# Predicting Reverberation Time: Comparison between Analytic Formulae and Computer Simulation

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To predict reverberation time, both analytic formulae and computer simulation models are being commonly used. This paper compares results by the two kinds of method. For the former, Sabine's formula, Eyring's formula, Millington-Sette's formula, Fitzroy's formula, Arau's formula, Fitzroy-Kuttruff's formula, Tohyama's formula, and the proposed calculation model of Annex D of the final draft of CEN prEN 12354-6 are considered. For the latter, the computer program CATT-Acoustic and a radiosity model are used. Two rectangular rooms with a variety of boundary absorption distributions are investigated. The result suggests that with unevenly distributed absorption it is essential to consider the boundary reflection characteristics because reverberation time resulting from geometrically and diffusely reflecting boundaries is systematically different.

## FORMULAE AND MODELS

The classic Sabine and Eyring reverberation time (RT) formulae are based on the assumption of a diffuse field [1,2], and may become inaccurate with unevenly distributed absorption [3,4] and/or extreme room dimensions [5]. The Millington-Sette formula is based on similar assumptions, but the average absorption is determined by considering the acoustic energy in a series of confined sound cones reflected in sequence by each of the room surfaces [6,7]. The Fitzroy formula is an empirically derived equation through extensive tests in a large number of rooms, where distribution of sound absorption varies widely in uniformity [8]. It is considered that the sound field may tend to develop reflection patterns involving the three major axes of a rectangular room, and that each of these patterns will undergo decay at different rates, dependent only on the average absorption of the pair of surfaces involved in each case. Based on Fitzroy's idea, Arau-Puchades proposed that the RT should be the area-weighted arithmetic mean of the reverberation in each one of the rectangular directions [9]. Kuttruff derived a correction to the Eyring absorption exponent to take into account the influence of unevenly distributed absorption on boundaries [10]. By modifying the Fitzroy formula in a similar manner, the prediction showed good agreement with measurement. In the proposed CEN prEN 12354-6 a method for estimating RT in irregular spaces and/or absorption distribution is also suggested [11]. Using wave theory, Tohyama and Suzuki gave a formula for calculating RT in an almost-two-dimensional diffuse field [12].

CATT-Acoustic [13] is a room acoustic prediction program based on the image source model for early part echogram qualitative detail, ray-tracing for audience area colour mapping and randomised tail-corrected cone-tracing for full detailed calculation. In the radiosity model [14] each boundary is divided into a number of patches, and the sound propagation is simulated by the energy exchange between patches. The energy reflected from a boundary is dispersed over all directions according to the Lambert cosine law.

## CONFIGURATIONS

Two rooms are considered. Room I is 10m long, 10m width and 8m high, and room II is 10m by 10m by 3m. For each room, eight absorption distributions are considered, as shown in Figure 1. A single point source is located at two positions, (S1: 2m, 2m, 1.5m) and (S2: 5m, 2m, 1.5m).

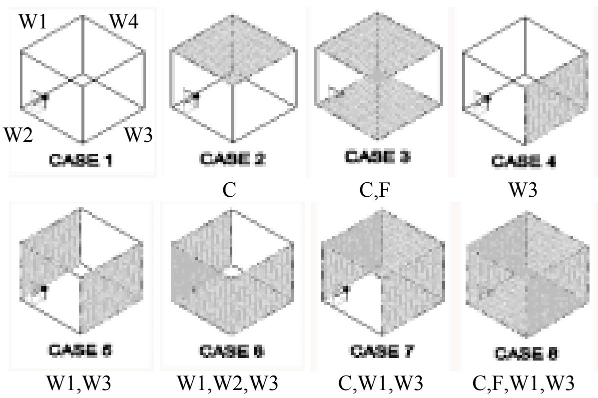


**Figure 1.** Absorption distributions in Room I. The grey areas represent surfaces with an absorption coefficient of 0.8. This is also indicated by the letters below each graph. The absorption coefficient of other boundaries is 0.05.

# COMPARISON

The calculation results for room I and II are shown in Tables 1 and 2, respectively. The given values are the mean value of 500 and 1000 Hz. For the two computer simulation programs, the values presented are based on five regularly distributed receivers. In the CATT-Acoustic program a constant diffusion factor of 10% is used.

**Table 1.** Calculation results in room I.

| Configuration | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Sabine | 4.53 | 1.27 | 0.71 | 0.48 | 0.87 | 0.61 | 0.57 | 0.43 |
| Eyring | 4.43 | 1.14 | 0.59 | 0.34 | 0.74 | 0.48 | 0.43 | 0.29 |
| Millington-Sette | 4.43 | 0.69 | 0.38 | 0.24 | 0.46 | 0.32 | 0.30 | 0.22 |
| Fitzroy | 5.10 | 3.26 | 3.15 | 2.11 | 3.67 | 2.20 | 1.83 | 0.33 |
| Arau | 4.86 | 1.93 | 1.29 | 0.58 | 1.68 | 0.81 | 0.67 | 0.30 |
| Fitzroy-Kuttruff | 4.43 | 0.93 | 0.58 | 0.34 | 0.63 | 0.41 | 0.36 | 0.27 |
| prEN 12354 | 5.26 | 2.32 | 1.94 | 0.59 | 1.90 | 0.80 | 0.73 | 0.52 |
| CM*,S1,T15 | 4.43 | 1.66 | 1.37 | 1.70 | 1.43 | 0.77 | 0.76 | 0.73 |
| CM,S1,T30 | 4.43 | 1.80 | 1.57 | 1.81 | 1.62 | 1.07 | 1.13 | 0.96 |
| CM,S2,T15 | 4.42 | 1.67 | 1.42 | 1.63 | 1.39 | 0.73 | 0.76 | 0.74 |
| CM,S2,T30 | 4.42 | 1.80 | 1.63 | 1.70 | 1.53 | 0.99 | 1.00 | 1.01 |
| RM^,S1,EDT | 3.80 | 0.95 | 0.57 | 1.21 | 0.70 | 0.46 | 0.42 | 0.28 |
| RM,S1,RT30 | 3.89 | 0.91 | 0.56 | 1.20 | 0.69 | 0.46 | 0.42 | 0.32 |
| RM,S2,EDT | 3.80 | 0.85 | 0.55 | 1.22 | 0.67 | 0.44 | 0.38 | 0.27 |
| RM,S2,RT30 | 3.89 | 0.82 | 0.57 | 1.24 | 0.69 | 0.46 | 0.42 | 0.32 |
| Tohyama | 2.98 | 1.32 | 0.80 | 0.36 | 0.80 | 0.55 | 0.55 | 0.39 |

* CM: CATT-Acoustic program
^ RM, radiosity model

Comparison of Case 1 (bare room) shows fairly similar values using classical formulae as well as the Fitzroy-Kuttruff equation and the CATT-Acoustic program, whereas Fitzroy, Arau and prEN reveal too high RT values. Under absorbent conditions, however, the values differ substantially. In general, the Fitzroy formula gives the highest values and the Millington-Sette's formula yield the lowest values. It may be concluded this is due to the difference in the reflection patterns assumed.

The radiosity model provides in average similar RT values compared to the Fitzroy-Kuttruff equation, with a typical difference of 10%. A reason for this may be that they both consider diffusely reflecting boundaries. The results are close to Eyring's results. It may be concluded that for unevenly distributed absorption Eyring's formula may still provide reasonable results if the boundaries are diffusely reflective.

The model of Annex D of prEN 12354-6 yield in most cases similar results to Arau's formula. It is noted that the values using the CATT-Acoustic program are systematically higher than using the radiosity model.

The difference between the results with two sound sources is not significant, typically within 10%. In general the EDT and the T15 values are shorter than the RT30 values, which is expected, especially with increasing absorption.

The Tohyama's formula yields for some cases extreme values and does not seem to be consistent.

**Table 2.** Calculation results in room II.

| Configuration | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Sabine | 2.85 | 0.53 | 0.29 | 0.45 | 0.78 | 0.57 | 0.35 | 0.23 |
| Eyring | 2.78 | 0.45 | 0.20 | 0.37 | 0.70 | 0.49 | 0.27 | 0.14 |
| Millington-Sette | 2.85 | 0.28 | 0.15 | 0.23 | 0.44 | 0.30 | 0.18 | 0.11 |
| Fitzroy | 3.05 | 1.29 | 1.18 | 1.96 | 2.52 | 1.99 | 0.76 | 0.16 |
| Arau | 2.96 | 0.66 | 0.34 | 0.81 | 1.55 | 0.99 | 0.35 | 0.14 |
| Fitzroy-Kuttruff | 2.85 | 0.35 | 0.20 | 0.37 | 0.62 | 0.43 | 0.21 | 0.13 |
| prEN 12354 | 3.59 | 1.63 | 1.35 | 0.54 | 1.26 | 0.71 | 0.46 | 0.34 |
| CM,S1,T15 | 2.93 | 1.19 | 1.13 | 1.21 | 1.01 | 0.50 | 0.64 | 0.59 |
| CM,S1,T30 | 2.95 | 1.38 | 1.52 | 1.29 | 1.19 | 0.53 | 1.05 | 0.65 |
| CM,S2,T15 | 2.94 | 1.37 | 1.10 | 1.23 | 1.00 | 0.50 | 0.67 | 0.62 |
| CM,S2,T30 | 2.95 | 1.61 | 1.55 | 1.30 | 1.17 | 0.52 | 1.11 | 1.08 |
| RM,S1,EDT | 1.68 | 0.31 | 0.19 | 0.95 | 0.53 | 0.38 | 0.18 | 0.12 |
| RM,S1,RT3 | 1.72 | 0.35 | 0.25 | 1.01 | 0.59 | 0.43 | 0.25 | 0.24 |
| Tohyama | 4.43 | 0.44 | 0.11 | | | | 0.50 | 0.14 |

# CONCLUSIONS

The results in this paper suggest that when predicting reverberation time in cases of unevenly distributed absorption, it is vital to consider the reflection characteristics of boundaries as well as appropriate diffusion coefficients. The classical Eyring formula may still be useful if boundaries are diffusely reflective.

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