e} \qquad (3)$$

where T_e and T_c are the evaporator and condenser temperatures, respectively, and subscripts s and u stand for shaded and unshaded cases.

A base case was considered where the simulation was conducted for a selected Carrier type chiller. A chiller was needed to extract data for simulation such as the compressor power (kW), condenser area and airflow, etc. The data used was obtained from Carrier website [4]. The evaporator temperature (T_e) was fixed at 5°C and the outdoor inlet temperature (T_a) to the condenser at 35°C. The solar flux received by the condenser was also estimated to be around 5.84 kW/m^2. At a later stage, after all parameters were calculated, the effect of outdoor air temperature and evaporator temperatures were investigated by varying T_a between 25-50°C and T_e between 5-10°C.

For the base case, the challenge was to determine the condenser temperature T_c for different cooling loads. The method started with an energy balance, assuming no losses, between shaded and unshaded condenser. Figure 1 is a schematic for the chiller showing major heat rates acting on the condenser. Since the shaded case does not have any solar flux hitting the surface area of the condenser, equation (4) was applicable.

$$Q_s \times A_c = Q_{c,u} - Q_{c,s} \qquad (4)$$

where Q_s is the solar flux (assumed 5.84 kW/m^2), A_c is the condenser face area (m^2), Q_c is the rejected heat by the condenser and again the subscripts s and u stand for shaded and unshaded cases, respectively.

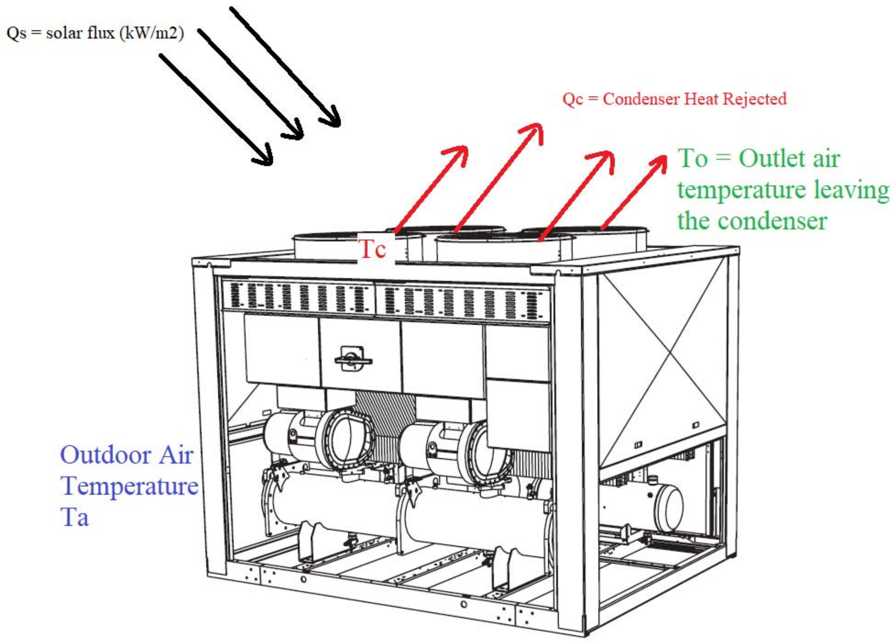

Figure 1. Schematic for the energy balance over the condenser

The unshaded condenser heat rejection rate ($Q_{c,u}$) was obtained from the catalogue used for the selected chiller. With the assumed value for the solar flux and the condenser areas for different units analyzed, the shaded condenser heat rate ($Q_{c,s}$) was estimated. Using equation (5) the logarithmic mean temperature difference (ΔTLM) was estimated for the shaded and unshaded cases using the corresponding $Q_{c,s}$ and $Q_{c,u}$, respectively. Assuming a constant value of 30˚C for the split temperature ($T_{ss} = T_c - T_a$) (T_a is the air inlet temperature or ambient), the temperature difference for ($T_{c,u} - T_{o,u}$) and ($T_{c,s} - T_{o,s}$) was obtained for unshaded and shaded cases by simultaneously solving equations (6) and (7), respectively.

$$Q_c = UA.\ \Delta TLM \qquad (5)$$

$$\Delta TLM_u = \frac{(Tc,u - To,u) - (Tc,u - Ta)}{ln\left(\frac{Tc,u - To,u}{Tc,u - Ta}\right)} \qquad (6)$$

$$\Delta TLM_s = \frac{(Tc,s - To,s) - (Tc,s - Ta)}{ln\left(\frac{Tc,s - To,s}{Tc,s - Ta}\right)} \quad (7)$$

where U is the overall heat transfer coefficient of the condenser and was estimated approximately 1.5 kW/(m^2.K) [4].

Finally, equations (8) and (9) were used to obtain the air outlet temperatures leaving the condenser, $T_{o,u}$ and $T_{o,s}$, respectively, which would allow estimation of the unshaded and shaded condenser temperatures and $T_{c,u}$ and $T_{c,s}$.

$$Q_{c,u} = \rho\dot{V} \times Cp_{air} \times (T_{o,u} - T_a) \quad (8)$$

$$Q_{c,s} = \rho\dot{V} \times Cp_{air} \times (T_{o,s} - T_a) \quad (9)$$

where ρ is the density of air, C_p is the specific heat of air, and $\dot{V}$ is the volumetric flow rate of air rejected by the condenser fans.

Results

The lower the condenser temperature, the higher the COP of the cycle was. Figure 2 shows how the COP decreases as T_c is increased. Thus, lowering the condenser temperature would allow higher COP and better cycle efficiency.

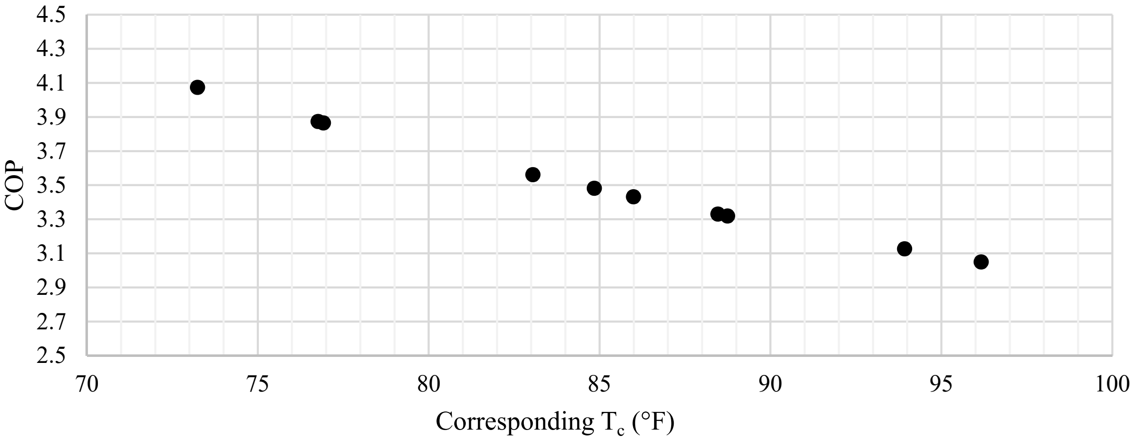

Figure 2. COP vs. condenser temperature T_c

The cycle COP was plotted against the condenser heat per condenser surface area for both cases, shaded and unshaded, in Figure 3. For the unshaded cases, as the condenser heat rejection flux (kW/m^2) increased, the COP_u decreased. For the shaded case, the COP_s was almost constant for various condenser heat rejection flux. The COP for shaded was also higher than that for the unshaded cases.

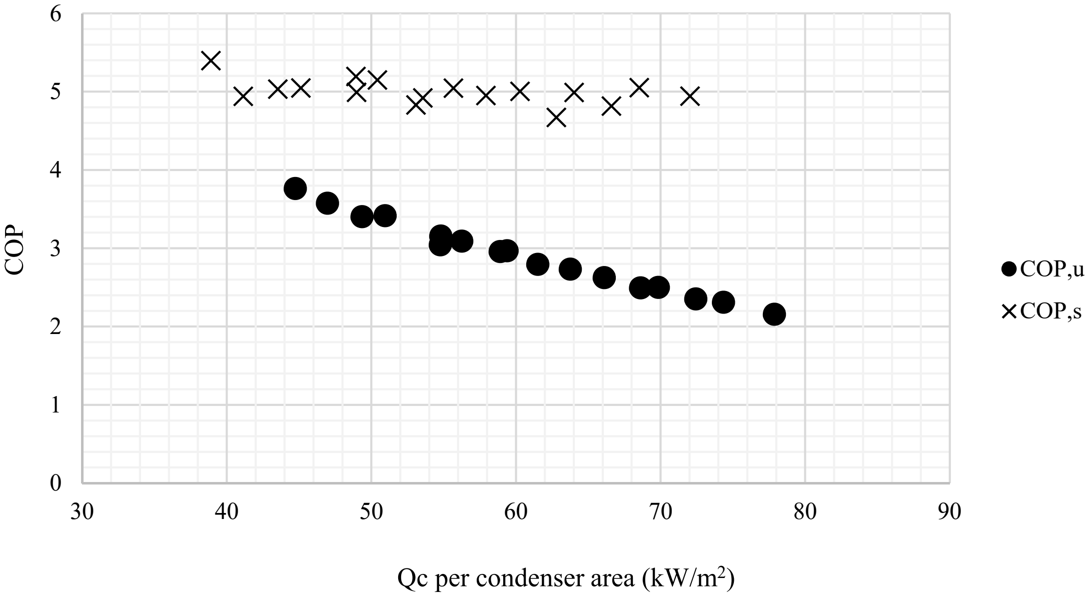

Figure 3. COP for the shaded (COP_s) and unshaded (COP_u) cases versus condenser heat rejection flux

Discussion

The improvement in COP for shaded over unshaded was estimated using equation (1) for various cooling loads and was plotted in Figure 4. For the base case with 35°C and 5°C for the condenser and evaporator temperatures, respectively, the improvement in COP for shaded over unshaded cases ranged between 10-15% for the cooling load range considered. The COP decreased as the cooling load was increased for the same unit size. Spikes were seen in the COP percent increase in Figure 4 when the size of the unit was changed due to bigger fan sizes and better performance at higher loads. However, for each unit size the COP decreased as the cooling load increased.

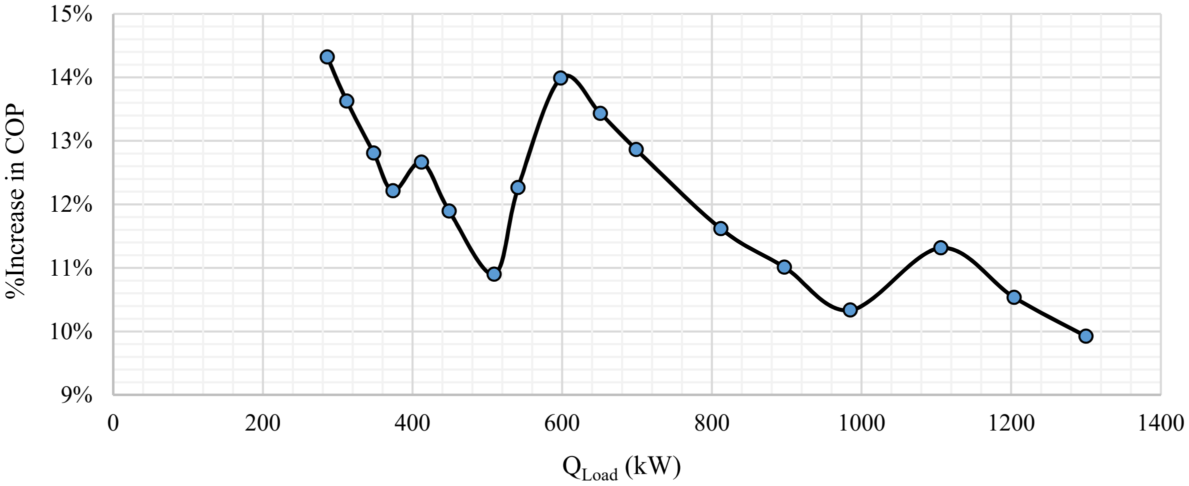

Figure 4. Percent increase in COP versus cooling load for the base case (T_c=35°C & T_e=5°C)

The dependence of the cycle COP on the inlet air temperature to the condenser (T_a) was plotted in Figure 5 while keeping the evaporator constant as in the base case at 5°C. The COP decreased as the outdoor ambient temperature was increased while keeping other parameters constant at various cooling loads. The drop in COP with outdoor air was less for higher cooling loads as the curves had more flattened slopes than with smaller cooling loads. When increasing the outdoor ambient temperature by 5°C, the drop in COP was approximately 1%. For lower cooling loads, the drop was approximately 0.7-1.5% for every 5°C increase in outdoor temperature, whereas for higher cooling loads this independence was less with drops in COP approximately between 0.3-1% for every 5°C increase.

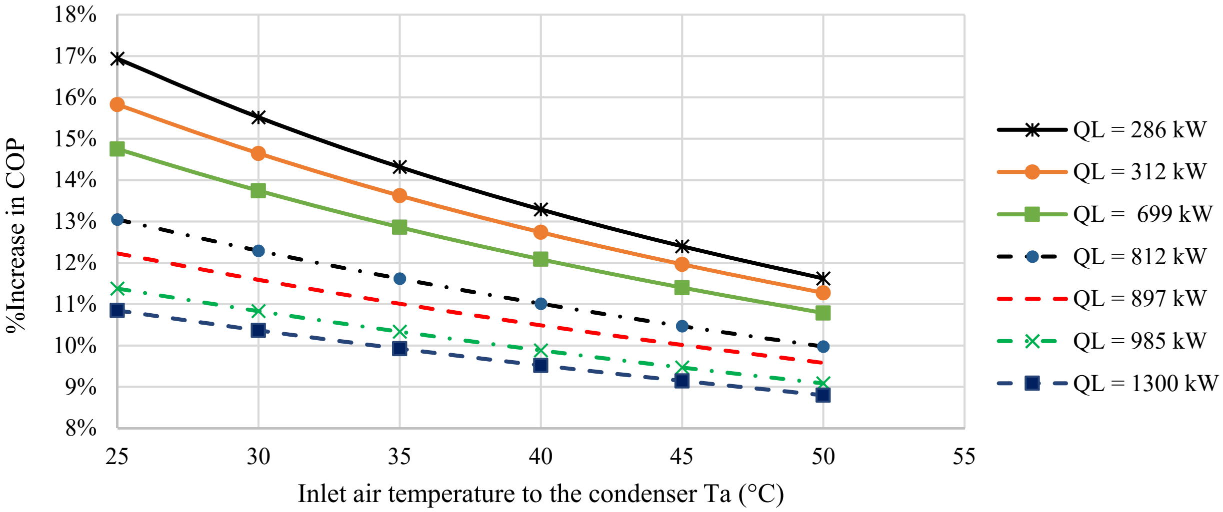

Figure 5. COP variations vs. outdoor ambient temperature (T_a) inlet to the condenser for multiple cooling loads

On the other hand, the dependence of the COP on evaporator temperature was investigated while keeping the air inlet temperature at 35°C. The evaporator temperature was varied between 5-10°C. Simulation results were plotted in Figure 6. The effect of evaporator temperature on COP was less significant than the outdoor temperature. In general, the COP increased with the evaporator temperature as it is expected to lower the cooling load. As the cooling load increased, the improvement in COP decreased. Again, the slopes for smaller cooling loads were steeper as for varying outdoor air temperature case, but in the opposite direction. In this case, higher cooling loads experience smaller improvements in COP. Thus, smaller cooling loads had better improvement in COP that larger cooling loads.

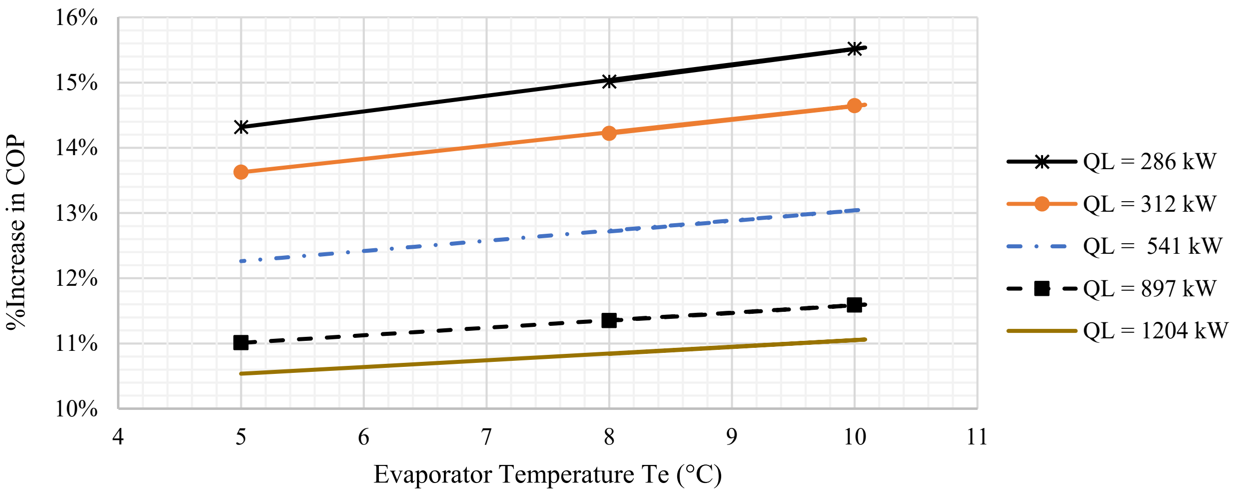

Figure 6. COP variations vs. evaporator temperature (T_e) for multiple cooling loads

Educational Outcomes and Assessments

Through the implementation of the project, the students got experiences in many aspects needed in industry after their graduation such as brainstorming, R&D skills, written and oral communication skills, and team work skills. The outcomes of the project were evaluated against ABET learning outcomes summarized in Table 1. The project contributed towards 25% of the final course score. The project grade consisted of progress reports (15%), final report (50%), presentation (25%), and team work evaluation (10%). Progress reports were submitted on biweekly reports and contributed towards 15% of the project grade. These reports summarized the work of the previous two weeks, to do list and any challenges. Progress reports gave the students an opportunity to receive continuous feedback from the instructor to improve their project. Team evaluation (10% of project grade) was evaluated using two split methods. The first half was assigned self-evaluation of the team members across each other where each student evaluated himself and the other team members. The other half was done through oral testing where the instructor asked each team member some questions and evaluated his contribution towards the project work.

Table 1. ABET ETAC students learning outcomes rubrics used for project assessment and the respective means used to meet these outcomes

ABET ETAC Rubric/Learning Outcomes		Assessment Methods
(1)	Apply knowledge, techniques and skills to engineering technology activities	Final report and progress reports
(2)	Apply knowledge of mathematics, science, engineering, and technology to engineering technology problems	Final report and progress reports
(4)	Problem Solving: ability to identify, formulate, and solve engineering problems	Project proposal and progress reports
(5)	Team work	Self-evaluation and instructor's evaluation (previously explained)
(6)	Effective Communication: ability to communicate effectively	Presentation and progress reports

Conclusions

A simulation for a refrigeration cycle performance was conducted with shaded and unshaded condensers. The dependence of the cycle on the condenser heat rejection, condenser area, evaporator temperature and air inlet temperature to the condenser was investigated. For constant evaporator and air inlet temperatures, the COP was higher with shaded condensers as the condenser temperature was less. The percent improvement in the COP for a selected chiller unit with selected capacities ranged between 10-15%. The COP dependence on the air inlet temperature to the condenser was higher than its dependence on the evaporator temperature. In general, as the outdoor inlet temperatures to the condenser increased, the COP of the cycles decreased whereas as the evaporator temperature increased, the COP increased. The COP for smaller unit sizes or smaller cooling loads were higher than with larger cooling loads.

The efficiency of the cycle did not take into consideration the changes or savings that could be done in the compressor work due to shading. If there had been any significant drop in the work done by the compressor, then the improvement in the efficiency of the cycle would be higher. To what degree and to what extent, it is unknown. This has to be experimentally investigated. Thus, the team decided to take this project into further analysis and decided to investigate this as part of their capstone project. The team is in the process of preparing to measure and monitor the condenser temperature during summer season for one-unit while being shaded and unshaded. The compressor power and evaporator temperatures are to be monitored and recorded, as well. This would allow more accurate analysis and it will give some comparisons for theoretical and actual measurements.

Further improvement could be done by using PV cells as the shading mechanism. The generated electricity by the PV cells could be integrated with the system to possibly run the condenser and evaporator fans and probably help in running the compressor of the cycle, if applicable. The system with PV solar shades could provide more energy consumption savings and thus would further improve the system efficiency.

Throughout the implementation of the project in this course, the students showed higher level of learning such as logical thinking, research & development, problem solving, applying knowledge, mathematics and science towards engineering application, team work, and communication. Many of these outcomes contribute towards ABET learning outcomes.

References

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