PREDICTION OF RAIN NOISE IN BUILDINGS USING EMPIRICAL MODELS FOR ARTIFICIAL AND NATURAL RAINFALL

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1 INTRODUCTION

The use of lightweight roofs and roof glazing can lead to problems with rain noise inside buildings that interferes with speech intelligibility, acoustic comfort and listening conditions. Laboratory measurement procedures are described in ISO 10140 using artificial rain. Such measurements can be used to compare individual roof elements with a specific type of rain, usually artificial 'heavy rain' because it generates sufficient levels above background noise and it can be seen as a 'worst case'. The artificial rain is defined by a single diameter drop size at a specified rainfall rate. However, it is not always clear how to interpret laboratory rain noise data that has been determined with a single raindrop diameter and rainfall rate in the context of natural rain (i.e. real rain). This paper discusses empirical models that have been developed to determine the time-dependent force on horizontal and inclined plates with artificial and natural rainfall. This has allowed the calculation of conversion factors between laboratory measurements with artificial rain to other situations with natural or artificial rainfall, and between measurements on roof elements that are inclined at different angles.

2 ARTIFICIAL AND NATURAL RAIN

Artificial rain is used for laboratory measurements as described in the International Standard, ISO 10140-5[1]. This prescribes use of a rain box to produce two types of artificial rainfall for measurements; these are 'intense' and 'heavy' rain which have rainfall rates of 15 and 40 mm/h respectively, and median drop diameters of 2 and 5 mm respectively. Note that the previous measurement standard, ISO 140-18[2], also defined 'moderate' rain[3] as having a rainfall rate of 4 mm/h and a 0.5 to 1 mm drop diameter but this was not intended for measurements because sound pressure levels would not always be measurable for highly insulated roofs. In many laboratories it is unusual to have sufficient headroom to elevate the rain box to a height that can provide drop impacts at terminal velocity, i.e. 6.6 m to give 6.2 m/s for 2 mm drops and 12 m to give 9.5 m/s for 5 mm drops. For this reason, ISO 10140-5 prescribes a fall height of ≈1 m to achieve 4 m/s for 2 mm drops (artificial intense rain) and a fall height of ≈3.5 m to achieve 7 m/s for 5 mm drops (artificial heavy rain); these are sub-terminal velocities.

Natural rain has a statistical distribution of raindrop sizes which varies with rainfall rate and the time period within the total time period of the rain event. Physical mechanisms that determine the raindrop size distribution are wind, temperature, relative humidity, evaporation, collision between drops and potentially the break-up of large drops due to aerodynamic forces. Whilst 'giant' raindrops (4 to 8mm diameter) have been found inside clouds[4], as raindrops descend from the clouds (anywhere in the world), collisions between drops causes their break-up and this process tends to remove larger diameter drops[5,6]. In some places in Europe, such as in the Mediterranean climate of south-east Spain, raindrop diameters have been measured during rainfall rates between 40 and 120 mm/h but no raindrops larger than 4 mm were found[7]. However 5mm drops may originate in cold rain from hailstones that melt during the descent[8].

The statistical distribution of drop diameters for natural rain can be modelled using the Marshall-Palmer distribution[9] to give $n(D)$ where $n(D)\delta D$ is the number of drops per cubic metre that have diameters between D and δD. When this model was proposed by Marshall and Palmer it demonstrated good agreement for rainfall rates of 1.0, 2.8, 6.3 and 23 mm/h in Ottawa, Canada.

Although a gamma distribution has also been proposed for drop size distributions, the Marshall-Palmer distribution is still considered to be robust nowadays[10] and can be considered to be sufficiently accurate for larger drop diameters that primarily determine rain noise. Figure 1 shows the Marshall-Palmer distribution for three different rainfall rates (4, 15 and 40 mm/h) which indicates how the number of larger diameter drops increases with increasing rainfall rate. Note that whilst 6 mm drop diameters are shown on this figure there is rarely a need to consider drop diameters larger than 5 mm in temperate climates as indicated by the discussion above. Hence all calculations for natural rain in this paper carry out calculations assuming that the largest drop diameter that occurs is 5 mm.

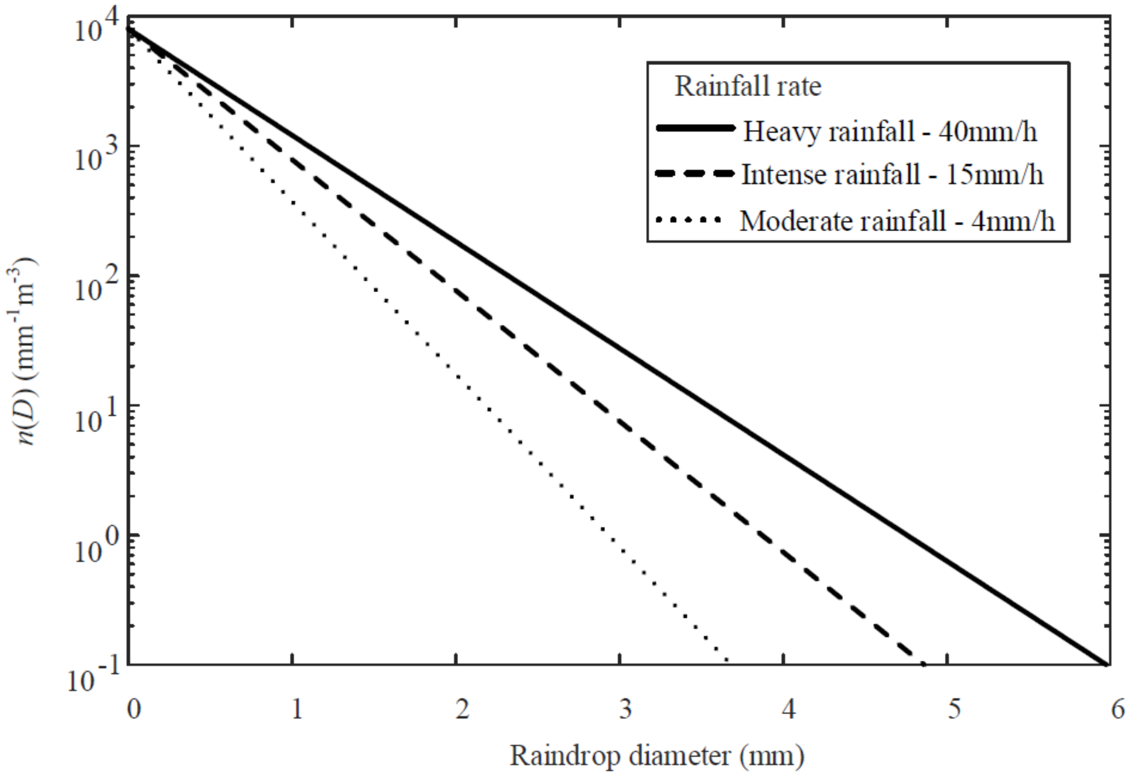

Figure 1. Examples of the Marshall-Palmer distribution for three different rainfall rates.

Rainfall rates can be highly variable both during and between precipitation events and can only usually be described ‘on average’. In temperate climates, natural heavy rain at a rainfall rate of 40 mm/h might only occur for 30 minutes with a return period every ten years (although global warming could be increasing heavy rain events) whereas in Sydney (Australia) it could occur for a 20 minute duration every year. Designing buildings to avoid rain noise problems would require rainfall statistics on Intensity – Frequency - Duration (corresponding to Rainfall rate - Return rate - Duration) but this information is not always easy to obtain for a specific location.

3 EMPIRICAL MODELS FOR ARTIFICIAL AND NATURAL RAINFALL

3.1 Recent research

In 2018, Yu and Hopkins[11] used an experimental approach using wavelets to measure the time-dependent force from a liquid water drop impact for a range of drop velocities up to and including terminal velocity, the latter being relevant to rainfall. This paper reports the more recent findings from Yu and Hopkins[12] in 2020 which demonstrate the potential to use validated models to calculate conversion factors between laboratory measurements with artificial rain to other situations with natural or artificial rainfall, and between measurements on elements that are inclined at different angles. The reason to look at different inclinations came from the fact that for a roof element under test, ISO 10140-5 refers to a pitch of 30° as the standard configuration. Whilst 30° is a reasonable value for the average roof pitch, roofs on buildings tend to be inclined at angles ranging between 5° and 75°. However, flat roofs also exist and the effect of the angle on the power injected into a plate by rain had not previously been established. In addition, as cars become quieter, rain noise inside car cabins can be important and whilst a panoramic glass roof is flat, the front windscreen and rear window can be at an angle that is steeper than 30°.

Empirical models were developed using experimental work with wavelet deconvolution for single drops impacting at terminal velocity on a horizontal glass plate with and without a water layer, and an inclined glass plate at various angles up to 60°. Use of the models to compare different types of rainfall was validated with artificial rain. The validated model has been used to calculate conversion factors between laboratory measurements with artificial rain to other situations with natural or artificial rainfall, and between measurements on roof elements that are inclined at different angles. For inclined plates as exist in buildings and cars, two empirical models were developed in the previous work[12]. The first approach used the empirical model for a horizontal plate (dry or with surface water) and converted it to an inclined plate by estimating the drop velocity in the direction perpendicular to the plate surface. The second approach extended a semi-empirical model for dry, horizontal plates so that it applies to drops falling at terminal velocity onto dry, inclined plates; this is referred to as the *angle-corrected semi-empirical model*.

Experimental work was carried out to validate the models. Measurements for single 4.5 mm drops impacting on plates inclined up to 60° showed better agreement with the second approach. Artificial rain measurements for rainfall rates between 24 and 30 mm/h confirmed the validity of this second approach even though it assumes a dry surface. However, for heavy and torrential rain (i.e. rainfall rates higher than 40 mm/h), the first approach to modelling does allow the option to include a 1 or 2 mm water layer on the surface. Based on comparisons between experiments and models it was decided that the validated model for the second approach was better suited to calculate conversion factors between different laboratory measurements with artificial rain, field measurements with natural rain and other conversions between artificial and natural rainfall for test elements inclined at different angles. This second approach is the angle-corrected semi-empirical model which is described below.

3.2 Angle-corrected semi-empirical model

A semi-empirical model for the time-dependent force from a liquid drop impact at sub-terminal drop velocity on a dry, horizontal surface was developed by Mitchell et al[13]. These measurements were carried out at sub-atmospheric pressure so that the drops remained spherical. However, 2 mm and 5 mm drops are expected to be ellipsoidal[12,14] at the drop velocity used for artificial rainfall measurements according to ISO 10140-5. Hence Yu and Hopkins[12] aimed to use the semi-empirical equation from Mitchell et al to determine a more flexible model with empirical constants that apply to ellipsoidal-shaped drops falling at any velocity up to and including terminal velocity, onto either a horizontal or inclined dry surface. This is referred to as the angle-corrected semi-empirical model and gave the time-dependent force, $f(t)$, as

$$f(t) = C\sqrt{\frac{tv_{\mathrm{d,n}}}{10^{-3}\tau D}}\exp\left[-\left(\frac{tv_{\mathrm{d,n}}}{10^{-3}\tau D}\right)^{\alpha}\right]10^{-6}\rho_{\mathrm{w}}D^{2}v_{\mathrm{d,n}}^{2} \tag{1}$$

where D is the drop diameter in mm, ρ_w is the density of water, v_d is the sub-terminal drop velocity, C and τ are empirical constants that were determined using experimental data with spherical drops at sub-terminal drop velocities, and θ is the angle at which the plate is inclined such that the constant, α, is given by

$$\alpha = \frac{1}{\cos(\theta)} \tag{2}$$

To produce a model for non-spherical drops that impact at terminal velocity on both horizontal and inclined surfaces, experimental data[11] for time-dependent force on horizontal plates was combined with other data[12] on an inclined surface. Constants C and τ were determined from regression analysis to give a relationship between the experimental data and highly idealised geometrical parameters that describe the impact of an ellipsoidal drop.

To extend the model to any drop diameter that occurs in natural rain, curve fitting was used to link the dimensionless parameter, l_{max}/D, that was calculated for an ellipsoidal drop, to the dimensionless time to peak force from the experimental data, $t_p/(10^{-3}D/v_{d,n})$. Curve fitting of the dimensionless parameter, S_{max}/D^2, calculated for an ellipsoidal drop was used to make a link to the dimensionless peak force from the experimental data, $f_p/(10^{-6}\rho_w v_{d,n}^2 D^2)$. This gave

$$\tau = (2\alpha)^{\frac{1}{\alpha}}\left[\exp(9.13\frac{l_{\max}}{D} - 6.33) + 0.05\right] \tag{3}$$

and

$$C = (2\alpha e)^{\frac{1}{2\alpha}}[\exp(10.10S_{\max}/D^{2} - 9.47) + 0.59] \tag{4}$$

The time-dependent force can be converted into a power input for which the model has been experimentally validated in Yu and Hopkins[12].

4 RESULTS

4.1 Simulation of artificial and natural rainfall

The angle-corrected semi-empirical model has been used to determine the structure-borne sound power input from artificial and natural rainfall into a dry 6 mm glass plate (ρ=2500 kg/m^3, c_L=5200 m/s) that is inclined at different angles from 0° up to 60° - see Figure 2. For artificial and natural rain this shows that as the angle increases, the power input decreases, and as the angle increases, there are also differences in the spectral shape between moderate, intense and heavy rain. For all rainfall rates, the difference between the power input at 0° and 15° is <1 dB up to 1k Hz; hence for shallow angle roofs the exact angle is not critical. Note that below 200 Hz the power input at 60° is ≈7 dB lower than at 30° for intense, heavy and moderate rain.

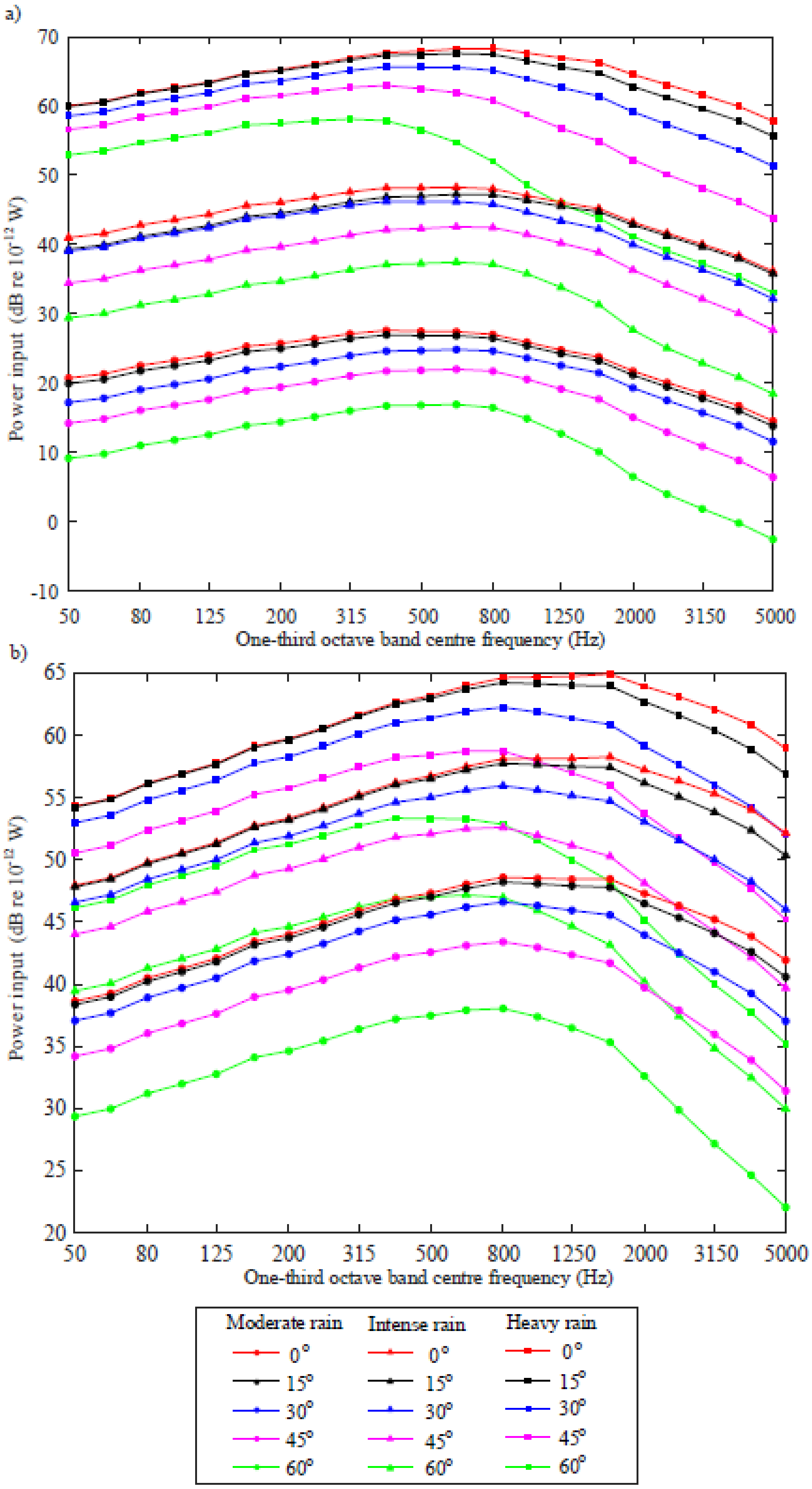

Figure 2. Power input from (a) artificial rainfall and (b) natural rainfall onto a dry glass plate when horizontal and inclined at angles up to 60°. All data are calculated using the angle-corrected semi-empirical model.

4.2 Conversion factors between different types of artificial and natural rainfall

For the comparison of test elements (or products) it is often necessary to convert a laboratory measurement of rain noise made with one type of artificial rain to a different type of artificial rain. Laboratory measurements are often made with the test element inclined at a specific angle (e.g. 30° as defined in ISO 10140) but for the field situation it may be necessary to know the rain noise when the element is installed at a different angle. For design work it is useful to be able to take a laboratory measurement with one type of artificial rain and convert it to a situation representing natural rain with a specified rainfall rate. Alternatively, a roof element may already exist for which a field measurement has been taken with natural rain at a known rainfall rate and the user needs to convert this to natural rain at a different rainfall rate for the new installation. All of the above conversions have been carried out using the prediction model.

As an example, Figure 3 shows the conversion factors to change from artificial heavy rain that is commonly used for laboratory measurements according to ISO 10140 to different types of natural rain (moderate, intense and heavy).

As an example of how these conversion factors are used, consider the curve corresponding to "Artificial Heavy to Natural Intense". The conversion factor in decibels is added to the measured radiated sound power in decibels when using artificial heavy rainfall in the laboratory to give an estimate of natural intense rainfall. Some of these conversion factors are sufficiently invariant with frequency that a single-number conversion factor can be calculated using an arithmetic average of the differences between the two power inputs between 50 and 5k Hz. More examples in graphical form are given in the paper by Yu and Hopkins[12] and these have been used to calculate conversion factors as given in Table 1; these apply to test elements where the driving point impedance is at least a factor of ten greater than the flow impedance[12] – in practice this would apply to almost all roof elements that are made of glass, metal or concrete. An indication of the robustness of these single-number values can be made by checking the maximum difference from the single-number value in any band between 50 and 5k Hz; the closer the difference is to 0 dB, the more reliable the single-number. For some conversions (e.g. artificial moderate to artificial intense) the conversion factor is sufficiently similar for all angles between 0° and 60° that a single arithmetic average of the tabulated values could be used as shown in the bottom row of the table.

5 CONCLUSIONS

An experimentally validated, angle-corrected semi-empirical model for the force applied by drops of water falling at terminal velocity has been used to calculate conversion factors between laboratory measurements with artificial rain to other situations with natural or artificial rainfall, and between measurements on roof elements that are inclined at different angles.

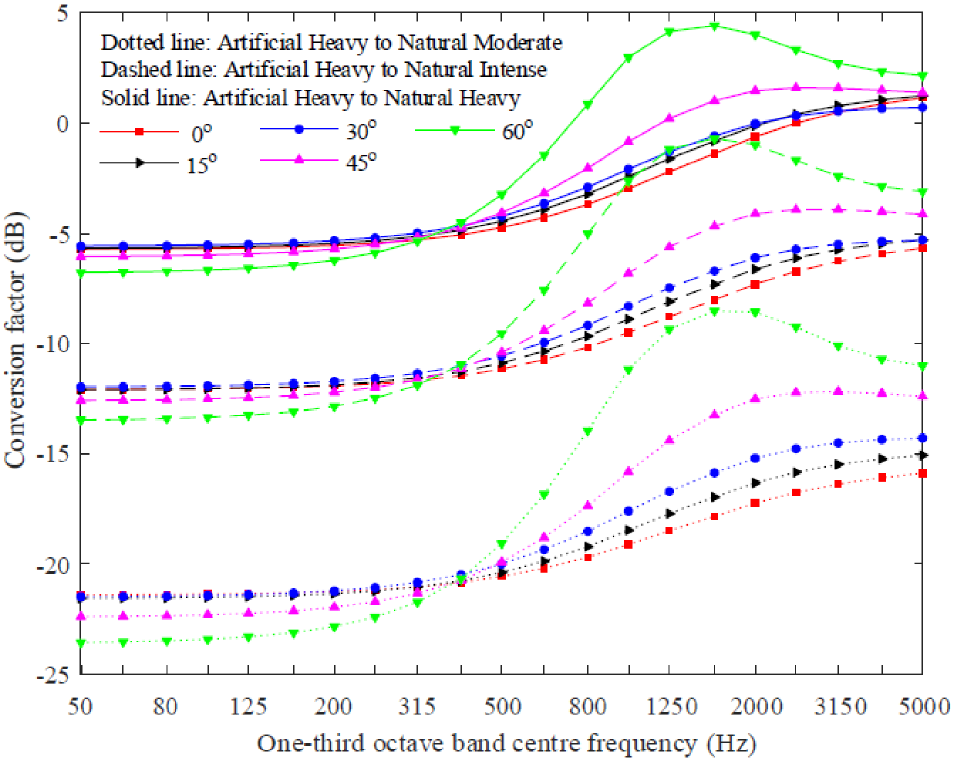

Figure 3. Conversion factors between the power input for artificial heavy rain used in the laboratory to different types of natural rainfall.

Inclination angle of the plate	Artificial Moderate to Artificial Intense (dB)	Artificial Intense to Artificial Heavy (dB)	Artificial Moderate to Natural Moderate (dB)	Artificial Intense to Natural Intense (dB)	Artificial Heavy to Natural Moderate (dB)	Artificial Heavy to Natural Intense (dB)	Artificial Heavy to Natural Heavy (dB)	Natural Moderate to Natural Intense (dB)	Natural Intense to Natural Heavy (dB)
0°	20.9 (0.8)	20.2 (1.5)	21.8 (5.9)	10.6 (5.8)	-19.3 (4.8)	-9.6 (4.7)	-3.1 (4.6)	9.7 (0.6)	6.5 (0.3)
15°	20.6 (1.4)	20.3 (0.4)	21.9 (5.1)	10.9 (3.8)	-22.1 (4.4)	-12.5 (4.3)	-2.9 (4.3)	9.6 (0.2)	6.5 (0.1)
30°	21.3 (0.7)	19.3 (0.2)	22.2 (3.3)	10.2 (3.6)	-18.5 (3.7)	-9.2 (3.7)	-2.9 (3.6)	9.3 (0.2)	6.3 (0.2)
45°	20.7 (0.6)	19.2 (3.3)	22.1 (3.0)	10.5 (1.6)	-17.9 (5.0)	-8.7 (4.5)	-2.6 (4.2)	9.2 (0.7)	6.1 (0.6)
60°	20.6 (0.6)	18.4 (6.4)	22.2 (3.9)	10.6 (1.9)	-16.8 (7.9)	-7.8 (6.8)	-1.8 (6.2)	9.0 (1.5)	6.0 (1.0)
Average (0° to 60°)	20.8	19.5	22.0	10.6	-18.9	-9.6	-2.7	9.4	6.3

Table 1. Conversion factors between the power input for different types of artificial and natural rainfall. These are calculated in terms of a single-number value which is the arithmetic average of the differences between two types of rainfall in one-third octave bands between 50 and 5k Hz. The value in brackets indicates the maximum difference from this single-number in any band.

6 REFERENCES

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