



Conceptual Design of a Condensing Heat Exchanger for Space Systems Using Porous Media

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ABSTRACT

Condensing heat exchangers are used in many space applications in the thermal and humidity control systems. In the International Space Station (ISS), humidity control is achieved by using a water cooled fin surface over which the moist air condenses, followed by "slurper bars" that take in both the condensate and air into a rotary separator and separates the water from air. The use of a cooled porous substrate as the condensing surface provides an attractive alternative that combines both heat removal as well as liquid/gas separation into a single unit. By selecting the pore sizes of the porous substrate a gravity independent operation may also be possible with this concept. Condensation of vapor into and on the porous surface from the flowing air and the removal of condensate from the porous substrate are the critical processes involved in the proposed concept. This paper describes some preliminary results of the proposed condensate withdrawal process and discusses the on-going design and development work of a porous media based condensing heat exchanger at the NASA Glenn Research Center in collaboration with NASA Johnson Space Center.

INTRODUCTION

Condensing heat exchangers (CHX) have been used for thermal and humidity control in every manned space flight system launched by the United States [1]. The control of temperature and humidity within a spacecraft requires removal of both sensible heat generated by power consuming equipment and humans, and water vapor primarily generated by evaporation from humans. A CHX is designed to accomplish both of these functions. The current system for control and humidity removal for the space shuttle and International Space

Station (ISS) utilizes a two-stage process. First, moisture is condensed onto the fins of a plate-fin heat exchanger which is then forced through the "slurper bars" by the air flow. The slurper bars take in a two-phase mixture of air and water that is then separated by a rotary separator. A drawing of the key components of the ISS condensing heat exchanger is shown in Figure 1 [2]. A brief description of this system can also be found in Ref. [3].

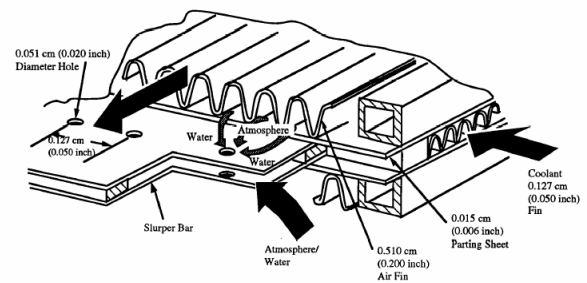


Figure 1. Illustration of the ISS Condensing Heat Exchanger.

A more efficient design of a CHX would condense and remove the water directly from the air stream without the need for an additional water separator downstream. In this paper we describe one such design that utilizes capillary forces to collect and remove water and is capable of operating in varying gravitational conditions including microgravity, Lunar and Martian gravity. The concept involves the use of a porous substrate with high thermal conductivity as the cold surface over which condensation occurs and liquid collects. The condensed water is then removed by an embedded porous media connected to a suction device. The thermal properties, the porosity and the wetting characteristics of the porous materials are judiciously chosen so that efficient

condensation is promoted and at the same time air penetration into the suction lines is avoided.

Before this heat exchanger concept can be used to design a humidity/thermal control system in an actual space mission several critical issues concerning the physical processes need to be resolved. The physical processes include heat and mass transfer rates, flow characteristics through unsaturated porous media in varying gravitational fields, and operational procedures including shut-down and start-up transients. A test bed that is capable of providing a conditioned moist air stream over a wide range of conditions anticipated in future space missions is being built at NASA Glenn Research Center. In this facility the test section along with the CHX can be rotated with respect to the gravity vector to simulate in a simple way the effects of varying gravity on the performance of the system. The CHX and the test-bed are instrumented to acquire the relevant information during the experiments. The data from these experiments are used to develop empirical correlations for heat and mass transfer and to validate theoretical and numerical modeling studies currently underway. Space-based flight experiments are also planned for the future to evaluate the performance of the condensing heat exchanger in a long duration microgravity environment.

It is anticipated that the porous media based condensing heat exchanger will provide a robust, lightweight passive condenser and liquid separator and it will be operationally simple. It applies to ISS and all advanced manned missions, a lunar habitat, Mars habitat and Mars transit vehicle for temperature and humidity control as well as separation of water from a mixture of water vapor and gases in in-situ resource utilization (ISRU) applications.

CONDENSING HEAT EXCHANGER CONCEPT

A schematic illustration of a specific design concept is shown in Figure 2. The system consists of a porous substrate with embedded porous tubes placed at regular intervals and connected to a suction device via a header assembly. The porous substrate also contains cooling copper tubes through which chilled water is circulated.

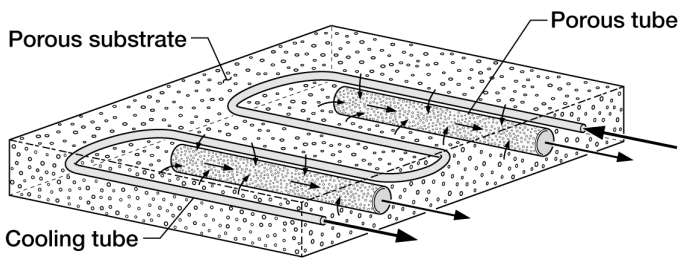


Figure 2. Composite porous media condensing heat exchanger concept.

Condensation of moist air occurs inside and over the porous substrate when it is cooled below the dew point.

The porous plate absorbs the condensate by capillary action and the accumulated water within the porous plate is selectively removed by the embedded porous tubes. Air penetration into the porous tubes is avoided by selecting tubes with a higher bubble pressure relative to the porous substrate. The porous tubes must be operated under a suction-head below its bubble pressure. However, care should be exercised to avoid bubble evolution from dissolved gases due to excessive lowering of pressure. This concept is illustrated in Fig. 3.

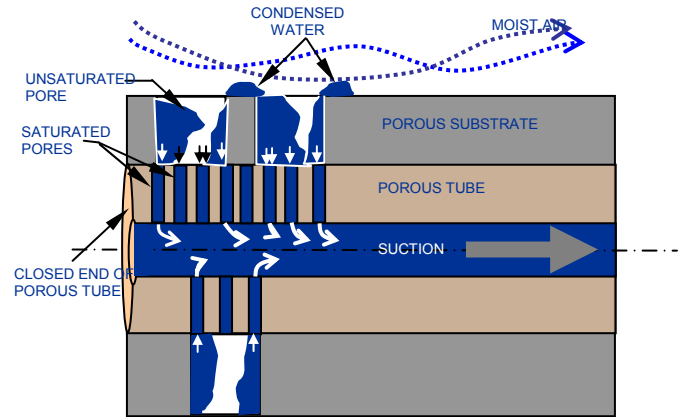


Figure 3. Porous substrate and condensate removal tubes with different pore sizes (not to scale).

PHYSICAL PROCESSES

The heat and mass transport phenomena of moisture condensation over cooled substrates and the hydrodynamics of air/water flow in porous media are reasonably well understood [4]. However, the unique geometrical configuration of the heat exchanger and the need for it to operate in varying gravity field including microgravity pose new challenges. In the following we examine some of the key physical processes mainly to prove the feasibility of the proposed concept.

CONDENSATION HEAT TRANSFER - The rate of condensation of vapor into and over the surface of the chilled porous substrate from the flowing moist air depends on the temperature gradient inside the porous media, flow through the saturated or unsaturated porous substrate, and the velocity, temperature and the dew point of the air stream. The rate of heat removal capacity per unit area, Q , of the porous plate for steady state condition may be estimated by

$$Q = \frac{T_d - T_c}{\delta / k_e + \delta_w / k_w} \quad (1)$$

Where, T_d and T_c are the dew point temperature and the centerline temperature of the plate, respectively. It is assumed that a thin condensate (water) film of thickness, δ_w is formed on the surface. The thickness of

the porous plate is δ and k_e and k_w are the thermal conductivities of the substrate and the condensate. The temperature profiles in the liquid film and in the porous substrate of thickness, δ are approximately linear. The heat flux, Q includes both the sensible heat and the heat of condensation. Theoretical solutions of the conjugate heat and mass transfer with condensation including porous substrate are being performed and will be reported elsewhere [5]. This analysis shows that

$$Pe_{\delta_w} = \ln \left[\left(1 + \frac{Ja_g}{\omega} + Ja_w \right) / \left(1 + \frac{Ja_g}{\omega} \right) \right] \quad (2)$$

where Pe_{δ_w} is the Peclet number based on δ_w and the velocity in the porous substrate, ω is the humidity ratio, and Ja_g and Ja_w are the Jacob numbers in the air stream and the water film. We postulate that if the porous plate remains unsaturated to a certain degree the formation of the liquid film may be avoided or its thickness can be greatly reduced due to imbibition of condensate into the porous plate. This enhances the heat removal capacity and eliminates or reduces the liquid carry-over with the flowing air stream.

CONDENSATE RETENTION IN THE POROUS SUBSTRATE – The capillary pores of a porous media, when hydrophilic, develops capillary suction pressure P_c given by

$$P_c = \frac{2\sigma}{r} \cos \theta \quad (3)$$

where, σ is the surface tension of the liquid to air and θ is the contact angle of water with the porous solid. The contact angle depends on the hydrophilic characteristics of the pore. A hydrophilic porous plate can effectively absorb and retain any liquid that comes in contact with its surface by its capillary pressure. The process would be equally effective in terrestrial and microgravity conditions. However, the capillary pressure of the pores diminishes with increasing degree of saturation. Therefore, the porous substrate would lose its liquid trapping capacity with increasing degree of saturation.

Once the saturation of the porous substrates reaches a certain level, water may be selectively extracted through the porous tubes by applying suction. This would reduce the degree of saturation of the porous substrate and restore the capillary suction.

SELECTIVE WATER REMOVAL BY SATURATED POROUS TUBES- For hydrophilic pores filled with water (wetting phase), a pressure equal to P_c is required to displace the water from the pores with air (non-wetting phase). This pressure corresponds to the 'bubble pressure'. As long as the external pressure is below the bubble pressure, air cannot migrate through the pores

while water is transmitted freely. Consequently, the porous media demonstrates selective permeability to the wetting phase. It is therefore possible to design a system for phase separation using a hydrophilic porous media. Because capillary pressure is not gravity dependent, a system so designed would be equally effective in terrestrial and microgravity conditions. Design of selective liquid separation by the embedded porous media is based on this concept.

WATER EXTRACTION FROM UNSATURATED POROUS MEDIA-The flow in an unsaturated porous media may be given by the Richard equation:

$$q = -K(w) - K(w) \left(-\frac{\partial h_c}{\partial w} \right) \frac{\partial w}{\partial z} \quad (4)$$

where, w is the volumetric water content, h_c is the suction potential, and $K(w)$ is the unsaturated hydraulic conductivity which depends on, among other things, the saturation of the pores and capillary suction corresponding to the degree of saturation. No universal law is available for correlating the unsaturated hydraulic conductivity with the volumetric water content and capillary suction. However, several empirical correlations and models exist for natural stones and granular materials. As an example, a simple empirical correlation suggested by Brooks and Corey [6] is considered:

$$K(w) = K_{sat} S^d \quad (5)$$

K_{sat} is the effective hydraulic conductivity at fully saturated condition, S is the effective degree of saturation and d is a constant dependent on the pore size distribution and typically varies in the range of 3 to 4. Brooks and Corey [6] suggested $d=4$ for rocks. Equation (5) shows that the unsaturated hydraulic conductivity reduces sharply as the degree of saturation reduces. This trend is expected during the water removal process from the external porous media (plate). Furthermore, the microgravity effects on the variation of hydraulic conductivity in unsaturated porous media are not well understood [7]. The implication of this behavior is that the water removal flow-rate will fluctuate significantly with the saturation state of the plate.

GROUND-BASED EXPERIMENTS

A successful demonstration of selective liquid extraction by a composite porous system is critical to the proposed concept. The following sections give an account of fabrication of a full-scale test module and some preliminary results of a bench scale setup.

FULL-SCALE MODULE- We have fabricated flat-plate heat exchangers using sintered porous bronze and graphite as the substrate materials. We have also

chosen porous ceramic tubes for the condensate withdrawal system. The graphite substrate (PG-45 National Electrical Carbon Products) had a porosity of 48% and an average pore size of 0.0023 inch. This particular graphite is chosen to obtain a “bubble pressure” of around 1 psia. The porous ceramic tubes had an average pore size of 6.7×10^{-5} inch to give a “bubble pressure” of approximately 14.7 psia. A simple flat-plate configuration was chosen for the condensing substrate geometry so that experimental results can be compared against analytical models of the problem. Full-scale tests using these condensing heat exchangers are currently underway in a test-bed at the NASA GRC. A drawing of the heat exchanger assembled inside the test-section of the test-bed is shown in Figure 4.

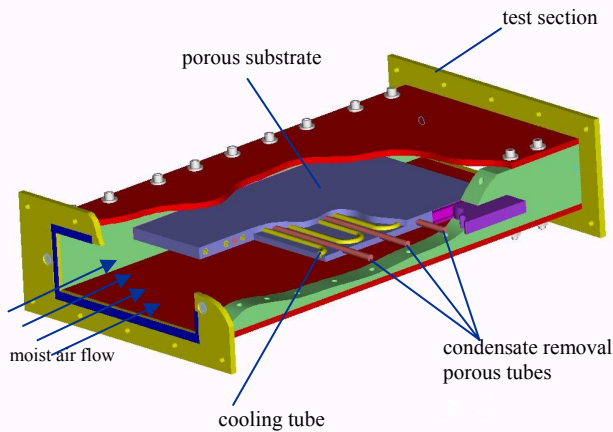


Figure 4. Flat-plate graphite condensing heat exchanger shown installed in the test-section.

BENCH SCALE TESTS-Besides the full-scale tests we have carried out a number of bench-top tests to verify the feasibility of the proposed heat exchanger concept. The results from these tests are described below. An experimental setup was constructed with a graphite block as the external porous substrate and ceramic porous tubes as the internal water-retrieving unit. The graphite block was 15 x 20 x 4.6 cm in dimension with three 1.08 cm diameter, 7.6 cm deep holes to accommodate the 1 cm diameter porous tubes (see, Fig.5). The graphite block bubble pressure was about 0.7 psi (assuming $\theta=0$ deg), and the bubble pressure of the ceramic tubes was about 14.7 psi. The low bubble pressure of the graphite block was chosen to minimize resistance of water flow under unsaturated conditions. The graphite block had very high hydraulic conductivity of 1.47×10^{-2} cm/s compared to that of the porous tubes (7.56×10^{-7} cm/s).

A schematic diagram of this experimental setup is shown in Figure 5. The range of suction pressure, ΔP was chosen between 3.5 and 7 psi. The upper limit of ΔP was selected to minimize the evolution of dissolved gases from the liquid phase. The pressure was

controlled by a proportional solenoid valve (Clippard Minimatics) and measured by a differential pressure transducer (Sensotec Model FDW Range 15psid). The extraction of the liquid from the graphite block was initiated at a known degree of saturation. The porous tubes primed to complete saturation were inserted into the graphite block and subjected to a desired suction pressure ΔP . The suction pressure was applied with a Drummond vacuum pump. Pressure and water outflow were recorded at different time intervals.

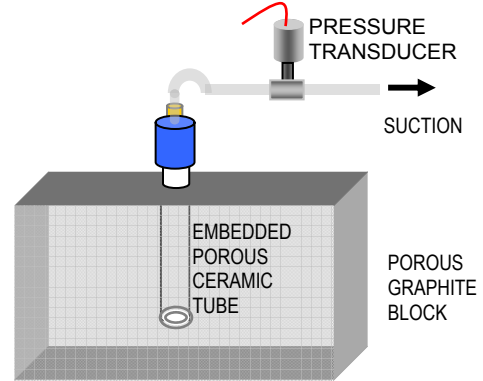


Figure 5. Schematic illustration of the bench-top test apparatus.

CERAMIC TUBE CHARACTERIZATION-The ceramic tubes are selectively permeable to water only under fully saturated conditions. In practice, however, complete saturation is difficult to attain. It was therefore necessary to evaluate if the porous tubes could function as a selectively permeable medium under moderate saturation, which involved immersion in water and pumping under a small suction pressure (about 3 psi).

The results of this experiment are shown in Figure 6. The test involves flow rate investigation in a ceramic tube at different submergence levels. The ceramic tube was first saturated by immersion in water and suction (3.5 psi) for about 10 minutes. It was then subjected to $\Delta P=3.5$ psi suction while the submergence in water was gradually reduced from 90% to 0%. The tube selectively extracted water even though a part was exposed to air. No significant gas bubbles were observed at any time during the experiment. The results indicate that the porous tube could be saturated to a satisfactory level with very little effort. The calculated flow rate in the tube is also shown for comparison.

It should be kept in mind that as the pressure is reduced from the liquid-gas interface, the partial pressure of the dissolved gases in the water reduces. This would release dissolved gases from the aqueous phase producing bubbles. Henry's Law gives the equilibrium between the concentration of a gas C_a in the aqueous phase and its partial pressure P_g in the gas phase:

$$C_a = k_H P_g \quad (6)$$

Where k_H is the Henry's constant. The values of k_H for predominant gases in air, oxygen and nitrogen, are $1.3E-3$ M/atm and $6.5E-4$ M/atm respectively. If the pressure is reduced from 14.7 psi to 11.2 psi ($\Delta P=3.5$ psi), about 24% of the gases will come out of the solution according to equation (6). Assuming the volume of a gas as 22.4 L/mole at STP, the total volume of expelled gas would be about 5.5 cc per liter of water. In the experimental setup, the volume of water subjected to the 11.2 psi pressure was about 100 cc. This translates into about 0.55 cc of degassing during the suction.

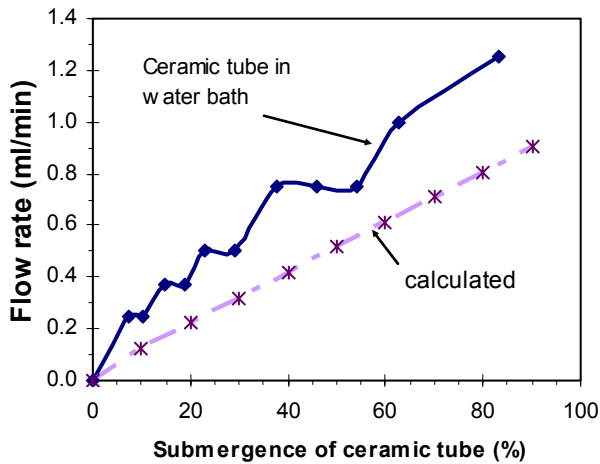


Figure 6. Selective removal of water by a ceramic tube submerged in water.

POROUS PLATE CHARACTERIZATION-The extraction of water from a porous media under unsaturated condition is dependent on the pore-size distribution, pore tortuosity, and the capillary pressure of the pores at various saturation conditions. The pressure-saturation curve of the graphite block material is shown in Figure 7. The experimental bubble entry point is about 0.6 psi, which is in good agreement with the theoretical value. As the pressure is increased, more and more pores are emptied and the degree of saturation reduces. This correlation has an important significance in choosing the operating suction pressure for the condensate withdrawal unit. For example, if the liquid withdrawal pressure is 2 psi, the saturation of the plate cannot be reduced below about 58%. Therefore, the suction should be discontinued at that point because no yield will occur. This type of plot could allow the designers to predict the volume of water that could be extracted from the condensing porous substrate.

SELECTIVE WATER EXTRACTION VERIFICATION-Experimental results of water extraction from the unsaturated graphite block under 3.5 and 7 psi suction pressures are shown in Figure 8. There was no influx of water in the graphite during the experiment. The initial saturation was about 90%. As water was removed, the saturation reduced and this resulted in a drastic reduction in the flow rate. For the 7 psi suction

pressure, the flow rate reduced from 3 ml/min to about 1 ml/min for a saturation reduction of about 5%. When the experiment was conducted at 3.5 psi, the flow rate reduced from 1.5 ml/min to 0.5 ml/min for the same reduction in saturation. No bubbles were observed at 3.5 psi, while some very tiny bubbles were observed in the suction tubes at 7.5 psi. However, this was not unexpected because, according to equation (6), pressure reduction by 7.5 psi would remove a considerable amount of the dissolved gases from the aqueous phase.

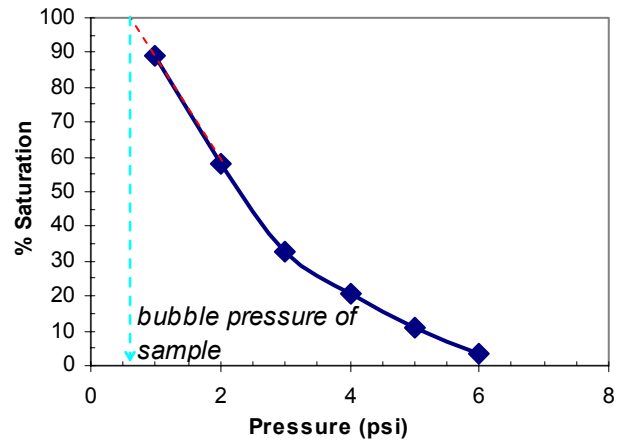


Figure 7. Pressure-saturation curve PG-45 graphite.

For a condensation rate of 1 lb/day, the required removal rate would be about 0.31 ml/min, which is less than the reduced flow rate at $\Delta P=3.5$ psi, *horizontal*. It appears that the proposed system could be designed to selectively remove water at a higher rate than the rate of moisture condensation on the porous substrate.

Flow rates at two different graphite block orientations with respect to gravity are also shown in Figure 8. Comparison of the vertical and horizontal flow rates at 3.5 psi shows reduced flow in the graphite block for the vertical orientation. The fluid extraction in the vertical direction was against the gravity. This result gives some indication about the possible effect of gravity on the performance of the proposed CHX. The variation of flow rates between these two orientations is likely dependant on the system geometry and is currently under investigation. The extent of dewatering of the graphite block that can be attained under a given suction head is also under study.

OPERATIONAL PROCEDURE - Based on the above discussions an operational procedure for the heat exchanger can be developed. The operation can start with the condensing substrate fully saturated or dry, but the condensate withdrawal tube must be primed to saturation. Assuming a porosity value of n and a substrate volume V , the amount of liquid the substrate can retain is nV . For a volume condensation rate of C ,

the time for saturation will be nV/C when starting from an initially dry state. For example, the time required for an 8 in X 10 in plate with 1 in thickness and 40 % porosity to reach 85% saturation will be about 24 hours for a condensation rate of 1 lb/day. At some high degree of saturation, the porous tubes will start extracting the water from the plate whose flow-rate will be a function of the saturation. Assuming that the hydraulic conductivity expressed as a function of the saturation can account for the diminishing flow-rate at reduced saturation, the system will come to a steady-state condition when the flow-rate corresponds to the rate of condensation. At this point the pump may be stopped to saturate the plate since the flow-rate becomes more efficient at higher saturation as seen from Fig.8.

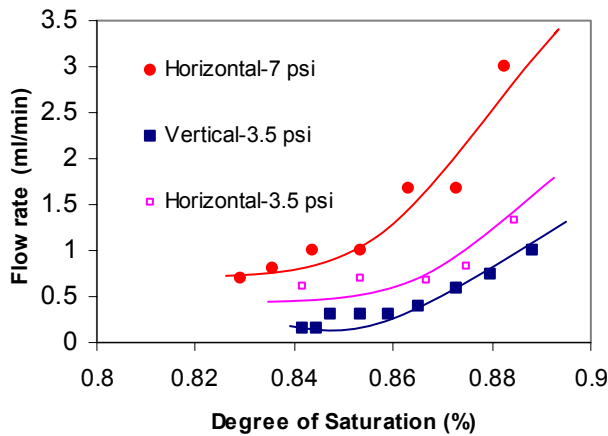


Figure 8. Selective extraction of water from an unsaturated graphite block at horizontal and vertical orientations.

FUTURE WORK

There are still a number of issues that need to be resolved before the CHX can be considered fully operational. One of the important unresolved issues is the ultimate geometrical configuration of the heat transfer surface. The current flat-plate geometry, though convenient for testing and interpretation of the test results using simplified theoretical models, may not be optimal in terms of efficient heat transfer. Other major issues are the performance of the CHX in a microgravity environment, the control of microbial growth, and long term maintainability of porous surface wettability.

CONCLUSION

A concept for the design of a condensing heat exchanger that is capable of operating under varying gravitational environments including microgravity has been proposed. The concept uses a composite porous media with two different average pore sizes and consequently two different bubble pressures. The surface over which condensation occurs has a larger pore size and collects the condensate using capillarity, and the tubes inserted into the substrate has a smaller pore size and selectively withdraws the condensate. Preliminary bench-top experiments have demonstrated the feasibility of this concept. Further work is currently underway to optimize the geometrical design of the condensing surface as well as demonstrating the function of this heat exchanger in a long duration microgravity environment.

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