589: Energy and Carbon Emission Savings due to Hybrid Ventilation of Office Buildings in Arid Climates

Sherif Ezzeldin, Simon Rees and Malcolm Cook

Institute of Energy and Sustainable Development, De Montfort University, Leicester, UK
E-mail: sezzeldin@dmu.ac.uk

Abstract

Hybrid Ventilation is an intelligent system of indoor environmental control in which passive cooling measures are supplemented by mechanical systems in order to maintain a satisfactory indoor environment with low energy demands. In order to evaluate hybrid ventilation performance for office buildings in arid climates, preliminary bioclimatic analysis and building dynamic thermal simulation methods have been applied for a single-zone office space with varying internal heat gains. The suitability of four locations for passive and hybrid ventilation strategies was tested through four bioclimatic analysis methods. The results of the bioclimatic analysis are compared with that of dynamic thermal simulations. Energy consumption of the prototypical office buildings using hybrid ventilation is compared to those using conventional cooling systems. The ability of hybrid ventilation strategies to maintain adequate comfort conditions in arid climates with reduced energy demand is demonstrated.

Keywords: Hybrid Ventilation, Office Buildings, Energy and Carbon savings, Arid Climates.

1. Introduction

Hot desert arid regions, where clear sky, high insolation and remarkably high diurnal and seasonal temperature variation exist, cover 14.2% of the earth's total land area [1] (Fig.1). Arid climate zones face particular challenges as a result of global warming and are expected to enlarge. The severity of the climate in arid regions means that mechanical cooling systems are often adopted in modern office building designs. The use of such mechanical cooling systems can be expected to grow as annual temperatures rise and so, by adding to carbon emissions, exacerbate climate change. A more sustainable approach to contemporary building development in arid climate zones should be sought.

Fig 1. The dark-grey hatch is highlighting Hot Desert Arid Zone (referred as BWh) according to the latest World Map of Köppen-Geiger Climate Classification

Buildings with Hybrid or Mixed-mode ventilation systems are designed to make maximum use of passive cooling methods but incorporate mechanical cooling systems for use in periods of high heat gain and elevated ambient temperatures. Energy can be potentially minimized using this approach while maintaining satisfactory comfort [2]. The design and operation of such systems, and the degree to which energy can be saved, is highly climate dependent.

Considerable research into hybrid ventilation has been carried out within the International Energy Agency IEA-Annex 35 but has mostly been concerned with applications in temperate climates such as that of northern Europe. The authors are not aware of any study of the design and effectiveness of Hybrid Ventilation in arid climates.

This paper is a presentation of the initial findings of a research project concerning the application of hybrid ventilation in arid climates. The project aims to examine the potential energy and emissions reduction benefits of hybrid strategies and to investigate design and simulation methodologies. Some of the questions that we seek to answer include:

- What bioclimatic design analysis methods are suitable for preliminary evaluation?
- What thermal comfort models and metrics are most useful?
- What ranges of energy savings are possible?

The project will consider a wide range of building types and forms but this paper is concerned with office buildings. When comparing the performance of air-conditioned and passive/hybrid designs, and when simulating their operation, it is important to make comparisons on the basis of similar comfort conditions being maintained. The following section discusses thermal comfort and alternative approaches to analysis that can be applied. Other aspects of the research methodology are discussed in section 3.

2. Thermal Comfort in hot arid climates

Thermal Comfort is seen as a state of mind where occupants desire neither a warmer nor a cooler environment to perform their activity. Since it varies physiologically and psychologically between occupants, neither perfect conditions nor well defined comfort boundary settings exist [3]. To optimize hybrid ventilation operation and energy savings it is necessary to determine at which times passive operation is appropriate without comfort being compromised. In the simplest terms one would like to know the maximum internal air and surface temperatures that could be tolerated before having to provide supplementary cooling.

As the building is intended to operate in passive and hybrid modes it is not possible to identify synoptic design conditions and calculate room set point temperatures. Rather, an annual analysis is necessary using representative annual climate and operating data. One issue that needs to be addressed is whether a hybrid building's comfort conditions should be evaluated using comfort models intended for air conditioned buildings, or those better suited to passive operation. These are discussed below.

2.1 Sealed Air-Conditioned Buildings

The PMV-Model of thermal comfort introduced by Fanger in 1970 is widely accepted and has been incorporated into a number of standards and design codes (for example, ISO-7730). It is formulated using a heat balance approach and accounts for variations in air temperature, mean radiant temperature, air velocity, humidity, activity level and clothing under steady-state conditions. The model is intended for application to situations similar to those of sealed air-conditioned buildings. Although recent field measurements derived in hot regions highlighted some inaccuracy of applying this model to air-conditioned buildings [4], it is commonly applied in the design of air-conditioned buildings in arid climate zones and has been applied in the analysis of fully air-conditioned buildings in the current work.

2.2 Passive and Hybrid Buildings

An alternative comfort model paradigm has been developed on the basis of field data rather than heat balance approaches that uses climate chamber data. These so called adaptive models of thermal comfort were initially derived from a high quality data set commissioned by ASHRAE (project RP-884 in 1995). The data was collected from 160 passive, active and hybrid office buildings in a number of climate zones, including those considered arid. These field investigations confirmed the inappropriateness of the PMV-Model for Passive and hybrid buildings as it over-estimates and under-estimates occupants' responses at high and low temperatures respectively [5]. This apparent acceptance of warmer temperatures is thought to be due to different psychological perception where occupants have opportunity to adapt their activities, clothing and ventilation in response to varying external conditions.

Adaptive models of thermal comfort seek to correlate perceived comfort with some measure of recent external temperatures and the current internal temperature. The external temperature is expressed as the mean monthly outdoor temperature in the ASHRAE standard 55-2004 and PrEN 15251 as they are based on earlier research by Bragger and de Dear [5]. The external temperature is expressed as an exponentially-weighted/running mean outdoor temperature (RMOT) in standard ISSO74 on the basis of the work of van der Linden *et al* who see the lower comfort limit identical to those in air-conditioned buildings that do not have opening windows [6]. These two adaptive approaches are thought to be the most suitable for office buildings with hybrid ventilation [7] and have been applied in the analysis of the passive and hybrid prototypical buildings studied in this work.

3. Research Methodology

The methodology adopted in the work reported here can be summarised as:

1. evaluation of climate data for worldwide locations in arid regions and development of four representative data sets,
2. application of four existing bioclimatic design methods,
3. development of Dynamic Thermal Simulation models of a prototypical office building,
4. parametric annual simulation of these models using passive, active and hybrid strategies and comparison of energy demands,
5. comparison of the predictions of the simulations and the bioclimatic analysis.

3.1 Representative Arid Cities

A wide range of climate data is available for what are commonly regarded as hot and dry climates. In order to arrive at a limited set of climate data that can be used in parametric building simulations, formal classification criteria have been applied and four representative cities identified. The Köppen classification system [1], introduced in 1936, is used for a wide number of applications, and those defined in the ASHRAE Standards 90.1 and 90.2 often used in the context of building simulation and load calculations. Both methods have been applied in this work. These classification schemes identify each zone (or cluster of locations) according to the monthly mean climatic factors. Arid zones are mainly classified according to both temperature and precipitation.

In the Köppen classification system, criteria defining the hot desert arid zone (three letter coding BWh) are formulated according to relatively high Mean Annual Temperatures MAT(°C) and relatively low Mean Annual Precipitation MAP(mm). The ASHRAE scheme is derived from Hierarchical Cluster Analysis [8] and offers eight main categories, with subdivisions, according to the number of degree days. Categories 1B, 2B and part of 3B and 4B are equivalent to the BWh of Köppen classification scheme.

Of the wide range of climate data available, distributed over the five continents and over the global arid regions, 50 could be identified as falling in the Köppen BWh 'hot desert arid ' class. These were also classified as hot-dry or warm-dry using the ASHRAE criteria. Three other cities were identified that fell in the ASHRAE hot-dry class but did not satisfy the Köppen BWh critera.

The main synoptic climatic data (annual degree days, mean annual moisture content etc) of these 53 arid cities were analysed. Unexpectedly, a wide range of mean relative humidity, from 25% to 83% was found. Hence, what are classified as arid climates (using precipitation criteria) include locations that could also be thought of as 'hot-humid' as well as 'hot-dry'. Since the temperature and relative humidity are the main factors that affect the bioclimatic design of a building, four representative arid cities were selected that represent the range of arid temperature and humidity conditions (Fig.2); Alice Springs in Australia, Bahrain, El-Arish in Egypt and Madinah in Saudi-Arabia.

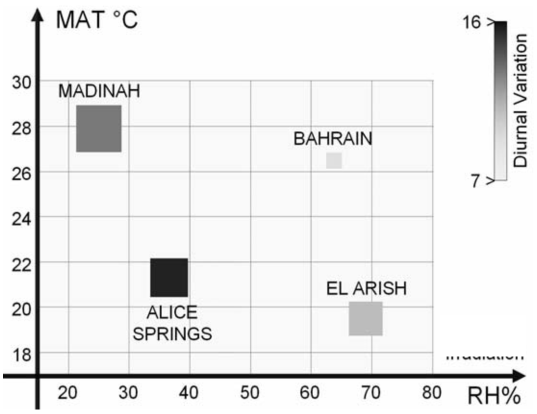

Fig 2. Mean Annual Temperature and Relative Humidity of the four representative arid cities. Symbol size and shading define the annual solar irradiation and average diurnal temperature variation respectively.

3.2 Preliminary Bioclimatic Analysis

Bioclimatic analysis methods are designed to assess climatic data in relation to comfort conditions at the early stages of building design using hourly annual climate data. They offer not only a satisfactory scale to the designer but also suggest boundaries/zones of effectiveness of several passive strategies such as natural ventilation or evaporative cooling. The three well-known bioclimatic charts used for this study are the Bioclimatic Chart introduced by Olgyay in 1953 and developed by Arens *et al.* in 1980 [9], the Building Bioclimatic Chart (BBCC) introduced by Givoni 1963 and developed by Milne and Givoni 1979 and 1992 [9] and the Control Potential Zone (CPZ) Method introduced by Szokolay 1986 [10]. These graphical methods were utilized to analyse the hourly weather data of the four representative arid cities. The methods are potentially very useful in the evaluation of hybrid ventilation strategies in that the percentage of hours where heating/cooling is required, and where passive strategies can be used to maintain satisfactory comfort, can be quantified (Fig.4).

Another quantitative approach that can be used to evaluate the suitability of direct and night-time ventilation cooling in particular climates is Climate Suitability Analysis developed by Axley *et al* [11]. The method uses a simple steady-state building heat balance that is used to calculate whether ventilation cooling is thermodynamically beneficial and what ventilation rate may be required to maintain conditions within predefined comfort temperatures. It assumes a single zone with uniform temperature distribution, small surface area to volume ratio and high thermal mass.

The method is useful in that flow rates can be predicted and variations in internal heat gain can be considered. The Climate Suitability Method has been applied to climate data for the four selected cities with the aim of calculating the percentage hours natural ventilation and night ventilation may be effective. These predictions are compared with those from the bioclimatic methods and dynamic thermal simulations.

3.3 Dynamic Thermal Simulation

Dynamic thermal simulations were performed for two reasons. Firstly, to evaluate the extent that passive operation could be maintained and secondly, to estimate the energy saving potential of hybrid ventilation. A prototypical office building has been simulated in three modes of operation. These are (case 1) passive natural ventilation, (case 2) active operation (year round air-conditioning), and (case 3) hybrid operation. Two levels of internal heat gain have been applied – 25 W/m² and 50 W/m². These variations, along with climate data from the four locations discussed above require 24 annual calculations. Simulations have been made with EnergyPlus [12] using its network airflow and hybrid system control components.

The prototypical office building is a single storey rectangular building with ratio 3:2 and internal dimensions of 30m x 20m x 3.5m (Fig. 3). The building envelope U-values and glazing SHGC were chosen to comply with ASHRAE standard 90.1. The requirements of the standard are similar to those of the International Energy Conservation Code (IECC) and a number of standards adopted by countries in arid zones.

Two sets of construction details were formulated. These were of low and high thermal mass but identical U-value. A Variable Air Volume (VAV) system with terminal reheat was selected for the simulation as being typical of modern air-conditioned building designs.

In order to allow reasonable comparisons between different modes of operation, and to represent good passive building design practice [13], some preliminary sets of calculations were performed to optimize the building. The design was optimized for best total annual energy demand by varying orientation, glazing percentage, shading devices, envelope construction and lighting control sensor location.

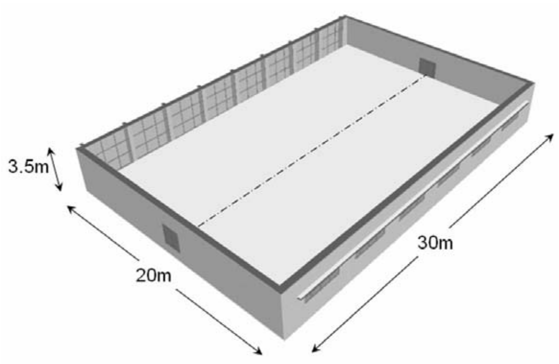

Fig 3. The Single-Zone Office Model geometry

The following features were found optimal:

- East-West orientation of the building axis
- 30% and 90% glazing for South and North facades respectively (North and South in the case of Alice Springs)
- 30cm vertical fins for the 90% glazing.
- 30cm overhangs for the 30% glazing.
- Applying exposed thermal mass for walls and roof for heavy-weight construction
- Daylight sensors located 2.5m from windows controlling the lights at up to 5m from the window.

The building with active control (case 2) has been modelled using the definition above but without external shading or lighting controls and with lightweight construction. This is believed more typical design practice.

Control of the building and its mechanical cooling system is viewed as a critical issue in hybrid ventilation. In this exercise it has been important to establish the best set point temperatures at which to apply mechanical cooling and at the same time provide good thermal comfort. This was investigated by a series of preliminary simulations and analysis of thermal comfort performance. The results of the simulations were evaluated using the Fanger PMV-model with 0.7Clo and 0.85Clo for summer and winter clothing values respectively for the active case, while the ASHRAE and the ISSO74 adaptive approaches with 0.5Clo and 1.0Clo for summer and winter clothing values respectively for the passive and hybrid cases.

In deciding control methods and temperatures, adequate thermal comfort performance was judged to be where every occupied hour showed no more than 20 Predicted Percentage Dissatisfied (PPD) (-0.85 > PMV-values > +0.85). The first finding was that when using the 24°C cooling setpoint temperature suggested by design guides for air-conditioned buildings, and controlling the building according to room air temperature, adequate comfort could not be maintained. This proved to be due to significant swings in radiant temperature. This suggests control based on air temperature would not be satisfactory unless room air set point temperatures were occasionally adjusted. The only way to mimic this, and show adequate control of thermal comfort, was to simulate control of the operative temperature at 24°C.

Hybrid ventilation strategies should – by virtue of allowing occupant adaptation – allow relatively higher effective set point temperatures. In other words, mechanical cooling should not need to be activated until higher temperatures have been reached. Hybrid system setpoint temperatures were established for each location by increasing operating temperatures until thermal comfort criteria could no longer be met for every occupied hour. In the case of the hybrid designs this was defined by the ASHRAE and ISSO74 adaptive comfort 80 PPD limits.

The appropriate air temperature set point temperatures for low internal gain cases were found to be 26°C for Alice-Springs, 28°C for both Bahrain and El-Arish, and 25°C for Madinah. For high internal gain cases these reached 26°C for Alice-Springs, 27°C for both Bahrain and El-Arish, and 26°C for Madinah.

4. Analysis and Simulation Results

4.1 Potential of Natural Ventilation

A summary of the bioclimatic analysis, using the four methods described above, for the four representative arid cities, are shown in Fig. 4. The stacked bars show the percentage of hours that cooling or heating are required or where passive operation will provide comfort. Separate bars show the proportion of required cooling that can be provided by day or night time natural ventilation.

The results using Olgyay's and Giovoni's methods (Figs. 4a and 4b) show very similar proportions of required heating and cooling. This may simply be because Olgyay's method was developed using some of Milne and Givoni's findings. The proportion of cooling is significantly higher in the hotter locations Bahrain and Madinah. This is expected, as only external temperature is considered and not system type or building internal gains.

The Szokolay CPZ method results (Fig. 4c) show relatively fewer hours when no heating or cooling is required. This is simply because the comfort zone is smaller, being partly defined according to moisture content limits (reflecting potential for skin evaporation) and not relative humidity [10].

In general, the number of hours of effective day and night ventilation depend on predefined zones of the climatic chart and not the comfort envelopes. These differ more noticeably between the three different graphical methods. This may also make the sensitivity to climate different for each method.

The levels of predicted useful daytime ventilation are similar in the case of the Szokolay and Olgyay methods (15 – 25%) and rather lower using the Givoni method (10-15%). In general there are much greater differences in predicted effective hours of night ventilation. Most noticeably the proportion suggested by the Szokolay CPZ method is higher. This is because its night ventilation envelope takes some account of the thermal mass.

Climate Suitability Analysis differs from the graphical methods in some important ways. Firstly, it takes account of the building heat balance and the thermodynamic benefits of ventilation in an explicit way. Secondly, comfortable operating conditions are defined according to dry-bulb temperature and no account is taken of humidity. Thirdly, internal heat gains can be explicitly accounted for. The results for this method (Fig. 4d) show effective daytime ventilation in the range 15-25%. According to this method the cities that can benefit from natural ventilation are those that are relatively cooler – this is not the case in other methods as these partly consider humidity and do not consider diurnal variation in an explicit way. The number of effective night ventilation hours predicted by the Climate Suitability Analysis is most similar to the dynamic simulation results.

Results of the dynamic simulations are presented in a similar manner to those of the bioclimatic analysis in Fig. 5. Adding the percentages of day and night ventilation together, natural ventilation is permissible from 38.7% to 50.6% of the total number of hours for low internal gain cases and from 34.8% to 45.9% for high internal gain cases.

One of the most noticeable features of the simulation results is that the number of hours where neither heating nor cooling are required is shown to be higher than other methods. In this case an adaptive thermal comfort model is being applied rather than a defined upper temperature limit and this model effectively allows some hours at higher external temperature to be considered comfortable.

In the simulations, the damping effect of the thermal mass – and particularly its moderation of radiant temperatures – is explicitly taken into

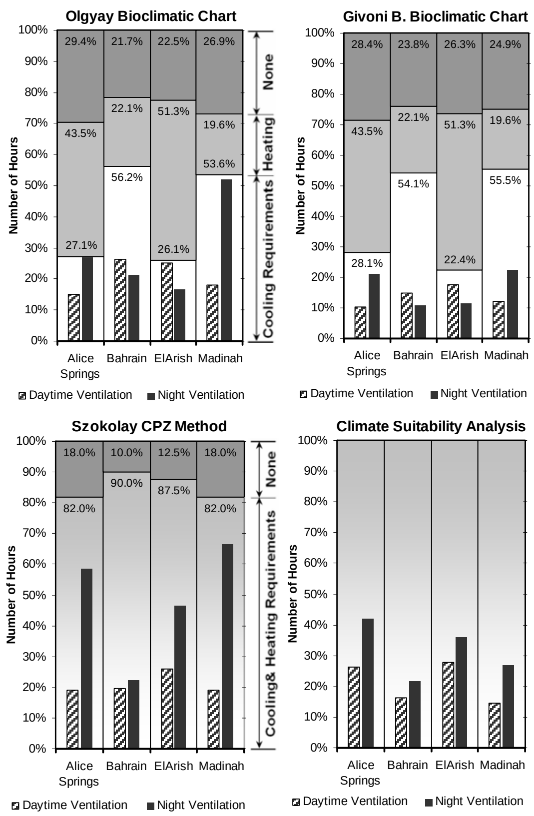

Fig 4. Bioclimatic Analysis methods of a) Olgyay, b) Givoni, c) Szokolay, and d) Climate Suitability Analysis

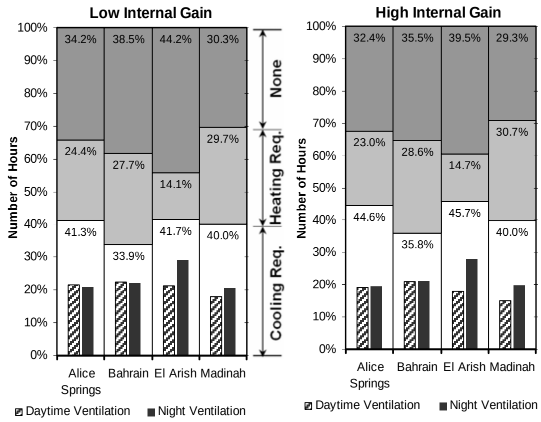

Fig 5. Permitted day and night ventilation using hybrid ventilation temperature control for arid cities

account. It can also be seen that there is less variation – using any measure – between cities. This is most likely due to the fact that internal gains are explicitly considered and reduce the relative differences in overall heat gain.

4.2 Energy Consumption

The extreme summer temperatures of the arid climate locations mean that equipments and lighting have relatively small portion of the overall energy use compared to cooling system demands. This is clear in the annual energy consumption calculated for active cooling shown in Fig. 6 – particularly in Bahrain and Madinah. Being able to reduce cooling system energy demands can therefore result in significant savings in overall demands and carbon emissions. These energy savings for heating and cooling consumption due to the use of hybrid ventilation varies from 60.5% to 83.4% for low internal gain cases (Fig.6a) and from 59% to 72.4% for high internal gain cases (Fig.6b), with highest and least savings in El-Arish and Bahrain respectively. Energy savings arise from reduced fan and pump usage as well as lower refrigeration system loads. Comparing monthly energy savings, for the four representative arid cities, hybrid ventilation is shown to be particularly advantageous during periods of moderate temperature such as spring and autumn.

5. Conclusions

Arid climate data has been analysed and four cities representative of variations in the data have been identified for bioclimatic analysis and computer simulation studies. Although these are arid locations there are noticeable differences in annual mean humidity levels. Three graphical and one quantitative bioclimatic analysis methods have been tested for these cities. These indicate that the number of hours where neither heating nor cooling should be necessary is sufficient to make hybrid ventilation strategies worth pursuing. A series of computer simulations using a model of a prototypical office building have been conducted. These have been simulated in fully air-conditioned mode as well as hybrid and fully passive modes. The simulated number of hours where cooling is required, and the number of hours where comfort can be maintained without a cooling system, have been compared with the predictions of the bioclimatic tools. For the office building that has been modelled the dynamic simulation results suggest there may be more hours where cooling would not be required than indicated by the bioclimatic design methods. This may partly be due to thermal comfort being assessed using an adaptive comfort model rather than a comfort envelope approach. The simulation results using hybrid ventilation controls show that more than 60% energy may be saved compared to similar conventional designs that are fully air-conditioned. Hybrid ventilation strategies are therefore very attractive and should be considered in the design of buildings in arid climates.

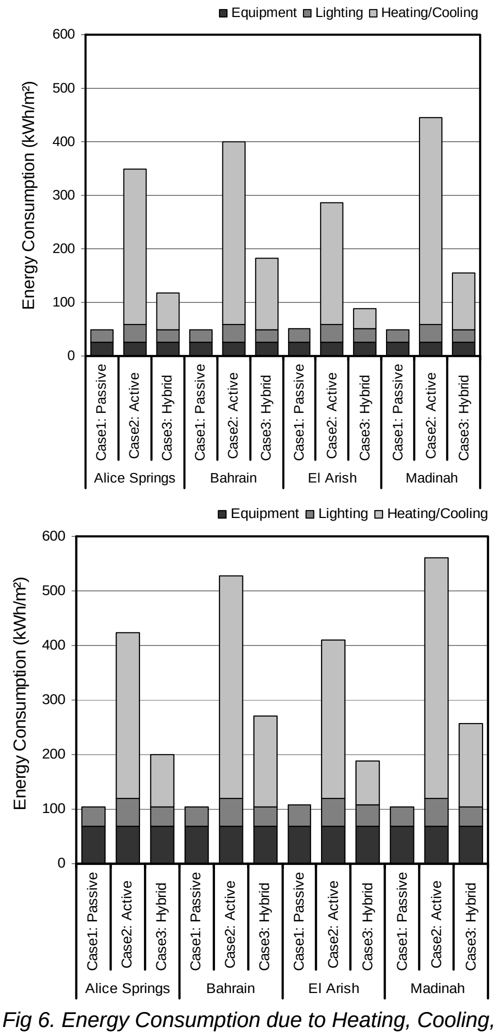

Fig 6. Energy Consumption due to Heating, Cooling, Lighting and equipments for a)Low Internal Gain Cases and b)High Internal Gain Cases

6. Further Research

This paper presents initial findings of a larger project. Further issues to be addressed are application of a range of low energy cooling technologies, alternative comfort models and advanced control strategies. It is planned that simulation methodologies and design guidance for architects will be developed.

7. Acknowledgements

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