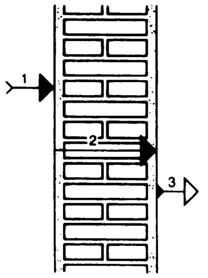
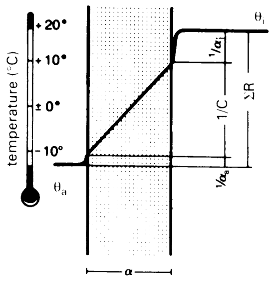
THERMAL INSULATION

Terminology and Mechanisms

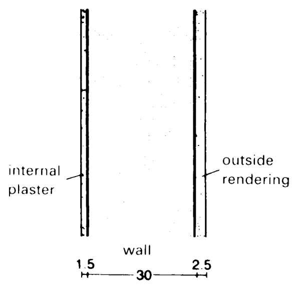


① **Principle of heat transfer through a component**



temperature drop corresponds to ΣR

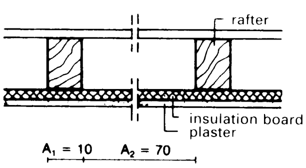
② **Temperature variation in a single-layer component**



	thickness l (m)		k (W/mK)		R (=l/k)
internal plaster	0.015	:	0.7	=	0.02
wall	0.30	:	0.22	=	1.36
outside rendering	0.025	:	0.87	=	0.03
1/C					1.41
$1/\alpha_i$					0.12
$1/\alpha_a$					0.04
ΣR					1.57
$U = \frac{1}{\Sigma R}$					0.64 (W/m²K)

example: wall made from aerated concrete, 500 kg/m³, 300 mm thick, plastered and rendered

③ **Calculation of the U value of a multilayer component**



$$U_m = \frac{A_1}{A} \cdot U_1 + \frac{A_2}{A} \cdot U_2 + \ldots + \frac{A_n}{A} \cdot U_n$$

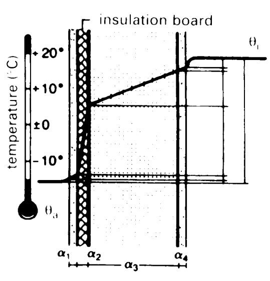
U, rafter area = 0.45
U, rafter field = 0.95

$$U_m = \frac{10}{80} \cdot 0.45 + \frac{70}{80} \cdot 0.95$$

$$= 0.056 + 0.83 = 0.89 \text{ (W/m}^2\text{K)}$$

example: section through an attic area

④ **Calculation of the mean thermal insulation value for combined components**



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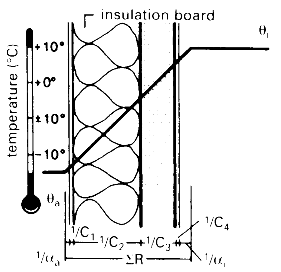
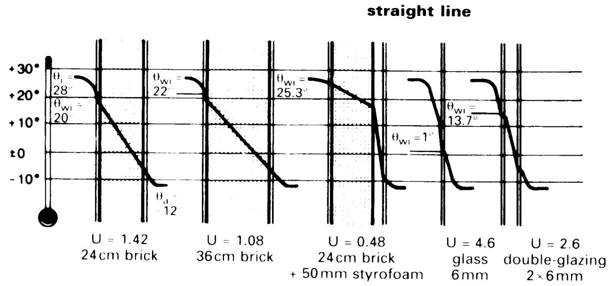


layers shown in proportion to their individual thermal insulation values

⑥ **As ⑤, but with distorted representation to show temperature variation as a straight line**



temperature of the inner surface of the wall θ_{wi} increases as the thermal insulation is improved

⑦ **Temperature variation across variously insulated components for an internal temperature θ_i = 28° and outside air temperature θ_a = -12°**

Thermal insulation should minimise heat loss (or gain) allowing energy savings to be made, provide a comfortable environment for occupants, and protect a building from damage that might be caused by sharp temperature fluctuations (in particular, condensation). Heat exchange – by thermal convection, conduction, radiation and water vapour diffusion – cannot be prevented, but its rate can be reduced by efficient thermal insulation.

Terms used in calculating thermal insulation values

Although temperature is often given in degrees Celsius (°C), kelvin (K) is also used (0K = –273.15°C).

Quantity of heat is expressed in watt hours (Wh). (1Wh = 3.6kJ.)

Thermal capacity, the heat necessary to raise the temperature of 1kg of material by 1K, is a measure of the readiness to respond to internal heat or to changing external conditions. 1kcal (= 1.16Wh) is the heat required to increase the temperature of 1kg of water by 1K.

Thermal conductance (C-value), in W/m²K, measures the rate at which a given thickness of material allows heat conduction, based on temperature differences between hot and cold faces; no account is taken of surface resistance. Thermal conductivity (k-value or λ specific to a given material), in W/mK (or kcal/mhK), measures the rate at which homogenous material conducts heat: the smaller the value, the lower the thermal conductivity. Thermal resistance (R-value = thickness/k), the reciprocal of thermal conductance (1/C), measures the resistance of material or structure with a particular thickness to heat transfer by conduction. Thermal resistivity (r-value), is the reciprocal of conductivity (1/k).

UK thermal insulation standards have risen since 1990, under the new Building Regulations, in which the thermal insulation value is used to evaluate temperature variation in, and possibility of damage to, a structural component due to condensation.

The thermal boundary layer resistance, $1/\alpha$, is the thermal resistance of the air 'boundary' layer on a structural component: $1/\alpha_a$ on the outside and $1/\alpha_i$ on the inside of the component. The lower the velocity of the air, the higher is the value of $1/\alpha$. Total resistance to heat flow ΣR is the sum of the resistances of a component against heat conductance: $\Sigma R = 1/\alpha_i + 1/C + 1/\alpha_a$.

The coefficient of thermal transmittance (U-value) – like thermal conductance – measures the rate at which material of a particular thickness allows heat conduction, i.e. the heat loss, and thus provides a basis for heating calculations, but the calculation is based on temperature difference between ambient temperatures on either side; account is taken of surface resistances of the structure. As the most important coefficient in calculating the level of thermal insulation, its value is specified in the Building Regulations, and is used by the heating systems manufacturer as a basis of measurement.

The mean U-value of window (w) and wall (W) is calculated as $U_{m(w+W)} = (U_w \times F_w + U_W \times F_W) \div (F_w + F_W)$, F being the surface area. Similarly, U_m, the coefficient of a building cell is calculated from the F and U values of the components making up the cell – window (w), wall (W), ceiling (c), floor surface (f) and roof area in contact with air (r) – taking account of minimum factors for roof and ground areas:

$$U_m = \frac{U_w \times F_w + U_W \times F_W + U_r \times F_r + 0.8U_c \times F_c + 0.5U_f \times F_f}{F_w + F_W + F_r + F_c + F_f}$$

Heat transfer through a component: a quantity of heat is conducted through the internal air boundary layer and then the inner surface of the component; some of this heat overcomes the thermal insulation value of the component to reach the outer surface, overcomes the outer air boundary layer and reaches the outside air → ①. Changes in temperature through the individual layers are in proportion to the percentage each contributes to the resistance to heat flow ΣR → ③.

Example: If $1/\alpha_i + 1/C + 1/\alpha_a = 0.13 + 0.83 + 0.04 = 1.00$, then $1/\alpha_i : 1/C : 1/\alpha_a$ = 13%:83%:4%. For a temperature difference of 40K between inside and outside, then: temperature difference across inner boundary layer = 13% of 40K = 5.2K; temperature across material = 83% of 40K = 33.2K; and temperature across outer boundary layer = 4% of 40K = 1.6K.

The lower the thermal insulation of the component, the lower is the temperature of the inner surface of the component → ⑦, and the easier it is for condensation to occur. Since the temperature varies linearly through each individual layer, this appears as a straight line if the component is represented to scale in proportion to the thermal insulation of the individual layers → ⑤ – ⑥; the interrelationships are then more easily seen. The variation of temperature is particularly important in considering the expansion of the component due to heat, in addition to the question of condensation → p. 112.

THERMAL INSULATION

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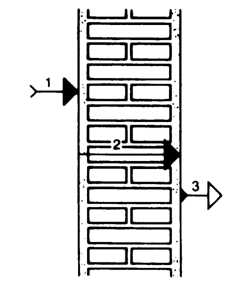

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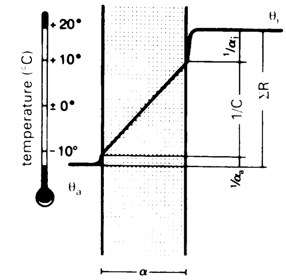

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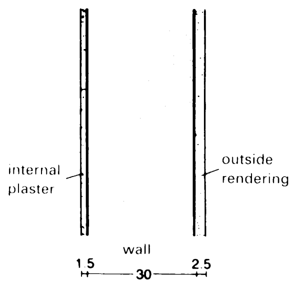

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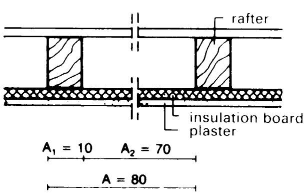

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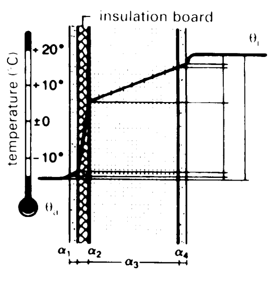

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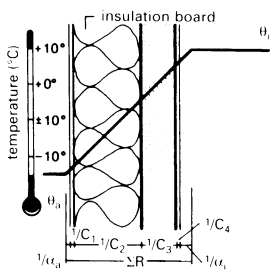

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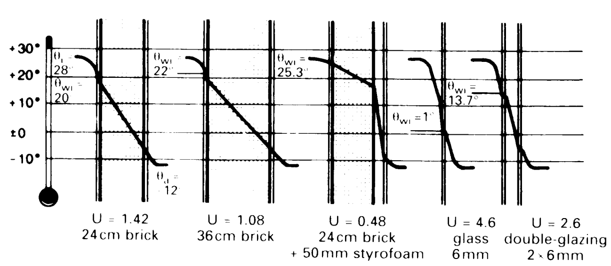

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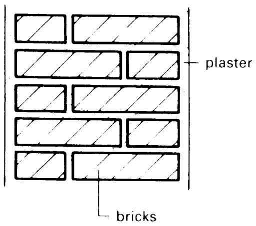
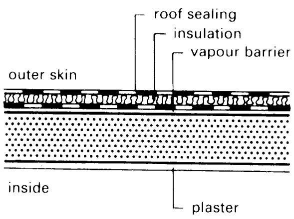
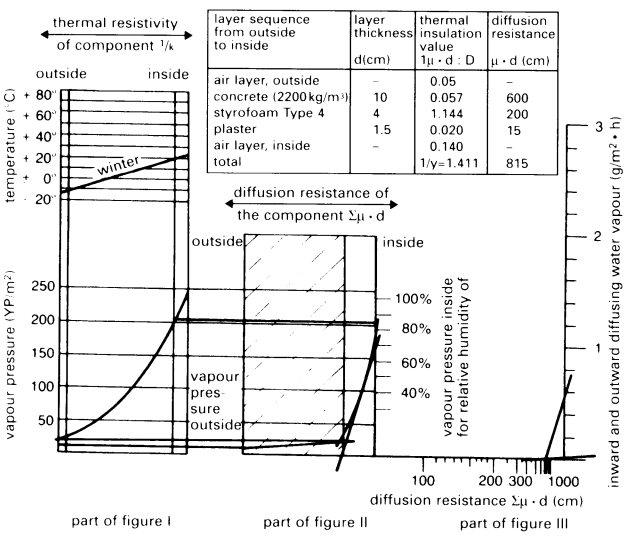
Types of Construction



① **Solid wall without insulation**

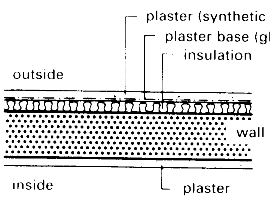


② **Solid roof with vapour-proof outer skin**

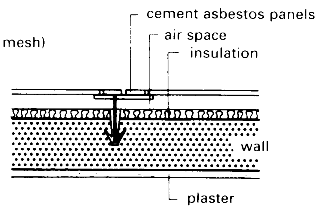


layer sequence from outside to inside	layer thickness d(cm)	thermal insulation value 1μ · d : D	diffusion resistance μ · d (cm)
air layer, outside	–	0.05	–
concrete (2200 kg/m³)	10	0.057	600
styrofoam Type 4	4	1.144	200
plaster	1.5	0.020	15
air layer, inside	–	0.140	–
total		1/y=1.411	815

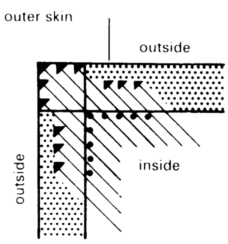
③ **Investigation of the production of water through condensation in a roof**



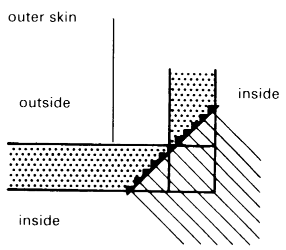
④ **Solid wall with vapour-proof outer skin**



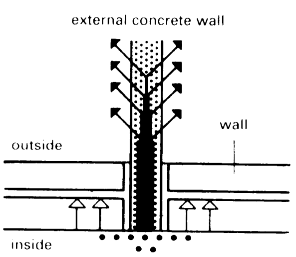
⑤ **Solid wall with rear-ventilated outer skin**



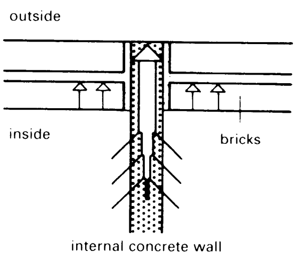
⑥ **Water from condensation occurs on inside surface of the outside corner**



⑦ **No water due to condensation occurs on the inside corner**



⑧ **Water from condensation occurs on large outer surface of the cold bridge (high heat extraction per unit area)**



⑨ **The heat extraction per unit area is significantly less on the large inside surface of the cold bridge**

Construction without vapour barrier → ①

Conventional construction contains no vapour retarding layers. Layers should be provided so that no condensation occurs: for sufficient thermal insulation, the layer factor λ should fall from inside to outside. In the case of very damp rooms (e.g. swimming pools), the vapour pressure variation should be checked either graphically or by calculation.

Note: on the outside of thermal insulation layers with normal plastering, there is a danger of cracking due to the build up of heat and low shear strength of the base material; therefore, glass fibre reinforced finishing plaster should be applied (but not in the case of swimming pools – see pp. 242–3).

Construction with vapour barrier → ②

In more recent building construction ('warm roof', 'warm façade'), there is a vapour impermeable outside layer, resulting in the necessity for an internal vapour barrier (→ p. 112). On vertical components, this is difficult to accomplish; a better form of construction is to provide a rear-ventilated outer skin (except for prefabricated walls). Note: the thermal insulation, including the air boundary layer on the layers up to the condensation barrier, must not exceed a specific level of contribution to the resistance to heat (p. 112). In solid constructions, protection of the vapour barrier against mechanical damage can be achieved by means of a protective layer. Since no high pressure – in the sense of a steam boiler – occurs on the inside of the vapour barrier, only vapour pressure (→ p. 112), the frequently recommended 'pressure compensation' provided by this layer, is not in fact required.

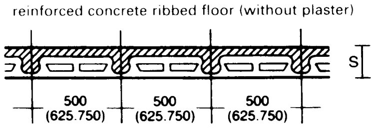
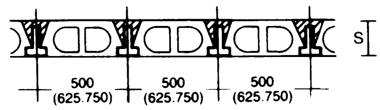
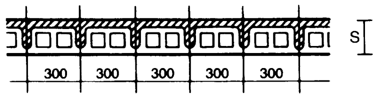
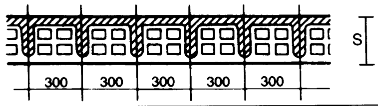
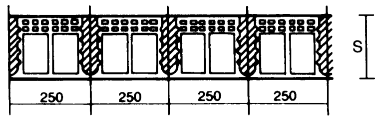
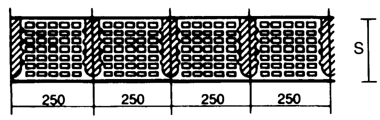
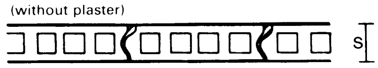
Construction with rear ventilated outer skin → ⑤

Rear ventilation avoids the vapour barrier effect of relatively vapour tight outer layers. It works by exploiting height difference (min. fall 10% between air inlet and air outlet). If there is only a small difference, then a vapour-retarding layer or vapour barrier is required (arrangement → construction with a vapour barrier), otherwise there will be excessive vapour transmission and condensation at the outer skin. The layering on the inner skin should be as for construction without a vapour barrier. However, the inner skin must always be airtight.

Cold bridges are places in the structure with low thermal insulation relative to their surroundings. At these places, the contribution of the air boundary layer to the resistance flow to heat increases, such that the surface temperature of the inner surface of the cold bridge reduces and condensation can occur there. The increase in heating costs due to the cold bridge, on the other hand, is insignificant, so long as the cold bridge is relatively small; this is not the case, however, for single-glazed windows which, in reality, are also cold bridges → ⑦ p. 111.

To avoid condensation on the surface of the component and its unwelcome consequences (mould growth, etc.), the temperature of the inner surface of the cold bridge must be increased. This can be achieved by either reducing the heat extraction through the cold bridge by means of an insulating layer against the 'outer cold' (increasing the thermal insulation reduces the percentage contribution of the air boundary layer to the resistance to heat flow ΣR), or increasing the heat input to the cold bridge by increasing the inner surface of the cold bridge, e.g. good conducting surroundings to the cold bridge, and/or blowing with warm air. This will result in an actual reduction in the inner surface resistance $1/\alpha_i$ in relation to the cold bridge and hence also the contribution of the air boundary layer to the resistance to heat flow ΣR. Typical examples are shown in ⑧. However, a normal outer corner in a building → ⑥, forms a cold bridge, since, at such a point, the opposite to that shown in ⑨ occurs; a large heat transmitting outer surface is in combination with a small heat inputting inner surface, so that the insulation of the air boundary layer in the corners is appreciably higher than that on the surface.

For this reason, condensation and mould are often seen in the corners of walls with minimal thermal insulation.

description and illustration	thickness S (mm)	thermal resistance 1/Λ m²K/W in the centre	in the worst position
1. reinforced concrete			
reinforced concrete ribbed floor (without plaster) 	120 140 160 180 200 220 250	0.20 0.21 0.22 0.23 0.24 0.25 0.26	0.06 0.07 0.08 0.09 0.10 0.11 0.12
reinforced concrete beamed floor (without plaster) 	120 140 160 180 200 220 240	0.16 0.18 0.20 0.22 0.24 0.26 0.28	0.06 0.07 0.08 0.09 0.10 0.11 0.12
2. reinforced concrete ribbed/beamed floors with hollow clay blocks			
hollow clay blocks as intermediate components without cross webs (without plaster) 	115 140 165	0.15 0.16 0.18	0.06 0.07 0.08
hollow clay blocks as intermediate components with cross webs (without plaster) 	190 225 240 265 290	0.24 0.26 0.28 0.30 0.32	0.09 0.10 0.11 0.12 0.13
3. reinforced concrete floors with hollow clay blocks			
hollow clay blocks for partly grouted butt joints 	115 140 165 190 225 240 265 290	0.15 0.18 0.21 0.24 0.27 0.30 0.33 0.36	0.06 0.07 0.08 0.09 0.10 0.11 0.12 0.13
hollow clay blocks for fully grouted butt joints 	115 140 165 190 225 240 265 290	0.13 0.16 0.19 0.22 0.25 0.28 0.31 0.34	0.06 0.07 0.08 0.09 0.10 0.11 0.12 0.13
4. reinforced concrete hollow beams			
(without plaster) 	65 80 100	0.13 0.14 0.15	0.03 0.04 0.05

(1) **Thermal resistance (thermal insulation values) 1/Λ m²K/W)**

type of concrete	raw weight of concrete (kg/m²)	thickness (cm) 12.5	18.75	25.0	31.25	37.5
aerated concrete, foam concrete, lightweight concrete, autoclaved concrete, autoclaved aerated concrete	400	0.89[3]	1.34[3]	1.79[2]	2.23[2]	2.68[2]
	500	0.78[3]	1.17[2]	1.56[2]	1.95[1]	2.34[1]
	600	0.66[3]	0.99[2]	1.32[1]	1.64[1]	1.97
	800	0.54[2]	0.82[1]	1.09	1.36	1.63
lightweight reinforced concrete in closed structure, using expanded clay, expanded slate, etc., without quartz sand	800	0.41[2]	0.63[1]	0.83[1]	1.04	1.29
	1000	0.33[2]	0.49[1]	0.66	0.82	0.99
	1200	0.25	0.38	0.50	0.63	0.79
	1400	0.20	0.30	0.40	0.50	0.60
	1600	0.17	0.26	0.34	0.43	0.51
lightweight concrete with porous additions, without quartz sand	600	0.57[3]	0.85[2]	1.14[1]	1.42[1]	1.70
	1000	0.35	0.52	0.69	0.87	1.04
	1400	0.22	0.33	0.44	0.55	0.66
	1800	0.14	0.20	0.27	0.34	0.41
reinforced concrete	(2400)	0.06	0.09	0.12	0.15	0.18

1) weight per unit surface area, including plaster ≥ 200 kg/m²
2) weight per unit surface area, including plaster ≥ 150 kg/m²
3) weight per unit surface area, including plaster ≥ 100 kg/m²

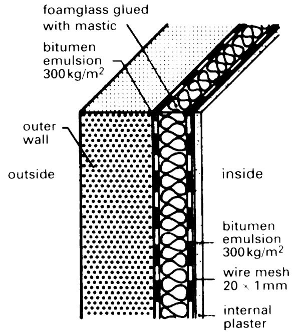
(2) **Thermal resistance 1/Λ (thermal insulation value; m²K/W) large format concrete components: the use of light reinforced concrete (e.g. for balconies) provides an improvement in thermal insulation of up to 68.3%**

Exterior Walls and Roofs

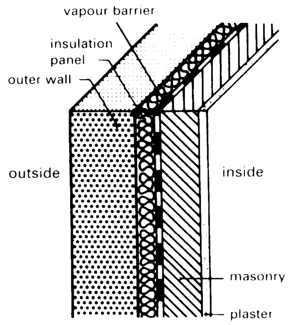
Mineral plaster should not be used with outer insulation; instead, a rear-ventilated type should be used → (5) or synthetic plaster (reinforced glassfibre), if necessary, with a mineral finishing plaster.

Critical detail points: Movement joint at flat roof junction → pp. 80–1 et seq.; radiator alcove → (6). Thermal insulation is essential to reduce costs (thin wall, higher temperature) for the window junctions → (6).

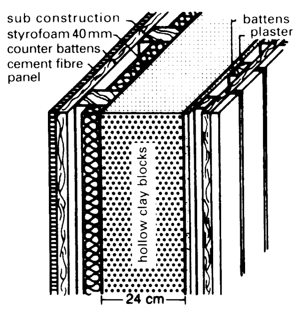
Special case of damp rooms (e.g. swimming baths): Greater insulation; max. contribution X of the inner layers (air boundary layer, layers up to the vapour barrier, → p. 113 is smaller. Synthetic plaster is used here, so a rear-ventilated cladding is a better barrier to condensation → (5); or use a construction incorporating a vapour barrier → (4).



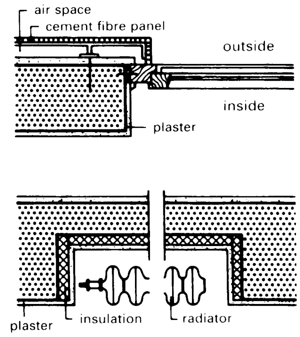
(3) **Multilayered wall with internal insulation**



(4) **Wall with internal vapour barrier**

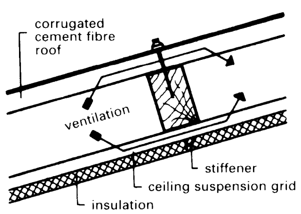


(5) **Multilayered wall without vapour barrier**

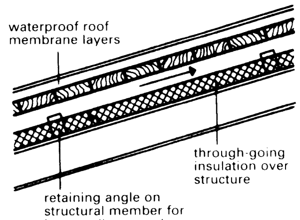


(6) **Insulation of a radiator recess**

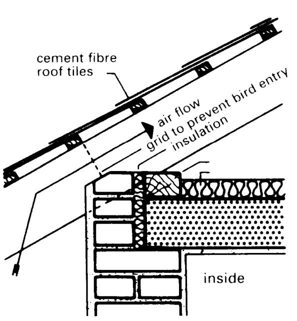
Thermal insulation details: Roof



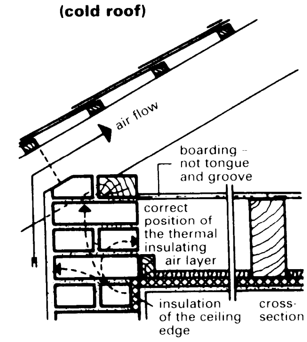
(7) **Hall roof in timber construction (cold roof)**



(8) **Hall roof in steel construction with aluminium covering (cold roof)**



(9) **Pitched roof with solid ceiling**



(10) **Pitched roof with timber beam ceiling**

item	material	gross density or gross density classification [1) 2)] kg/m³	calculated value of thermal conductivity λ_R [2)] W/(m · K)	standard value of water vapour diffusion resistance coefficient μ [4)]
1 render, screed and other mortar layers				
1.1	lime mortar, lime cement mortar, mortar from hydraulic lime	(1800)	0.87	15/35
1.2	cement mortar	(2000)	1.4	15/35
1.3	lime plaster, plaster, anhydrous mortar, anhydrous lime mortar	(1400)	0.70	10
1.4	stucco without additives	(1200)	0.35	10
1.5	anhydrous screed	(2100)	1.2	
1.6	cement screed	(2000)	1.4	15/35
1.7	magnesia screed			
1.7.1	sub-floors and underlayers of two-layer floors	(1400)	0.47	
1.7.2	industrial floors and walkways	(2300)	0.70	
1.8	poured asphalt floor covering, thickness > 15mm	(2300)	0.90	5)
2 large format components				
2.1	standard concrete (gravel or broken concrete with closed structure; also reinforced)	(2400)	2.1	70/150
2.2	light concrete and reinforced concrete with closed structure manufactured with the use of additions with porous surface with no quartz sand additions	800	0.39	70/150
		900	0.44	
		1000	0.49	
		1100	0.55	
		1200	0.62	
		1300	0.70	
		1400	0.79	
		1500	0.89	
		1600	1.0	
		1800	1.3	
		2000	1.6	
2.3	steam hardened aerated concrete	400	0.14	5/10
		500	0.16	
		600	0.19	
		700	0.21	
		800	0.23	
2.4	lightweight concrete with porous structure			
2.4.1	with non-porous additions e.g. gravel	1600	0.81	3/10
		1800	1.1	
		2000	1.4	5/10
2.4.2	with porous additions with no quartz sand additions	600	0.22	5/15
		700	0.26	
		800	0.28	
		1000	0.36	
		1200	0.46	
		1400	0.57	
		1600	0.75	
		1800	0.92	
		2000	1.2	
2.4.2.1	using exclusively natural pumice	500	0.15	5/15
		600	0.18	
		700	0.20	
		800	0.24	
		900	0.27	
		1000	0.32	
		1200	0.44	
2.4.2.2	using exclusively expanded clay	500	0.18	5/15
		600	0.20	
		700	0.23	
		800	0.26	
		900	0.30	
		1000	0.35	
		1200	0.46	
3 construction panels				
3.1	asbestos cement panels	(2000)	0.58	20/50
3.2	aerated concrete building panels, unreinforced			
3.2.1	with standard joint thickness and wall mortar	500	0.22	
		600	0.24	
		700	0.27	
		800	0.29	
3.2.2	with thin joints	500	0.19	5/10
		600	0.22	
		700	0.24	
		800	0.27	
3.3	wall construction panels in lightweight concrete	800	0.29	5/10
		900	0.32	
		1000	0.37	
		1200	0.47	
		1400	0.58	
3.4	wall construction panels from gypsum, also with pores, cavities, filling materials or additions	600	0.29	5/10
		750	0.35	
		900	0.41	
		1000	0.47	
		1200	0.58	
3.5	gypsum board panels	(900)	0.21	8
4 masonry work, including mortar joints				
4.1	masonry work in wall bricks			
4.1.1	solid facing brick, vertically perforated facing brick, ceramic facing brick	1800	0.81	50/100
		2000	0.96	
		2200	1.2	
4.1.2	solid brick, vertically perforated brick	1200	0.50	5/10
		1400	0.58	
		1600	0.68	
		1800	0.81	
		2000	0.96	
4.1.3	hollow clay blocks	700	0.36	5/10
		800	0.39	
		900	0.42	
		1000	0.45	
4.1.4	light hollow clay blocks	700	0.30	5/10
		800	0.33	
		900	0.36	
		1000	0.39	
4.2	masonry work in limy sandstone	1000	0.50	5/10
		1200	0.56	
		1400	0.70	
		1600	0.79	15/25
		1800	0.99	
		2000	1.1	
		2200	1.3	
4.3	masonry work in foundry stone	1000	0.47	70/100
		1200	0.52	
		1400	0.58	
		1600	0.64	
		1800	0.70	
		2000	0.76	
4.4	masonry work in aerated concrete blocks	500	0.22	5/10
		600	0.24	
		700	0.27	
		800	0.29	
4.5	masonry work in concrete blocks			
4.5.1	hollow blocks of lightweight concrete, with porous additions without quartz sand addition			
4.5.1.1	2-K block, width ≤ 240mm 3-K block, width ≤ 300mm 4-K block, width ≤ 365mm	500	0.29	5/10
		600	0.32	
		700	0.35	
		800	0.39	
		900	0.44	
		1000	0.49	
		1200	0.60	
		1400	0.73	
4.5.1.2	2-K block, width = 300mm 3-K block, width = 365mm	500	0.29	5/10
		600	0.34	
		700	0.39	
		800	0.46	
		900	0.55	
		1000	0.64	
		1200	0.76	
		1400	0.90	
4.5.2	solid blocks in lightweight concrete			
4.5.2.1	solid blocks	500	0.32	5/10
		600	0.34	
		700	0.37	
		800	0.40	
		900	0.43	
		1000	0.46	
		1200	0.54	
		1400	0.63	
		1600	0.74	10/15
		1800	0.87	
		2000	0.99	
4.5.2.2	solid blocks (apart from solid blocks S-W of natural pumice as for item 4.5.2.3 and of expanded clay, as for item 4.5.2.4)	500	0.29	5/10
		600	0.32	
		700	0.35	
		800	0.39	
		900	0.43	
		1000	0.46	
		1200	0.54	
		1400	0.63	
		1600	0.74	10/15
		1800	0.87	
		2000	0.99	
4.5.2.3	solid blocks S-W of natural pumice	500	0.20	5/10
		600	0.22	
		700	0.25	
		800	0.28	
4.5.2.4	solid blocks S-W of expanded clay	500	0.22	5/10
		600	0.24	
		700	0.27	
		800	0.31	

(1) **Characteristic values for use in heat and humidity protection estimates**

item	material	gross density or gross density classification 1) 2) kg/m^3	calculated value of thermal conductivity λ_R 2) $W/(m \cdot K)$	standard value of water vapour diffusion resistance coefficient μ 4)
4.5.3	hollow blocks and T hollow bricks of standard concrete with a closed structure			
4.5.3.1	2-K block, width ≤ 240mm 3-K block, width ≤ 300mm 4-K block, width ≤ 365mm	(≤1800)	0.92	
4.5.3.2	2-K block, width = 300mm 3-K block, width = 365mm	(≤1800)	1.3	
5 thermal insulation materials				
5.1	light wood fibre board panels panel thickness < 25 mm = 15mm	 (360–480) (570)	 0.093 0.15	 2/5
5.2	multilayer light building panels of plastic foam sheets with coverings of mineral bound wood fibre plastic foam panels wood fibre layers (individual layers) 10mm < thickness < 25mm > 25mm wood fibre layers (individual layers) with thickness < 10mm must not be considered when calculating the thermal resistance 1/Λ	 (≥15) (460–650) (360–460) (800)	 0.040 0.15 0.093	 20/70
5.3	foam plastic manufactured on the construction site			
5.3.1	polyurethane (PUR) foam	(≥37)	0.030	30/100
5.3.2	urea formaldehyde resin (UF) – foam	(≥10)	0.041	1/3
5.4	cork insulation material cork sheets thermal conductivity group 045 050 055	 (80–500)	 0.045 0.050 0.055	 5/10
5.5	foam plastic			
5.5.1	polystyrene (PS) rigid foam thermal conductivity group 025 030 035 040 polystyrene particle foam polystyrene extruded foam	 (≥15) (≥20) (≥30) (≥25)	 0.025 0.030 0.035 0.040	 20/50 30/70 40/100 80/300
5.5.2	polyurethane (PUR) rigid foam thermal conductivity group 020 025 030 035	 (≥30)	 0.020 0.025 0.30 0.035	 30/100
5.5.3	phenolic resin (PF) – rigid foam thermal conductivity group 030 035 040 045	 (≥30)	 0.030 0.035 0.040 0.045	 30/50
5.6	mineral and vegetable fibre insulation materials thermal conductivity group 035 040 045 050	 (8–500)	 0.035 0.040 0.045 0.050	 1
5.7	foam glass thermal conductivity group 045 050 055 060	 (100 to 105)	 0.045 0.050 0.055 0.060	 5)
6 wood and wood materials				
6.1	wood			
6.1.1	pine, spruce, fir	(600)	0.13	40
6.1.2	beech, oak	(800)	0.20	
6.2	timber materials			
6.2.1	plywood	(800)	0.15	50/400
6.2.2	chip board			
6.2.2.1	flat compressed panels	(700)	0.13	50/100
6.2.2.2	extruded panels (full panels not planking)	(700)	0.17	20
6.2.3	particleboard			
6.2.3.1	dense particleboard	(1000)	0.17	70
6.2.3.2	porous particleboard and bitumen wood particleboard	200 300	0.045 0.056	5
7 coverings, sealing materials and sealing rolls				
7.1	floor coverings			
7.1.1	linoleum	(1000)	0.17	
7.1.2	cork linoleum	(700)	0.081	
7.1.3	linoleum composite coverings	(100)	0.12	
7.1.4	plastic coverings, e.g. including PVC	(1500)	0.23	
7.2	sealing materials, sealing rolls			
7.2.1	asphalt mastic, thickness ≥ 7mm	(2000)	0.70	5)
7.2.2	bitumen	(1100)	0.17	
7.2.3	roofing strip, roof sealing rolls			
7.2.3.1	bitumen roof rolls	(1200)	0.17	10000/ 80000
7.2.3.2	bare bitumen roof rolls	(1200)	0.17	2000/ 20000
7.2.3.3	glass fibre – bitumen roof rolls			20000/ 60000
7.2.4	plastic roof rolls			
7.2.4.1	PVC soft			10000/ 25000
7.2.4.2	PIB			400000/ 1750000
7.2.4.3	ECB 2.0K			50000/ 75000
7.2.4.4	ECB 2.0			
7.2.5	sheets			
7.2.5.1	PVC sheets, thickness ≥ 0.1mm			20000/ 50000
7.2.5.2	polyethylene sheets, thickness ≥0.1mm			100000
7.2.5.3	aluminium sheets, thickness ≥0.05mm			5)
7.2.5.4	other metal sheets, thickness ≥0.1mm			5)
8 other useful materials				
8.1	loose ballasting, covered			
8.1.1	of porous materials: expanded perlite expanded mica cork scrap, expanded blast furnace slag expanded clay, expanded slate pumice grit lava crust	 (≤100) (≤100) (≤200) (≤600) (≤400) (≤1000) ≤1200 ≤1500	 0.060 0.070 0.050 0.13 0.16 0.19 0.22 0.27	
8.1.2	of polystyrene plastic foam particles	(15)	0.045	
8.1.3	of sand, gravel, chippings (dry)	(1800)	0.70	
8.2	flagstones	(2000)	1.0	
8.3	glass	(2500)	0.80	
8.4	natural stone			
8.4.1	crystalline metamorphous rock (granite, basalt, marble)	(2800)	3.5	
8.4.2	sedimentary rock (sandstone, metamorphic, conglomerate)	(2600)	2.3	
8.4.3	natural porous ignous rock	(1600)	0.55	
8.5	soil (naturally damp)			
8.5.1	sand, sand and gravel		1.4	
8.5.2	cohesive soil		2.1	
8.6	ceramic and glass mosaic	(2000)	1.2	100/300
8.7	thermal insulating plaster	(600)	0.20	5/20
8.8	synthetic resin plaster	(1100)	0.70	50/200
8.9	metals			
8.9.1	steel		60	
8.9.2	copper		380	
8.9.3	aluminium		200	
8.10	rubber (solid)	(1000)	0.20	

1) the gross density values given in brackets are only used to determine the surface area related quantities, e.g. to demonstrate heat protection in summer

2) the gross density values relating to stone are descriptions of class corresponding to the related material standards

3) the given calculated values of thermal conductivity λ_R of masonry work may be reduced by around 0.06W/(mK) when factory standard light masonry mortar from additions with a porous structure, without quartz sand additions are used – with a solid mortar gross density ≤ 1000kg/m³, however, the reduced values for aerated concrete blocks – item 4.4 and the solid blocks S-W of natural pumice and expanded clay – items 4.5.2.3 and 4.5.2.4 – must not be less than the corresponding items 2.3 and 2.4.2.1 and 2.4.2.2

4) the respective, least favourable values, should be used for building construction

5) in practice, vapour tight s_l ≥ 1500m

6) in the case of quartz sand additions, the calculated values of thermal conductivity increase by 20%

7) the calculated values of thermal conductivity should be increased in the case of hollow blocks with quartz sand additions, by 20% for 2-K blocks and by 15% for 3-K blocks and 4-K blocks

8) panels of thickness < 15mm must not be taken account of in thermal insulation considerations

9) in the case of footstep sound insulation panels in plastic foam materials or fibrous insulation materials, the thermal resistivity 1/Λ is stated on the packaging in all cases

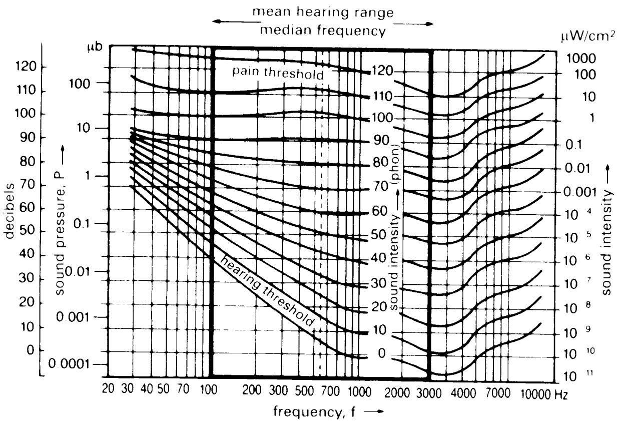
10) the given calculated values of thermal conductivity λ_R apply to cross grain application in wood and at right angles to the plane of the panel in the case of timber materials. In the case of wood in the direction of the grain and for timber materials in the plane of the panel, approx. 2.2 times the values should be taken, if more accurate information is unavailable

11) these materials have not been standardised in terms of their thermal insulation values; the given values of thermal conductivity represent upper limiting values

12) the densities are given as bulk densities in the case of loose ballasting

① **Characteristic values for use in heat and humidity protection estimates**

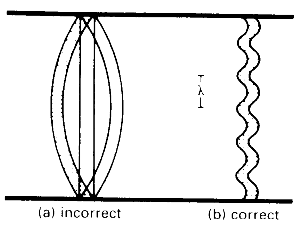
SOUND INSULATION



(1) **Relationship between loudness intensity (phon), acoustic pressure (µb), sound level (dB) and acoustic intensity (µW/cm²)**

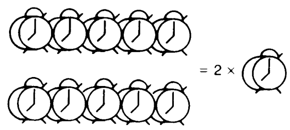
0–10	hearing sensitivity commences
20	soft rustle of leaves
30	lower limit of noises of everyday activities
40	mean level of noises of everyday activities, low level of conversation; quiet residential road
50	normal level of conversation, radio music at normal room level in closed rooms
60	noise of a quiet vacuum cleaner; normal road noise in commercial areas
70	a single typewriter; or a telephone ringing at a distance of 1 m
80	road with very busy traffic; room full of typewriters
90	noisy factory
100	motor horns at a distance of 7 m; motor cycle
100–130	very noisy work (boilermakers' workshop, etc.)

(2) **Scale of sound intensities**



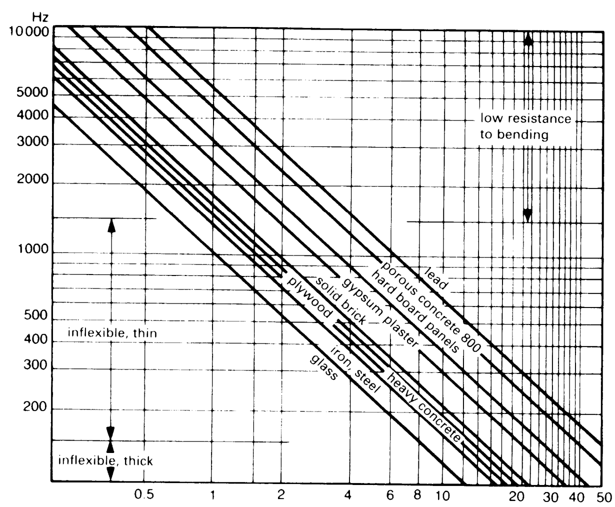
the wall (a) does not oscillate as a whole, but rather (b) in parts which vibrate in opposition to one another

(3) **Representation of transverse waves on a wall at normal frequencies**



in general, humans hear a sound as having increased in intensity only twofold when, in fact, it has increased tenfold

(4) **Sensitivity to sound intensity**



(5) **Boundary frequency of panels in various building materials**

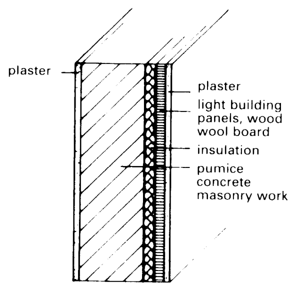
Even if propagation of sound is avoided, complete elimination of a noise is impossible. If the sound source and the hearer are located in the same room, then some reduction takes place through sound absorptivity → p. 120. If they are in separate rooms, then sound insulation is the main remedy.

A distinction is made between sound insulation of airborne sound and sound insulation of structure-borne sound: airborne sound sources initially disturb the surrounding air, e.g. radio, shouting or loud music; with structure-borne sound, the sound source is propagated directly through a structure, e.g. movement of people on foot, noise from plant and machinery. Sound from a piano is an example of both airborne sound and structure-borne sound.

Sound is propagated by mechanical vibration and pressure waves – very small increases and decreases in pressure relative to atmospheric pressure of the order of a few microbars (µb). (The pressure fluctuation generated by speaking in a loud voice is about one millionth of atmospheric pressure.) Sounds and vibrations audible to humans lie in the frequency range 20 Hz–20000 Hz (1 Hz = 1 cycle per second). However, as far as construction is concerned, the significant range is 100–3200 Hz, to which the human ear is particularly sensitive. In the human audible range, sound pressures extend from the hearing threshold to the pain threshold → (1). This hearing range is divided into 12 parts, called bels (after A. G. Bell, inventor of the telephone). Since 0.1 bel (or 1 decibel = 1 dB) is the smallest difference in sound pressure perceptible to the human ear at the normal frequency of 1000 Hz, decibels are a physical measure of the intensity of sound, related to unit surface area → (1). Usually, noise levels of up to 60 dB are expressed in dB(A); those of more than 60 dB in dB(B), a unit which is approximately equivalent to the former unit, the phon.

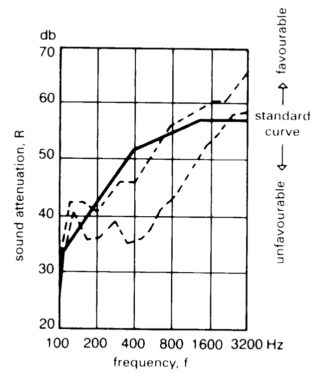
For airborne sound, the sound level difference (between the original sound level and the insulated sound level) serves to indicate the degree of sound insulation. For body-propagated sound, a maximum level is given, which must remain from a standard noise level. Sound insulation, principally due to mass, is provided by the use of heavy, thick components in which the airborne sound energy is initially dissipated through transfer of the airborne sound into the component, then through excitation of the mass of the component itself and then, finally, by transfer back into the air. If the component is directly excited (body sound), then its insulation is naturally lower.

Light sound-damping construction → (6) makes use of multiple transfer (air to component to air to component to air) in providing sound insulation; better insulation, relative to that expected due to component mass, only occurs above the resonant frequency, however, which consequently should be below 100 Hz. (This is comparable to the resonant frequency of the oscillation of a swinging door which is already swinging due to light impacts. It is simple to slow the motion of the door by braking; to make it move more quickly is more difficult and requires force.) The intermediate space in double-shell construction is filled with sound-absorbing material, to avoid reflection of the sound backwards and forwards. The sound propagates in the air as a longitudinal wave → (3), but as a transverse wave in solid materials. The speed of propagation of longitudinal waves is 340 m/sec but, within materials, this depends on the type of material, layer thickness and frequency. The frequency at which the velocity of propagation of a transverse wave in a structural component is 340 m/sec, is called the boundary frequency. At this frequency, the transfer of sound from the air into the component and vice versa, is very good; therefore, the sound insulation of the component is particularly poor, poorer than would be expected from the weight of the wall. For heavy, quite inflexible building components, the boundary frequency is close to the frequency range of interest and therefore exhibits reduced sound insulation properties; for thin, flexible components, the boundary frequency is below this frequency range → (5).



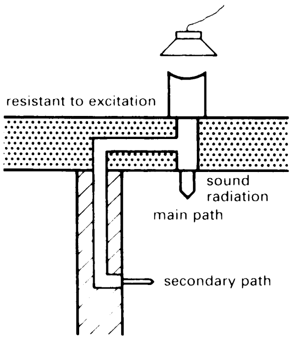
facing panel of plastered wood fibre board; light construction panels 15 mm plaster; 115 mm pumice concrete masonry; 16 mm expanded styrofoam; 25 mm light wood wool building panels – nailed, with large separation between nails; 20 mm gypsum-sand-plaster

(6) **Light sound-damping construction**

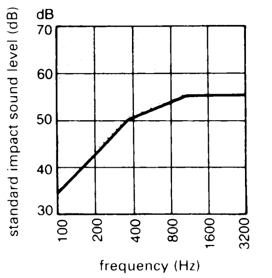


(7) **Airborne sound insulation of the wall → (1) from measurements by Prof. Gäsele: sound insulation without covering –7 dB; with covering +2 dB**

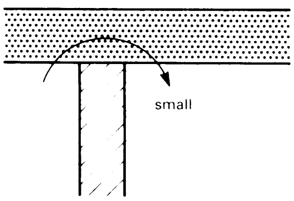
SOUND INSULATION



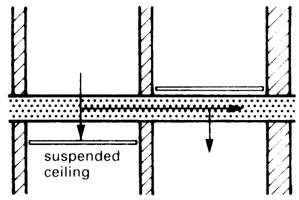
① **Airborne sound**



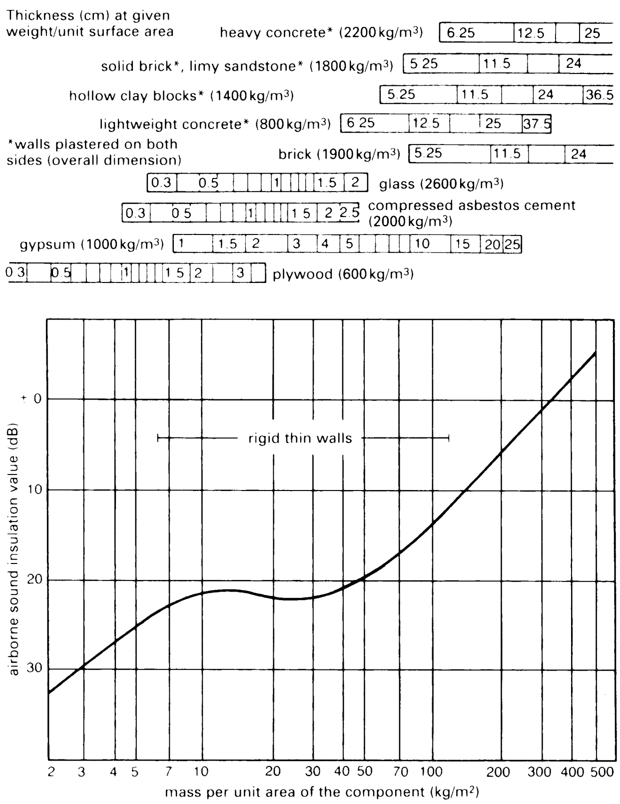
② **Standard curve for airborne sound**



③ **Secondary path via bordering single layer component**



④ **Diagonal transmission**



⑤ **Airborne sound insulation, weight/unit surface area and component thickness (Gäsele)**

1	simple door with threshold, without special sealing	up to	20db
2	heavy door with threshold and good sealing	up to	30db
3	double doors with threshold, without special sealing, opening individually	up to	30db
4	heavy double doors, with threshold and sealing	up to	40db
5	simple window, without additional sealing	up to	15db
6	simple window, with good sealing	up to	25db
7	double window, without special sealing	up to	25db
8	double window, with good sealing	up to	30db

⑥ **Sound insulation of doors and windows**

With airborne sound, the aerial sound wave excites the component → ①; hence, the effect of the boundary frequency on the sound insulation increases → ⑤.

The standard curve shows how large the sound level difference must be at the individual frequencies, as a minimum, so as to achieve a level of sound insulation of ±0dB. Prescribed values → ②; required wall thicknesses → ⑦.

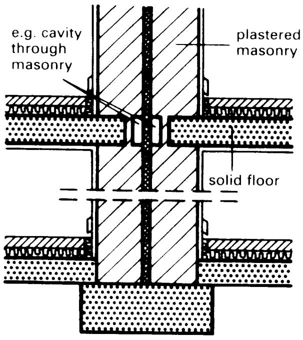
However, the effect of sound transmitted by 'secondary paths' (e.g. sound from foot steps) can be more disruptive than that from impact, so these must be taken into account in the sound insulation calculations. (For this reason, test results should always be drawn up for sound insulating walls with due consideration of the usual secondary paths.) Components which are stiff in bending, with weights per unit surface area of 10–160kg/m², are particularly likely to provide secondary paths. Therefore, living room dividing walls – which are contacted by such components in the form of lateral walls – should have a weight of at least 400kg/m². (Where the contacting walls have a surface weight of over 250kg/m², this value can be 350kg/m².)

Doors and windows, with their low sound insulation properties → ⑥, have a particularly adverse effect on insulation against airborne sound; the small proportion of the surface occupied by the openings is usually subject to a sound insulation value which is less than the arithmetic mean of the sound damping of wall and opening. Therefore, the sound insulation of the door or window should always be improved where possible. Walls which have insufficient sound insulation can be improved through the addition of a non-rigid facing panel → ⑥ p. 117. Double walls can be particularly well soundproofed if they contain soft, springy insulating material and are relatively flexible → ⑥ p. 117, or if the two wall panels are completely separately supported. Flexible panels are relatively insensitive to small sound bridges (by contrast to rigid panels). Type testing methods of construction should always be employed on sound insulating double walls. Covering layers of plaster on insulation materials of standard hardness (e.g. on standard styrofoam) considerably reduces the sound insulation.

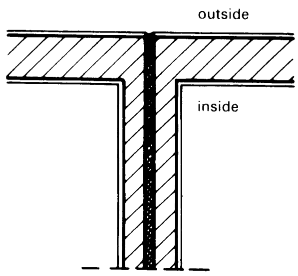
item	description	gross density (kg/dm³)	wall weight >400kg/m²		wall weight >350kg/m² <400kg/m²	
			mm	kp/m²	mm	kp/m²
	masonry work in solid, perforated and hollow blocks, plastered on both sides to a thickness of 15mm					
1		1	365	450	300	380
2	perforated brick, solid brick	1.2	300	445	240	360
3		1.4	240	405	–	–
4	solid engineering brick	1.8	240	485	–	–
5		1.9	240	505	–	–
6			–	–	300	380
7	hollow sand lime bricks	1.2	300	440	240	360
8		1.2	300	445	240	360
9	sand lime perforated bricks	1.4	240	405	–	–
10		1.6	240	440	–	–
11		1.6	240	440	–	–
12	solid sand lime bricks	1.8	240	485	–	–
13		2	240	530	–	–
14	foundry stone	1.8	240	485	–	–
15	hard foundry stone	1.9	240	505	–	–
16	2- or reversed laid,	1	300	420	–	–
17	3-chambered with cavities	1.2	300	460	–	–
18	hollow filled with	1.4	240	410	–	–
19	concrete sand	1.6	240	440	–	–
20	blocks	1	365	400	–	–
21	without	1.2	–	–	–	–
22	sand filling	1.4	–	–	300	355
23		1.6	300	430	240	380
24		0.8	365	405	–	–
25	lightweight concrete	1	365	450	300	380
26	solid blocks	1.2	300	445	240	360
27		1.4	240	405	–	–
28		1.6	240	440	–	–
29	aerated/foamed concrete	0.6	–	–	490	390
30	blocks	0.8	490	485	365	380
	lightweight concrete and concrete in unjointed walls and storey-depth panels, 15mm plaster on both sides					
31	aerated/foamed concrete blocks	0.6	–	–	500	350
32		0.8	437.5	400	375	350
33	pumice/bituminous coal slag,	0.8	437.5	400	375	350
34	concrete with brick debris,	1	375	425	312.5	360
35	or similar	1.2	312.5	425	250	–
36		1.4	250	400	–	350
37		1.6	250	450	187.5	350
38		1.7	250	475	187.5	370
39	concrete with porous debris,	1.5	250	425	–	–
40	with non-porous additions,	1.7	250	475	187.5	370
41	e.g. gravel	1.9	187.5	405	–	–
42	gravel or broken concrete with closed structure	2.2	187.5	460	150	380

⑦ **Minimum thicknesses of single-layer walls for airborne sound insulation ≥ 0dB**

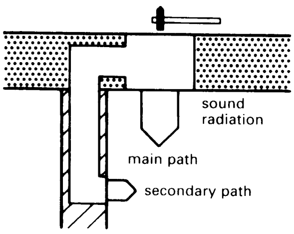
SOUND INSULATION



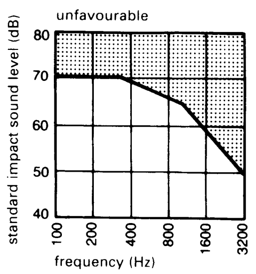
① **Double skin dividing wall with continuous cavity**



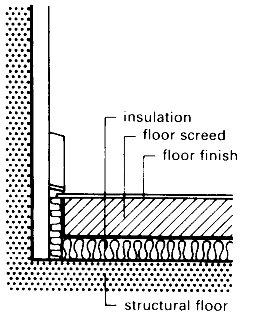
② **Plan view** → ①



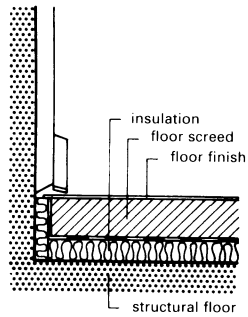
③ **Sound conduction through solid structure**



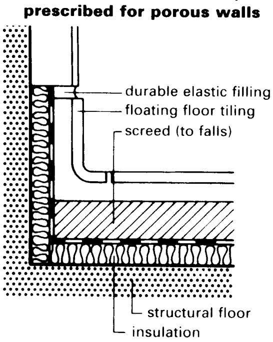
④ **Standard curve for impact sound**



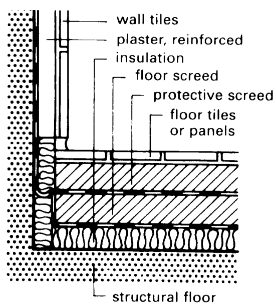
⑤ **Plaster applied down to floor level before floor screed; prescribed for porous walls**



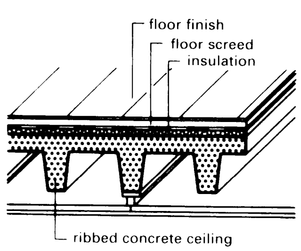
⑥ **Plaster applied after floor screed, on solid walls**



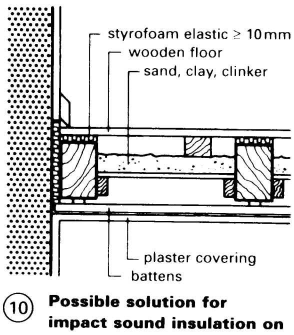
⑦ **Floating tiled floor (baths)**



⑧ **Floor construction with ceiling for bathrooms with shower**



⑨ **Soft, pliable suspended ceiling**



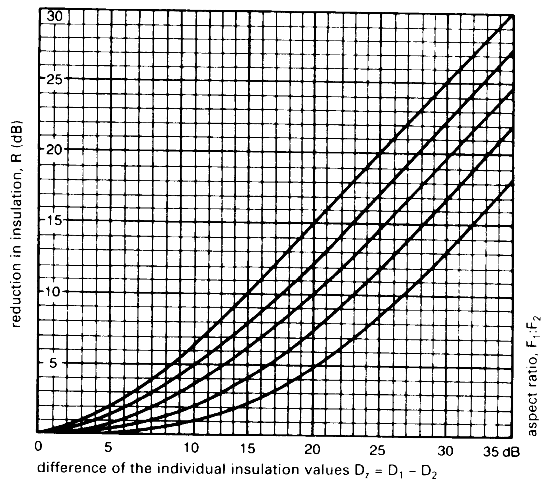
⑩ **Possible solution for impact sound insulation on a timber joist ceiling**

House dividing walls

House dividing walls constructed from wall leafs with leaf weights per unit surface area < 350 kg/m² must be separated by a cavity over the entire depth of the house; their mass should be ≥150 kg/m² (200 kg/m² in multi-storey residences). If the dividing wall commences at the foundations, no additional precautions are necessary; if it commences at the ground level (as for dividing walls between separate residential accommodation), the floor above the cellar must have a suspended floor or a soft springy covering. The cavity should be provided with filling material (foam panels, etc.) preferably with staggered joints; small jointing areas can reduce the sound insulation, because the structure is resistant to bending.

Composite walls

In this case (including any walls with areas of different sound insulation properties, e.g. with a door), the total insulation value D_g is obtained after deducting the insulation reduction R from the overall insulation value → ⑪.



⑪ **Determination of reduction in insulation**

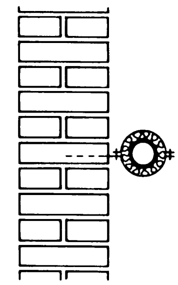
calculation procedure:
1 establish the difference of the individual insulation values $D_z = D_1 - D_2$ (where $D_1 > D_2$)
2 determine aspect ratio of the insulating wall components
3 reduction in insulation R is given by the point of intersection of aspect ratio with the vertical ordinate D_z

Impact sound insulation

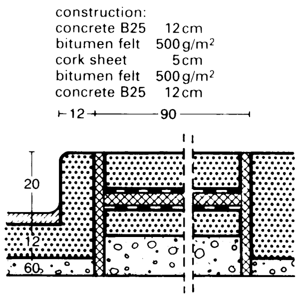
In the case of impact sound (e.g. noise due to footsteps), the ceiling is directly excited into vibration → ③. The standard curve → ④ gives a standardised impact sound level, i.e., the maximum that should be heard in the room below when a standard 'tramper' is in action above. To allow for ageing, the values achieved immediately after construction must be 3 dB better than the values shown.

The usual form of impact sound insulation is provided by 'floating' screed, i.e. a jointless, soft, springy insulating layer, covered with a protective layer and, then, a screed of cement concrete, anhydrous gypsum or poured asphalt. This simultaneously provides protection against airborne sound and is therefore suitable for all types of floors (floor groups I and II). The edge should be free to move, and mastic joint filler with enduring elasticity should always be used, particularly with tiled floors → ⑦, since the screed is thin and stiff, and is therefore extremely sensitive to sound bridges. With floors whose airborne sound insulation is already adequate (floor group II), impact insulation can also be provided by using a soft, springy floor finish → ⑧. Floors in floor group I can be upgraded to group II by the provision of a soft, springy suspended floor → ⑨. The degree to which this floor finish improves the impact sound insulation is judged from the improvement in dB attenuation.

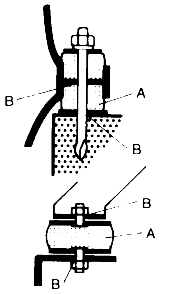
SOUND INSULATION



(1) **Sound insulation of pipework**

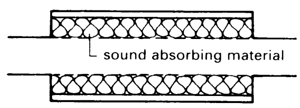


(2) **Sound insulated boiler foundation 90cm wide**

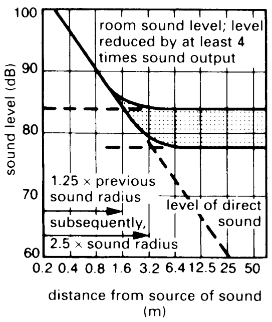


A = sound insulating material, e.g. rubber
B = air space – if necessary, filled with sound insulating material

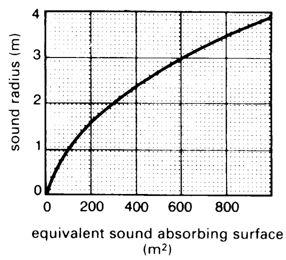
(3) **Metal/rubber element**



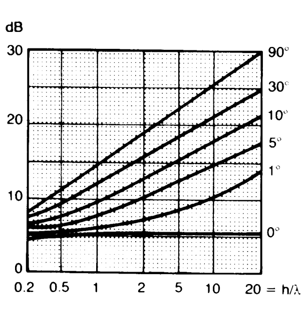
(4) **Duct packed with sound absorbing material (transmitted sound damper)**



(5) **The level of reflected sound can be reduced by sound absorption measures; the sound radius increases but, at the same time, the noise level reduces outside the previous sound radius**

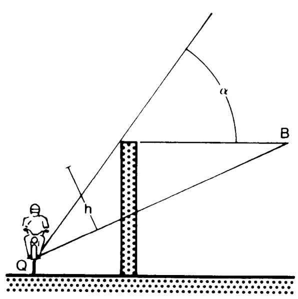


(6) **Sound radius and sound absorbing capability of a room**



read off the shielding ordinate as a function of angle α → (8), and height (m)/sound wavelength
example: α = 30°, h = 2.50m: at 500Hz (med. freq. range) = 340/500 = 0.68; wavelength is h/λ = 2.5/0.68 = 3.68, hence shielding effect = 17dB

(7) **Sound proofing due to outside barriers**



Q = sound source
B = hearer

(8) **Diagram → (7)**

Noise from services

Noise from services can occur as plumbing fixture noise, pipework noise and/or filling/emptying noises:

- For plumbing fixture noise, the remedy is provided by sound-insulated valves with inspection symbols (test group I with at most 20dB(A) overall noise level, test group II with at most 30dB(A) only permissible for internal house walls and adjoining service rooms). All installations are improved, among other measures, by sound dampers.
- For pipework noise due to the formation of vortices in the pipework, the remedy is to use radiused fittings instead of sharp angles, adequate dimensioning, and sound damping suspensions → (1).
- For filling noise caused by water on the walls of baths, etc. the remedy is to muffle the objects, fit aerator spouts on the taps, and to sit baths on sound damping feet (and use elastic joints around the edges).
- For emptying noise (gurgling noises), the remedy is correct dimensioning and ventilation of drain pipes.

The maximum permissible sound level due to services in adjoining accommodation is 35dB(A). Sound generating components of domestic services and machinery (e.g. water pipes, drain pipes, gas supply pipes, waste discharge pipes, lifts) must not be installed in rooms intended for quiet everyday activities (e.g. living rooms, bedrooms).

Sound insulation for boilers can be effected by sound-damped installation (isolated foundation → (2), sound-absorbing sub-construction), sound-damping hood for the burner, connection to chimney with sound-damping entry, and connection to hot pipework by means of rubber compensators.

In ventilation ducts of air conditioning systems, noise from sound transmission is reduced by means of so-called telephonic sound dampers; these comprise sound-absorbing packings, between which the air flows. The thicker the packing, the lower the frequencies which are covered. The ventilation ducts themselves should also be sound insulated.

Sound absorption

In contrast to sound insulation, sound absorption does not usually reduce the passage of sound through a component. It has no effect on the sound which reaches the ear directly from the source; it merely reduces the reflected sound.

Although the direct sound diminishes with distance from the source, the reflected sound is just as loud, or louder than the direct sound, at a distance greater than the 'sound' radius about the sound source → (5). If the reflection of sound is reduced, then the level of the reflected sound is reduced outside the original 'sound' radius, while the sound radius itself increases. Nothing changes within the original sound radius.

The sound absorption capability of a room is expressed in m² equivalent sound absorption, i.e. the ideal sound absorbing surface that has the same absorption capability as the room itself. For a reverberation time of 1.5 sec. – ideal for private swimming baths, etc. – the equivalent sound absorption surface A must be 0.1 m² for every m³ of room volume v (the sound radius would then be only 1.1 m in a room 6 × 10 × 2.5 m) and twice as large to achieve half the reverberation time.

Example: Swimming bath

40 m² water × 0.05	=	2.00 m²
100 m² walls and floor × 0.03	=	3.00 m²
60 m² acoustic ceiling × 0.4	=	24.00 m²
		29.00 m²

$A = \frac{29}{150} \approx 0.2V$; reverberation time is thus 0.75 seconds.

Protection against external noise

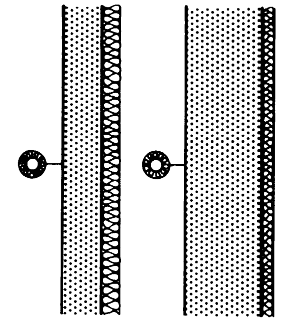
Precautions can be taken against external noise (traffic, etc.):

- Appropriate planning of the building, e.g. living/recreation rooms away from sources of noise
- Sound insulation of outer walls, particularly window and outer door insulation; fixed glazed installations with ventilation systems
- Installation of sound insulation shields in facades
- Sound protection through landscaping, e.g. embankments, walls or planted areas

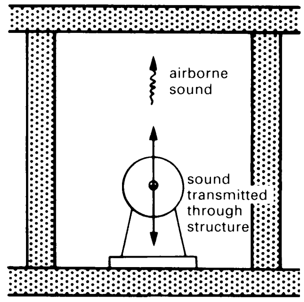
In the case of embankments, walls and other screens, the sizing of the protective device can be obtained → (7) for the various wavelengths (wavelength is approx. 340 m/frequency). It can be seen how important dimension h is, as given by angle α.

VIBRATION DAMPING

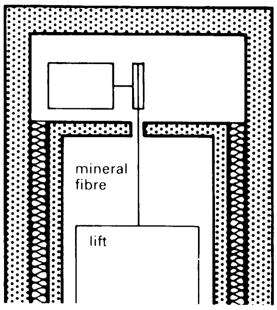
Sound Conduction Through Structures



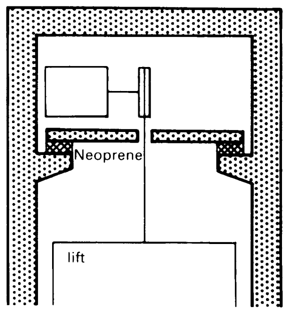
① **Light wall – high excitation**
Heavy wall – less excitation



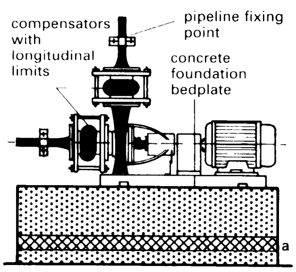
② **Causes of structure-borne sound**



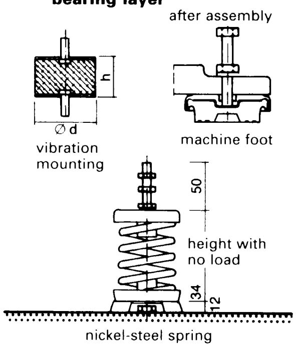
③ **Separate lift shaft with >30 mm mineral fibre lining**



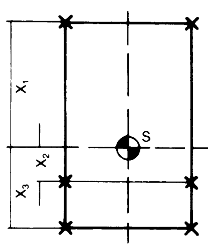
④ **Top of shaft with Neoprene bearing layer**



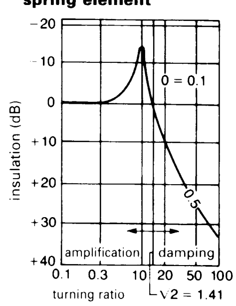
⑤ **Equipment installation with elastic insert in foundation**



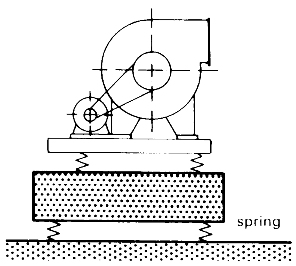
⑥ **Example of individual spring element**



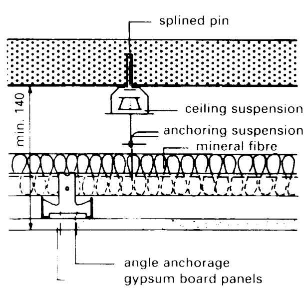
⑦ **Alignment of spring with centre of gravity**



⑧ **Effect of elastic bearing**



⑨ **Double elastic suspension for ventilator**



⑩ **Example of vibration mounting ceiling element**

Vibrations in solid bodies, 'structure-borne sounds', are created either by sound in air, or directly, by mechanical excitation → ① + ②.

Since the alternating mechanical forces are usually higher than any produced by fluctuating air pressure, the audible radiation is usually greater in the case of direct excitation. Frequently, resonance phenomena occur, which lead to higher audible radiation in narrow frequency ranges.

If the radiated sound remains monotonic, the cause is usually the result of direct excitation of the structure. Anti 'structure-borne sound' measures must therefore seek to reduce this direct excitation and its further propagation.

Precautions to combat structure-borne sound transmission
In the case of water installations, only valves carrying inspection symbols in accordance with group I or II should be used. The water pressure should be as low as possible.

The water velocity plays a subordinate role.

Pipework should be attached to walls in accordance with good practice, with surface loading m″ ≥ 250 kg/m².

Baths and tanks should be installed on floating screed and separated from walls. Walled enclosures should be flexibly jointed to the primary walls. Wall-suspended WC fittings cause direct excitation of the structure; however, rigid fixing is unavoidable, so if necessary, elastic layers should be introduced.

Water and drainage pipes must be fixed using elastic materials and should not be in direct contact with the structural wall.

Lifts should be installed in separate shafts → ③ and joints filled with at least 30 mm mineral fibre, or the top of the shaft provided with Neoprene bearing strips → ④.

Pumps and equipment must be installed on structure-borne sound insulated foundations and elastically connected.

Compensators are subject to tensile stresses, since the internal pressure also acts on the longitudinal axis of the assembly → ⑤.

Rubber granulate panels are particularly suitable as insulating material for foundations, due to their high compressive strength. If required, impact sound insulating materials of mineral fibre and plastic foam can be built in. Cork and solid rubber are unsuitable, since these materials are too stiff. The more the insulating materials are compressed together under load, without being overloaded, the better is the insulating effect.

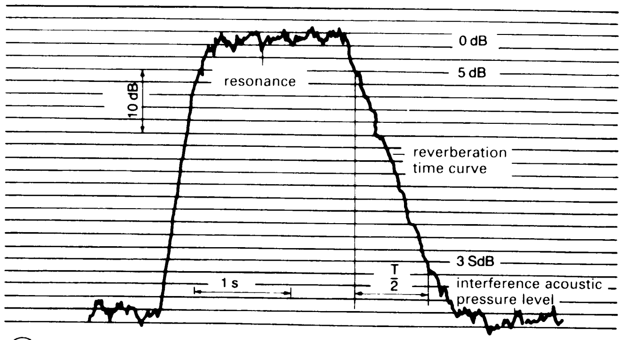
With flat insulating materials, the loading must usually be greater than 0.5 N/mm². If this cannot be guaranteed, then individual elements are required, effectively to add to the weight of the equipment.

The insulating effect is also greatest here if the elements are loaded to a maximum, without becoming overloaded. The individual elements can be of Neoprene or steel → ⑥.

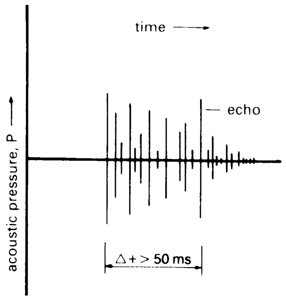
Steel springs provide the best structural sound insulation, due to their low stiffness. In special cases, air springs can be used. In the case of individual springs, attention must be paid to the centre of gravity, to ensure the elements are uniformly loaded → ⑦.

In the case of periodic excitation (e.g. due to oscillating or rotating masses), the frequency of excitation must not coincide with the natural frequency of the elastically suspended system. Large motions result from the reverberation which, in the case of elements with low damping, can lead to structural failure → ⑧. Particularly high insulating properties may be obtained by using doubled elastic suspensions → ⑨. Unfavourable interaction between foundations on floating layers can lead to a reduction in insulation.

ROOM ACOUSTICS



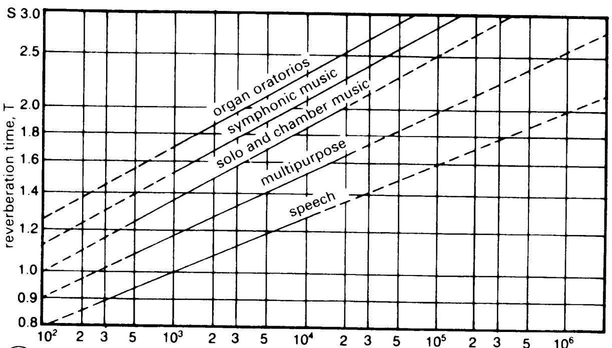
① **Measurement of reverberation time**



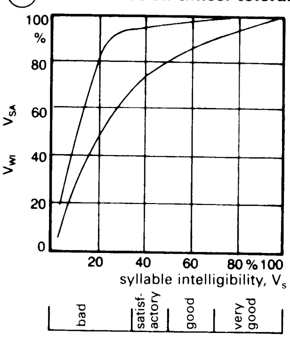
② **Echo criterion**

room function	reverberation time (s)	
speech	cabaret	0.8
	drama	1.0
	lecture	
music	chamber music	1.0...1.5
	opera	1.3...1.6
	concert	1.7...2.1
	organ music	2.5...3.0

③ **Reverberation times: optimum range**



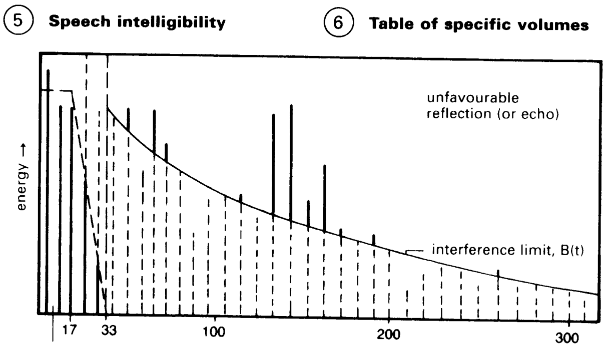
④ **Reverberation times: tolerance ±20%**



⑤ **Speech intelligibility**

purpose	characteristic volume (m^3 per seat)	max. volume (m^3)
spoken theatrical work	3...5	5000
multipurpose: speech and music	4...7	8000
musical theatre (opera, operetta)	5...8	15000
chamber music concert hall	6...10	10000
symphony music concert hall	8...12	25000
rooms for oratorios and organ music	10...14	30000

⑥ **Table of specific volumes**



⑦ **Reflection sequence in the room**

Room acoustic planning should ensure that optimum audible conditions are created for listeners in rooms where speech and music are to be carried out. Various factors should be considered, of which the two most important are reverberation time, and reflections (as a consequence of the primary and secondary structure of the room).

(1) Reverberation time
This is the time taken for the decay of a noise level of 60 dB after the sound source has been switched off → ①. Evaluation is carried out over the range −5 to −35 dB.

(2) Absorption surface
The absorption surface is determined by the amount of absorbing material, expressed as an area having complete absorption (open window):
$A = \alpha_s \times S$
where α_s is the degree of sound absorption from echo chamber measurements, and S is the area of surface portion.
The reverberation time is calculated from the absorption surface from:
$t = 0.163 \times V \div \alpha_s \times S$ (after Sabine)

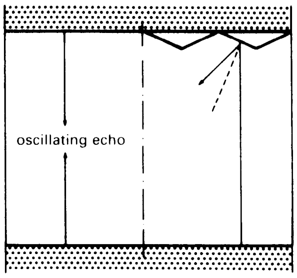
(3) Echoes
When individual, subjectively recognisable peaks are superimposed on a smoothly falling reverberation time curve → ①, these are described as echoes → ②. Various values of time and intensity apply as the echo criterion for speech and music. Rooms devoted to music should have a longer reverberation time, but are usually regarded as less critical from the point of view of echoes.

Requirements for rooms

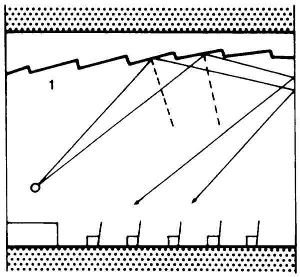
(1) Reverberation time
The optimum value for reverberation time is dependent on the particular use and room volume → ③. In general, reverberation time is frequency-dependent (longer at low frequencies, shorter at high frequencies.) For f = 500 Hz, surveys have shown that approximations may provide optimum values → ④.

(2) Speech intelligibility
This is used to judge the degree of audibility of the spoken word → ⑤. It is not standardised, so various terms – sentence intelligibility, syllable intelligibility, evaluation with logatomes – are usual. In determining the intelligibility of speech, a number of collectively heard individual syllables of no significance (logatomes such as lin and ter) are noted; the correctness is used to make an assessment – a score of more than 70% implies excellent speech intelligibility. Newer, objective, methods make use of modulated noise signals (RASTI method) and lead to reproducible results at low expense.

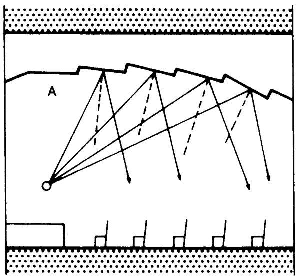
(3) Impression of space
This is determined by the reception of reflections with respect to time and direction. For music, diffuse reflections are favourable for sound volume, while early reflections with delays of up to 80 ms (corresponding to 27 m path difference) with respect to the direct sound promote clarity → ⑥. Speech requires shorter delays (up to 50 ms) so as not to degrade the intelligibility.



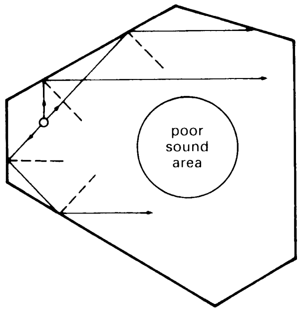
① **Prevention of oscillating echoes**



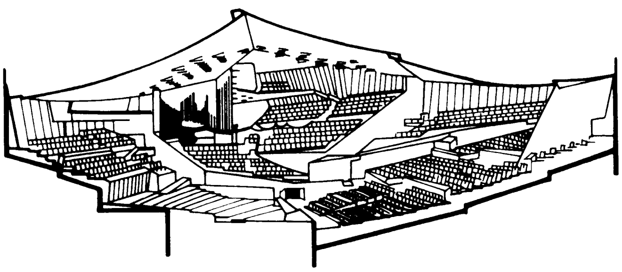
② **Unfavourable ceiling shape**



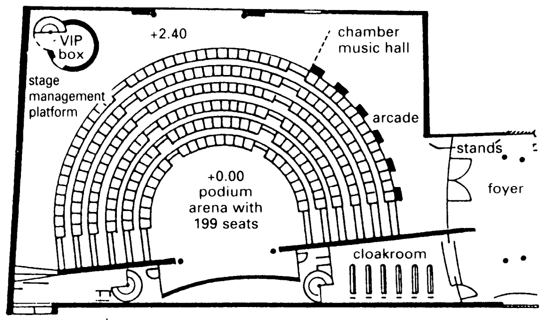
③ **In one plane for music; inclined downward towards the back for speech**



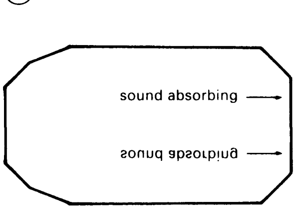
④ **Less favourable platform**

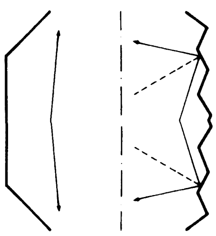


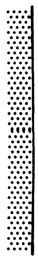
⑤ **Berlin Philharmonic – staggering the auditorium**



⑥ **Podium with small chamber music hall – Beethoven Archive, Bonn**







⑥ **Podium with small chamber music hall – Beethoven Archive, Bonn**
emergency exit
emergency exit
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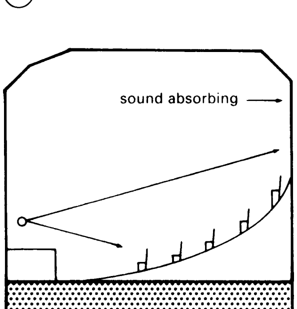
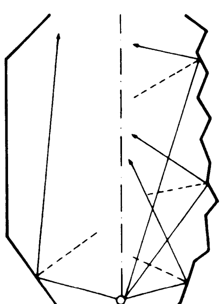
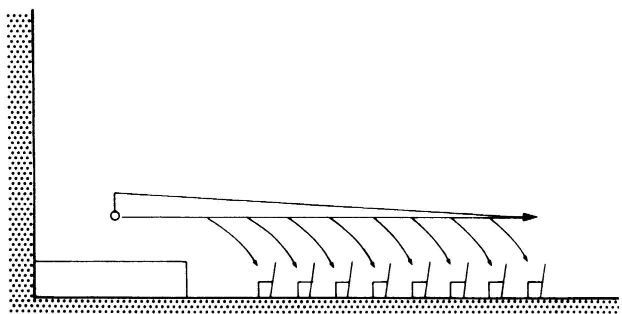






For the music listener, early sideways reflections are better than ceiling reflections, even at very low delay times (asymmetry of the acoustic impression), since each ear receives a different signal. Narrow, high rooms with geometrically reflecting walls with multiple angles and diffusely reflecting ceilings are the simplest from the point of view of room acoustics.

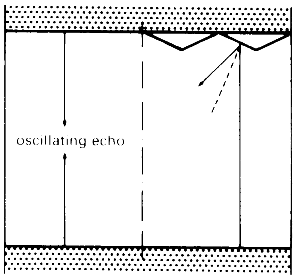
Primary structure of rooms

Volume is application dependent → ⑥ p. 122: 4 m^3/person for speech, 18 m^3/person for concerts; too small a volume results in insufficient reverberation time. Narrow, high rooms with walls with multiple angles (early sideways reflections) are particularly suitable for music. For early initial reflections and balance of the orchestra, reflection surfaces are needed in the vicinity of the podium. The rear wall of the room should not cause any reflections in the direction of the podium, since these can have the effect of echoes. Parallel, planar surfaces should be avoided, to prevent directionally oscillating echoes due to multiple reflections → ①. Providing projections in the walls, at angles greater than 5°, avoids parallel surfaces and allows diffuse reflection to occur. The ceiling serves to conduct the sound into the back part of the room and must be shaped accordingly → ③. If the ceiling shape is unfavourable, large differences in sound intensity occur due to sound concentrations. Rooms where the walls are further apart at the back than at the front of the room produce unfavourable effects, since the reflections from the sides can be too weak → ④; this disadvantage can be compensated by the using additional reflection surfaces (Weinberg steps) – as in the Berlin and Cologne Philharmonics → ⑤ – or the walls may be provided with pronounced folding to guide the sound.

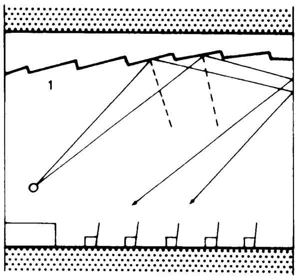
Wherever possible, the podium should be on the narrow side of the room; in the case of the spoken word or in small rooms (chamber music), it may even be arranged on a long wall (Beethoven Archive → ⑥). Multipurpose rooms with variably arranged podia and plain parquet floors are frequently problematic for music. The podium must be raised in relation to the parquet, so as to support the direct propagation of the sound; otherwise, the level of the sound propagation would fall too quickly → ⑨. Providing an upward inclination of the seating levels, to obtain a uniform level of direct sound at all seats gives better visibility and acoustics → ⑦; the slope of the seating levels should follow a logarithmic curve.

Secondary structure

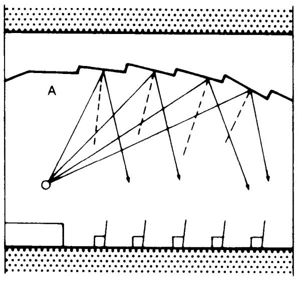
Reflection surfaces can compensate for an unfavourable primary structure: projections on the surface of walls which diverge, ceiling shapes produced by hanging sails or the use of individual elements → p. 124.



① Prevention of oscillating echoes



② Unfavourable ceiling shape



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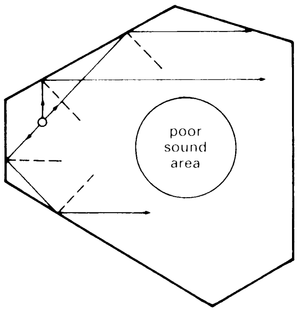
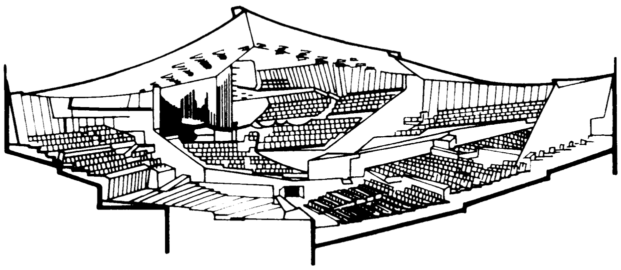
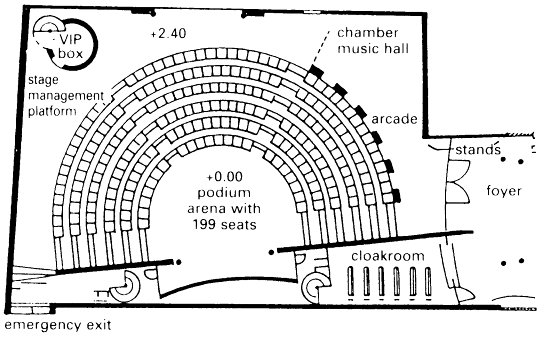


④ Less favourable platform



⑤ Berlin Philharmonic – staggering the auditorium



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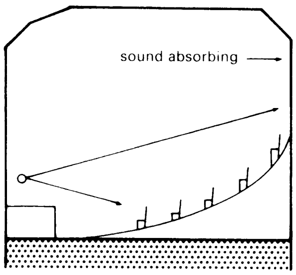
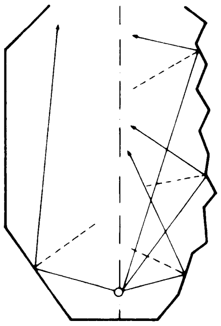
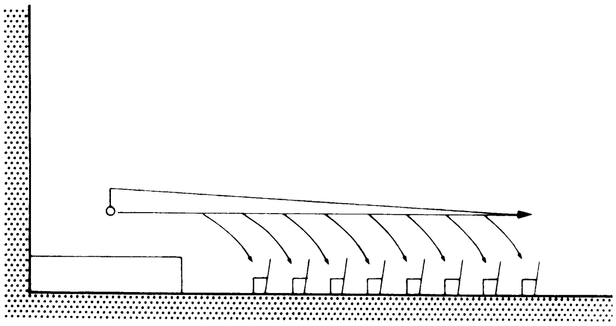


⑦ Seats on ascending logarithmic curve



⑧ Folding wall surface



⑨ Drop in sound level over absorbing surface

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