SUSTAINABLE COOLING SCHEMES FOR THE LONDON UNDERGROUND RAILWAY NETWORK

Dr G.G. Maidment BEng, PhD, CEng, MIMechE, AMInstR, FRSA
&
Dr J.F. Missenden BSc, PhD, CEng, MCIBSE, FRSA

School of Engineering Systems and Design, South Bank University, 103 Borough Road, London, SE1 0AA, United Kingdom
Tel 0044 (0) 207 815 7626, Fax 0044 (0) 207 8157699 Email maidmegg@sbu.ac.uk

ABSTRACT

In London and Merseyside, which are served by deep underground railway networks, rising water tables are proving an increasing problem, leading to a serious deterioration of track, traction supply and signalling systems. Also in these transport systems there is an increasing demand for an energy efficient and environmentally sustainable comfort cooling system. This paper outlines a novel cooling system that aims to reduce the water table by using the groundwater for 'free' cooling the railway network.

This paper investigates the potential for cooling the underground network and trains in this way. It uses a purposely-developed mathematical model to show that additional cooling to the existing rolling stock may be provided, by cooling the tunnels within which they operate. It has been shown theoretically, that by cooling the air within the tunnels by 9K, the temperature in the typical carriage operating under peak load conditions will reduce by approximately 6K to a much more acceptable level. Finally the paper identifies areas for further work, that are required in order to realise the preferred way of achieving a sustainable cooling scheme.

KEYWORDS

Metro, train, railway, underground, cooling, air conditioning, groundwater

NOMENCLATURE

g_{ai}	kg/kg	Internal air moisture content	g_{ao}	kg/kg	External air moisture content
m_{air}	kg/s	Air mass flow rate	Q_{condf}	kW	Conduction gain through floor
Q_{condg}	kW	Conduction gain through glass	Q_{condr}	kW	Conduction gain through roof
Q_{condw}	kW	Conduction gain through walls	Q_{lat}	kW	Total latent gain
Q_{light}	kW	Lighting gain	Q_{plat}	kW	People latent gain
Q_{psens}	kW	People sensible gain	Q_{sens}	kW	Total sensible gain
t_{ai}	^{o}C	Internal air temperature	t_{ao}	^{o}C	External air temperature

1.0 INTRODUCTION

The reduction of activity by heavy industry has resulted in rising water tables in certain areas. In two conurbations, London and Merseyside, which are served by deep underground railway networks, this is proving an increasing problem. Not only are there additional pumping costs incurred to remove excess water but there is also a serious deterioration of track, traction supply and signalling systems. In some instances this has resulted in the closure of rail lines for over one month, in order to carry out remedial works [Anon, 1995].

At the same time, rising comfort expectations show public transport in a worsening light, in view of the high temperatures and humidities experienced. There is pressure for improved comfort through a wider adoption of air conditioning. Conventional air-conditioning as applied in the Hong Kong Metro is both capital- and energy-intensive, and consequently comfort cooling of this kind is unlikely to be implemented [Mass Transit Railway, 2000].

An alternative means of providing cooling to these underground networks with minimal emission of greenhouse gases is a groundwater-cooling scheme. In this system, groundwater, which is normally at about $12^{o}C$ is passed through heat exchangers within the tunnels and these directly cool the air. This cold air will then provide cooling of the carriages directly through the ventilation system and indirectly through conduction via the car body. As well providing a low cost, environmentally friendly method of comfort cooling this scheme also provides a demand for the groundwater, which will help reduce the water table.

This paper investigates the potential for cooling the underground network and trains using groundwater. It uses a purposely-developed mathematical model to investigate whether sufficient cooling of the existing rolling stock may be provided. The paper initially describes a mathematical model simulating the heat transfer processes taking place in a typical railway carriage. This is then used to investigate the effect of a groundwater-cooling scheme and the paper discusses the results.

2.0 MATHEMATICAL MODEL

A mathematical model was initially constructed to evaluate the heat transfer taking place between the underground tunnel network and a typical railway carriage operating under conventional conditions. The thermal storage of the carriage was neglected and heat transfer was evaluated under a steady state worst case scenario. The following loads were considered in the analysis:-

- Conduction
- Occupancy
- Equipment
- Ventilation

The treatment of these loads is shown below:-

2.1 Conduction though the car body

The geometry of the car used in this analysis is shown in Figure 1.

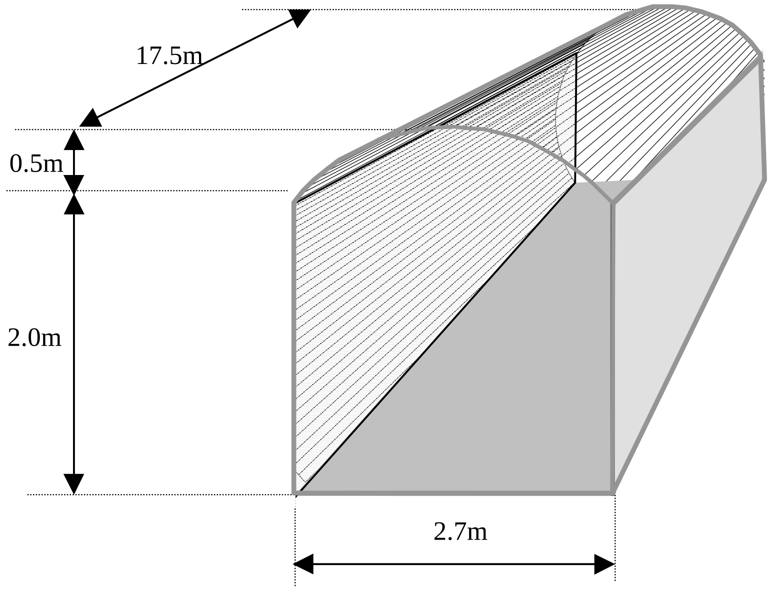


Figure 1. Geometry of a typical tube carriage.

Based on the above the total surface area each car is calculated to be:

- Roof 57.75m^2
- Floor 47.25m^2
- Walls 81 m^2

Of which 70% is assumed to be wall area with the remainder of the construction glazing.

The construction of the car walls/ roof/ floor was assumed to be 50mm thick polyurethane insulation. The external / internal skin of this construction was ignored as it would have small thermal conductive effect. The external surface heat transfer coefficient (h_{co}) was assumed mainly convective and was determined using:

$$h_{co} = 7.8V^{0.8} \qquad [1]$$

where V is the air velocity (>5m/s). The velocity used was an assumed average speed for the car of 10m/s, this is assumed to be an average of the total journey speed including platform stops.

The internal surface heat transfer heat transfer coefficient (h_{ci}) used was: -

$$h_{ci} = 0.123 \mathrm{W/m2K}$$

The U value used for the cars glazing was 3.674 W/m2K, which assumes severe external air velocity. The conductive heat transfer for the walls, floor and glazing was determined using equation 2.

$$Q=U*A*(t_{ao}-t_{ai}) \qquad [2]$$

Where t_{ao} & t_{ai} are the respective outside and inside air temperatures, and the peak outside air temperature used was 27^{o}C.

2.2 Occupancy

In evaluating the occupancy load it was assumed that 50 people could be present in a car under peak conditions. To account for the variable internal temperatures that can occur with the carriages and the effect of these on the occupancy load, the sensible and latent loads were calculated using equations 3 and 4.

$$Q_{psens} = -3.6517t_{ai} + 168.15 \qquad [3]$$

$$Q_{plat} = 3.6517t_{ai} - 28.146 \qquad [4]$$

These were determined by fitting trendlines to heat emission data for occupants involved in light activity [CIBSE, 1986]. This is shown in Figure 2.

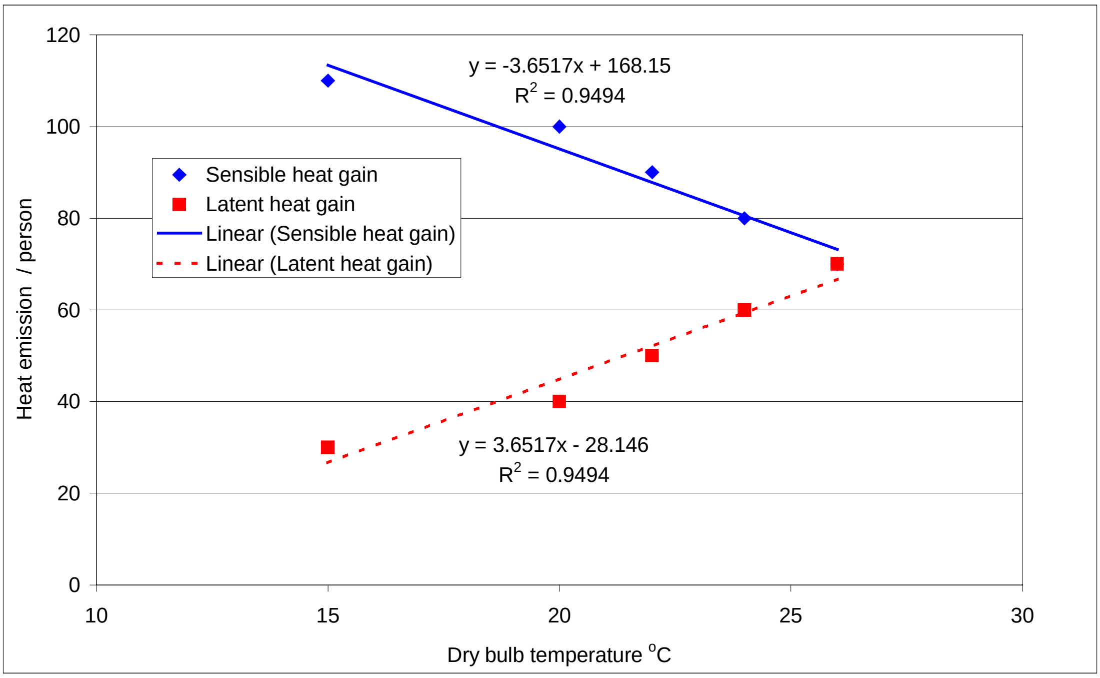


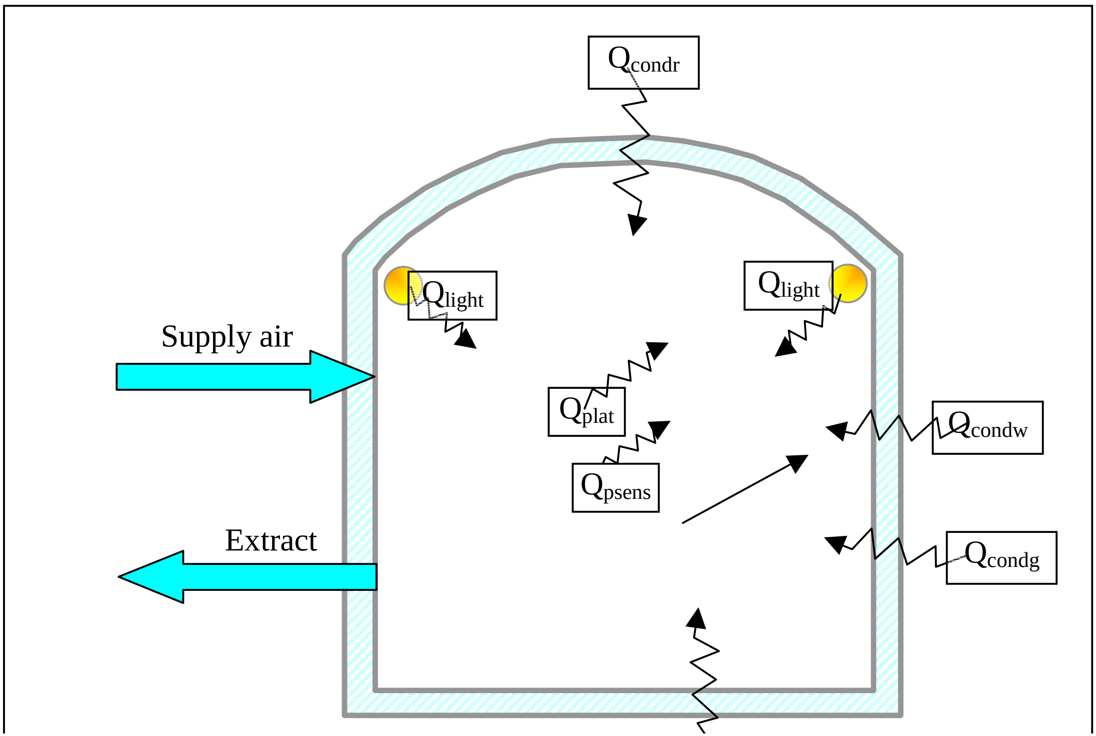
Figure 2 Heat emission per person against dry bulb temperature

2.3 Lighting

In each car it was assumed that 20 fluorescent luminaires each of 50W output would be used.

2.4 Peak loads and Ventilation

A forced ventilation system was assumed providing a minimum ventilation rate to the car of 8 l/s per person and this gives an air change rate of approximately 13 air changes per hour. The condition of the incoming air under peak conditions was assumed to be 27°C, 50% RH. The incoming air was assumed to mix completely with the air within the carriage, absorbing the gains before being expelled to atmosphere, as shown in Figure 3.



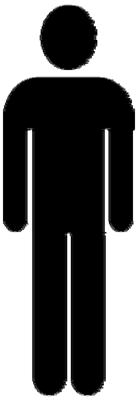


Figure 3.Treatment of heat loads within carriage

The peak sensible and latent heat loads that contribute to a change in temperature and moisture content within the carriage are defined using equations 5 & 6.

$$Q_{sens}= Q_{light} +Q_{psens} +Q_{condg} +Q_{condw} +Q_{condf} +Q_{condr} \quad [5]$$

$$Q_{lat} = Q_{plat} \quad [6]$$

The ventilation air was then assumed to be supplied into the carriage to balance the

$$Q_{sens}=m_{air}*1.02*(t_{ai}-t_{ao}) \quad [7]$$

$$Q_{lat}=m_{air}*2450*(g_{ai}-g_{ao}) \quad [8]$$

2.5 Model Software Used

The model was written using EES which is an engineering equation solving language. The advantage of using EES in this context is that it includes built in psychrometric functions, which enables air humidity as well as temperature in the occupied carriage to be predicted. Furthermore, EES incorporates a function that enables parametric studies to be carried out.

3.0 INVESTIGATIONS WITH THE MODEL

3.1 Heat Transfer Analysis under Conventional Conditions

Initially the model was used to evaluate operation under peak load conditions. This was assumed to be when operating fully loaded at midday in August. The model predicted an internal temperature within the space of 33.1 ^{o}C and 50% RH, when operating in an ambient air temperture of 27^{o}C. A breakdown of the heat loads contributing to this high temperature are shown in Table 1.

Description of gain	Load kW
Conduction via floor	-0.139
Conduction via glass	-0.449
Conduction via walls	-0.144
Conduction via roof	-0.169
Lighting load	1
Occupancy sensible	2.372
Occupancy latent	4.629
Total sensible load on carriage	2.472
Total latent load on carriage	4.629

Table 1. Results of heat transfer analysis for operation underground

The total gains to the carriage are 2.472 kW sensible and 4.629 kW latent The sensible load is mainly a result of the loads due to lighting and people, whereas the latent load is solely dependent on the load due to people. Also it can be seen that the conductiove loads through the floor, glass and walls provide a small amount of cooling to the carriage.

3.2 Free Cooling of the Existing Rail Stock

The initial results indicate that unacceptable temperatures can occur in the carriage under peak conditions. With the existing railstock cooling may be provided by using groundwater to cool the air within the tunnels. This is achieved by colder ventilation air and by increased conductive cooling.

To demonstrate and quantify this, the model was used to perform a parametric study showing the influence of tunnel temperature on comfort with the carriage space. The results from this invesitigation are shown in Figure 4. This demonstrates that if the tunnel temperature is reduced to 18^{o}C, the carriage temperature reduces to a much more acceptable temperature of 24.7^{o}C. However, the lower temperature also realise a lower latent heat emmission from the carriage occupants, and this realises a lower moisture content and acceptable relative humidity also as shown in Figure 4.

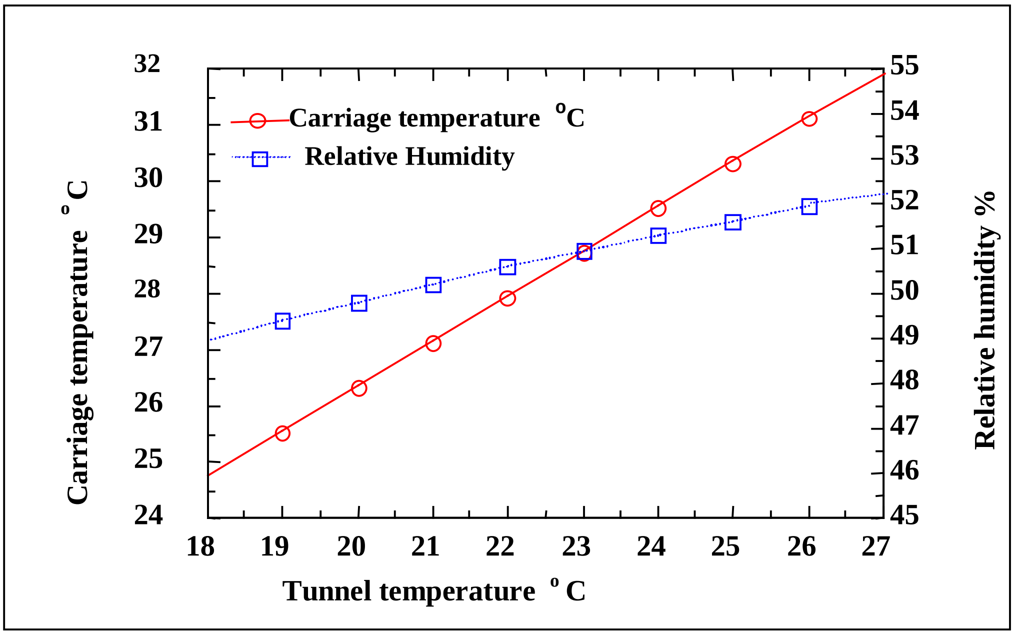


Figure 4. Influence of tunnel temperature on carriage comfort conditions

3.3 Free Cooling of the Modified Rail Stock

The benefit of colder ventilation air and conductive cooling on the existing rolling stock was shown above. By making modifications to the design of this rail carriage it is possible to increase the cooling effect of the conduction and the ventilation air. These factors were investigated using the model.

To investigate the conductive cooling effect the model was modified to simulate the effect of thermal conductivity of the wall structure on comfort conditions. A parametric study was carried out allowing the thermal conductivity to be varied between 0.05 to 1 W/mK. The results from this investigation are shown in Figure 5 and these demonstrate that further improvements in comfort conditions maybe achieved by using a higher conductivity wall construction, however a similar result is obtained if single glazing is used rather than double glazed units. However, before any changes to rail carriage design is carried out the effect of insulation properties on acoustic comfort within the carriage would require evaluation.

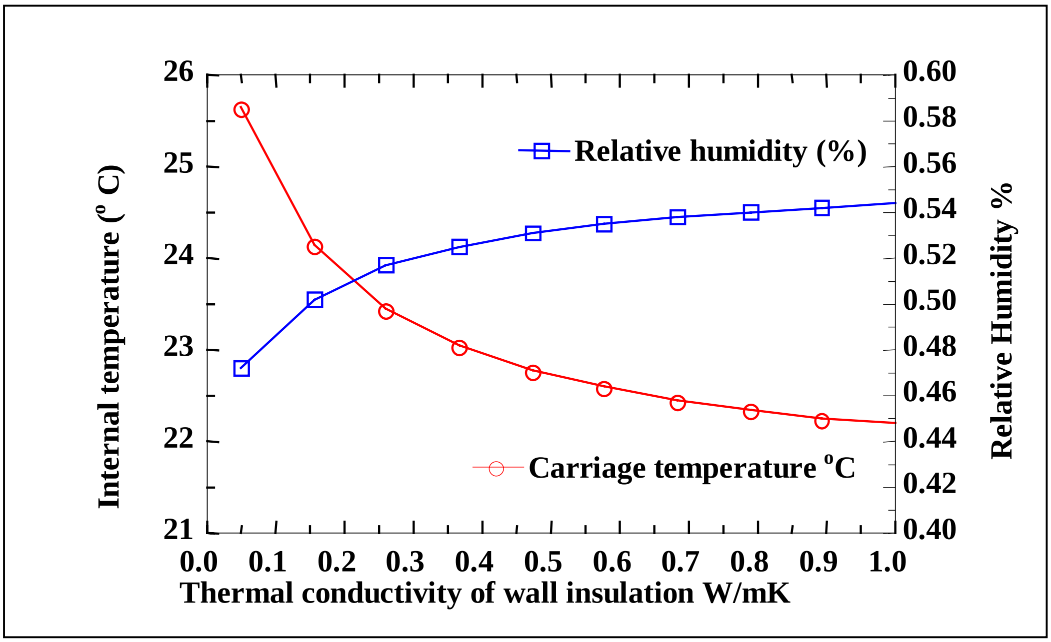


Figure 5. Influence of wall thermal conductivity on carriage comfort conditions

With modifications to the rolling stock it may be possible to increase the ventilation rate. The effect of air change rate on comfort conditions was investigated. The results from this investigation are shown in Figure 6 and this demonstrates that comfort conditions maybe further improved if a high air change rate can be achieved. However, the results also indicate that with reduced ventilation rates, both temperature and humidity levels within the carriage are unacceptable. The maximum air change rate that may be achieved will depend upon the size of diffuser area and also the maximum air velocity that may be tolerated within the space. Faber & Kell[1995] give a maximum hourly air change rate of 20 for effective air distibution.

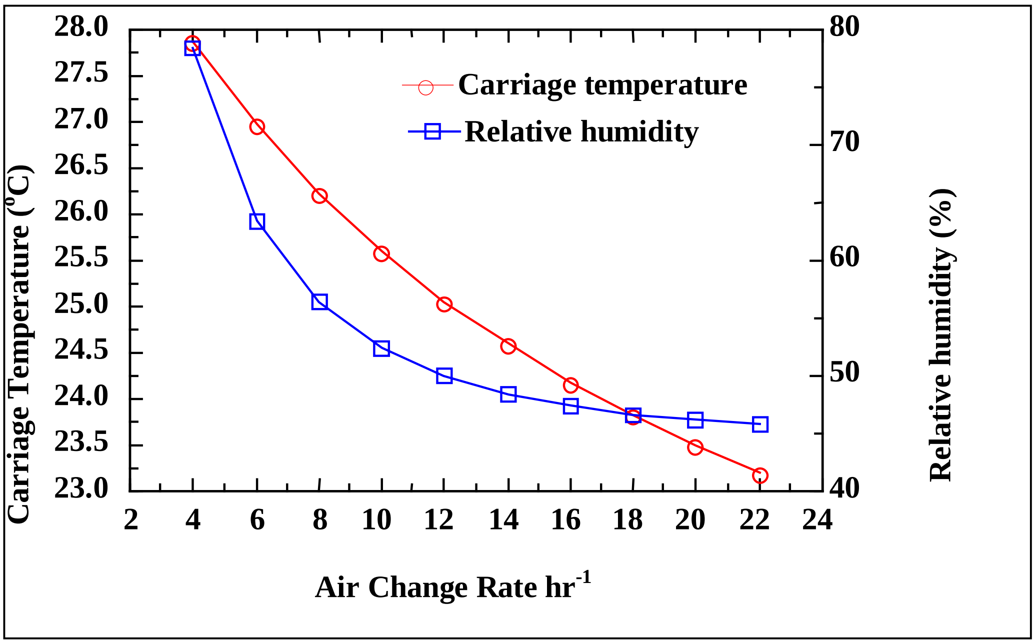


Figure 6. Influence of air change rate on carriage comfort conditions

CONCLUSIONS

This paper outlines a novel cooling system that may be used to cool underground railway networks. This system uses groundwater is naturally at around 12°C to cool the tunnel networks / trains and is energy efficient and environmentally friendly. However, the system also provides a demand for groundwater and this will assist in the reduction of water levels, which in recent years has presented increasing problems for deep underground railway networks.

This paper investigates the potential for cooling the underground network and trains in this way. It uses a purposely-developed mathematical model to show that additional cooling to the existing rolling stock may be provided, by cooling the tunnels within which they operate. It has been shown theoretically, that by cooling the tunnels by 9K, the temperature in the typical carriage operating under peak load conditions will reduce by approximately 6K to a much more acceptable level. The paper also quantifies the effect of modifications to the railway carriage design that will further improve the comfort conditions.

This paper has shown that free cooling is theoretically possible, by cooling the tunnel networks to 18°C. There are a number of ways of achieving this through the use of a distribution pipe/ heat exchanger as used in the Channel Tunnel [Ellison, 1993], extended surface heat exchangers, or an evaporative cooling system.

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