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ACOUSTIC CHARACTERIZATION OF THEATER RIBEIRO CONCEIÇÃO (LAMEGO - PORTUGAL)

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ABSTRACT

This paper describes the objective acoustic characterization of the Theater Ribeiro Conceição (Lamego, Portugal) inaugurated in 1929. The main mean results of the acoustic parameters measured were: L_{Aeq}(HVAC) with 31 dB, STI (Speech Transmission Index) from 0.44 to 0.70, Reverberation Time (mean 500-1k Hz) of 1.0 s, Clarity C_{80} (mean 500-1k Hz) of 5.6 dB, Definition D_{50} (mean 500-1k Hz) of 0.65, and Center Time ts (mean 500-1k Hz) of 58 ms. A comparison is made with two other horseshoe-type theaters in Portugal: Theaters Sá de Miranda (Viana do Castelo) and S. João (Porto) and with several international horseshoe-type theaters.

Keywords: *theater, reverberation time, speech intelligibility, clarity, definition.*

1. THEATER RIBEIRO CONCEIÇÃO

The Theater Ribeiro Conceição (in Lamego, Portugal) was inaugurated in 1929 and, after closing in 1989, was acquired by the Lamego City Council and reinaugurated in 2008. It has a horseshoe shape with a seating capacity for 417 spectators (Fig. 1 and 2).

In situ measurements were done at 14 positions represented in Figure 3. The background noise sound pressure levels were obtained at seven points in 1/3 octave bands (16 to 16k Hz), with and without the HVAC on, with measurements between 3 to 5 minutes.

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The difference in overall sound pressure levels with the HVAC system on and off was calculated by frequency band (Fig. 4) where the variation in background noise sound pressure levels can be compared when the ventilation system is the contributing factor. Table 1 shows the variation in equivalent sound pressure levels (*Leq*) with and without HVAC and Table 2 shows the Noise Criterion (NC) and Noise Rating (NR) values.

According to the RRAE (Portuguese Regulation for Acoustic Requirements in Buildings), the equivalent continuous sound level (L_{Aeq}) in performance venues (except cinemas) must comply with the maximum limit of 30 dB(A), considering a legal measurement uncertainty of 3 dB(A) to be subtracted from the in situ measured values. The measured L_{Aeq} values with and without the HVAC system in operation, presented in Table 3, show the required legal limit is achieved.

The empty room reverberation time (RT) values for the measured points are represented in 1/3 octave frequency bands (100 to 5k Hz) (Fig. 5). The RT predicted values with occupancy was made for a fully occupied room (100%) and a half room occupancy (50%) (Fig. 6). As the Theater Ribeiro Conceição is a multipurpose hall, there are values considered ideal for each type of function (Tab. 4).

The Portuguese Regulation for the Acoustic Requirements of Buildings (RRAE) specifies a maximum value for the average Reverberation Time (500 to 2k Hz) based on the volume of the empty room and when its primary function involves activities centered on speech. Table 5 is in line with the requirements set forth in that legal regulation.

The Speech Transmission Index (*STI*) evaluates the effectiveness of verbal communication in the room between the emitter (at the center of the stage) and a

receiver. The tests were conducted at fourteen points (*P1* to *P14*), and for each the *global average STI* was obtained with and without the operation of the HVAC system (Fig. 7). Figures 8 and 9 show the values obtained for C_{80} and D_{50} at each point. The Central Time (*ts*) is essential for assessing the clarity and acoustic quality of a space and Figure 10 presents their average values with and without the operation of the HVAC system.

The acoustic effect of the HVAC is show in Table 6. The parameters *RT*, C_{80}, D_{50}, *ts*, and *BR_RT* are not affected by the operation of the HVAC system, as the intrinsic acoustic characteristics of the space remain unchanged. However, the HVAC system influences other parameters, such as the Noise Criteria (NC) and Noise Rating (NR), sound pressure levels and *STI*, due to the background noise it generates. This noise increases the equivalent sound level (+6 dBA) which can cause acoustic discomfort, especially at low frequencies, and reduce speech intelligibility (lower *STI*). The noise from the HVAC system can mask desired sounds, such as music or speech, and increase the overall perception of noise in the environment, compromising acoustic comfort.

Figures 1 and 2 – Theater Ribeiro Conceição (in Lamego, Portugal) [1]

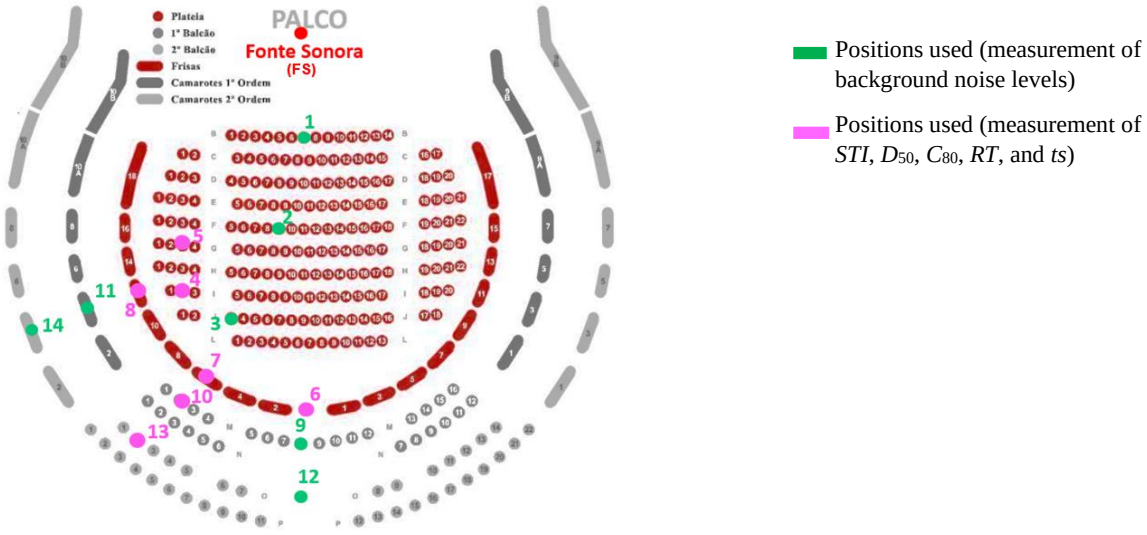

Figure 3 - Floor plan of Theater Ribeiro Conceição with sound source (*FS*) and measurement positions. *L* (HVAC noise), *RT*, ts, C_{80}, D_{50}, and *STI*: points 1, 2, 3, 4, 5, and 6 in the audience area; 7 and 8 in the boxes; 9, 10, and 11 on 1st balcony 1st level; 12, 13, and 14 on 2nd balcony 2nd level (adapted from [2]).

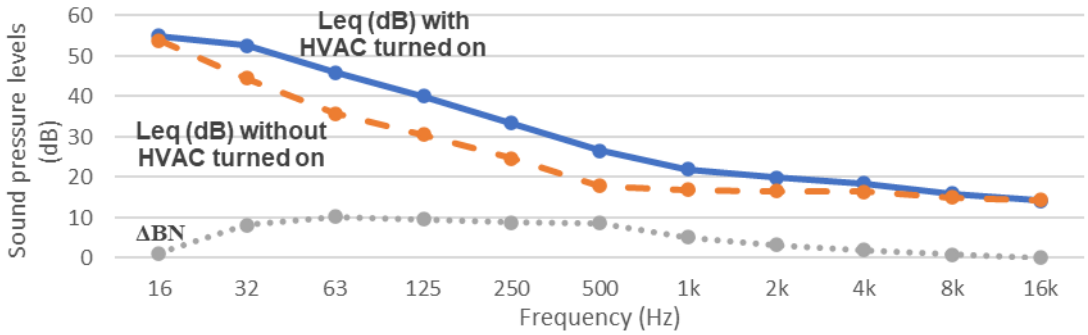

Figure 4 - Comparison among the average *L* values of background noise (BN) sound pressure levels in 1/3 octave frequency bands, with and without the HVAC system on, and the variation in sound pressure levels.

Table 1 - Equivalent sound pressure levels (L_{eq}) with HVAC on and off.

Position	P1	P2	P3	P9	P11	P12	P14
L_{eq} (dB) with HVAC on	57.9	57.9	59.0	59.3	59.1	59.4	59.0
L_{eq} (dB) without HVAC on	52.7	53.2	55.1	52.5	50.2	60.0	60.6
Δ Background Noise (dB)	+5.2	+4.7	+3.9	+6.8	+8.9	≈ 0	≈ 0

Table 2 - Calculated values of Noise Criteria (NC) and Noise Rating (NR) according to the operation of the HVAC system and their variation, compared to the maximum recommended values [3].

	NC	NR	Recommended Maximum Values (*Drama* and *Music*)
With HVAC	22	24	22 a 30
Without HVAC	19	22	20 a 30
Variation (Δ HVAC)	+3	+2	

Table 3 – Legal regulatory assessment (RRAE) of the equivalent continuous sound level at the theater [4].

Use	Measurement	L_{Aeq} (dB)	Legal uncertainty (I) dB(A)	L_{Aeq} + legal uncertainty (I) (dB)	RRAE L_{Aeq} (dB)	Verification
Performance venues (except *cinema*)	With AVAC	31	3	28	≤30	O.K.
	Without AVAC	25	3	22	≤30	O.K.

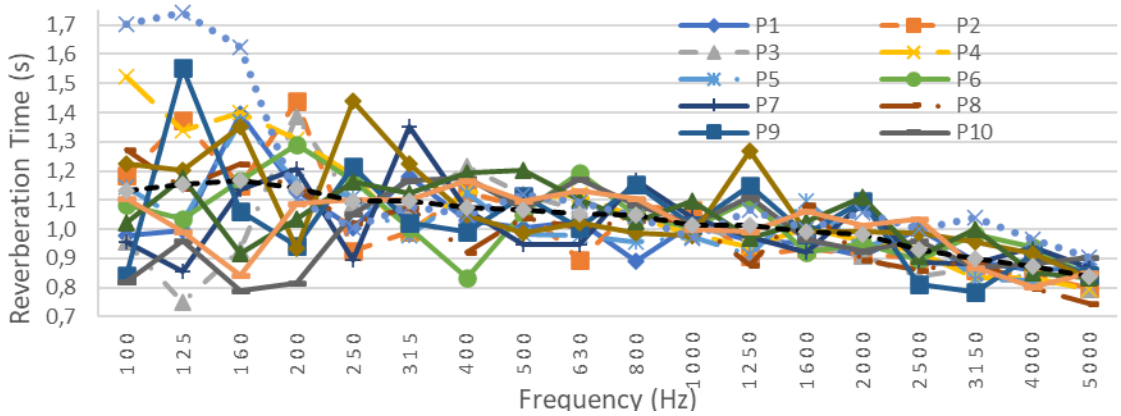

Figure 5 - Reverberation Time values for points *P1* to *P14* in 1/3 octave freq. bands (HVAC off).

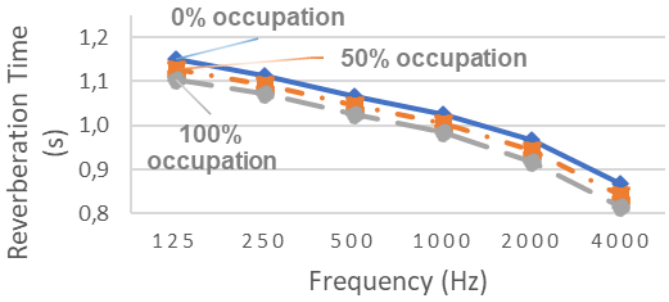

Figure 6 - Reverberation Time values with 0%, 50% and 100% room occupancy (1/1 octave bands).

Table 4 - Verification of the ideal values for average RT according to the function of the theater [3].

Function	Ideal range RT [500, 1k Hz] (s) [3]	Measured RT [500, 1k Hz] (s)	Assessment
Auditorium (speech)	0.7 - 0.8	1,0	Tolerable
Theater (drama)	0.7 - 0.9		Tolerable
Cinema	0.8 - 1.0		Adequate
Opera: non-Wagnerian	1.3 - 1.7		Tolerable
Wagnerian	1.8 - 1.9		Unsuitable
Symphonic music: Baroque	1.4 - 1.6		Unsuitable
Classic	1.6 - 1.8		Unsuitable
Romantic	1.9 - 2.2		Unsuitable
Modern	1.4 - 1.9		Unsuitable
Popular music	0.8 - 1.0		Adequate
Organ music	2.5 - 3.5		Unsuitable
Gregorian Choirs	3.0 - 4.0		Unsuitable

Table 5 – Portuguese legal regulatory analysis (RRAE) of the average Reverberation Time [4]

Freq. 1/1 oct. (Hz)	RT (s)		RT max. RRAE (s)	Uncertainty (I)	RT average - (I) (s)	Opinion for "speech" (RRAE)
	measured	average				
500	1.07	1.02	0.94	35% (=0.33 s)	0.69	O.K.
1000	1.03					
2000	0.97					

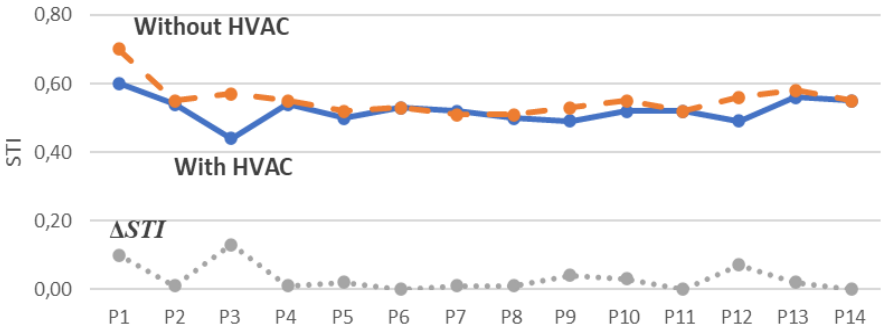

Figure 7 - Comparison of the average STI values for points *P1* to *P14* with and without HVAC, with the corresponding variation between them.

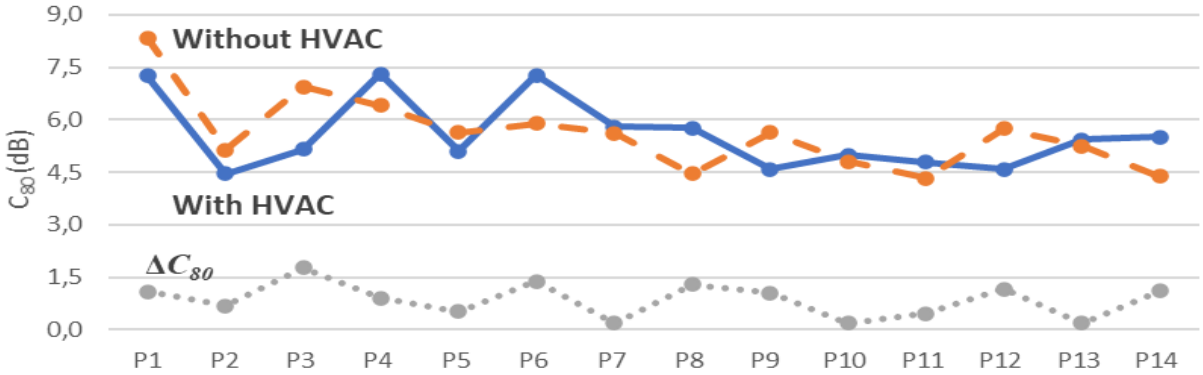

Figure 8 - Average values of Clarity (C_{80}) [500, 1k Hz] for points *P1* to *P14* with/without HVAC and their variation.

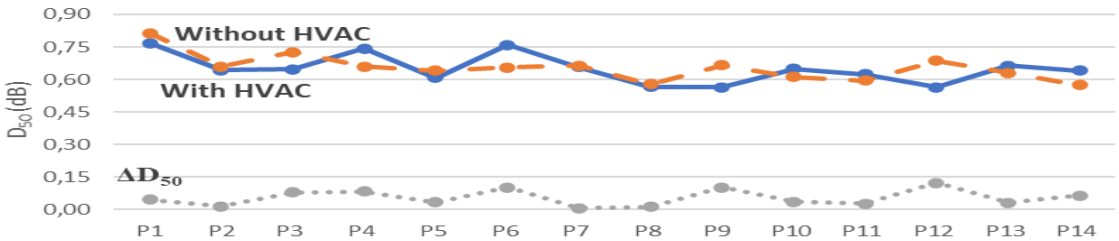

Figure 9 - Definition (D_{50}) average values [500, 1k Hz] (points *P1* to *P14*) with/without HVAC and their variation.

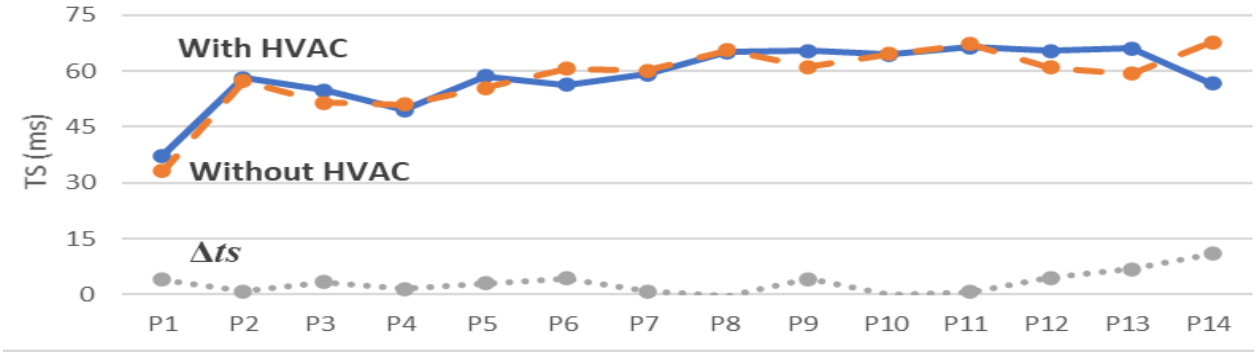

Figure 10 - Central Time (*ts*) average values [500, 1k Hz] for points *P1* to *P14* with/without HVAC and their variation.

Table 6 - Effect of HVAC operation in Theater Ribeiro Conceição.

Parameters		Effect of HVAC
Reverberation Time (s) [500, 1k Hz]		≈ 0
Clarity (C_{80}) (dB) [500, 1k Hz]		≈ 0
Definition (D_{50}) [500, 1k Hz]		≈ 0
Central Time (*ts*) (ms) [500, 1k Hz]		≈ 0
Bass Ratio (*BR_RT*)		≈ 0
Annoyance Curves	NC (Noise Criteria)	+ 3
	NR (Noise Rating)	+ 2
Equivalent sound level (L_{Aeq}) (dB)		+ 6.1
Equivalent sound pressure level (L_{eq}) (dB)		+ 2.3
Speech Transmission Index (*STI*)	Maximum value	- 0.10
	Mean value	- 0.03
	Minimum value	- 0.07

2. COMPARISON WITH OTHER THEATRES

A comparison was made with several international theaters of the same shape (*horseshoe*). When analyzing the data in Table 7, the Theater Ribeiro Conceição (TRC) shows with the highest C_{80} and a comparatively low mean RT due to its smaller size. The two smaller rooms have similar average *RT* values (0.7-0.8 s) and not very distant from the TRC. Comparatively, considering its volume and the number of seats, the Theater Ribeiro Conceição has a higher Reverberation Time value than those two smaller theaters but smaller that the larger rooms presented.

Table 8 compares three Portuguese horseshoe theaters and shows that Theater Ribeiro Conceição, with a larger volume than the Theater Sá Miranda and similar to the Theater São João, has a mean *RT* value of 1.1 seconds. This indicates greater sound absorption, suggesting that the materials and components of the room are more acoustically efficient, keeping a low *RT* despite the larger volume. For C_{80}, the Theater Sá Miranda has the lowest energy in the first 80 ms making it ideal for opera. The Theater Ribeiro Conceição is suitable for speech. The Theater São João does not reach ideal values, being somewhat unsuitable for opera and only reasonable for speech.

The average D_{50} values for the theaters are all within the adequate range, with the Theater Ribeiro Conceição

standing out as the 'most suitable' for acoustic clarity for speech, due to its higher value. For the average *ts*, the Sá Miranda Theater (73 ms) is the most reverberant, while the Theater Ribeiro Conceição (58 ms) receives sound energy earlier, being less reverberant. All theaters have values below 80 ms (ideal for drama theater), confirming that they are suitable for performances focused on speech.

The average *STI* (Speech Transmission Index) values are quite similar (about 0.54) and are considered adequate for speech intelligibility, confirming that the three theaters provide good acoustic conditions for drama performances.

Table 7 - Average unoccupied Reverberation Time (*RT*) and Clarity (C_{80}) values [500, 1k Hz], for several international horseshoe-shaped theaters and the Theater Ribeiro Conceição, with volumes and number of seats. [5, 8]

Theater	Number of seats	Volume (m^3)	*RT* (s) [500, 1k Hz] unoccupied	C_{80} (dB) [500, 1k Hz] unoccupied
Theatre Royal, Bristol, UK	638	2170	0.8	-
Wyndham`s Theatre, London, UK	724	2490	0.7	-
Usher Hall, Edinburgh, UK	2550	16000	1.7	- 1.3
Teatro alla Scala, Milan, Italy	2289	9012	1.4	2.9
Royal Opera House, London, UK	2120	12250	1.2	4.8
Opera Garnier, Paris, France	2131	10000	1.2	4.4
Wiener Staatsoper, Vienna, Austria	1709	10665	1.8	2.7
Academy of Music, Philadelphia, USA	2827	15100	1.3	1.7
Theater Ribeiro Conceição, Lamego, PT	417	4184	1.1	5.1

Table 8 – Average values [500, 1k Hz] for *RT* (Reverberation Time), C_{80}, D_{50}, *ts*, and *STI* (Speech Transmission Index) for Theater Sá Miranda, Theater São João, and Theater Ribeiro Conceição, and their volumes. [6, 7]

Parameter	Theater Sá de Miranda (Viana do Castelo, PT)	Theater São João (Porto, PT)	Theater Ribeiro Conceição (Lamego, PT)
Reverberation Time (*RT*) (s)	1.21	1.17	1.05
Clarity (C_{80}) (dB)	3.5	5.1	5.6
Definition (D_{50})	0.54	0.61	0.66
Central Time (*ts*) (ms)	73	61	58
Average *STI*	0.53	0.55	0.55
Volume (m^3)	2491	4560	4184

3. CONCLUSION

The study conducted in situ acoustic objective characterization of the Theater Ribeiro Conceição. The results were compared with international and national theaters with similar horseshoe geometry. The analyses allowed for verification of compliance with the limits established by the Portuguese Noise Code and comparison with ideal values. The results are summarized in Table 9, providing a comprehensive overview of the acoustic performance of the Theater Ribeiro Conceição in relation to some other similar national and international rooms.

Table 9 - Summary of the parameters measured in the Theater Ribeiro Conceição with the regulatory (Portuguese Noise Code: RRAE) and functional evaluation.

Parameter	Condition HVAC	Symbol	Value measured	Value + legal uncertainty	Legal max. value (RRAE)	Assessment for…		
						Drama Theater	Opera	Popular music
Background Noise	With/Without	L_{Aeq} (dB)	31/25	28/22	30	*A*	*A*	*A*
Annoyance Curves	With	*NC*	22	-	[20 to 30]	*A*	*A*	*A*
		NR	24	-		*A*	*A*	*A*
	Without	*NC*	19	-		*T*	*T*	*T*
		NR	22	-		*A*	*A*	*A*
Reverberation Time (s)	With/Without	RT [500, 1k Hz] unoccupied	1.1	0.73	0.94 (speech)	*T*	*U*	*A*
	With/Without	*RT* [500, 1k Hz] 100% occupancy*	1.0	0.67		*T*	*U*	*A*
Speech Transmission Index	With	STI maximum	0.60	-	-	*Reasonable*		
		STI average	0.52	-	-	*Reasonable*		
		STI minimum	0.44	-	-	*Insufficient*		
	Without	*STI* maximum	0.70	-	-	*Good*		
		STI average	0.55	-	-	*Reasonable*		
		STI minimum	0.51	-	-	*Reasonable*		
Clarity (dB)	With/Without	C_{80} [500, 1k Hz]	5.6	-	-	*T*	*U*	*T*
Definition	With/Without	D_{50} [500, 1k Hz]	0.65	-	-	*Reasonable*		
Central Time (ms)	With/Without	*ts* [500, 1k Hz]	59	-	-	*A*	*U*	
Bass Ratio	With/Without	*BR_RT*	1.04	-	-	*A*	*U*	

A - Adequate, U – Unsuitable, T – Tolerable, ***** *prediction*

4. REFERENCES

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