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Modelling the full cycle of air-borne spores in buildings

Hiba AJIB ^{a,b,c}, Bénédicte WALL-RIBOT ^{a,c}, Sébastien LABBÉ ^{a,c}, Marc ABADIE ^{b,c}, Karim LIMAM ^{b,c},
Thierry DUFORESTEL ^{a,c}.

^a EDF R&D, Moret-sur-Loing, France, hiba.ajib@edf.fr

^b Laboratory of Engineering Sciences for the Environment LaSIE (UMR CNRS 7356), La Rochelle University, France

^c 4evLab, CNRS, La Rochelle University, Electricité de France EDF, Avenue Michel Crépeau, 17042 La Rochelle Cedex 1, France

Abstract. Predicting mould growth in buildings is essential to avoid environmental, financial and health damage. It is an important factor in evaluating indoor air quality through the quantification of spores emitted by the fungal colonies. Most of the spores that are found indoors are transported from outside either by ventilation or by the occupants and in favourable conditions these spores germinate, grow and emit spores indoors. The aim of this paper is to model the full cycle of air-borne spores from their exchange between indoor and outdoor environments to their deposition on indoor surfaces, germination, growth, and multiplication. Two mould growth models, i.e., the VTT and the isopleth models, are implemented in 0D/1D components in the BuildSysPro QAI library to evaluate the mould contamination on surfaces. Three different air change rates (ACR) are considered to study their effect on mould formation (0.5 h^{-1} , 0.3 h^{-1} and 0.2 h^{-1}). The mould index and the mycelium length are compared in these three scenarios. The results show that even at a very low air change rate (0.1 h^{-1}), resuspension of spores from the floor does not have a significant impact on the concentration of spores in the air.

Keywords. air-borne spores, mold growth, indoor air, modelling, BuildSysPro QAI, office and residential buildings.

1. Introduction

Recent thermal and environmental regulations have led to a decrease in indoor air temperatures and ventilation rates, leading to an increased confinement of indoor spaces. These conditions increase the risk of mould formation which can deteriorate the indoor air quality. According to ANSES (Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail) the presence of mould in dwellings is estimated between 14 and 20% in France and 20% in Europe and North America (ANSES, 2016). Moulds emit spores, microbial volatile organic compounds (mVOC) and mycelium fragments that can have adverse health effects often linked to respiratory illnesses such as asthma and chronic bronchitis (Hulin et al., 2013). The growth of mould is initiated by the germination of spores, so to avoid mould contamination, a deeper comprehension of the spore behaviour is needed.

Most of the spores that are found indoors are transported from outside either by ventilation or by the occupants and pets (Lehtonen et al., 1993). These spores either remain suspended in the air or they deposit on surfaces and germinate in case of

favourable conditions. In the absence of mould growth, the concentration of spores indoors follows the outdoor spore concentration. However, in the presence of fungal contamination local emission increases the indoor spore concentration (Haas et al., 2007; Hyvärinen et al., 2001). Both external sources and the emission of spores from fungal colonies (Górny et al., 2001) should be considered when estimating the concentration of spores indoors. Aerosolization of spores due to activities also plays an important role when determining the indoor spore concentration (Lehtonen et al., 1993; Li et al., 2022).

Several models that predict the growth of mould exist in the literature and details on each model can be found in (Vereecken & Roels, 2012). However, among these models, the VTT (Hukka & Viitanen, 1999) and the isopleth model (Sedlbauer, 2002) are considered in this work due to their wide use in the literature. The VTT model allows a direct estimation of the infected surface, whereas the isopleth model allows an estimation of the mycelium length, which can be indirectly used to estimate the infected surface.

The aim of this paper is to compare the VTT and the isopleth models and to identify the main drivers of

indoor spore concentration by comparing indoor and outdoor spore levels. This is achieved by modelling the full cycle of air-borne spores from their flow between indoor and outdoor environments to their emission by fungal colonies.

2. Methods

This study is performed based on a modelling approach using the BuildSysPro QAI library. To estimate the mould growth on the surface, the VTT and the isopleth models are integrated in this library. The emission of spores is then estimated based on the principle of resuspension of particles (Thatcher & Layton, 1995).

2.1 Modelling library: BuildSysPro QAI

The BuildSysPro library, developed by EDF R&D (Plessis et al., 2014; Schumann et al., 2016) under the Dymola environment and using the Modelica language, is dedicated to the thermal modelling of buildings and energy systems. In order to study the indoor air quality (IAQ), a new library, BuildSysPro QAI, was developed (Picard, 2019; Tourreilles, 2015) that takes into consideration the thermo-hygro-aerodynamic-IAQ phenomena by solving the energy and mass conservation equations. This library permits simultaneous modelling of building energy performance and IAQ. This multi-physical approach allows to simultaneously simulate:

- The aerodynamics of the different zones (air exchange between indoors and outdoors, infiltration, Air Handling Units (AHU), ventilation systems ...).
- The hygrothermal properties on the wall surface.
- The interaction between the wall and the pollutants (deposition and resuspension for particulate pollutants; adsorption and desorption for gaseous pollutants).
- The concentration of particulate and gaseous pollutants.

The moisture content at the wall surface is estimated using the EMPD (Effective Moisture Penetration Depth) model (Cunningham, 1992). The deposited particle flow is governed by the balance between those deposited and those resuspended for each class of particles considered. The deposition velocity is calculated based on the model described in (K. Lai & Nazaroff, 2000) which depends on the particle diameter and its density.

2.2 VTT model

The VTT mould prediction model presented in (Hukka & Viitanen, 1999) is an empirical model based on

regression analysis of laboratory studies on pine and spruce sapwood. It uses surface readings of relative humidity and temperature to calculate the mould index M by solving a differential equation representing the variation of the mould index with time. This mould index varies between 0 (no growth) and 6 (all the surface covered with mould), and it gives an indication of the percentage of the surface infected by mould.

2.3 Isopleth model

The isopleth model represents a system of isolines relating the temperature and the relative humidity on the surface of the material. Germination isopleth system is used to calculate the time needed by the spores to germinate while the growth isopleth system determines the growth of mould represented by the mycelium length.

The existing isopleth models (Ayerst, 1969; Smith & Hill, 1982) were developed for complete culture media, so in order to consider the influence of the material, the isopleth model was extended by subdividing the materials into categories (Sedlbauer, 2002). A system of isopleths for the germination time and the mycelium growth rate was developed for each category. Figure 1 represents the system of isopleths of category 1 that is used in this study to estimate the time needed by the spores to germinate and then to calculate the mycelium length. Category 1 represents biologically recyclable materials (Sedlbauer, 2002).

2.4 Emission of spores

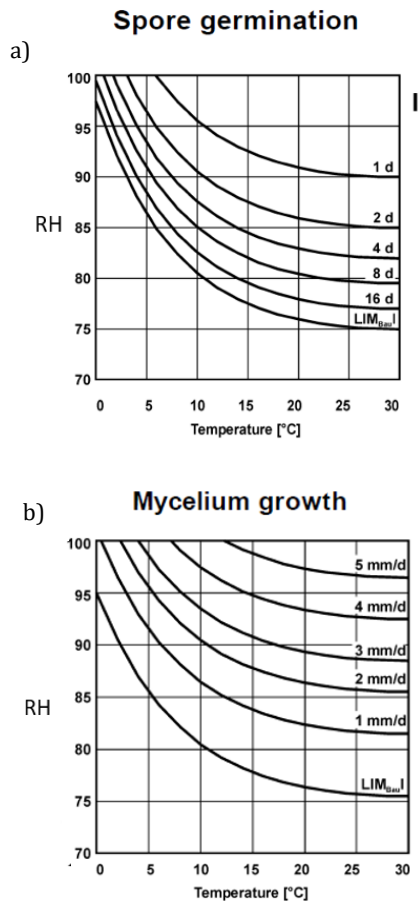
The aerosolization of spores from fungal colonies is a complex mechanism that depends on different physical and biological parameters. For the spores to detach from their colonies, the external detachment force should exceed the binding force between the spores and colonies. The binding force depends on the growth age of the fungal colony and the fungi specie, whereas the detachment force depends on the environmental conditions (air velocity, vibrations, relative humidity,...) (Li et al., 2022). The complexity of the mechanism, along with the uncertainty in determining the detachment and binding forces, makes it hard to estimate the concentration of the released spores.

Some studies estimated the rate of spore release (Kildesø et al., 2003; Sivasubramani et al., 2004); however, these rates are based on particular environmental conditions and are specific to certain fungal species.

In this study, we opt for a simpler approach where we model the aerosolization of spores based on the resuspension of particles. Moreover, the indoor spore concentration is estimated based on the difference between the deposited and resuspended particles.

Figure 1

Isopleth systems of category 1; a) spore germination system b) mycelium growth system (Sedlbauer, 2002)



2.5 Case study

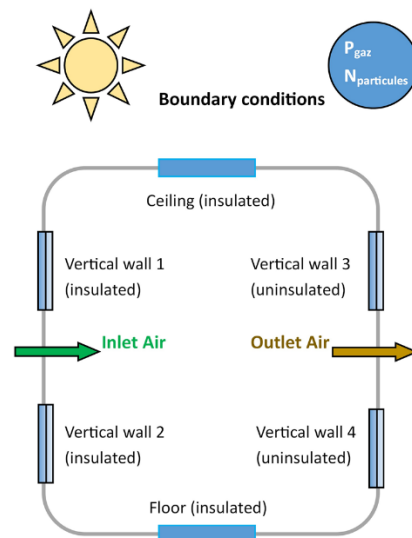
The objective of this case study is first to verify the consistency of our results under the BuildSysPro QAI library with the VTT and the isopleth models, second to compare the results of these two models under different ACR and third to estimate the concentration of spores indoors. *Cladosporium* spores are considered in this study as they are one of the most monitored and abundant species indoors and outdoors. The outdoor yearly concentration profile is taken from the study of (Sindt et al., 2016), which represents the mean values of five stations in France. The considered spores belong to the class of particles with a diameter ranging between 1 and 2 μm (Reponen et al., 1996) and a density of around 2 g/cm^3 . These properties play an important role in calculating the deposition velocity of spores on the surface.

Several simulations are carried out on a building of 36 m^2 (volume: 90 m^3) represented by one homogeneous zone surrounded by 4 walls, 1 floor and 1 ceiling and predefined boundary conditions (Figure 2). The surface of each wall is equal to 15 m^2 . The inner most

layer of the vertical walls and the ceiling is plasterboard and that of the floor is PVC linoleum. These layers are in direct contact with the indoor air and are subjected to mould formation. Inlet and outlet components ensure the thermo-hygro-aerodynamic-IAQ exchange between indoors and outdoors by determining the desired ACR (air change rate).

Figure 2

Schematic representation of the simulated model



2.5.1 Configuration A

In this configuration, constant boundary conditions are considered to verify the results of mould growth on the surface.

A temperature of 22°C and a relative humidity of 97% are chosen to verify the consistency of our results with the VTT model. The results are compared to those presented in (Viitanen et al., 2011).

To verify our results with the isopleth model, a temperature of 20°C and a relative humidity of 97 % are chosen. The results are compared to those found in (Vereecken & Roels, 2012).

2.5.2 Configuration B

Two simulations are carried out for 1 year each. In the first simulation, spore emission is not taken into account, so the velocity of the resuspended particles is equal to zero. The results of the VTT and the isopleth models are compared for 3 different air change rates: 0.5 h^{-1} , 0.3 h^{-1} and 0.2 h^{-1} . These ACR values are chosen to simulate mould growth in energy efficient French buildings. Two types of vertical walls are studied, insulated and uninsulated. The thermal insulation material of two vertical walls, ceiling and floor was kept throughout the simulation, whereas the thermal insulation of the other two vertical walls was removed. In the second simulation, the emission of

spores is assessed based on the resuspension of particles. A resuspension rate of $1.8 \times 10^{-5} \text{ h}^{-1}$ is considered following (Thatcher & Layton, 1995) which corresponds to the resuspension due to the movement of the occupants. An ACR of 0.1 h^{-1} is considered to limit the effect of external spore concentration. In both simulations, transient boundary conditions are considered, and the meteorological data used are those of the city of Paris. A heating system is used from October to April to maintain the indoor air temperature at 20°C . Moreover, a vapor production scenario of 3.6 kg per day is considered to account for indoor activities and the presence of occupants. This value is based on the studies presented in (Leprince, 2011).

3. Results

In this section, the simulation results of the studies performed under configurations A and B, described in Sec. 2.5, are presented.

3.1 Configuration A

Figures 3 and 4 below show the results obtained from the implementation of the VTT and the isopleth models respectively in the BuildSysPro QAI library compared to real data reported in (Viitanen et al., 2011; Vereecken & Roels, 2012). A good consistency between simulation results and these data is observed.

In particular, Figure 3 shows that the mould index reaches the same maximal value as that reached by the VTT model. Furthermore, the different mould indices are reached at the same time and the results are consistent for the different sensitivity classes.

On the other hand, the mycelium length calculated under the BuildSysPro QAI library is coherent with that calculated in (Vereecken & Roels, 2012). However, a slight difference exists between the two results. After 180 days, the simulated mycelium length reaches 867 mm, but it reaches 882 mm according to the isopleth model which corresponds to a 1.7 % error. This difference could be due to the inaccuracy of the model between the different zones of the isopleth system where a linear interpolation was adopted. Note that, according to (Sedlbauer, 2002), the mycelium length after a certain time should be considered only qualitatively and for comparative studies.

3.2 Configuration B

Figures 5, 6 and 7 show the variation of the mould index M and the mycelium length throughout the year for an ACR of 0.5 h^{-1} , 0.3 h^{-1} and 0.2 h^{-1} respectively. As it can be seen, for an ACR of 0.5 h^{-1} , the mycelium length is equal to zero and the mould index M is less

than 1, so no mould growth is observed under both models, even on the uninsulated walls.

Figure 3

Variation of the mould index M with time under constant T (22°C) and RH (97%) for the different sensitivity classes. vs: very sensitive, s: sensitive, mr: medium resistant, r: resistant,

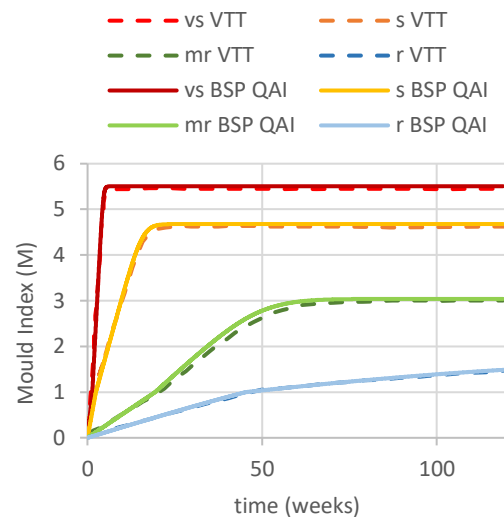
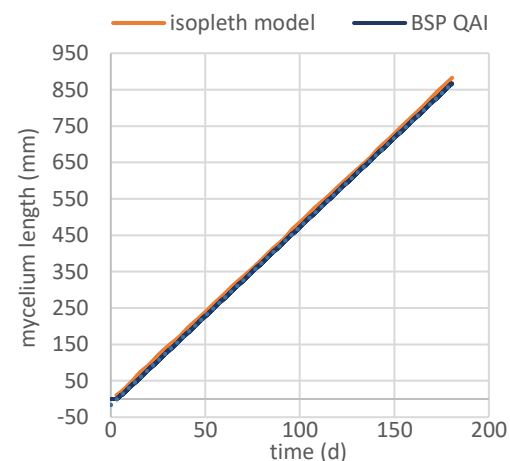


Figure 4

Variation of the mycelium length with time under constant T (20°C) and RH (97%).



By decreasing the ACR to 0.3 h^{-1} mould growth is observed under the isopleth model but not under the VTT model ($M < 1$). And finally, by considering an ACR of 0.2 h^{-1} mould growth is observed under both models.

The effect of wall insulation can be seen in all cases. In Figure 7, for example, where an ACR of 0.2 h^{-1} is considered, the mould growth on the uninsulated wall starts 50 days in advance compared to the insulated

one and reaches values which are greater than those of the insulated wall ($M=4.6$ for the uninsulated wall and 2.4 for the insulated wall, mycelium length = 920 mm for the uninsulated wall and 500 mm for the insulated wall).

Figure 5

Variation of the mould index M and the mycelium length throughout the year, for insulated and uninsulated wall and for ACR of 0.5 h^{-1}

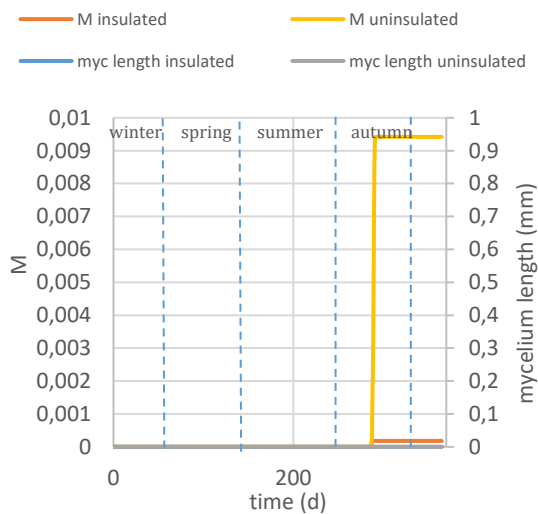
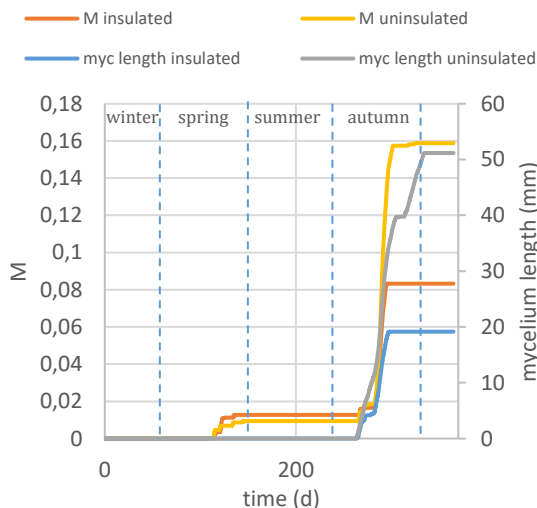


Figure 6

Variation of the mould index M and the mycelium length throughout the year, for insulated and uninsulated wall and for ACR of 0.3 h^{-1}

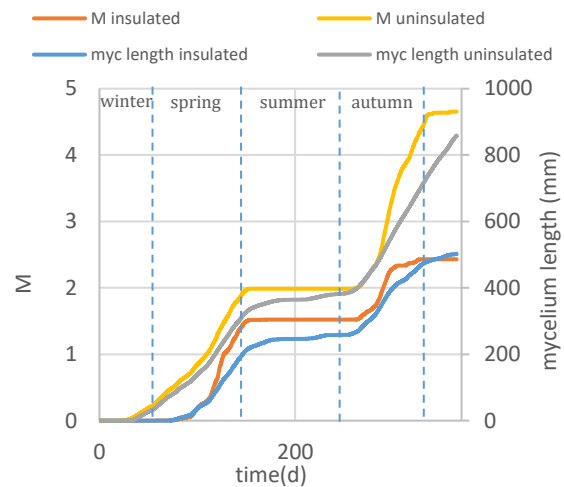


A similar behaviour of mould growth can be observed under both models. During winter, no mould growth is observed, as a result of the constant temperature (20°C) and the relatively low relative humidity due to the heating system. During spring, the heating system is turned off, so the indoor temperature decreases and the indoor relative humidity increases (above 80%)

leading to mould growth. During summer, no growth is observed and both the mould index and the mycelium length remain approximately constant. In autumn, due to low temperatures and high relative humidity, mould growth reappears. It should be noted that the decline of mould growth in the VTT model is not considered in this study.

Figure 7

Variation of the mould index M and the mycelium length throughout the year, for insulated and uninsulated wall and for ACR of 0.2 h^{-1}



To estimate the concentration of indoor spores resulting from resuspension, an ACR of 0.1 h^{-1} is considered to reduce the effect of outdoor spore concentration. Figure 8 represents the volume spore concentration outdoors and indoors for a resuspension rate (R) of $1.8 \times 10^{-5} \text{ h}^{-1}$ (value proposed by Thatcher model) and 0 (no resuspension). It is observed that the indoor spore concentration does not vary with $R=1.8 \times 10^{-5} \text{ h}^{-1}$ and $R=0$. The rate of resuspension has, therefore, no significant effect on the indoor spore concentration which follows the outdoor spore concentration. In Figure 9, we compare the particle flow rate entering the building and the particle flow resulting from resuspension. The results show that the particle flow rate resulting from resuspension is negligible compared to the outdoor particle flow rate.

However, the resuspension rate considered represents the aerosolization of spores due to the movement of occupants. The emission of spores depends also on biological phenomena (see section 2.4) which are not taken into consideration. As mentioned in section 1, in the presence of mould, at least one study considers that the concentration of indoor spores increases.

Figure 8

Comparison between the outdoor spore concentration and the indoor spore concentration when $R=1.8 \times 10^{-5} h^{-1}$ and $R=0$

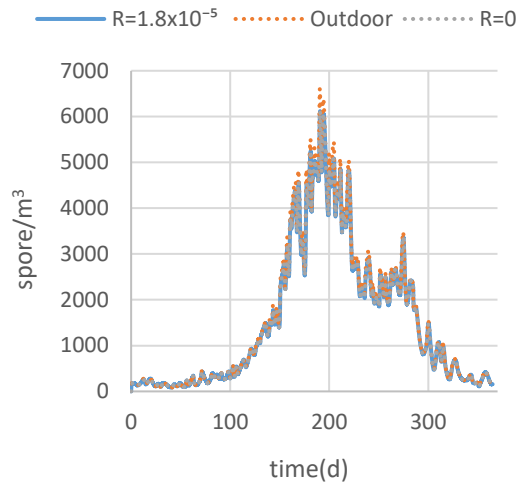
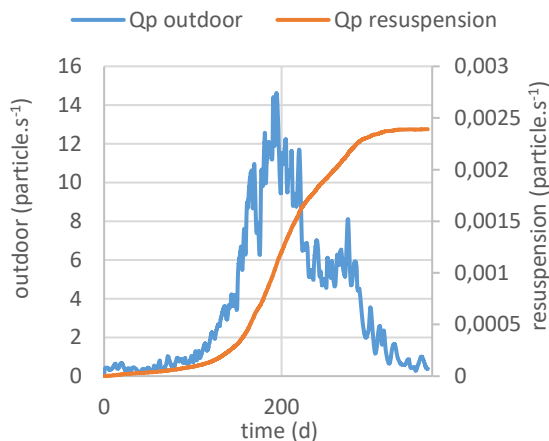


Figure 9

Comparison of the outdoor particle flow rate and the resuspension flow rate



4. Discussion

The simulation results described in the previous section show that the implementation of the VTT and the isopleth models in the BuildSysPro QAI library provide coherent results compared to real experimental data. This demonstrates the feasibility of using such modelling tools to simulate and predict the growth of mould on indoor surfaces while considering the thermo-hygro-aerodynamic phenomena taking place.

The comparison between the two models has shown similar results when it comes to the behaviour of mould growth. However, mould growth estimated under the isopleth model starts ahead of that in the VTT model in all considered cases. This difference

might be due to the difference in the critical relative humidity between the two models. In the VTT model, at a temperature of 15°C, the critical relative humidity is 80 %, however in the isopleth model it is 77%. Spore germination in the isopleth model might, as a result, start before that in the VTT model. For a better comparison, an estimation of the percentage contamination of the surface under both models could be calculated. The results of this comparison will be presented in future work.

On the other hand, the effect of the ventilation rate on the growth of mould was analysed. To guarantee no mould formation, an ACR of 0.5 h^{-1} proved to be essential. It should be noted that a moderate scenario of vapour production is considered in this study (3.6 kg per day).

Finally, the spore emission was estimated based on the resuspension of particles. We observed, however, that the resuspension rate due to movement of the occupants has no significant effect on the indoor spore concentration. Other biological phenomena must be taken into account to ensure a proper estimation of the effect of the emission of spores on the total spore concentration.

5. Conclusion

In this paper, we present a comparison of simulation results obtained under the BuildSysPro QAI library of the VTT and the isopleth mould growth estimation models. The two models are also compared to each other under multiple realistic conditions. Moreover, the growth of mould is studied for different ACR values, and different insulation level of walls. The effect of resuspension resulting from the movement of the occupants is analysed. Some other factors that could be taken into account in future work are the surface spore concentration and the spore emission resulting from varied biological phenomena. It could also be interesting to compare the VTT and the isopleth models by estimating the percentage surface contamination.

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