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BUILDING RESEARCH TRANSLATION

Weak Thermal Points Or Thermal Bridges

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[1] Headquarters and Laboratories at Gaithersburg, Maryland, unless otherwise noted; mailing address Washington, D.C. 20234.
[2] Part of the Center for Radiation Research.
[3] Located at Boulder, Colorado 80302.
[4] Part of the Center for Building Technology.

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FOREWORD

The United States/French Cooperative Program on Building Technology entails an exchange of personnel between the National Bureau of Standards (Center for Building Technology) and the Centre Scientifique et Technique du Bâtiment (CSTB) of France. The program also involves the exchange of information between the two research organizations.

It is felt that some of the documented information can be usefully shared with the U.S. building industry; and, therefore, certain papers were selected for reproduction in media on sale to the public by the Government Printing Office. It should be understood that the CSTB documents made public through such media as this TECHNICAL NOTE do not necessarily represent the views of the National Bureau of Standards on either policy or technical levels.

At the same time, building researchers at the National Bureau of Standards consider it a public service to share with the U.S. building industry certain insights into French building technology.

James R. Wright

James R. Wright, Director
Center for Building Technology
Institute for Applied Technology
National Bureau of Standards

WEAK THERMAL POINTS OR THERMAL BRIDGES[1/]

by

J. Berthier

Uniformity of temperature on the internal face is one of the essential hygro-thermal qualities for a wall.

Cold bridges, which are the cause of uneven temperatures, constitute a weakness which ought to be corrected.

The author describes a large number of tests carried out with various types of wall (dense walls and lightweight panels) in order to assess the importance of cold bridges and to determine the effectiveness of possible remedies; he shows that the accepted theory used in the calculations of U-coefficients is unsatisfactory when estimating surface temperatures. The results obtained can be explained, however, by means of two simple hypotheses; on the basis of these there are practical rules which can be used in establishing the importance of cold bridges, and recommendations for reducing them.

Key words: Floors and panels; moisture condensation: thermal bridges; thermal insulation; U-values of walls.

[1/] This paper is translated from the French original and is published under the Center for Building Technology, Centre Scientifique et Technique du Bâtiment information exchange program.

INTRODUCTION

Considerations of comfort, economy and health require the U value of the external walls of a building to be kept small. The upper limit depends on a number of factors, for example:

--the function of the wall (roof, facade, gable, etc.);

--the type of building (school, office, various categories of dwelling);

--geographical location of the building (climatic zone);

--the wall mass.

Tables published in C.S.T.B. Cahiers No. 34 and the building rules contained in R.E.E.F.-58 (Bib. 2, 3) give maximum recommended U values in each case.

Merely to follow these rules, however, is not enough to assure satisfactory hygrothermal behavior of the wall. For this the ideal would be for the temperature to be the same at every point on the interior face of the wall. In the case of a homogeneous wall separating two spaces, when the interior temperature is T_i and the outside temperature is T_e, the temperature θ_i on the interior surface of the wall under a steady state condition, is given by the equation

$$\theta_i = T_i - \frac{U}{h_i}(T_i - T_e)$$

where U is the overall heat transmission coefficient and h_i is the inside surface conductance*.

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*The coefficient characterizes the thermal exchanges between the air and the surface of the wall. It depends to a small extent on surface condition and much more on the velocity of the air in contact with it.

The above equation shows that there are two causes of non-uniformity in the surface temperatures. First there is heterogeneity in the wall, producing different local U values. This is very frequent because materials with different thermal coefficients are increasingly being placed side by side in constructions, for example:

--a filling of hollow bricks next to a framing of reinforced concrete;

--a metal framing around a panel of a facade or its internal framing, next to the insulation which it encloses.

All those elements which have less insulating effect than the main part of the wall are weak points from the thermal point of view. They are commonly known as "thermal bridges".

The second cause is a variation of surface heat exchange resulting in a variation of the coefficient h_i. These variations may be produced by a decrease in the heat transfer due to radiation (on an aluminium moulding, for example) or convection (at corners, behind furniture).

Generally speaking, the observed phenomena are the results of these various causes and it is impossible to determine the share of each.

The disadvantages of non-uniformity of surface temperatures are numerous.

In summer thermal bridges lead to warmer interior temperatures. In a temperate climate this is not very serious and the wall does not suffer from it. During cold weather, however, when the temperature of a thermal bridge is lower than the main part of the wall the situation is different. Several phenomena may then be observed.

The main one is condensation of moisture from the room air on the surface of the wall. This will happen as soon as the dew-point of the humid air of the room is above the temperature of the thermal bridge surface. Condensation will occur first at this point and the amount of condensation will be greatest either during a period of high humidity or one of severe cold.

It is not our purpose here to study this phenomenon and its consequences in detail, but we wish to point out that a cold spot on the surface of a wall is its primary cause. The extent of condensation will depend, of course, on the conditions of the building occupancy (production of moisture, ventilation, heating, etc.) but before attempting to protect against the effects of this phenomenon it appeared necessary that the wall itself should be designed to prevent condensation by providing a sufficiently uniform temperature on the interior face.

Furthermore, in the absence of any humidity in the room, a cold spot gives rise to another phenomenon known as dust patterns. Even in rooms used as offices, where the atmosphere is always dry, the cold zones resulting from the beams, ties or even joints between masonry blocks eventually become stained by a considerable deposit of dust. This phenomenon can apparently be explained as follows:

The dust particles are kept in suspension in the air by molecular agitation and the shocks resulting from it. This agitation increases with increasing temperature. In the vicinity of a cold spot a turbulence occurs in the interaction, and the dust particles are thrown against the cold spot. Since the latter is generally moist as a result of even very slight condensation, the dust particles readily cling to the surface.

Photo 1

Traces of condensation on the ceiling of a basement apartment room on cold spots produced by the tie beam and the joists of the ground floor.

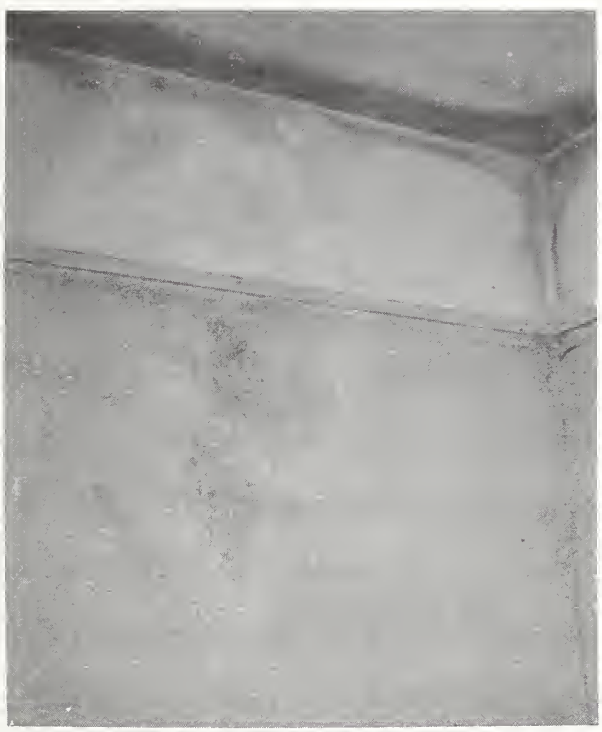

Photo 2

Condensation traces in the room of a ground floor apartment at the gable end on cold spots produced by the corners of the floors and the external walls.

Although this phenomenon is not as serious as condensation, it indicates that whatever the type of construction, a thermal bridge is always a defect.

The purpose of the present article is to report on the studies made by C.S.T.B. with a view to investigating practical methods of obtaining satisfactory uniformity of temperatures on interior surfaces.

Part I will be devoted to a qualitative study of the phenomena.

Part II will report on some artificial quantitative tests carried out on a number of special cases.

Part III will attempt to explain the results on the basis of a simplified theory. From this we shall be able to generalize in a number of simple cases.

Finally, in Part IV, drawing conclusions from our study, we shall give practical rules for estimating the effect of a thermal bridge and correcting it.

PART I: QUALITATIVE APPROACH TO THE PROBLEM BY SEMI-NATURAL TESTS

PRINCIPLE OF SEMI-NATURAL TESTS

The principle underlying these tests is as follows.

In a building, whose external walls are to be studied, a warm and humid atmosphere is produced during the winter in the interior close to the inside surface of the wall. The external conditions are natural.

These tests were carried out only on walls of the reinforced concrete frame type filled with lightweight masonry.

To facilitate our study we have chosen for the filling cellular concrete of density 0.6 kg/dm^3 (k = 0.3 kcal/mh°C) which is decidedly more insulating than the mass concrete of the framework (d = 2.2; k = 1.5).

Three types of thermal weak points have been considered.

--total bridge, with framework traversing the wall completely;

--partial bridge with internal or external insulation;

--bridge and internal concrete slab diffusing the heat flux.

In the second case the width of the thermal bridge was varied as well as the thickness of the insulation.

These walls had an external coating of lime-cement mortar and an interior coating of plaster 1 cm thick. A water reactive paint was applied over the plaster in order to emphasize the condensation and to permit a rough estimation of its extent.

TEST RESULTS.

Figure 1, shows the construction of the different bridges, and the results obtained by testing follow:

In the case of the total bridge, i.e. the framework traversing the entire thickness of the wall, either for the wide bridge (vertical framing member in the center of the figure) or the narrow bridge (horizontal frame member to the left), very considerable traces of condensation appeared.

At the extreme left, on the thermal bridge with diffused heat flux the mildews are definitely less apparent.

At the right, on the various partial cold bridges with interior insulation, the traces of condensation are practically non-existent. No difference can be discerned between the wide and narrow ones on the one hand and the more or less insulated ones on the other.

However, to the left, on the two partial cold bridges with external insulation the condensation traces are very marked, practically similar to those obtained on the total cold bridges.

At first glance this appears to be a surprising result. Actually, the calculated thermal conductance of the wall at the thermal bridge is theoretically the same whether the insulation is placed inside or outside. Similarly the thermal bridge with diffused heat flux has the same U value as the total bridge.

Actually, these results show that the problem is much more complicated. They also indicate that the problem definitely cannot be solved by considering solely the ratio of U factors at right angles to the thermal bridge and in the main ("running") part of the wall. Moreover, such limited consideration even precludes predicting what form or direction the phenomena will take.

Because of these difficulties we conducted much more accurate and detailed artificial tests enabling us to quantify these phenomena.*

PART II: QUANTITATIVE STUDY - ARTIFICIAL TESTS

CHARACTERISTICS OF A THERMAL BRIDGE

The problems presented by thermal bridges can be reduced to the determination of the temperatures on the interior face of the heterogeneous wall when the latter is situated in a cold external and warm internal environment. The curve giving the temperature distribution on the internal surface, as shown for example in fig. 2, then enables us to characterize the thermal bridge. Two elements must be considered, first the spreading

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* Translated by the Joint Publication Research Service, U.S. Department of Commerce, Washington, D.C.

out of the curve which enables us to determine the width of the zone where condensation is to be anticipated, and second, the temperature of the coldest spot. The absolute value of this temperature is not so important because it depends essentially on the interior and exterior temperatures. We, therefore, introduce a coefficient which characterizes the heterogeneity of the interior surface temperature:

$$\rho = \frac{T_i - \theta}{T_i - \theta_c}$$

where T_i is the interior air temperature, θ the interior surface temperature of a point in the thermal bridge zone and, θ_c the interior surface temperature at a point remote from the thermal bridge in the main part of the wall.

In part III it will be shown that this ratio is practically independent of the interior and exterior temperatures. Denoting the maximum value of ρ by ρ_m, then

$$\rho_m = \frac{T_i - \theta_m}{T_i - \theta_c}$$

where θ_m is the temperature of the coldest point on the thermal bridge.

This coefficient, which we shall call the coefficient of interior surface temperature heterogeneity, indicates to a certain extent by how much the coldest point is colder in relation to the internal air temperature than the main part of the wall.

We shall wish to compare this coefficient to the coefficient ρ_c (theoretical calculated coefficient) which is determined from the wall U value at the thermal bridge (U_p) and the wall U value away from the thermal bridge (U_c) as follows:

$$\rho_c = \frac{U_p}{U_c}$$

Test Method

The exact determination for the calculation of the curve of ρ is impractical.

The method of direct observation is delicate, because the measurement of a surface temperature is difficult to carry out with precision. However, it is the only way in which the various factors which may influence ρ can be taken into account.

The tests were carried out in the thermal test chamber of the Champs-sur-Marne experimental station[1] (Fig. 3).

The wall containing the thermal bridges to be studied divided the room into two spaces. The interior warm space was kept at a controlled temperature of approximately 30°C while the exterior cold space was kept at about -5°C. The interior temperature was placed intentionally higher than average room temperature in order to increase the difference between the two environments, thereby enhancing the accuracy of the measured interior surface temperature. This will not affect the results because the values of ρ are practically independent of temperature. Air temperatures were recorded continuously during the test by means of resistance thermometers connected to a recording potentiometer. Furthermore, since the purpose of the study was to eliminate condensation, experiments were designed so that the thermal characteristics of the materials and their temperature would not be affected by condensation. The atmosphere of the interior room was dry (approximately 35% relative humidity) so that no condensation would take place on the cold spots.

The wall surface temperatures were measured with iron-constantan thermocouples 1/10 mm in diameter. These thermocouples were connected to a 12-point recording potentiometer. Temperatures were thus recorded simultaneously at 12 points on the zone in question. We thus obtained an accurate profile of the surface temperature curve (Fig. 2).

Note 1:

We should like to recall one of the heat-chamber characteristics essential to the study in question. This characteristic involves surface heat transfers between environments and wall. A certain number of measurements taken on homogeneous walls revealed that ventilation conditions created in both chambers, enabled us to obtain, for walls with a U factor of approximately 1.2 $kcal/(m^2h^oC)$, surface heat transfers of close to 7$kcal/(m^2h^oC)$ for the outside environment. It was most important that during our tests, inside surface transfers for the test wall be close to the actual transfers, or at least to theoretically determined transfer values (i.e., $hi=7kcal/(m^2h^oC)$. It may, in fact, be assumed that the secondary phenomena acting upon them will cause them thus to vary in accordance with their real law of variation.*

Note 2:

Some investigators have taken advantage of the similarity between the equations of electrical transmission and those of heat transmission in order to construct electric models of walls (Bibliography 9). Thus a continuous model can be obtained with electrolytes. The determination of temperatures is then replaced by a determination of voltage, which is much more accurate.

* Translated by the Joint Publication Research Service, U.S. Department of Commerce, Washington, D.C.

However, these provide only approximate solutions, for the following two reasons:

Surface conductance, represented by fixed resistances in such a model, is a function of the temperature difference between the environment and the wall, which is precisely what we are trying to determine. A method involving successive approximations should enable us to take the variation of surface conductance into account. Accuracy may be decreased, however, since the way in which surface conductance varies with temperature is not very well known.

The second reason is much more serious, because there is no simple way of avoiding it. This has to do with the fact that heat exchange between two materials in contact is dependent not only on their conductivity coefficient but also on their specific heat and density. Electrical analogy methods cannot reproduce conductivity ratios and do not take into account thermal capacity.

Choice of types of thermal bridges

The test method used is not very quick. It is necessary to wait for the establishment of steady state heat flow conditions for each wall. This may take ten or more hours for light panels and as much as forty-eight hours for heavy masonry walls.

Once steady state has been established with the thermocouples in place from the beginning of the test, air and surface temperatures can be recorded in fifteen minutes. The actual measuring time is thus very small compared with the time required to reach steady state. As a result several test models, generally four, are grouped in a single wall. Only the most characteristic types are studied.

Our choice was guided by one prime consideration. We classified the walls in three categories according to the thermal characteristics of the materials from which they are made:

First, we have pure masonry walls, in which reinforced concrete is next to light masonry (hollow brick, artificial stone, light-weight concrete, etc.). These walls may be constructed in the traditional manner or may consist of large prefabricated panels containing these elements. The thickness of these walls varies between 20 and 30 cm, the ratio of densities of the materials present is between 2 and 4 and that of the thermal conductivities between 3 and 5.

Next, we have mixed walls in which reinforced concrete and very light insulating materials are used side by side; these are generally large prefabricated panels. They have about the same thickness as the above walls, but the ratio of densities of the materials varies between 20 and 100 and the ratio of conductivities between 30 and 50.

Finally, we have light walls, of thickness between 3 and 5 cm, which consist of very light insulating materials standing next to wood or metals.

The cahracteristics of the materials constituting the different types of walls are summarized in the following table:

Types of wall		Density in kg/m^3	Conductivity k in kcal/(mh°C)
Heavy walls	Reinforced CONCRETE frame and...	2200	1.5
	LIGHT WEIGHT MASONRY filling...	600 to 1000	0.3 to 0.6
	Large prefabricated concrete	2200	1.5
	panel incorporating very light INSULATION	20 to 100	0.03 to 0.05
Light walls	Curtain or panel facade walls with a framing of WOOD.......	400 to 700	0.1 to 0.15
	or METAL......................	3000 to 8000	50 to 170
	and very light INSULATION.......	20 to 100	0.03 to 0.05

Reinforced concrete framework with light-weight masonry filling or large, light weight masonry panels

We have adopted the same types of thermal bridges that had been studied previously in the semi-natural tests. For convenience the models consisted of blocks of cellular concrete (d = 600 kg/m^3, k = 0.3) interrupted by a dense concrete framing (d = 2,200, k = 1.5).

Total bridge. In addition to the total thermal bridge (Fig. 4), for which we took the same two widths as studied in the semi-natural tests, namely 7.5 and 22.5 cm, (Table I, models A_1 and A_2)*, we studied various arrangements in which, a priori, it was possible to obtain more uniform interior surface temperatures. The different arrangements studied can be reduced to two.

First arrangement: Thermal bridge with interior diffusion layer (Fig. 5). One solution consists in diffusing the surface temperatures by placing a comparatively conductive material over the entire interior surface of the wall.

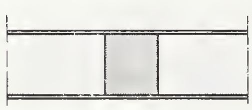


Figure 4 Total bridge

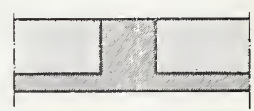


Figure 5 Thermal bridge with interior diffusion layer

The effectiveness of this method had been demonstrated in the semi-natural tests. In the artificial tests we attempted to calculate it.

Starting with a bridge comprising a framework of compact concrete intersecting a cellular concrete block wall 20 cm thick, we studied the effect of a compact slab of concrete 5 cm in thickness (B_1) for frame

*Table I contains models A_1 and A_2, B-B_5, C_1-C_4, D_1-D_4, as referred to throughout the following pages.

widths of 7.5 and 22.5 cm. We thought it would be interesting to increase the conductivity of this slab in the lateral direction, perpendicular to the framing. For this purpose, additional slabs, identical to the preceeding ones except that they were strongly reinforced with iron rods running perpendicular to the framework (B_4), were applied to the interior surface.

Similarly, we tried to increase the effectiveness of a plaster coating (of relatively low conductivity) by reinforcing it strongly with two layers of grillwork (B_5).

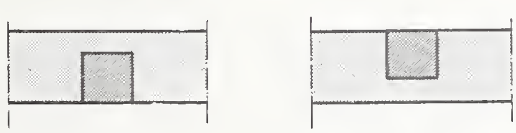
Still other specimens were constructed to determine the effect of various degrees of flaring of the framework.

Finally we sought to determine the effect of a framing which by projecting greatly on the exterior forms a cordon, and hence a kind of cooling fin, by increasing the area of the exterior surface.

Second arrangement: Insulation of thermal bridge.

Two solutions have been studied:

(1) Partial bridges (Fig. 6). In this solution the framing does not go all the way through the wall and is thus insulated by a certain thickness of the material which constitutes the main part of the wall.



(a) (b)

Figure 6 Partial bridge
(a) Exterior insulation
(b) Interior insulation

The semi-natural tests demonstrated that there was a great difference in effectiveness depending on whether the insulation was placed inside or outside. With a view to determining these effects more accurately we studied the same types of thermal bridges in the artificial tests.

For this purpose a cellular concrete wall 20 cm thick was constructed. This wall was partially intersected by two dense concrete frameworks, one 7.5 cm wide and the other 22.5 cm wide. The residual thickness of the cellular concrete was 5 cm and 7.5 cm, respectively. Four specimens were thus available. This wall was tested on both sides so that the insulation could be placed successively on the inside and on the outside.

(2) Corrected bridges (Fig. 7). This term refers to a bridge insulated by very effective insulating material, the thickness of which was calculated so that the U value at right angles to the insulated framework would be equal to that calculated for the main part of the wall. (We then have $\rho_c = 1$.) We again took the case of wall A, where the thermal bridge consisted of a dense concrete framework intersecting a 20 cm thick wall of cellular concrete covered by a plaster coating 2.5 cm thick. In the first test the plaster was removed opposite the frames which were 7.5 and 22.5 cm wide, and replaced with 2 cm of aerated polystyrene.

Figure 7 Corrected bridge
(a) Exterior insulation
(b) Interior insulation

One test was carried out with polystyrene on the interior and one with polystyrene on the exterior.

The 2 cm thickness was chosen in such a way that $U_p = U_c$, i.e. $\rho_c = 1$.

Large concrete panel with very light insulating materials incorporated in it.

In general, these panels are built in sandwich fashion; a very good insulating material, which provides good thermal insulation, is sandwiched between two concrete slabs of various thicknesses which perform the other functions of the wall (mechanical strength, permeability, thermal inertia, etc.).

Very frequently, then, thermal bridges are formed by the concrete joining strips between the outer and inner slabs or by the joints between two panels. The difference between the conductivities and specific gravities of the different materials involved (k = 1.5 kcal/(mh°C); d = 2,200 kg/m^3 for the concrete and k = 0.03 to 0.05; d = 20 to 100 for the insulation) results in very substantial thermal bridges.

In this case we tried to determine precisely the respective role of the two concrete slabs, especially that of the interior one.

The walls studied had the following thicknesses:

A concrete slab of 5 cm; a slab of polystyrene 3 cm thick (giving a useful thickness of about 2.5 cm, since the concrete penetrated slightly into the polystyrene on both its faces); and a concrete slab 15 cm thick. Openings 7.5 cm, 15 cm, 22.5 cm and 45 cm wide were provided in the polystyrene, thus constituting a link between the two slabs, and a thermal bridge. These walls were tested with the 5 cm slab and the 15 cm slab successively on the warm side.

Special thermal bridges

We also initiated a study of thermal bridges existing at corners. The study is even more complex, because it is necessary to distinguish between the corner where two identical external walls join (Fig. 8) and the corner where an external wall is joined by a partition or floor (Fig. 9).

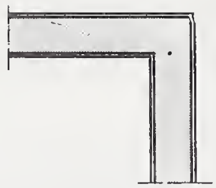


Figure 8 Corner between two external walls

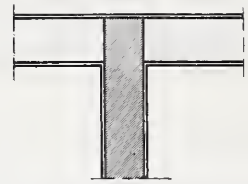


Figure 9 Partition or floor

Thermal bridges at the corner between two external walls. In this case, even with two walls having the same U value, the temperatures at the corner will be different from the temperatures elsewhere on the walls. There are two reasons for this:

First the surface area of the external wall is greater than that of the internal wall. The same flow of cold from the exterior will thus lead to lower temperatures than on a wall with parallel faces.

Then, there is a reduction in the radiation and convection surface heat exchanges. This further contributes to the lowering of the temperature on the inside surface.

Artificial tests on this type of thermal bridge are rather uncertain and it is doubtful whether or not the surface heat exchanges can be exactly reproduced. On the other hand, we possess the results of natural tests carried out in Germany at the Holzkirchen Station (Bibliography 7), where temperatures were measured on the interior surface of the northwest corner of more than 20 houses with different kinds of walls.

Partitions and floors. Where an external wall meets a partition or floor the problem is very different. The partition or floor is at the interior room temperature (we assume that the wall or floor separates two equally heated spaces). The exterior surface area is not as large as the interior surface area. Thus the two effects mentioned previously oppose one another. Furthermore, the partition or floor often differs greatly in its thermal characteristics from the exterior wall.

Finally, both partitions and floors can terminate flush with the facade, or before reaching the facade, or can even extend beyond it, forming a cordon. Only the corner between the exterior wall and the partition has been studied. For this purpose a structure representing the partition was joined at right angles to the 22.5 cm wide frames of walls A, B and C. This structure was constructed from solid blocks identical with the concrete of the frame.

In the case of wall B we also studied the influence of an exterior structure forming a cordon and cooling fin.

Light walls (curtain wall, facade panels)

One of the essential features of this kind of construction is the very small thickness of the wall which is made possible by the use of good insulation: the same U value can be obtained with a wall using a 2 cm thickness of good insulation (k = 0.03 to 0.05) as with one 20 cm thick in light masonry.

In order to compensate for their lack of thermal capacity these walls must have very good U values (around 1.0). Such coefficients are easily obtained with small thicknesses of insulating material.

When this insulation is interrupted by a frame which is also very thin, significant thermal bridges are formed.

We shall distinguish between thermal bridges produced by wooden members which generally make up the internal framing of panels and those produced by metal frames, whether they are internal frames, as are frequently used in this type of construction to ensure rigidity and ease of assembly, or are external frames in which the homogeneous panel is placed.

Wooden or similar framing

Total bridge. The main part of the models was constructed of 3 cm thick expanded polystyrene (k = 0.03 kcal/(mh°C); d = 20 kg/m^3).

We studied the effect of the width of the frame. For this purpose the insulation was interrupted by members having the same thickness as the panel (3 cm) but of different widths (0.6, 1, 3 and 6 cm).

In order to estimate the effect of changing the ratio of thermal characteristics of the materials, models identical with the above were built, but in which the wood was replaced by pressed wood that was more insulating and lighter (k = 0.06 and d = 500 kg/m^3) than the wood used in the previous test.

Bridge with interior diffusion layer. We again wished to determine the effect of a conducting layer on the interior surface. Some panels use aluminium foil under the interior layer as vapor barriers. It is quite possible that this highly conductive material significantly diffuses the temperatures despite the small thicknesses employed. In order to calculate this phenomenon we cemented first a sheet of aluminium 1/10 mm thick on to the models (k = 170 kcal/mh°C) and then a sheet of copper 2/10 mm thick (k = 350 kcal/mh°C).

These sheets had been painted grey to maintain the same surface heat transfer coefficient as before.

Metal framing

Total bridge. To begin with we studied total bridges formed with various steel sections intersecting a polystyrene panel 3 cm thick.

We then sought to determine the influence of increasing or decreasing the projection of an exterior cordon constituting a cooling fin.

Interrupted bridge. Seeking a remedy to this type of thermal bridge we studied, for a simple theoretical case, the effect of an interruption in the thermal bridge, or more exactly a decrease in the metal cross-sectional area and an increase in the thermal path length.

Practical examples. Finally, we studied some practical examples of thermal bridges at the joint between two panels. Again, seeking to correct the thermal bridge, we studied the effect of interrupting the framing and its insulation with various types of interior and exterior mouldings.

RESULTS

Heavy walls

Walls with reinforced concrete framing and light masonry filling

The results obtained are shown in Table I, where we give the values of ρ_m determined from the measured temperatures and those of ρ_c calculated from the ratio U_p/U_c.

Total bridge. Actually a true total bridge was not tested since no such bridge exists in practice. There are always interior and exterior finish. The first tests carried out on walls A (A_1-A_2) enabled us to obtain the real value of the total bridge in a wall with coatings and we found that:

$$\rho_m = 2.1 \text{ for the 7.5 cm width;}$$

$$\rho_m = 2.3 \text{ for the 22.5 cm width.}$$

We note that the narrower the framing the smaller ρ_m, and that in both cases it is less than ρ_c : $\rho_c = 2.4$.

Thermal bridge with interior diffusion layer. The effect of the concrete slab placed on the interior surface is to flatten the curve of interior surface temperatures. The important improvement obtained with a simple slab (B_1) must be noted:

ρ_m changes from 2.1 to 1.4 for the 7.5 cm width;
and from 2.3 to 1.7 for the 22.5 cm width.

These values are far less than ρ_c, which is still equal to 2.4:

--The flaring of the framework (B_2 - B_3) makes it possible to obtain still smaller ρ_m values. In this way we achieved values of 1.3 for $\ell = 7.5$, and 1.45 for $\ell = 22.5$;

--Putting reinforcement (B_4) in the slab makes very little difference. Depending on the width, ρ_m changes from 1.4 to 1.35 and from 1.7 to 1.65.

We also tested the effect of reinforcement in the plaster slab installed in such a way as to make the relatively insulating plaster more conductive in the lateral direction. Again (B_5) the results were inconclusive; ρ_m changes, depending on the width, from 1.95 to 1.9 and from 2.2 to 2.15. The effect is thus negligible.

Generally speaking ρ_m decreases as ℓ decreases and it is always less ρ_c.

Note. The effect of an exterior fin (B) is also comparatively slight in this case; it causes ρ_m to change from 1.7 to 1.8 (B compared to B_1).

Partial bridges. The reader will note the large difference in the shape of the curves obtained when the insulation is on the inside (C_1 and C_2) and when it is on the outside (C_3 and C_4).

(a) In the case of interior insulation a very good correction of the thermal bridge is obtained, and the narrower the frame to be protected, the better the correction. The coldest point is directly opposite the center of the frame. The small difference obtained with different thicknesses of insulation should be noted (C_1 compared to C_2).

Note again that $\rho_m < \rho_c$

(b) When the insulation is placed on the exterior there is no improvement and now it seems as though the smaller the width of the frame, the more pronounced is the effect of the thermal bridge. The thickness of the insulation is more significant.

We again note that the position of the coldest point is situated opposite to the frame, but near the edge. Note also the existence of a warm spot near the frame. The temperature there is higher than in the main part of the wall.

Finally it must be emphasized that ρ_m is decidedly greater than ρ_c. It is thus an error to suppose that the classical calculation always yields a margin of safety. These results are absolutely opposite to those obtained for interior insulation.

We shall explain this in Part III

Corrected bridges. (a) The above results, in the case of exterior insulation, are rather surprising; the tests carried out on wall D with exterior correction have confirmed them. Although conditions were chosen so that the U value of the wall at the frame would be the same as in the main part of the wall (ρ_c =1), very different temperatures are observed on the interior surface.

In particular, for the 7.5 cm width replacing the exterior plaster coating with 2 cm of polystyrene has practically no effect on the temperatures and gives substantially the same value for ρ_m.

An improvement of the thermal bridge can be obtained by having the insulation overlap the frame considerably on both sides, but the results remain unspectacular. For a narrow bridge an overlapping on both sides of 7.5 cm equal to ℓ still gives a high ρ_m value (1.65). For a wider bridge an overlapping on both sides of 22.5 cm (equal to ℓ) gives ρ_m=1.5.

(b) In the case of interior correction, the temperature opposite the frame is higher than on the main part of the wall; the coldest spot, however, is displaced outside the frame. The wider the frame, the colder this spot will be.

In tests D_4, where the insulation overlaps the frame, good improvement can be observed. However, it does not appear that the width of the insulation required to obtain a given ρ_m is a linear function of the width of the frame. An overlapping of 7.5 cm for a frame width of 7.5 cm is sufficient (ρ_m = 1.25), while an overlapping of 22.5 cm for a 22.5 wide frame is excessive (ρ_m = 0.87).

Finally, we note the difference of form in the temperature curves obtained between the case where the insulation is inside, and that where it is outside. To show this result more clearly we have plotted the values of ρ for both of these cases on the same graph (Fig. 10) - tests D_1 and D_3. Although the ρ_m values are not very different the curve of ρ for interior insulation is much less flat in the zone of $\rho > 1.5$ than the curve obtained for exterior insulation.

Large concrete panel incorporating light insulation

The results are given in Table II.

The very high value of ρ_m obtained when the framing is very wide ($\rho_m = 3.2$) should be noted.

With the 15 cm slab on the inside, the best correction is obtained with the narrow thermal bridge. A width of 7.5 cm still gives a high ρ_m value (1.8).

With the 15 cm slab on the outside, the values of ρ_m remain very high (above 3). For the larger bridge widths (15 and 22.5 cm) they are slightly above ρ_c ($\rho_c = 3.4$).

Special thermal bridges

Partitions and floors. Table III shows the results obtained in the four cases studied.

The coldest point is found on the partition a few centimeters away from the corner.

In the last column of Table III are given values of ρ_m obtained on thermal bridges at walls without partitions. Those obtained with partitions are always lower. This is due to the fact that the concrete partition, away from the corner, is at temperature T_i through its entire mass so that there is a considerable flow of heat in the direction of the corner.

The total bridge (A) now gives a ρ_m value of only 1.9 instead of 2.4.

We again find that good diffusion is obtained with the internal concrete slab, enabling the attainment of $\rho_m = 1.5$ without a cordon and

$\rho_m = 1.55$ despite a large cordon. External insulation continues to be ineffective ($\rho_m=1.7$).

Corner between two outside walls. At a corner between two external walls values of ρ_m, which can be derived from German tests (Bibliography 7), are higher. For walls with U values of 1.2 to 1.5 they are in the vicinity of 1.8, while for walls with U values of less than 1 they reach 2.5.

The shape of the curve is then different.

Figure 12 shows the temperatures obtained at the corner between the west and north walls, which were solid brick 38 cm thick. The curve shows a sharp peak; the result is a colder but less extensive area. Thus the effect of the maximum ρ_m which is obtained can be less severe.

Light walls (curtain walls, facade panels)

Wooden framing

Total bridge. The results are given in Table IV. The narrower the framing, the smaller the ρ_m values. They are always smaller than ρ_c, which for wood is equal to 2.8 and for pressed wood 1.7.

For wooden framing the surface temperature curve shows a rather sharp drop at the edges of the framing.

In the case of pressed wood framing, however, the curve is flatter.

Thermal bridge with interior diffusion layer. The technical difficulty of obtaining a perfect thermal contact between the metal foil and the wall without an intervening cushion of air made it impossible to determine accurately the effectiveness of diffusing the heat flux. On the other hand, foils are generally put underneath the interior plaster, which adds an effect of its own. Our tests indicate, however, that for the wooden framing it seems possible to diffuse the heat flux sufficiently in this way in order to obtain acceptable surface temperatures. Thus it should be possible to obtain ρ_m = 1.5 with a 1/10 mm aluminium foil under a covering of plaster board or plywood on a wooden framework less than 2 cm wide for the hardwood (oak) used in the tests, or 3 cm for soft wood (fir).

Metal frameworks

Theoretical cases. The main part of the wall consisted of 3 cm expanded polystyrene framed with steel sections of various shapes.

The tests showed that the temperature on the metal part was practically uniform, with a sudden drop occurring at the edge of the section (Fig. 13).

The results are collected in Table V. We have included at the same time values of $\rho_m = \frac{T_i - \theta_m}{T_i - \theta_c}$ and of $\mu = \frac{T_i - \theta_m}{T_i - T_e}$. In part 3 it will be shown that for this case θ_m is practically independent of θ_c, so that the ratio μ will remain essentially constant regardless of the U value of the main part of the wall. This is why μ is of interest here.

This ratio establishes the surface temperature of the framework in relation to the internal and external temperatures.

Thus $\mu = 0.5$ indicates that the surface temperature on a framework is the arithmetic mean of T_i and T_e.

If $\mu < 0.5$, this temperature is closer to T_i than T_e; if $\mu > 0.5$, it is closer to T_e than T_i.

Two types of thermal bridges may be distinguished.

(1) Total bridge (top of Table V). The smallest value of μ is obtained for the T-section with the flange on the interior. What we get,

in effect, is a diffusion by the flange. If the flange were wider the value of μ would certainly be smaller.

When the flange of the T is to the outside the situation is reversed, with the result that $\mu = 0.8$. The wider the flange, the greater this effect would be. The I-section gives a μ which is practically an average of the two preceding ones.

(2) Thermal bridge with fin (center of Table V). The value of μ is decidedly higher, corresponding to a lower temperature than for the same test without a fin. The larger the fin the more pronounced this effect.

(3) Interrupted thermal bridge (bottom of Table V). Decreasing the area of metallic section between the two iron plates helps to decrease the value of μ. The curve of Fig. 16 shows that in the last test, which corresponds to an area of 1 cm per m of the section, the ratio μ has practically attained its limiting value, given by the heat exchange through the layer of air between the two iron plates. However, a layer of air in this kind of panel is itself a thermal bridge. In order to obtain a satisfactory effect the joining member between the two plates should pass through the insulation.

<u>Practical Examples</u>. The results obtained in the following three examples have confirmed and supplemented the results previously obtained in the theoretical cases.

(1) Example of a total bridge with fin. We first studied the thermal bridge produced by a large metal framework containing homogeneous panels. The panel had a U value of approximately 1 kcal/m^2h°C. The framing, which

projected considerably on the outside, forms a definite cooling fin. Figure 17 shows a plan section of the framing and the temperature curve obtained. From this we calculate

$$\rho_m = 5.7$$

$$\text{and } \mu = 0.75,$$

very high values from which we may deduce that for T_i = 18°C and T_e = -6°C the temperature on the framing will be 0°C.

This very high μ value is due largely to the fin, but probably also to an appreciable decrease in the radiation exchange between the metal surface and the interior.

(2) Examples of improvement of a total bridge by interruption and by interior mouldings.

Another, more classical example is the facade panel bounded by an omega-shaped frame (Fig. 18).

The test panel had a U value of approximately 0.9 kcal/(m^2h°C).

Several tests have been carried out on the joint between two panels. First the thickness of the framing head was varied; then an attempt was made to reduce the heat flow area by providing holes or slots and to lengthen the thermal path or to interrupt the thermal bridge in one way or another.

Finally the effect of an internal moulding either or wood or polystyrene (which insulated the interior side of the thermal bridge) was studied.

The results are shown in the curves of Fig. 18.

(a) Interrupted thermal bridge

The circular perforations are relatively ineffective since the reduction in heat flow area and the increase in path length is slight.

On the other hand three rows of slots in staggered array reduce ρ_m from 4 to 2.7, which, however, is still a very high value.

(b) Interior moulding

The application of a moulding has the effect of moving the coldest spot to the edge. The result is the same as for the case of the thermal bridge corrected by an interior insulation. It is important to note that the diffusions obtained with the wooden moulding is better than that obtained with the expanded polystyrene moulding. The latter slightly decreases the temperature variation opposite the frame, but the variation is increased at the edge of the moulding. The width of the moulding seems to be more important than its insulating power. To obtain satisfactory results it should be quite wide.

(3) Example of improvement by an exterior moulding.

In the third example exterior insulation was the chief subject of investigation. The panel was again bounded by a metal frame of a rather elaborate form shown diagrammatically in Fig. 19. The main part of the panel had a U value of 1 kcal/(m^2h°C).

The joint between the two panels was covered with an exterior steel moulding and an interior plastic moulding.

We decided to test this joint, as just described, after filling the space between the exterior moulding and the panels with glass wool, and finally with an additional filling of light insulation between the exterior moulding and the panels.

The results obtained are shown in Fig. 19. Again we find the relative ineffectiveness of exterior insulation and of too narrow an interior moulding.

Part III

Theoretical Considerations - Practical Rules

Theoretical Considerations

We shall briefly consider the elementary theory currently accepted for the determination of U values and will show where it is inadequate; with the aid of supplementary hypotheses we shall attempt to explain the phenomena observed in our tests. The latter will enable us in a few simple cases to generalize the results obtained and to provide rules by which the effectiveness of the systems employed to reduce the heterogeneity of surface temperatures can be estimated.

Elementary Theory

We assume that the heat flow is perpendicular to the parallel faces of the wall.

This is tantamount to neglecting the lateral heat exchange between materials placed next to each other.

We then consider that both parts of the wall - the main part (C) and the part consisting of the thermal bridge (P) are two independent walls and to each we apply the equations of a homogeneous flat wall or of a wall consisting of homogeneous parallel sheets.

The U value of each of these walls is given by the equations:

$$\text{(C)}\quad 1/U_c = \frac{1}{h_i} + \sum \frac{(e)}{(k)}_c + \frac{1}{h_e} \qquad\qquad \text{(P)}\quad 1/U_p = \frac{1}{h_i} + \sum \frac{(e)}{(k)}_p + \frac{1}{h_e}$$

and the temperature of their interior surface by the equations:

$$T_i - \theta_c = \frac{U_c}{h_i}(T_i - T_e) \qquad\qquad T_i - \theta_p = \frac{U_p}{h_i}(T_i - T_e)$$

In the case of a homogeneous wall traversed by a total bridge we obtain, for example, the temperature profile of Fig. 20.

We have seen that the thermal bridge is characterized by the coefficient:

$$\rho_m = \frac{T_i - \theta_m}{T_i - \theta_c}$$

Elementary calculation leads us to take

$$\rho = \frac{U_p}{U_c}$$

over the entire width of the thermal bridge.

ρ is thus independent of the interior and exterior temperatures; it is a characteristic of the wall.

Note:

This further assumes that the surface conductance h_i is the same opposite the main part of the wall as opposite the thermal bridge; since this coefficient depends on $T_i - \theta$ it will vary. In fact the variation is very slight and can be neglected here at least as far as masonry walls are concerned.

Graphical Representation

The temperature profiles for the two parts of the wall can be drawn. Taking the example of the homogeneous wall traversed by a total bridge we obtain the diagram of Fig. 21.

Note that the two curves obtained intersect inside the wall at an abscissa point x measured from the interior surface. In this plane the temperature is the same both in the main part of the wall and in the thermal bridge. This is an isothermal plane for the wall. x may easily be calculated:

$$x = \frac{h_e}{h_i + h_e} e \quad ; \quad x = \frac{18}{18 + 7} e = 0.72e$$

a value independent of k_p and k_c.

Let us take another example. Fig. 22 represents a wall composed of three materials: C, P and I.

These materials are chosen such that $k_p > k_c > k_i$.

In practice this may represent a wall of cellular concrete interrupted by a dense concrete frame and carrying on this frame an insulating material of very low conductivity such as polystyrene.

The thickness of most insulating materials (I) may always be chosen such that the U_c value in the main part of the wall and U_p opposite the cold bridge are the same when calculated by elementary theory.

In the case of a 20 cm wall of cellular concrete interrupted by a dense concrete frame, ε (insulation thickness) would be of the order of 2 cm.

The elementary calculation then gives the same surface temperatures at C and at P and does not differentiate between the cases where the material (I) is placed on the exterior surface, and on the interior surface of the wall, or even in the middle.

The graphical representation serves to distinguish between the different cases.

If a sign be applied to the areas bounded by the temperature profiles - positive if the profile traced in the main part of the wall is above that in the thermal bridge, otherwise negative - then the algebraic sum of the areas in question will vary. It will be positive when the insulation is placed inside and negative when it is placed outside. It will be zero when it is put in the center of the wall.

Supplementary Hypotheses

The elementary theory assumes that the heat flux lines are perpendicular to the parallel faces of the wall.

In reality, near the plane of contact of the two materials the flux lines are deformed (Fig. 23).

If we take the flux vector φ to be tangent to a flux line, it can be divided according to two axes into φ_T perpendicular to the wall faces and φ_L parallel thereto.

The sum of all the vectors $\varphi_T = \Phi_T$ will be called the transverse flux and that of the vectors $\varphi_L = \Phi_L$ the lateral flux.

It is very difficult to determine the exact values of Φ_L and Φ_T and it is not the aim of the present paper to make them explicit.

With the aid of certain simplifying hypotheses, however, approximate values can be attained.

1. Φ_T: consider the part of the wall forming the thermal bridge. For Φ_T we shall take the value given by the elementary theory, namely

$$\Phi_T = U_p S \ (T_i - T_e)$$

where S is the area of the material (P) for 1 meter of length.

$$S = \ell \times 1 \quad \text{and} \quad \Phi_T \doteq \ell U_p \ (T_i - T_e)$$

2. Φ_L: the graphical representation gives us a picture of Φ_L.

In the preceding examples, if S_1 and S_2 are the area of the triangles formed by the temperature profiles, Φ_L is a function of S_1 and S_2.

Φ_L could be evaluated more accurately if we knew the temperature profile in the plane of contact, T, between the two materials. In fact, these temperatures depend not only on the conductivities of the materials involved, but also on their density and specific heat, or more exactly on the relative product of these three values k, c, d, known as the coefficient of thermal contact. The heaviest material (highest k c d) tends to impose its temperature in some manner.

In the particular case of two semi-infinite materials in contact with mass temperatures at θ_P and θ_C the temperature θ_T of the plane of contact is given by

$$\frac{\theta_C - \theta_T}{\theta_T - \theta_P} = \sqrt{\frac{(kcd)_P}{(kcd)_C}}$$

The actual case of the wall is not exactly this theoretical case, but we will assume that the temperature profile in the plane of contact (T) can be deduced from the temperature profile in the planes (P) and (C). The wider the thermal bridge the more accurate this will be.

The lateral flux can then be evaluated from curves C and T in Fig. 24. It will have the following form for 1 meter of wall:

$$\Phi_L = 2 \int d\varphi \qquad \text{with}$$

$$d\varphi = \frac{k}{\ell/2} (\theta_P - \theta_T) dx$$

$$\Phi_L = \frac{4}{\ell} \int k \, (\theta_P - \theta_T) dx$$

$$\Phi_L = \frac{4}{\ell} \Sigma k\sigma$$

where σ is the area bounded by the two temperature profiles in the planes T and P on one hand and the faces of the material on the other hand, and k is the conductivity of the corresponding material.

In fact σ is an increasing function of ℓ so that Φ_L is not inversely proportional to ℓ.

<u>Sign Convention</u>

We consider as positive the areas bounded by the temperature profiles where the profile traced in the plane (P) is below that traced in the plane T and as negative the areas where the temperature profile traced in the plane (P) is above that traced in the plane T (Fig. 24).

Let ρ_m be the maximum real value of the ratio $\frac{T_i - \theta}{T_i - \theta_c}$ in the zone of the thermal bridge. We shall put $\alpha = \frac{\rho_c - \rho_m}{\rho_c - 1}$.

α represents the percentage by which the real value of ρ_m departs from the value ρ_c equal to the ratio U_p/U_c.

Having stated this we shall now make the following two hypotheses:

1. α is an increasing function of Φ_L/Φ_T.

2. $\rho_c - \rho_m$ has the same sign as Φ_L/Φ_T i.e., the same as Φ_L.

These two hypotheses are logical: as the absolute value of Φ_L/Φ_T, increases, i.e., as the lateral heat transfer increases compared with Φ_T, the greater will be the difference between the calculated value which neglects lateral heat transfer and the true value . The absolute value of the ratio $\frac{\rho_c - \rho_m}{\rho_c - 1}$ will therefore increase.

If Φ_L/Φ_T is positive, i.e., if $\Phi_L > 0$, the direction of lateral heat transfer, neglected in the calculation of ρ_c, is from the main part of the wall towards the thermal bridge. The true value of ρ_m must therefore be less than that of ρ_c. The opposite will be true if the direction of lateral heat transfer is away from the thermal bridge towards the main part of the wall ($\Phi_L < 0$); then $\rho_c < \rho_m$.

These supplementary hypotheses will enable us to explain the results of our tests.

<u>Application to certain types of thermal bridges that have been studied</u>

<u>Total bridge</u>

The temperature profiles in the planes (C), (T) and (P) form two triangles with the faces of the wall (Fig. 25).

We have seen that $x = \frac{h_e}{h_i + h_e} e$

The fact that $h_e > h_i$ means that $\sigma_1 > \sigma_2$

Now, $\Phi_L = \frac{4}{\ell} k\rho(\sigma_1 - \sigma_2)$.

Hence $\Phi_L / > 0$.

From this we deduce $\rho_c > \rho_m$.

On the other hand Φ_L/Φ_T is a decreasing function of ρ, hence the larger the value of ℓ the closer ρ_m will be to ρ_c.

To determine the role of the thermal characteristics of the materials in question we take the example of a pressed wood frame, a wooden frame and an iron frame interrupting polystyrene. The characteristics of these materials are given in the following table:

	k kcal/m·h·°C	d kg/m³	c kcal/m³	kcd
Polystyrene	0.03	20	0.33	0.2
Pressed wood	0.06	500	0.35	10
Wood	0.15	650	0.35	34
Iron	50	7 700	0.12	46,200

We thus have the following ratios of the coefficients of thermal contact

--pressed wood/polystyrene ....= 50

--wood/polysytrene ....= 170

--iron/polystyrene ....= 231,000

As this ratio increases θ_T approaches θ_m and Φ_L decreases. Thus for constant ℓ the greater the difference between the coefficients of thermal contact of the materials, the greater will be ρ_m.

In conclusion, in a total thermal bridge the wider the bridge the closer ρ_m is to ρ_c, and for a constant bridge width, the greater the difference between the coefficients of thermal contact of the materials, the closer ρ_m is to ρ_c.

In other words the narrower the thermal bridge and the more similar the materials are with respect to their thermal characteristics, the smaller will be ρ_m.

Thermal Bridge with Interior Diffusion

The presence on the interior surface of the wall of an additional thickness of conductive material will appreciably reduce the value of Φ_T and considerably increase that of Φ_L in which the term $\frac{\varepsilon k}{\ell}$ is contained. The ratio Φ_L/Φ_T will thus increase with decreasing ℓ (width of thermal bridge), increasing ε (thickness of slab) and increasing k (conductivity of materials). The flaring of the thermal bridge can be compared to a slab of variable thickness, which increases ε still further in comparison with the simple slab.

Reinforcement of the slab also helps to increase Φ_L without changing Φ_T. Comparing the products εk for a concrete slab and for reinforcement respectively, we obtain $\varepsilon k = 0.075$ for a 5 cm concrete slab. To obtain the same product with reinforcement would require a cross-sectioned area of $0.075/50 = 0.0015\ m^2$, corresponding to a reinforcement weight of almost 12 kg per m^2 of slab, which is difficult to imagine. We had at our disposal only 6 kg per m^2, which can be considered a maximum. The effect was insignificant.

Note: Thermal bridge with exterior diffusion

In the case of an exterior concrete slab Φ_T is always appreciably decreased, but the same also is true of Φ_L, which becomes negative as soon as the slab exceeds a certain thickness. At this moment Φ_L/Φ_T is negative and must result in $\rho_m > \rho_c$.

We did not test this type of thermal bridge unless we consider the test on the insulated concrete wall with the 15 cm slab is on the outside. The above note explains why the values of ρ_m are noticeably greater than ρ_c.

When the wall has an exterior coating this coating acts as an exterior diffusion layer. However, the k value of a mortar coating is less than that of dense concrete, so that in comparison to the total bridge Φ_T decreases more than in the case of a slab of concrete, and Φ_L decreases less. The ratio Φ_L/Φ_T then remains essentially the same as for a total bridge.

Partial Thermal Bridge

This is the case where the elementary theory is most at fault. It is, in fact, incapable of explaining the differences obtained for different positions of the insulation.

The supplementary hypotheses which we have formulated lead to surprising results, but these conform to the experimental evidence.

We shall examine this case in greater detail in order to explain the results obtained in the tests.

The tested wall was constructed of cellular concrete blocks (k = 0.3; d = 600), the frames of dense concrete (k = 1.5; d = 2,200); its thickness e = 0.2 m.

Interior Insulation

We shall try to determine the shape of the curves representing the function α (ε,ℓ).

Our tests give us four pairs of points:

ℓ = 7.5 cm	ε= 5 cm	and	ε= 7.5 cm
ℓ = 22.5 cm	ε= 5 cm	and	ε= 7.5 cm

When ε= 0 we have a total thermal bridge and when ε= e we have a homogeneous wall. In this latter case $\alpha = 0$

when	$\ell \rightarrow 0$	$\alpha \rightarrow 1$
when	$\ell \rightarrow \alpha$	$\alpha \rightarrow 0$

We can draw the curves of Fig. 26. Note that α is always positive and is a maximum at approximately 5 cm.

The shape of these curves can be found with the aid of our hypotheses and a consideration of the ratio Φ_L/Φ_T.

If we draw the temperature profile in the planes (P) and (T) we conclude that Φ_L is positive, resulting in $\alpha > 0$.

Φ_T decreases with increasing ε.

It may be shown that Φ_L passes through a maximum so that Φ_L/Φ_T passes through a maximum, resulting in a maximum for α.

Finally for ε = constant Φ_L/Φ_T decreases as ℓ increases and hence α must decrease.

Consideration of the ratio Φ_L/Φ_T enables us to extrapolate the two curves obtained for other values of ρ (Fig. 26). From these curves we shall deduce the graphs of Part 4.

Exterior Insulation

Once more we obtained 4 pairs of values of the function α (ε, ℓ).

The values found experimentally are negative, that is to say $\rho_m > \rho_c$.

Following the curves of Fig. 26, α, starting from a positive value (for $\varepsilon = 0$), decreases, passes through 0 at ε approximately 2 cm, then through a negative minimum at ε approximately 10 cm, after which it increases to 0 for $\varepsilon = e$.

The shapes of these curves can be found again by consideration of the ratio Φ_L/Φ_T. The temperature profiles in the planes (P) and (T) show that $\Phi_L > 0$ for $\varepsilon = 0$, becomes 0 for a particular value of $\varepsilon (\varepsilon = 2)$, and then becomes negative. When ε increases the absolute value of Φ_L passes through a maximum and decreases to become 0 when $\varepsilon = e$.

From this we derive a similar variation for α. This shows that in the case where $\varepsilon > 2$ cm the value of ρ given by elementary theory is too small. As the width of the thermal bridge decreases P deviates further from the real value. These conclusions are exactly the opposite to what we obtain when the insulation is placed inside.

Note: Thermal bridge corrected by exterior insulation. The conclusions of the theory are the same as in the preceding case: $\rho_m > \rho_c$, the difference increases as the thermal bridge becomes narrower. This is substantially what we have found, but this theory predicts that for even smaller widths we can find a thickness of insulation which will obtain ρ_m values greater than those obtained without insulation.

We tried to confirm this result experimentally. We measured the interior temperature on a joint approximately 2 cm wide between two cellular concrete blocks. Then, scraping the outside of the joint we successively insulated it with thicknesses of 0.6, 1 and 1.4 cm of polystyrene.

The results of the following table show that the ratio μ passes through a maximum, which confirms our predictions.

ε	T_i	θ_m	$T_i - T_e$	$T_i - \theta_m$	$\mu = \frac{T_i - \theta_m}{T_i - T_e}$
0	19.5	10.5	25	9	0.360
0.6	20.0	10.7	25.5	9.3	0.365
1	19.5	10.1	25	9.4	0.376 maximum
1.4	19.6	11.1	35.1	8.5	0.338

Part IV

Practical Rules - Conclusion

We shall now draw conclusions from our tests in the light of the study which we have just outlined. For this purpose we shall classify thermal bridges according to the kinds of walls and their types and we shall try in each case to provide simple rules by which the effect of the thermal bridge or the effectiveness of its correction can be judged.

It will be noted in what follows that the effect of thermal bridges will be judged in relation to the value $\rho_m = 1.5$. That is to say, without prejudicing eventual rules which may be drawn up with respect to materials, we acknowledge that this value appears to be a reasonable limit. It will be shown specifically on all the graphs.

Heavy walls

Reinforced concrete frame walls with masonry filling or light masonry panels

All our tests dealt with walls consisting of cellular concrete blocks 20 cm thick.

It is of little practical interest to try to extrapolate the results for other thicknesses of this type of wall, since the U value requirements impose a minimum thickness (which is 20 cm for cellular concrete).

On the other hand it would be more useful to be able to extend the results obtained to filling materials other than cellular concrete. When we consider on the one hand that by using a less insulating material than, for example, cellular concrete as a filling, smaller values of ρ_m are obtained, since the materials in contact are thermally closer to each other, whereas on the other hand, in order to retain an acceptable U value it is necessary to increase the thickness of the wall, resulting in an increase in ρ_m , then in first approximation it may be assumed that the results we have obtained and the rules which we shall deduce from them will be applicable to all light masonry fillings, that is to say:

--hollow and perforated terra cotta blocks;

--hollow heavy and light concrete artificial stone;

--veneered light concrete;

--cellular concrete blocks

intersected by concrete frames, and having a U value corresponding to our requirements.

Total bridge

Fig. 27 gives the variation of ρ_m with width ℓ of the thermal bridge.

It will be noted that in order to have ρ_m smaller than 1.5, ℓ must be less than 2 cm, i.e., approximately the width of a joint between masonry blocks. Generally speaking these will be the only acceptable total thermal bridges.

Before considering the various remedies for the total bridge, let us note that interior diffusion and insulation are two good solutions. Exterior insulation is a poor solution, while correction of the thermal bridge is fairly good with interior insulation but mediocre with exterior.

Bridge with interior diffusion coating

Fig. 28 gives a chart by which it is possible to determine the supplementary thickness of an interior slab of dense concrete as a function of the width ℓ of the frame, in order to obtain the desired ρ_m.

For example, a frame of 15 cm width will give $\rho_m < 1.5$ if the interior face of the wall is furnished with a slab of concrete of thickness $\varepsilon > 6$ cm.

Partial bridge

Interior insulation

Fig. 29 is a chart from which we can find the thickness of the material ε to be left in front of the frame in order to obtain the desired ρ_m as a function of the width ℓ of the frame.

For example, for a frame 15 cm wide it will be sufficient to place in front of it a thickness of material greater than 5 cm in order to have a ρ_m less than 1.5.

Exterior insulation

The results obtained and the explanations deduced from our hypotheses indicate that this solution in practice cannot provide a satisfactory result.

Corrected bridges

It may be recalled that this is a thermal bridge which has been insulated with a calculated thickness of insulation so that the U value opposite to the insulated frame shall be equal to that calculated for the middle of the wall.

Interior correction

While our hypotheses may enable us to predict the existence of a higher temperature opposite the frame than at mid-wall, they do not enable us to determine the value of ρ_m, since the cold point has been displaced outside the frame. The values of ρ_m found where the insulation does not overlap the frame are rather high. This solution is therefore ineffective and we shall not give any curves for it.

It is necessary, therefore, to overlap the insulation. Several factors are involved in determining the width: the thickness of the wall, the width of the thermal bridge, the conductivity of the insulation being applied.

Extrapolation of the results obtained in the course of our tests makes it possible to indicate approximately the width of insulation required in order to have $\rho_m < 1.5$. These are:

Narrow bridge: $\ell < e$; $x > 1.5\,\ell$

Wide bridge: $\ell > e$; $x > 2\,\ell$

for an insulation having a k value equal to 0.03 or 0.04 kcal/(mh°C). For higher k values (less insulating materials require a greater thickness) the width to be applied will be slightly less.

It is not necessary, in fact, to apply a thickness of insulation such that the U values will be equal. A better diffusion of temperatures will probably be obtained by using a somewhat smaller thickness of insulation.

Exterior correction

The conclusions are completely opposite. The narrower the thermal bridge, the larger and more important must be the overlap. In order to have $\rho_m < 1.5$ with an insulation of k = 0.03 or 0.04 it is necessary to take:

Narrow bridge: $\ell < e$; $x > 4\,\ell$

Wide bridge: $\ell > e$; $x > 3\,\ell$

For higher k values the width of the insulation would be even greater.

Finally, it would be advantageous to apply an insulation of greater thickness, giving a smaller U value opposite to the thermal bridge.

NB: Plastered walls.

Outside mortar coating:

We saw at the end of the paragraph relating to "Thermal bridge with interior diffusion" (page 39) that the two effects of an exterior coating on the inside surface temperature of the wall cancel each other out (increasing the insulation opposite to the thermal bridge tends to decrease ρ_m while the flux on the outside tends to increase it). The preceding charts can therefore be directly applied.

Interior plaster coating:

Plaster coating is generally used on walls which do not have an interior concrete cover (partial bridge with interior insulation: Fig. 29). Since the thermal characteristics of plaster are similar to those of light masonry, we could deduce from the thickness given by the chart for an uncoated wall, the imaginary thickness given by the expression $\frac{k_c \varepsilon_0}{k_e}$ where k_c and k_e are respective conductivities of the material and of the plaster (k_e = 0.5) and ε_0 is the thickness of the plaster coating.

Large concrete panel incorporating a light insulation

a) Thick interior slab

The values of ρ_m depend essentially on the thickness of the incorporated insulation. Fig. 30 gives a chart for the case where the useful thickness of the insulation is 2.5 cm, which corresponds to an initial thickness of approximately 3 cm for rigid and relatively non-porous materials. The concrete always penetrates slightly into both faces of the materials.

This is a thickness that can be recommended. It leads to U values at midwall of the order of 0.9 to 1, depending on the thickness of the concrete slabs.

For walls having an exterior concrete slab 5 cm thick and a useful insulation thickness of 2.5 cm this chart gives values of ε (thickness of interior slab) as a function of ℓ (width of frame) in order to get a desired ρ_m. Actually ε is generally determined by structural considerations, since the interior concrete cover frequently has a load bearing function. A thickness of 20 cm is normal; in order to get $\rho_m < 1.5$ it is then necessary to have $\ell < 7.5$ cm.

This width is adequate for "ladder" joints between slabs, but the joints between two panels result in much wider thermal bridges.

A satisfactory solution can, however, be reached by applying an equal thickness of insulation in the joint (Fig. 31).

This assembly is roughly equivalent to two thermal bridges of width ℓ with a diffusion slab of thickness ε .

Finally, let us note that a greater thickness of the exterior slab would have an unfavorable effect.

If this thickness was substantially greater than 5 cm ε would have to be appreciably increased in order to achieve the same result.

b) Thick exterior slab

When the thickness of the exterior slab is much greater than that of the interior (approximately twice as thick), the diffusion effect obtained by the thin interior slab is cancelled out by the external one, which channels the heat flow into the bridge, with the result that the ρ_m value is close to that of the total bridge calculated by the elementary theory. It can even be greater than this if the exterior slab is still thicker. Any concrete joint, however thin, results in an unacceptable cold spot.

Special thermal bridges

Corner between two exterior walls

Although no test has been made on this type of thermal bridge, it is well known, and the German experiments show, that the corner between two external walls forms an important thermal bridge.

However, although ρ_m is large, the ρ curve is favorable inasmuch as it is peaked in the zone where $\rho_m > 1.5$, i.e., the zone where $\rho > 1.5$ is a narrow band.

The quantities of water condensing will thus be smaller than on a wall where the curve is spread out. This must result in a higher admissible ρ_m. $\rho_m < 2$ appears to be a reasonable limit.

The problem changes when a post is located in the corner (Fig. 32). To the effect of the corner itself, resulting in a $\rho_m = 1.8$, is added that of the thermal bridge produced by the post. Note that this is a bridge partially insulated inside by a layer of material of variable width (approximately $\varepsilon = \frac{\ell}{2}$, corresponding to $\rho_m = 1.4$.)

It may be shown that in first approximation

ρ total = ρ corner x ρ thermal bridge

i.e. $\rho_m = 1.8 \times 1.4 = 2.5$

Hence this is an unacceptable thermal bridge. Its correction is difficult. One solution consists in cutting off the corner in such a way as to reduce the factor 1.8 (Fig. 33).

Corner between partition or floor and exterior wall

Because of the small number of tests available and the lack of precision in the calculations we are as yet unable to give precise rules for this case. The conclusions which follow should be regarded only as orders of magnitude. To begin with a distinction should be made between the partition and the floor, since the surface heat exchanges are different in the two cases. The tests have dealt with partitions. The case of the floor is less favorable. There are fewer remedies than for the wall. Only interior diffusion and exterior correction are really effective.

Exterior insulation (case of the partial thermal bridge) requires a considerable thickness in order to be really effective.

It has been shown that the values of ρ_m found for a partition are less than those obtained for the same thermal bridge in a wall.

1. In the case of floors (less favorable than partitions) the same rules can be applied as given for walls, namely:

Interior diffusion:

- light masonry (fig. 28);

- concrete and light insulation incorporated in it (Fig. 30, leading to division of the thermal bridge - Fig. 34).

Exterior correction: $x > 3\ell$

- the thermal bridges being wide (Fig. 35).

2. In the case of partitions somewhat less severe rules can be adopted:

- Interior diffusion: the values of ε as a function of ℓ given by Fig. 28 for light masonry and Fig. 30 for concrete walls incorporating light insulation, can be reduced by 30%.

- Exterior correction: we may take: $x > 2\ell$ (Fig. 35).

The general observations of page 53 are still valid.

N.B. A solution often used is that of forming a partial thermal bridge with exterior insulation, so that the floor or partition does not extend to the bare exterior of the wall. Despite its thermal ineffectiveness this method has the advantage of providing a homogeneous wall section on the outside, which is advantageous from various points of view, especially for the adhesion of coatings.

Insulation 1/3 of the wall thickness must be considered a minimum (Fig. 36a).

To the exterior insulation can be added interior diffusion (Fig. 36b) in order to obtain a satisfactory solution. At the limit (Fig. 36c) the thermal bridge disappears.

Light walls - curtain walls - facade panels

Wooden frame

The curve of Fig. 37 gives the values of ρ_m as a function of the width of the wood frame.

We find that in order to get $\rho_m < 1.5$, ℓ must be the order of a millimeter; the total bridge is thus always unacceptable.

In this connection note that the ratio of the coefficient of thermal contact between the wood and the very light insulation is greater than that between the concrete and the light masonry (8 times on the average). The latter two materials are more similar in their thermal properties than wood and light insulations. In addition, the k values are roughly only 1/10 as much and therefore the same applies in general to the thicknesses of the walls. Thus even when we divide the width of the frame by 10 we have a ρ_m value greater than that obtained in masonry walls. In the latter, in order to have $\rho_m < 1.5$ it would be necessary to have $\ell < 2$ cm. In the case of wood with light insulation ℓ would have to be of the order of a millimeter.

Actually, while the total bridge does not exist in practice as far as masonry walls are concerned because of the coatings applied, we are even less concerned with them in curtain or facade panel walls with internal wood framing. The interior finish generally has an appreciable thickness relative to the thickness of the panel and this finish acts as an interior insulation or diffusion layer.

Because of the variety of finish used (plasterboard, cement asbestos, plywood, sheet metal) we are unable to give any general rule, but a framing width of 2 cm must be considered a maximum in order to obtain $\rho_m < 1.5$. The interposition of a thick aluminium foil (0.1 or 0.2 mm) beneath the finish to act simultaneously as a vapor barrier would make it possible to use widths up to 3 cm.

One solution would consist in placing under the finish another continuous material that is sufficiently rigid and insulating ($k = 0.06$ to 0.1) and a thickness - 1 to 2 cm depending on the width of the framing member and the k of the material used (Fig. 38).

<u>Metal framing</u>

The ρ_m values found in the case where the framing passes through the whole panel are always very high (4 to 6) and the proposed remedies are few.

The most effective remedy seems to be interrupting the thermal bridge, e.g. by using two frames separated by a good insulator and joined here and there by bolts passing through the insulation. A bolt cross section smaller than 1 cm^2/m of section length seems to be acceptable.

The other solution consists of correcting the thermal bridge by insulating mouldings.

We have seen that an interior moulding need not be too insulating, but must be wide. The width depends, of course, on the framing width, and in general this solution results in very wide, unattractive mouldings. A complete covering would be preferable.

The exterior moulding, on the other hand, must be very insulating and still wider.

Without interruption of the thermal bridge it appears difficult to obtain a satisfactory result without using both exterior and interior moulding.

Conclusion

In closing we must refer again to an important point which our tests brought out, namely the discrepancy between the values of the coefficient ρ_c as calculated by the classical method and those of ρ_m obtained by measurement.

Although it is true that for a total thermal bridge ρ_m is always less than ρ_c, the discrepancy increasing with decreasing width of the bridge and increasing similarity in the thermal characteristics of the materials in contact, this is not a general rule. As soon as we try to correct the thermal bridge, whether by insulating it or diffusing it, we change completely the form of the flux lines and of the isotherms, and adhering to elementary theory may lead to ineffective solutions and even to a worsening of matters.

We believe we have sufficiently emphasized the basic differences between interior and exterior insulation, both for partial and corrected thermal bridges.

We would nevertheless mention once more the good results obtained when there is a layer of homogeneous material on the interior face of the wall. Whether this material is insulating or conducting is a matter of little importance. The essential point is that it should be continuous and sufficiently thick. Thus the two solutions represented in Fig. 39 both give a coefficient $\rho_m = 1.5$.

In addition to the lower values of ρ_m obtained there is another advantage in having a layer of homogeneous material on the interior face. That is that the moisture absorbed during temporary condensations, which are always possible, will be distributed more uniformly.

From this point of view interior correction, which introduces a third material, creates a new discontinuity. Although it provides a satisfactory result from the thermal point of view it should be avoided as far as possible.

It thus appears that for heavy walls it is relatively easy to obtain by these methods a wall which, although heterogeneous, has on its interior face a surface temperature which is uniform enough to avoid serious risks of condensation.

For light walls our study has not enabled us to give precise and directly usable information as for the case of heavy walls. It has, however, brought the problem into sharp focus. The thinness of the good insulating materials used means that a piece of wood, or even an air gap constitute thermal bridges that are at least as severe as a concrete frame in a traditional wall for which the wood and air gaps had an insulating effect. As far as metal framing is concerned, without thermal interruption its correction is very difficult. The solution using two mouldings remains very uncertain.

However, structural devices should render such thermal bridges acceptable. For example panel joints may be put opposite to partitions and floors, or else the thermal bridge can be accepted and the panel thus treated as a problem in carpentry involving condensation gutters.

Every case is separate and can only be judged as a unit: panel, joint, fastening.

This, together with the wide diversity of finishes used, makes it impossible for us to give precise rules here for these cases.

Appendix

Effect of Thermal Bridges on the Overall U-Value

It was not the aim of our study to determine experimentally the overall U values of walls containing frames and thereby to check the values that can be obtained by the elementary theory; we shall however conclude with a few remarks on this subject because it appears necessary to recall the limitations of this therory.

We assume that the flow of heat is perpendicular to the faces of the wall so that the wall may be divided perpendicularly to its faces into slices containing the same layers of material. The thermal resistance of these slices, calculated by taking into account their areas, are assembled in parallel, and from the equivalent resistance obtained the U value of the wall can be derived.

In conventional walls where the materials used do not possess very different thermal characteristics the value thus obtained seems accurate enough for heat loss calculations.

However, the same does not necessarily hold for more complex walls in which good insulating materials such as the very light ones are used side by side with conducting materials such as concrete or even highly conducting ones like the metals.

Actually U value tests carried out on very theoretical cases for demonstration purposes have shown substantial differences between measured and calculated values.

We measured the U value of a sandwich panel having a core of 3 cm polystyrene between two slabs of insulating fibreboard. This panel was first tested by itself and then interrupted by flat iron bars 5 mm thick spaced 20 cm apart then by iron T bars with the flanges on the interior face, and finally by I bars.

The Table* shows the results obtained by measurement and by calculation using the elementary method. The calculated results are almost the same for the three types of reinforcement but the measured results are very different.

In particular, placing the flange as the inside for either the T or the I bars provides a considerable increase.

It is probable that the diffusion of the flux produced by a conducting interior slab provides, in the case where the frame members are near to each other, a considerable increase in the flux traversing the wall. It may be noted, moreover, that in our tests the temperature differences between the ambient air and the main part of the wall are systematically higher in tests B than in tests C, although the differences between the interior and exterior temperatures are substantially the same, and that wall B containing 5 cm more concrete has a lower calculated U value. This probably results in a considerable increase in U value due to the fact that the slab of concrete diffuses the flow of cold from the frames and from each of the joints separating the blocks of cellular concrete.

The case of the large heavy concrete panels with incorporated insulation raises the same problem. Having a thick slab of concrete on the inside makes the temperatures of the interior surface more uniform but certainly leads to a substantial increase in the overall U value. The closer the bridges are together and the thicker the interior slab, the greater this increase will be.

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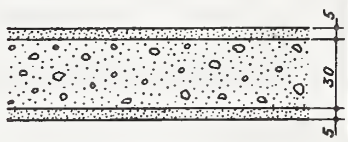
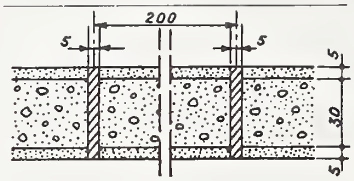
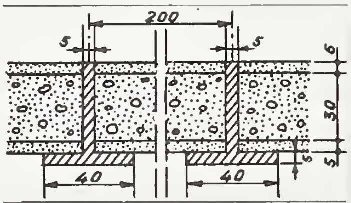
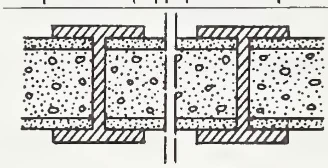
* See Table page 58

The phenomenon would be even more evident in the case of a wall, using metal sheets for its interior and exterior finishes and an internal metallic frame. The losses through such a panel depend more on the separation between the frames than on the filling insulation and calculation by the classical method has no significance.

Panel	Measured U-value	Calculated U-value
	0.8	0.8
	1.3	0.9
	1.5	0.9
	2.3	0.9

B I B L I O G R A P H Y

France

1. "La Chambre thermique de la Station expérimentale de Champs-sur-Marne" (The thermal chamber of the Experimental Station of Champs-sur-Marne), Cahier du C.S.T.B., (C.S.T.B. Official Report), no. 24-25 (Section 216).

2. "Recommandations pour l'emploi des maconneries légères en considération de leurs caractéristiques thermiques utiles" (Recommendations for the use of light-weight masonry with respect to their thermal characteristic uses.), Cahier du C.S.T.B. no. 34 (Section 277).

3. R.E.E.F.-58 (Volume I, page 603).

4. Manuel des Industries Thermiques (Thermal Industries Handbook), Volume I.

Canada

5. G.O.Handegord "Wall Surface Temperatures", ASHAE journal Section Heating Piping and air Conditionning (June 1957).

England

6. N.S.Billington "Thermal properties of Building".

Publications of the Technical Institute of Stuttgart.

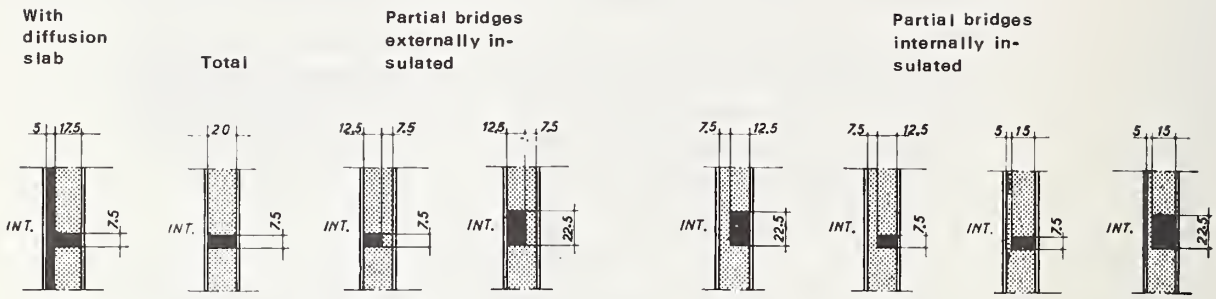
Germany

7. M.Reiher, D.V .Sodem, H.Kunzel "Wärme-und Feuchtigkeitsschutz in Wohnbauten" (Heat and Moisture Protection in Housing Structures), (1958).

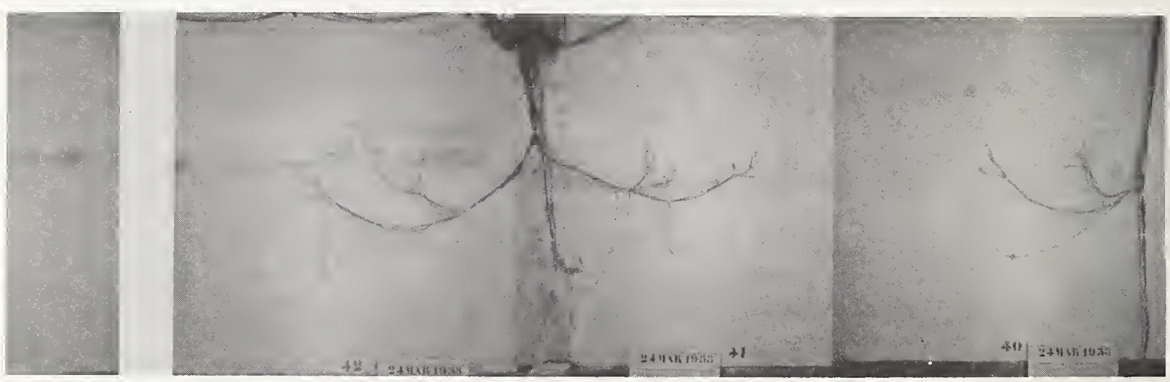
8. Cahier 29 (1954). W.Schüle, H.Schäcke "Wärmebrücken im Wohungsbau" (Thermal bridges in Housing Structures), (Translation by C.S.T.B.

9. Cahier 29 (1954). W.Schüle, H.Künzel "Modelluntersuchungen über die Wirkung von Wärmebrücken in Wänden" (Model Analysis on the Effect of Thermal Bridges in Walls), Translation by C.S.T.B.

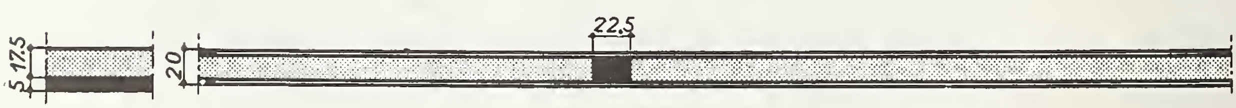
Figure 1. Study of thermal bridges



Vertical sections showing horizontal thermal bridges



Interior view, condensation on the reactive paint



Horizontal section showing the vertical thermal bridge

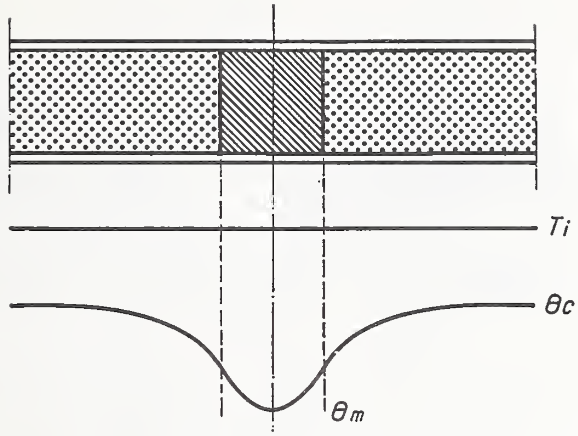
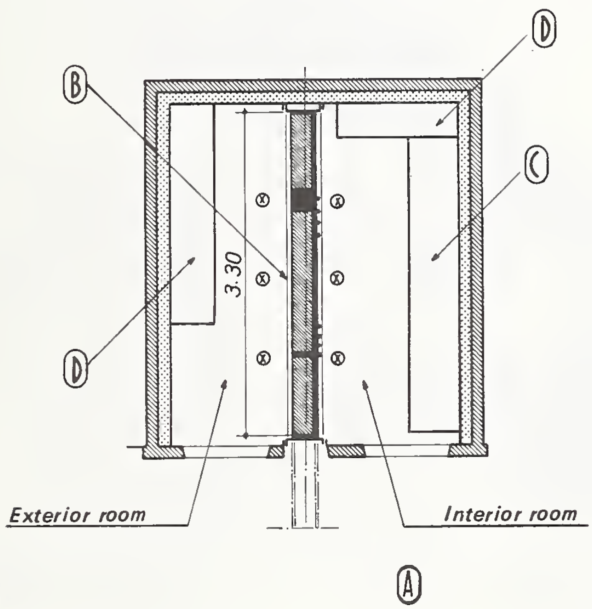


Figure 2. Distribution of temperature at the surface of a heterogeneous wall

Figure 3 Plan of thermal room



A — Introduction of wall
B — Wall under test
C — Ventilation ducts
D — Air conditioning unit — hot — cold — humidity
X — Thermometers
● — Thermocouples

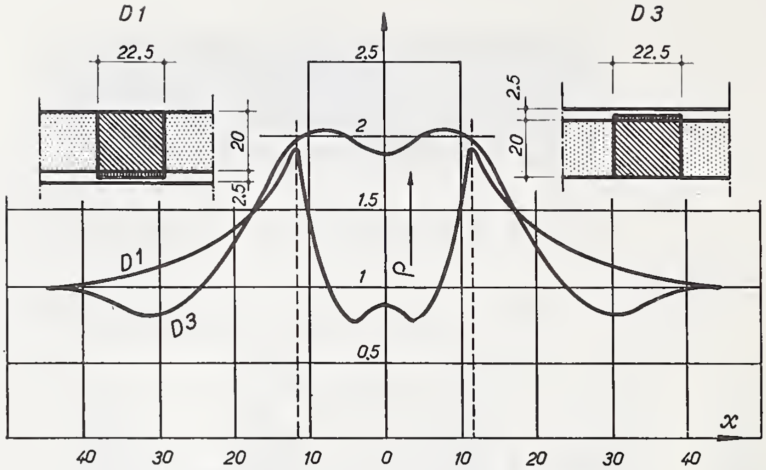


Figure 10. — $\rho^{(D)}$ curves for interior (D_1) or exterior (D_3) insulation

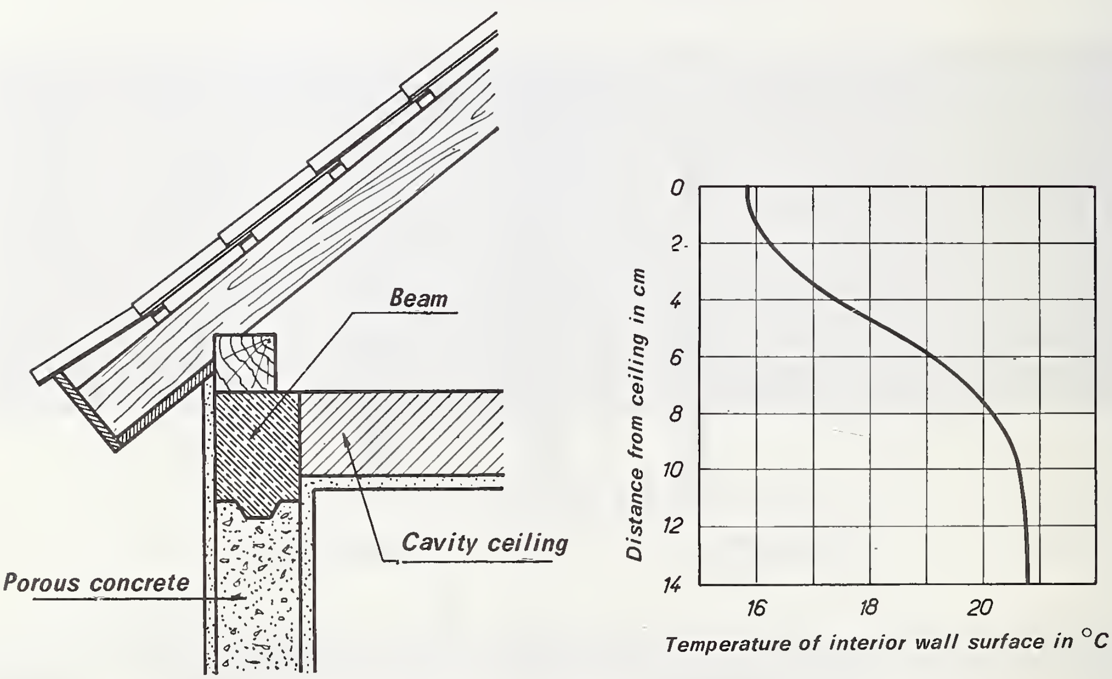


Figure 11. Distribution of temperatures at the surface of a wall near a thermal bridge produced by the corner of a wall and an attic floor and the beam between them[8]

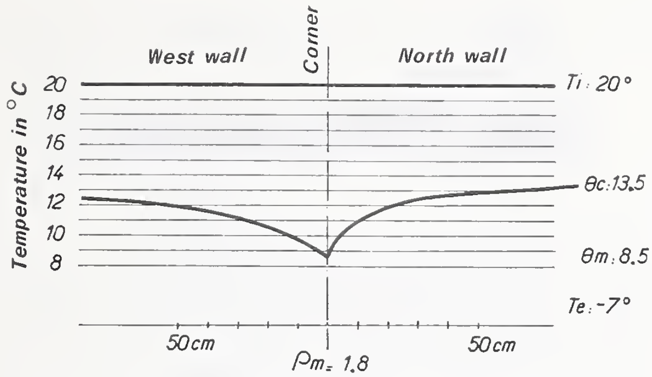


Figure 12. Temperature curves at the corner between two homogeneous external walls[7]

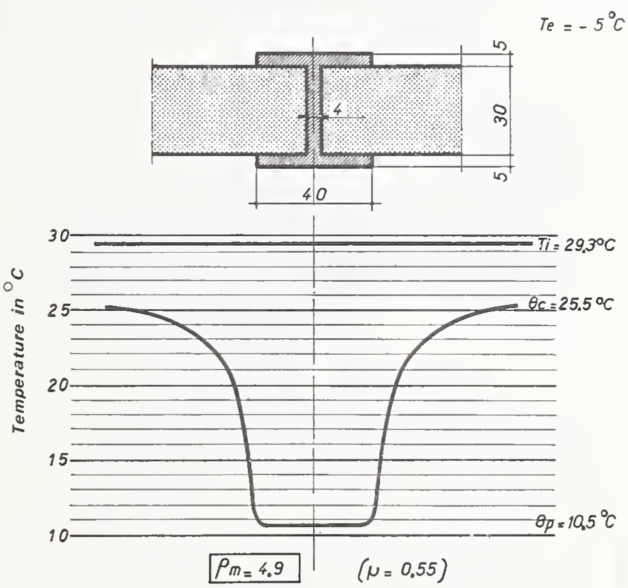


Figure 13. Light wall — Total bridge — Metal frame

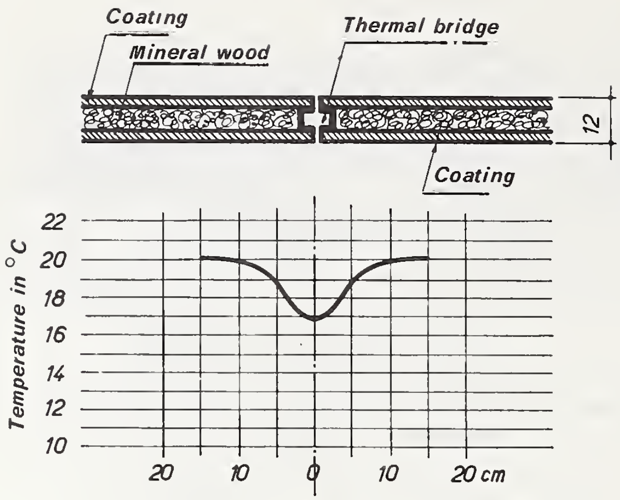


Figure 14. Distribution of temperatures on the interior surface of a wall close to a thermal bridge produced by a metal frame in the interior of a light panel. Note the diffusion obtained by the interior coating. Nevertheless the thermal bridge is very evident[8]

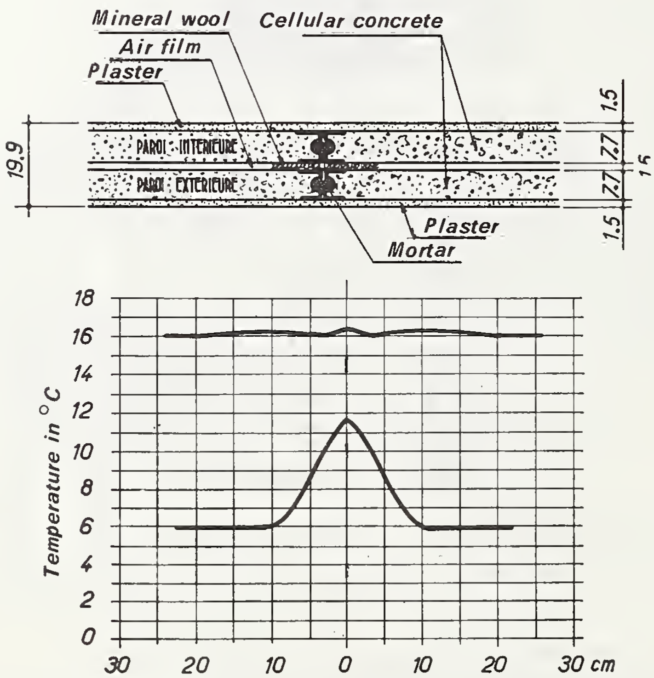


Figure 15. Distribution of temperatures on the interior surface of the exterior wall, lower curve; and on the interior surface of the interior wall, upper curve. Note the good correction of the thermal bridge by complete interruption of the two frames by a good insulator[8]

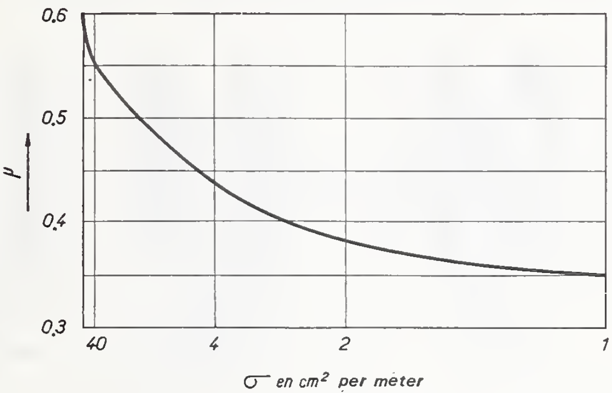


Figure 16. Interrupted bridge. Value of is in terms of the path cross-sectional area

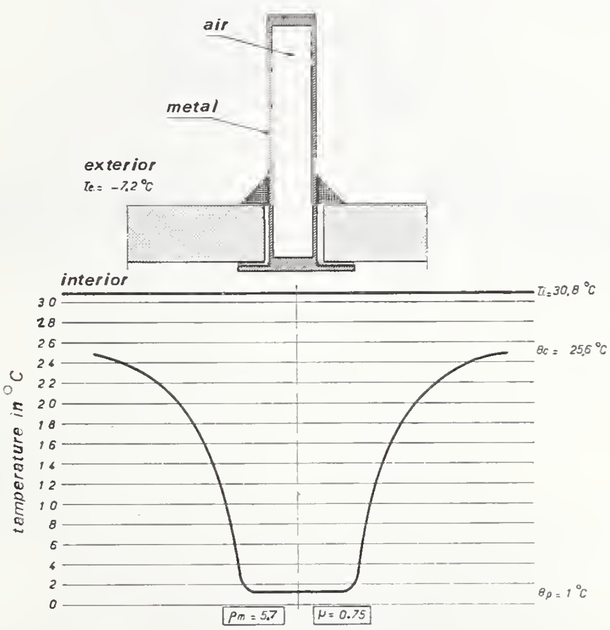


Figure 17. Light wall. Total bridge with fin

Figure 18. Light wall. Total bridge. Practical example of correction by interruption of the cold bridge and by interior moulding

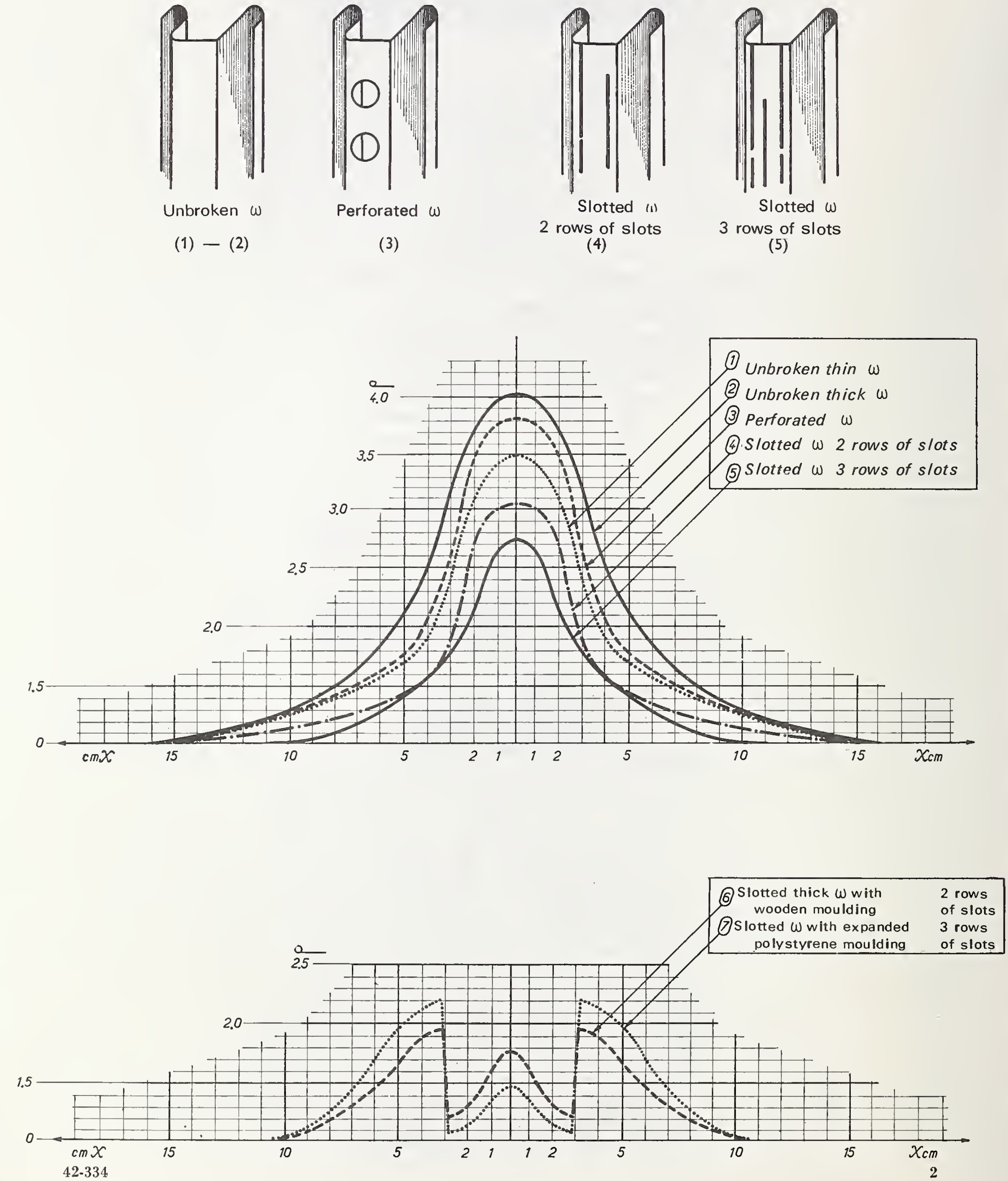
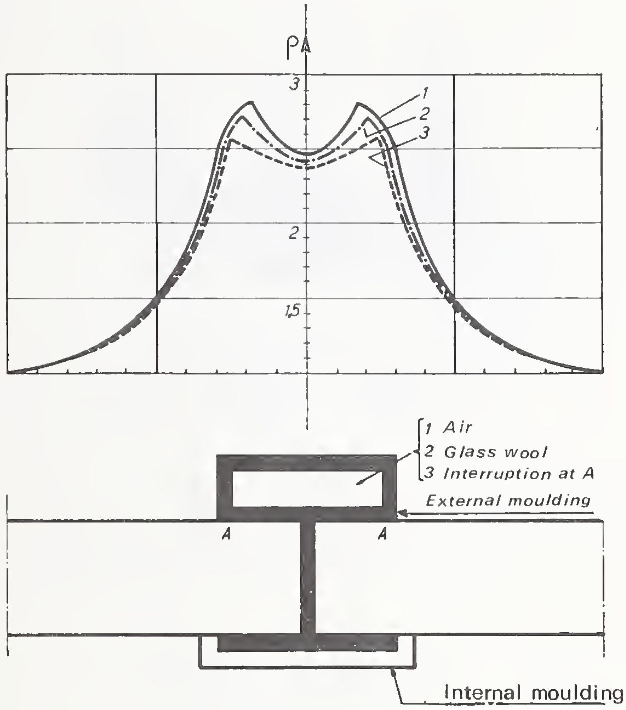


Figure 19. Light walls. Metal frame. Practical example of correction by interior and exterior moulding



1 Joint by itself
2 Filled with glass wool
3 With insulation at A

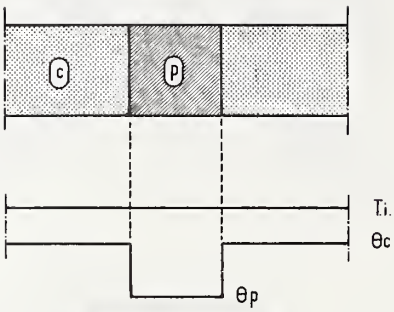


Fig. 20 — Total bridge.
Curve of temperatures given by the elementary theory.

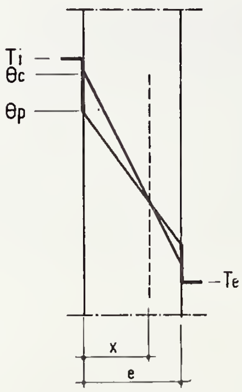


Fig. 21. — Total bridge.
Temperature profiles in the thickness of the wall given by the elementary theory.

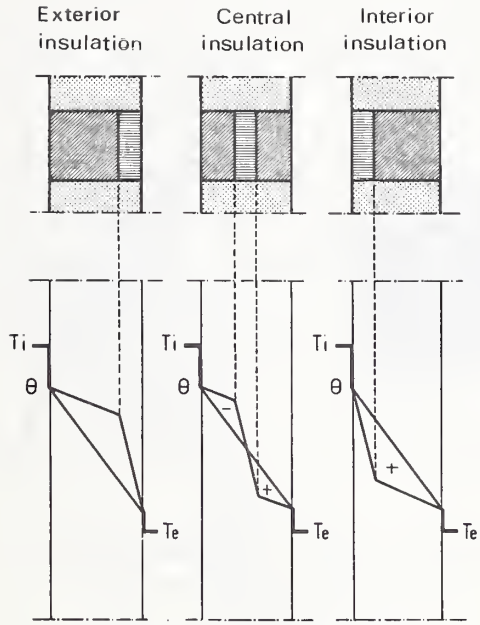


Fig. 22. — Corrected bridge. Temperature profiles through the thickness of the wall

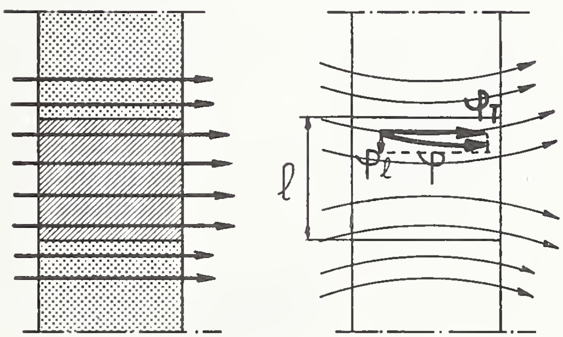


Fig. 23. — Left, flux lines of elementary theory right, true flux lines.

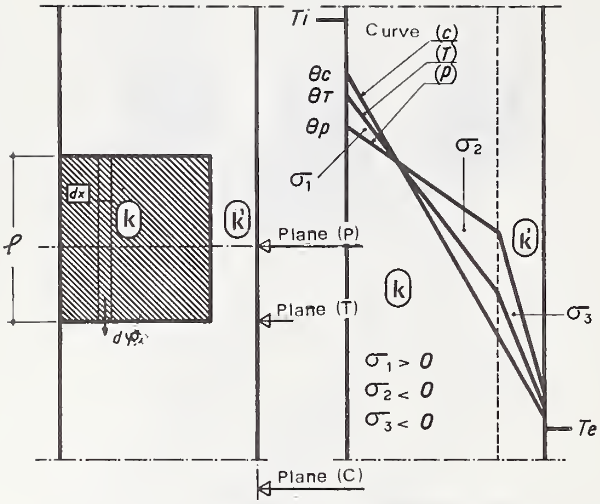


Fig. 24. — Example for the calculation of L
Convention of signs

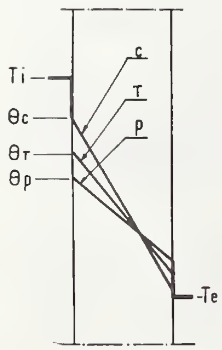


Fig. 25. — Total bridge.
Temperature profiles

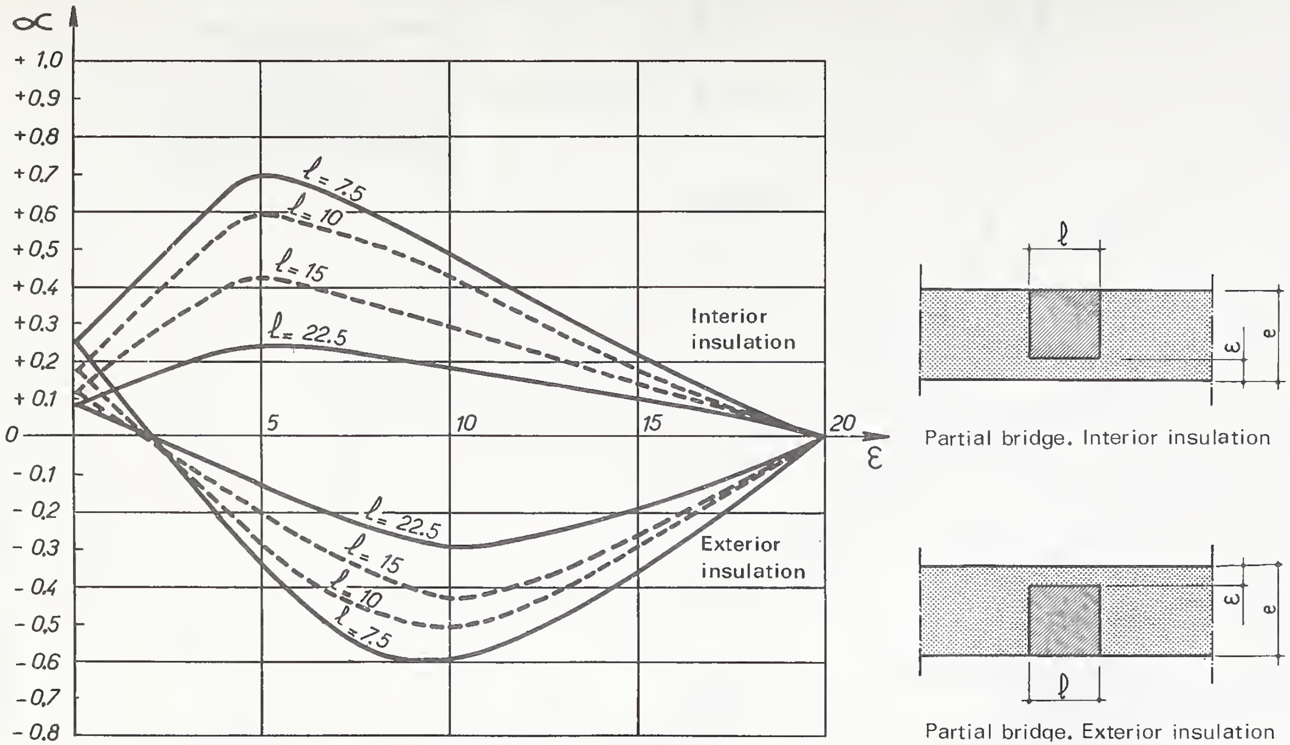


Fig. 26 — Partial bridge. Curve $\alpha(\varepsilon l)$ with interior and exterior insulation.

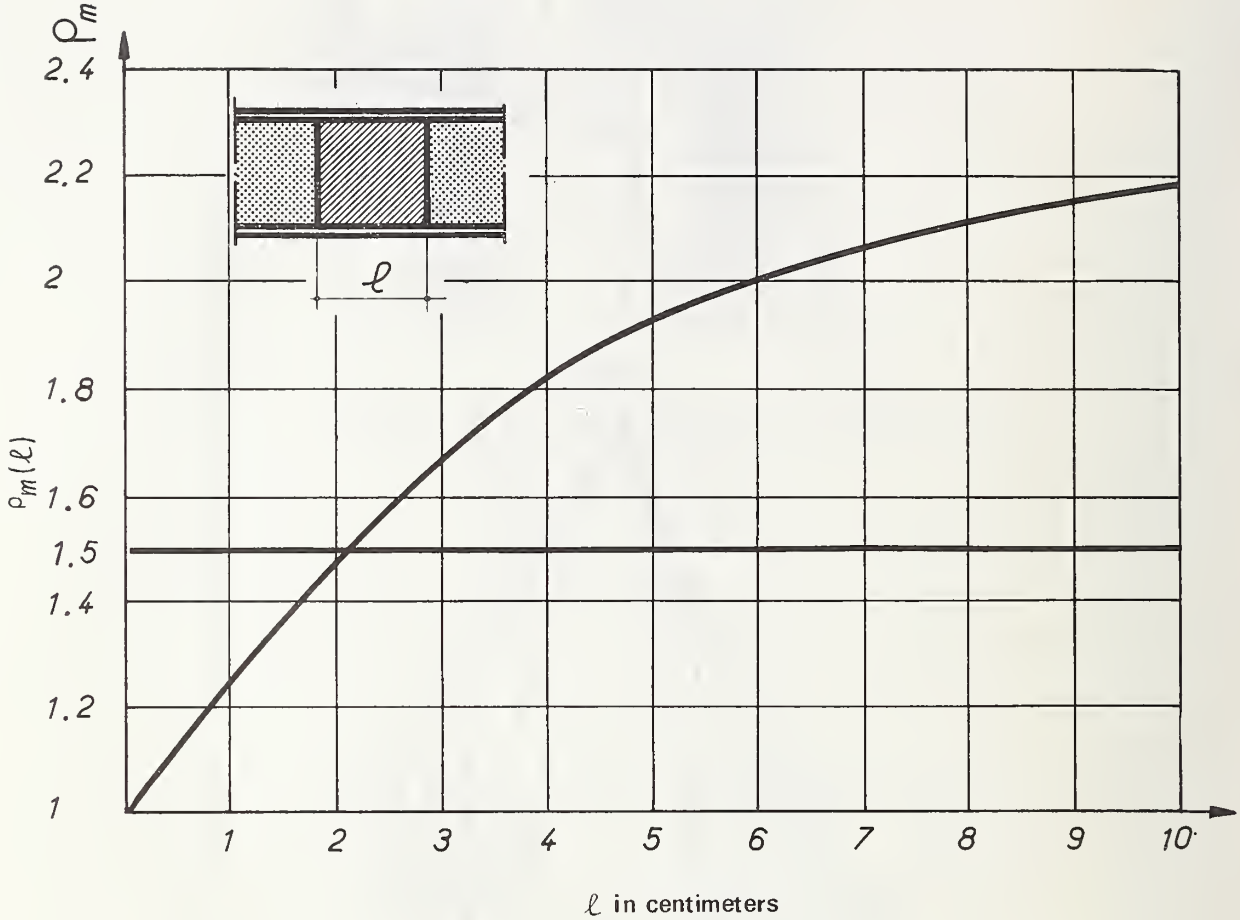


Fig. 27 — Heavy wall. Total bridge $\rho_m(l)$ curve with coatings.

Fig. 28 — Heavy wall. Light masonry and reinforced concrete frame.
— Thermal bridge with diffusion layer provided by an interior concrete slab.
— Graph $\rho_m(\varepsilon, l)$.

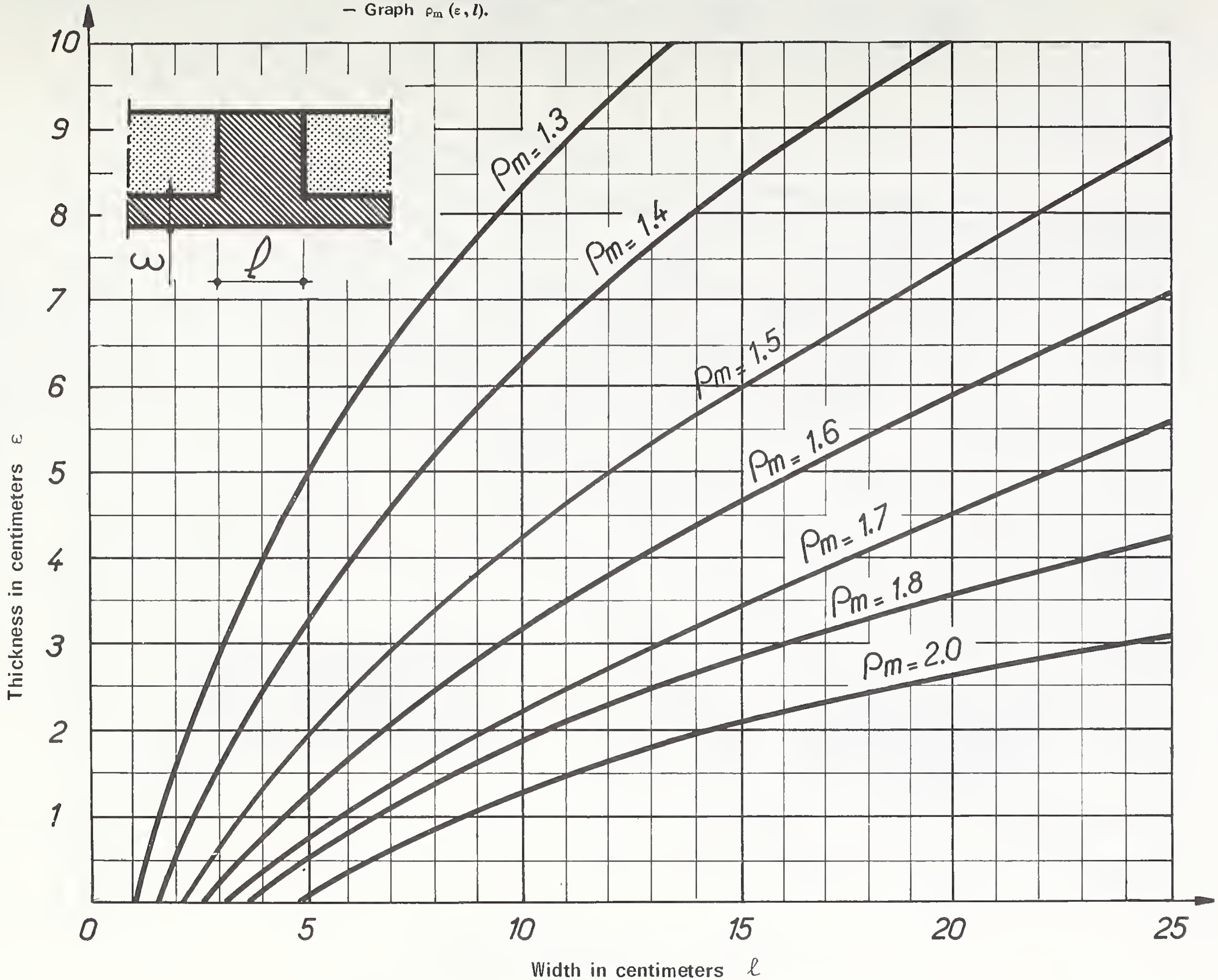


Fig. 29. – Heavy wall. Light masonry and reinforced concrete frame.
– Partial bridge insulated on the interior side.
– Graph ρ_m (ε, ℓ)

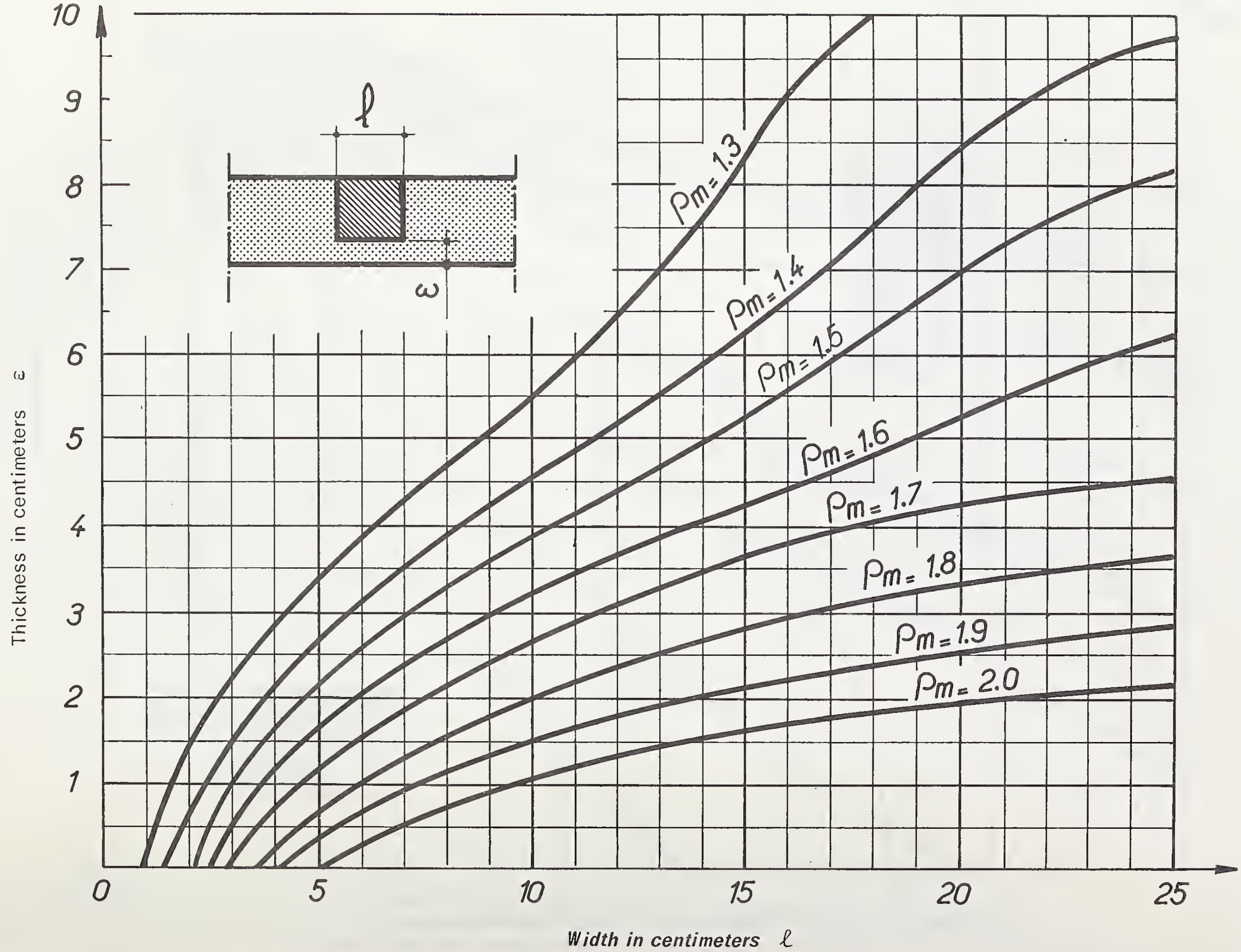
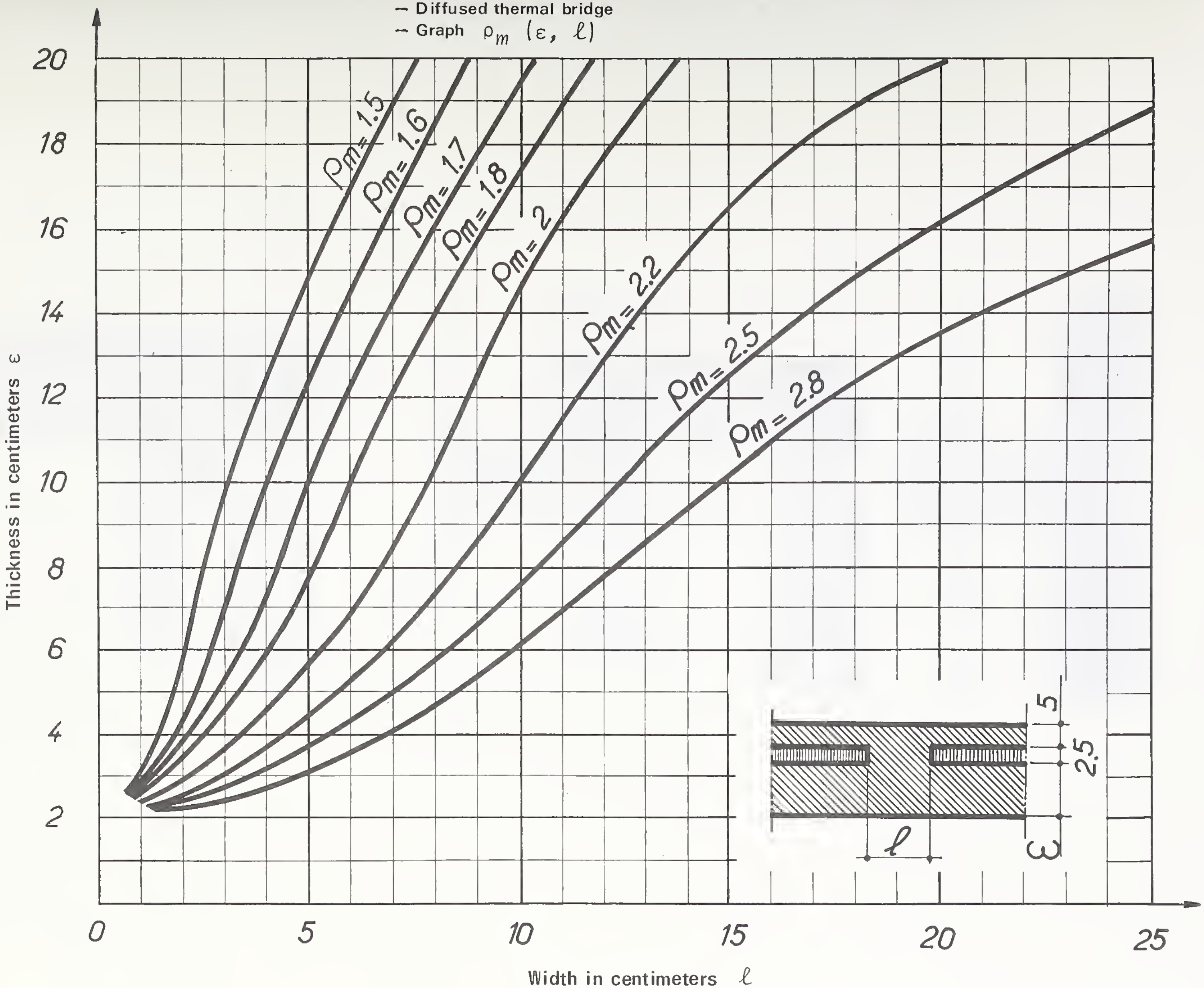


Fig. 30. – Heavy wall. Concrete panel incorporating light insulation
– Diffused thermal bridge
– Graph ρ_m (ε, ℓ)



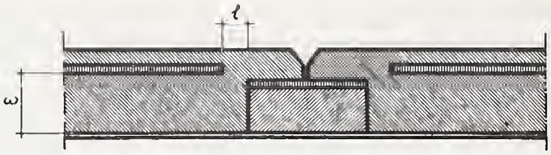


Fig. 31. — Concrete wall incorporating light
insulation joint between two panels.

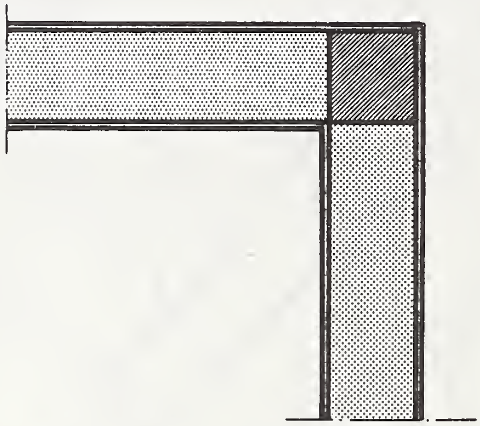


Fig. 32. — Corner of two exterior walls incorporating
a post case of light masonry

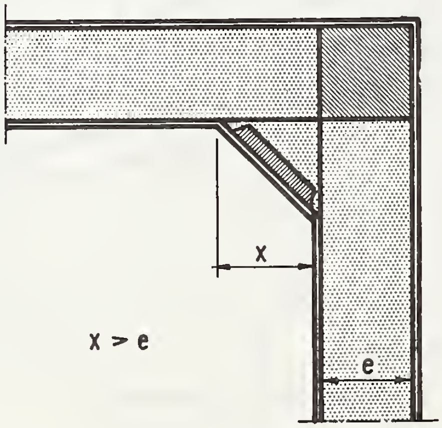


Fig. 33. — Correction of the thermal bridge
in the corner

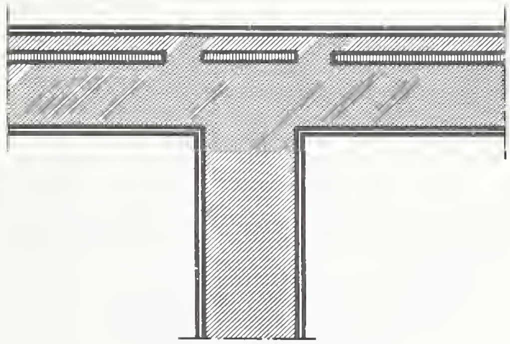
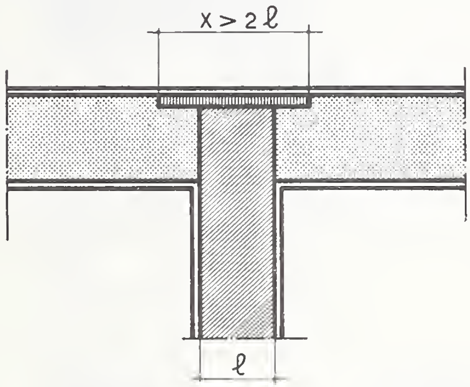
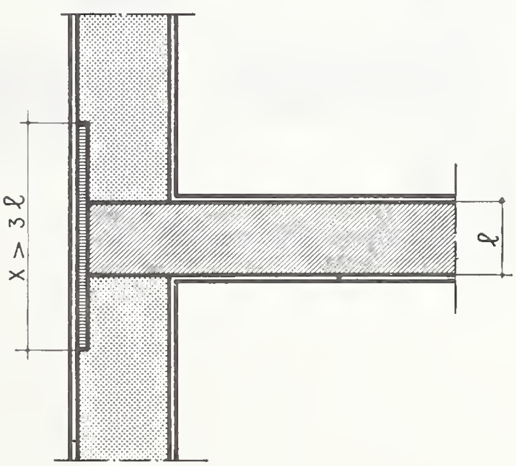


Fig. 34. — Partition, Floor.
Case of concrete panels incorporating light insulation.



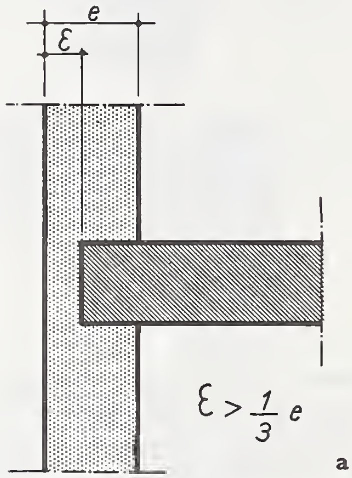
a) Partition.



b) Floor.

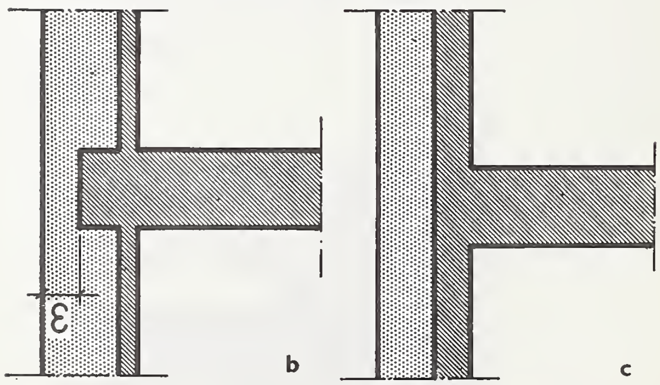
Fig. 35. — Corrected bridges.

Fig. 36. — Partition. Floor.



Partial bridge. Exterior insulation

Combined exterior insulation
and interior insulation



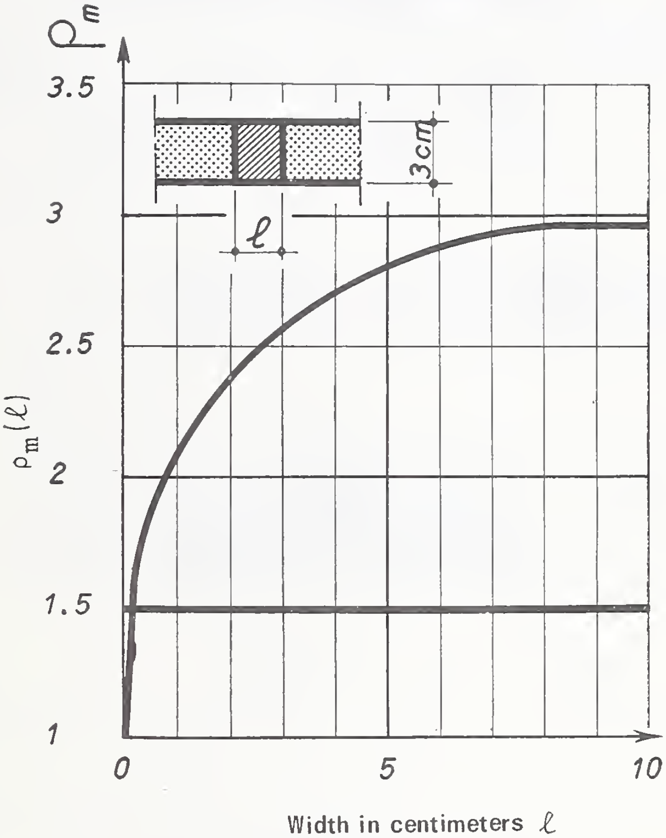


Fig. 37. — Light wall. Total bridge. Wood framing curve $\rho_m(\ell)$

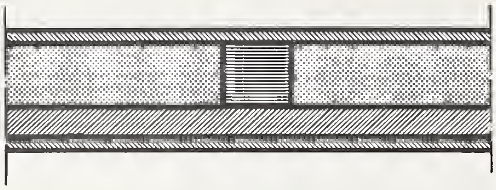
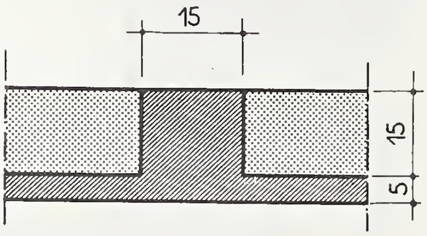
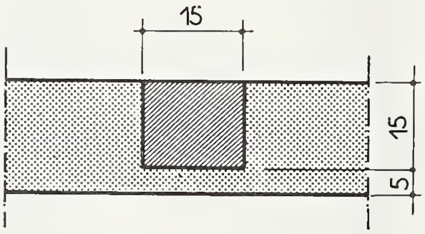


Fig. 38. — Light wall. Example of correction of a thermal bridge produced by internal framing



a) Interior diffusion



b) Interior insulation

Fig. 39. — Two equivalent solutions, $\rho_m = 1{,}5$

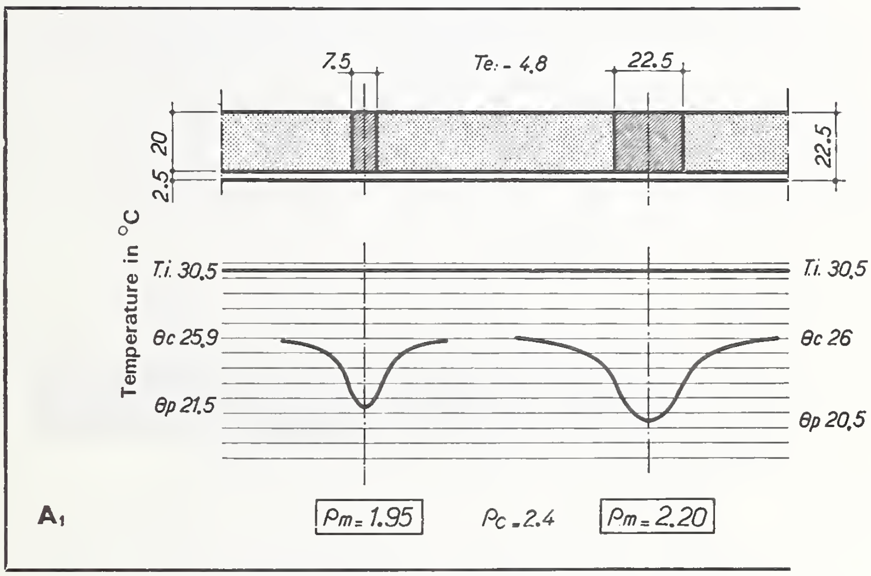
Table I

Heavy walls: Reinforced concrete frame – Light masonry filling or large panel of light masonry

Compact concrete — Cellular concrete

Reinforcement — Plaster — Expanded Polystrene

TOTAL BRIDGES



TOTAL BRIDGES

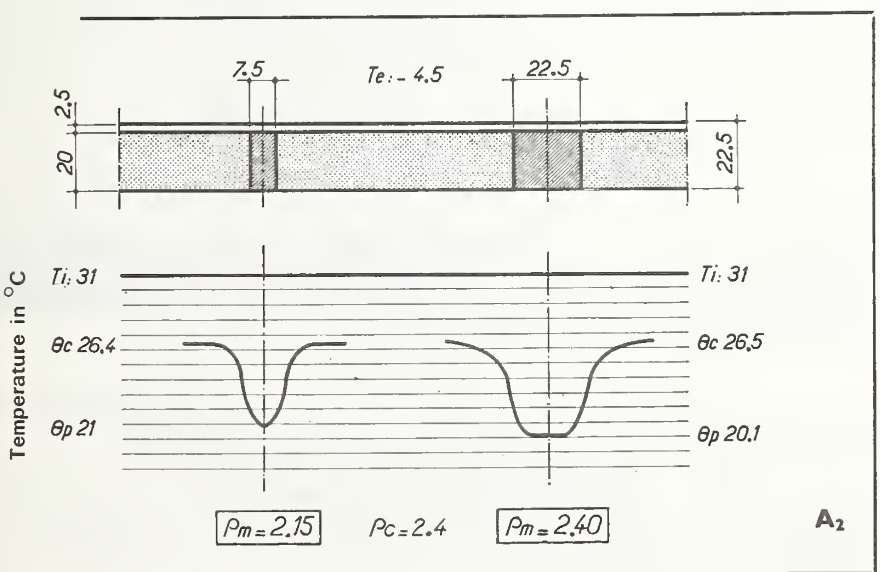
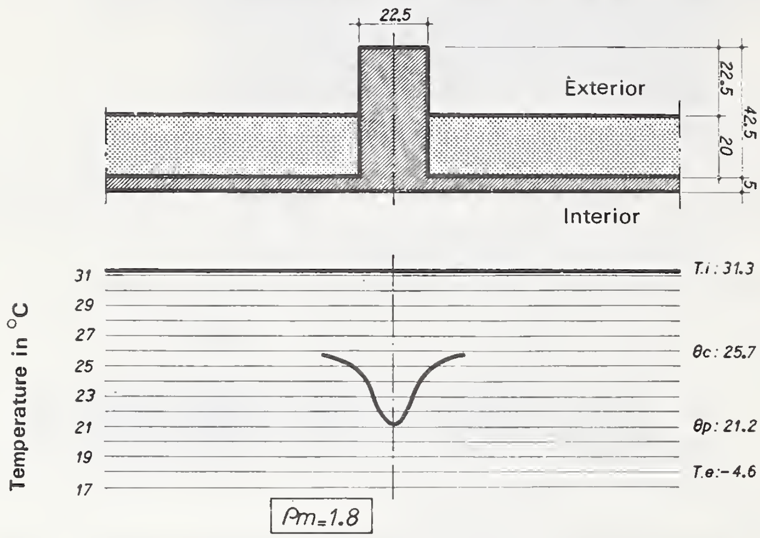
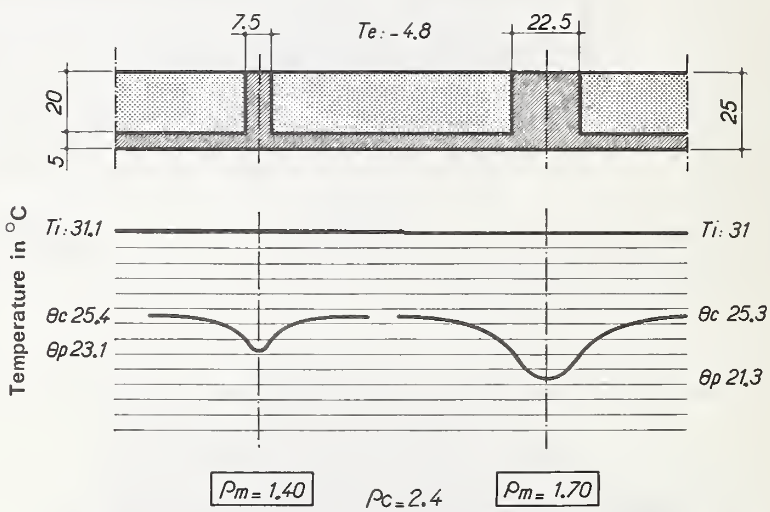


Table I (cont'd)

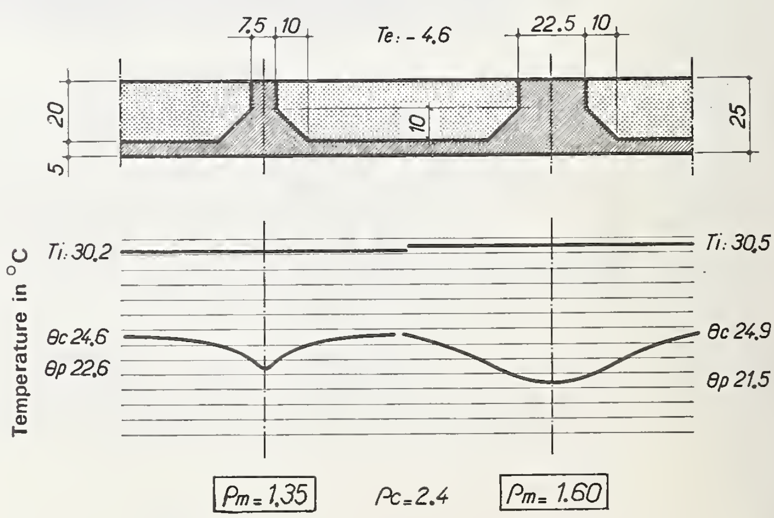
BRIDGES WITH INTERIOR DIFFUSION LAYER



B



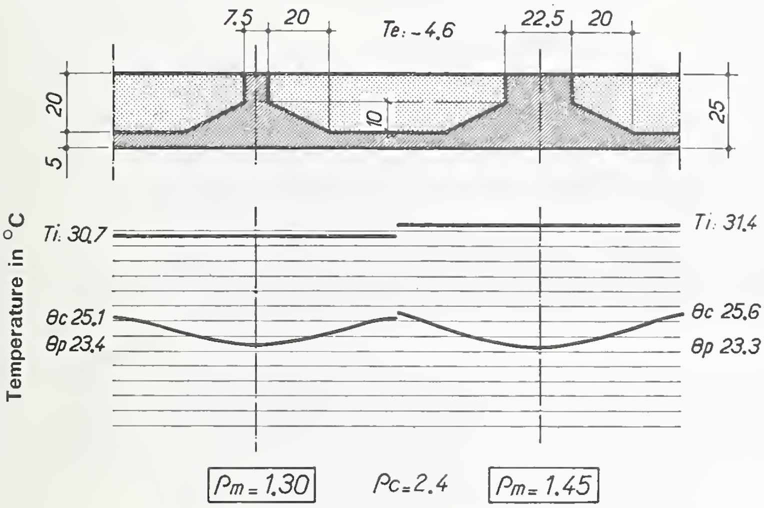
B₁



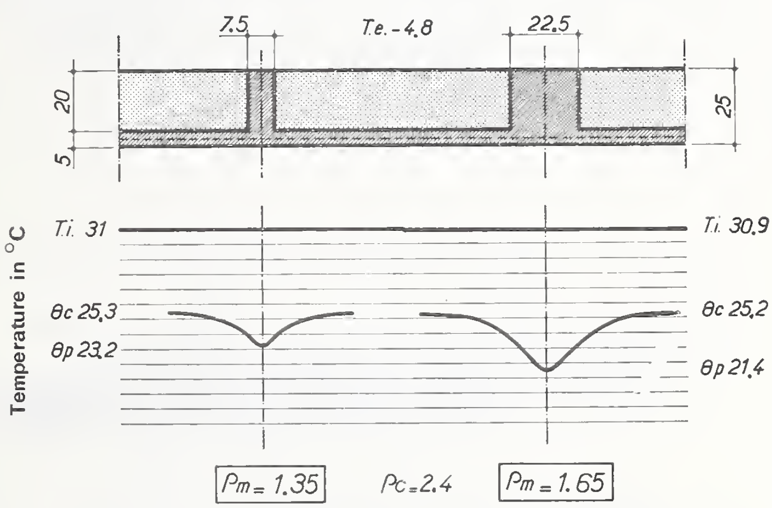
B₂

Table I (cont'd)

BRIDGES WITH INTERIOR DIFFUSION LAYER (cont'd)



B₃



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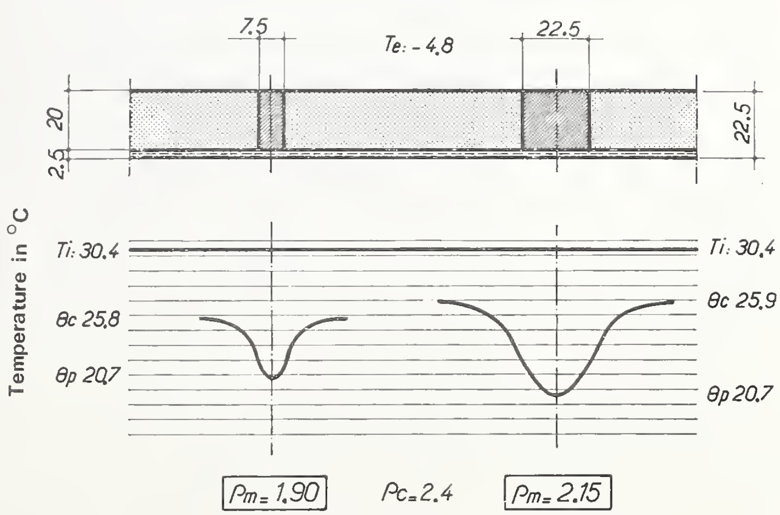
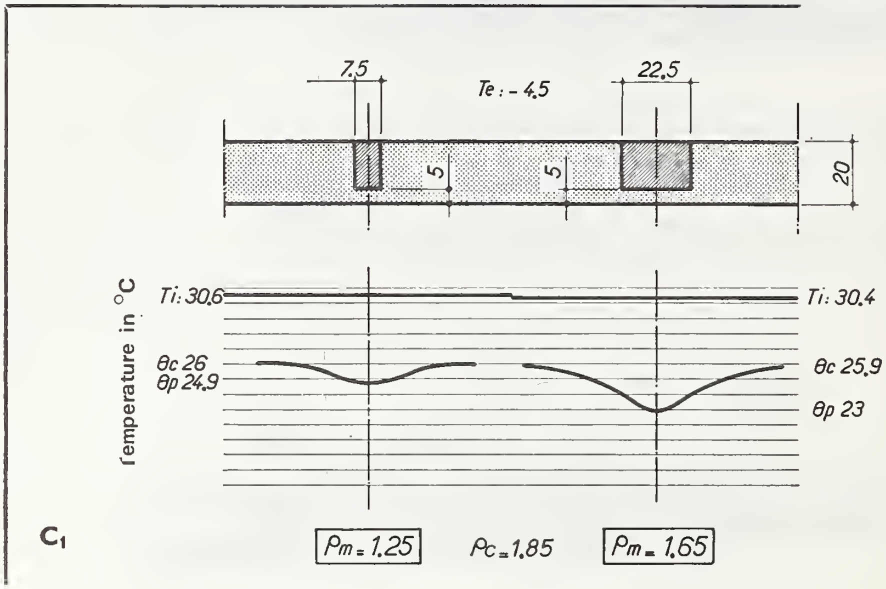
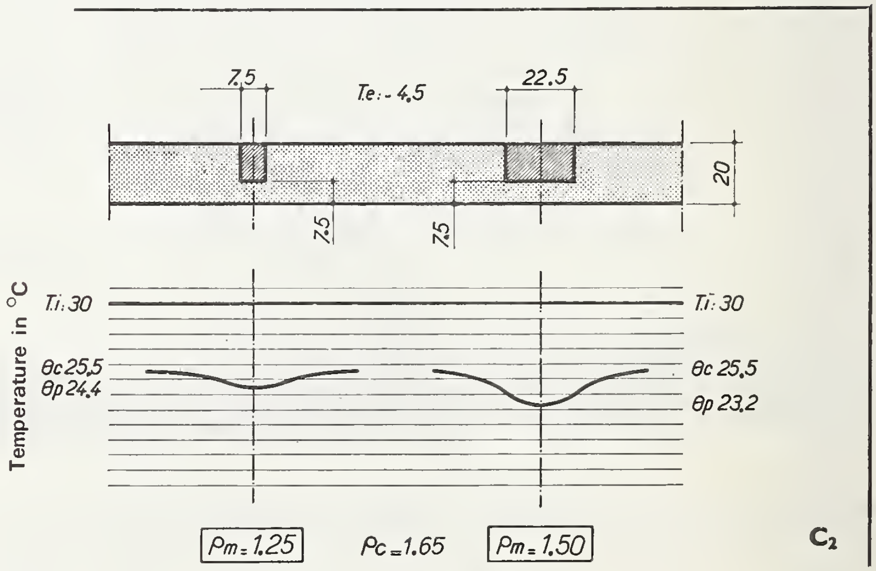


B₅

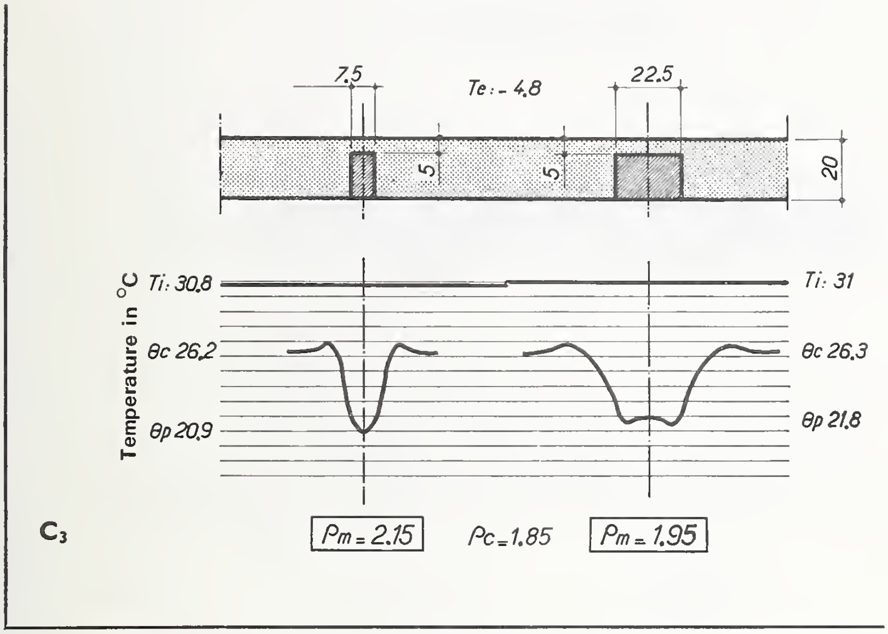
Table I (cont'd)

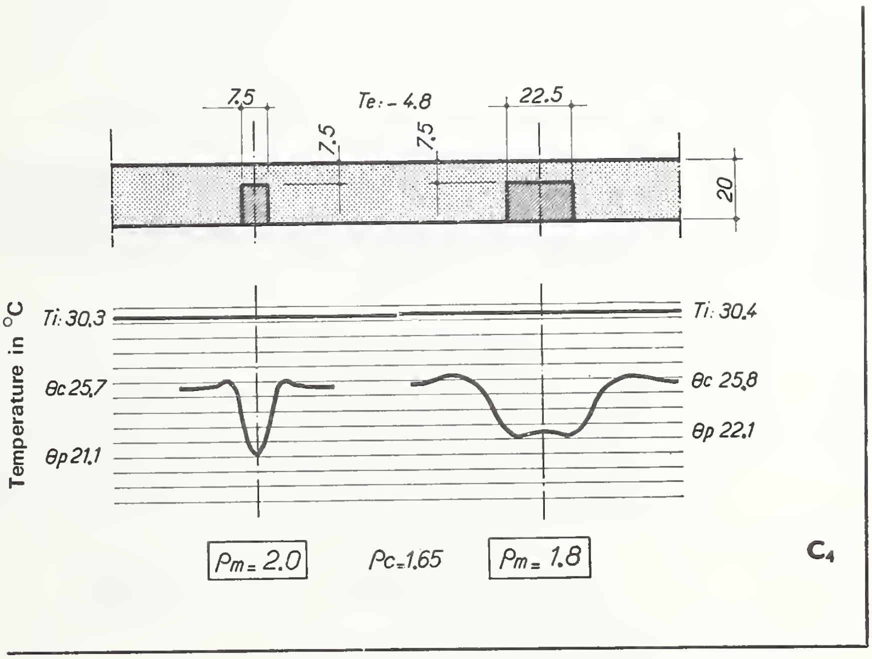
PARTIAL BRIDGES



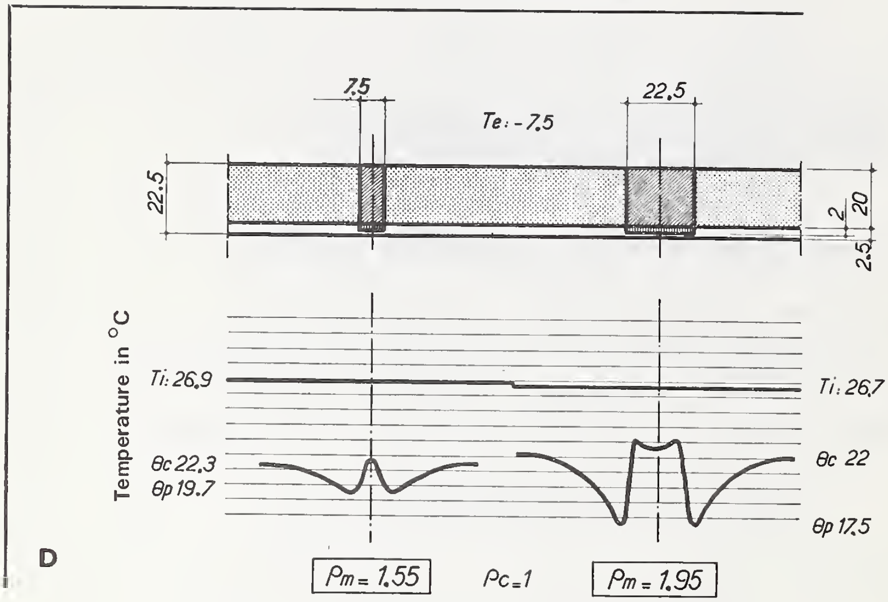


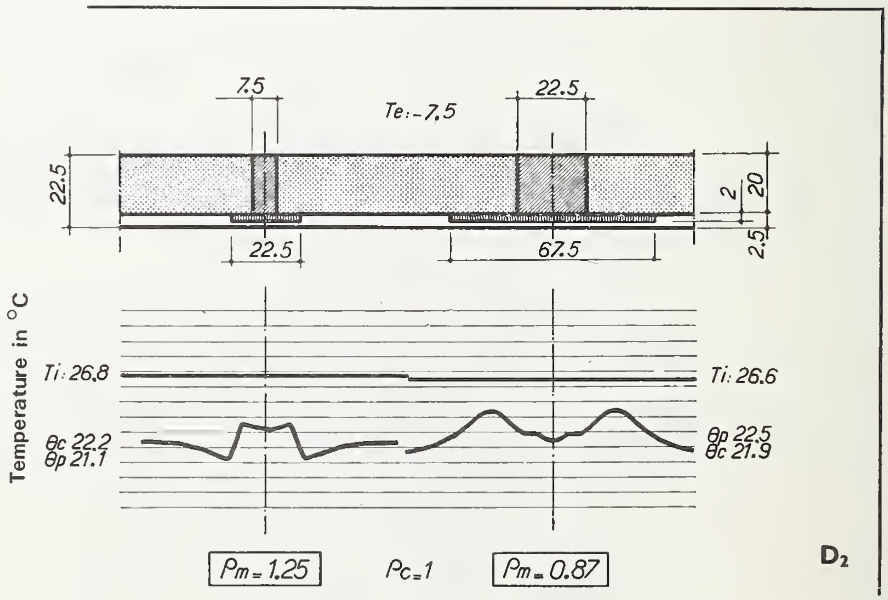
PARTIAL BRIDGES (cont'd)



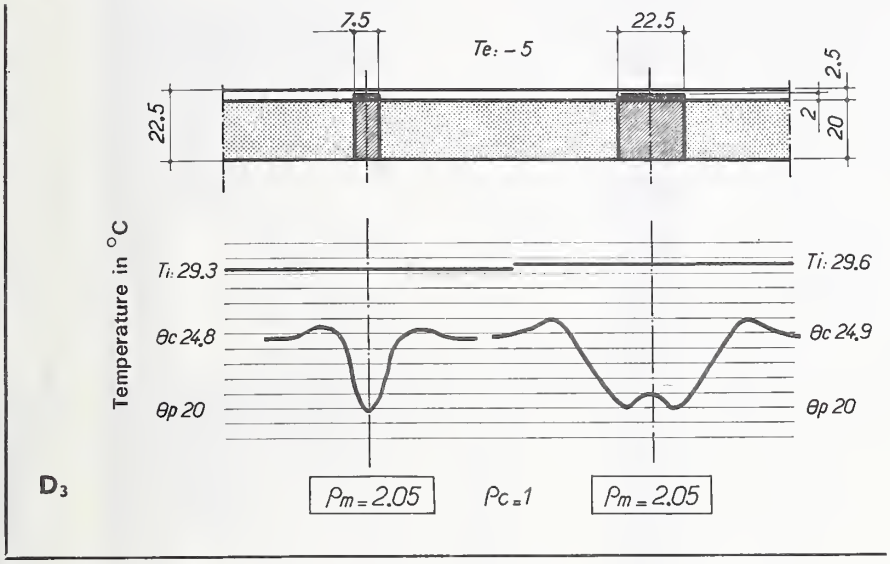


CORRECTED BRIDGES

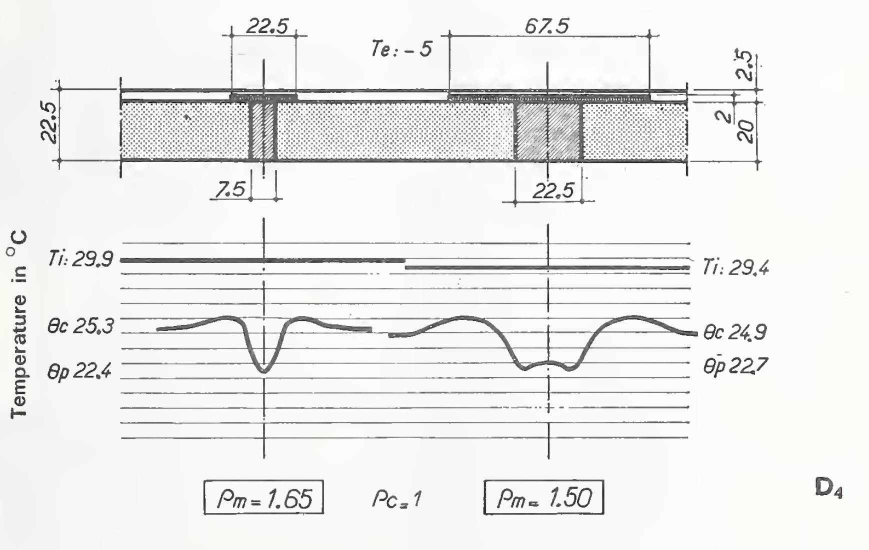




CORRECTED BRIDGES (cont'd)

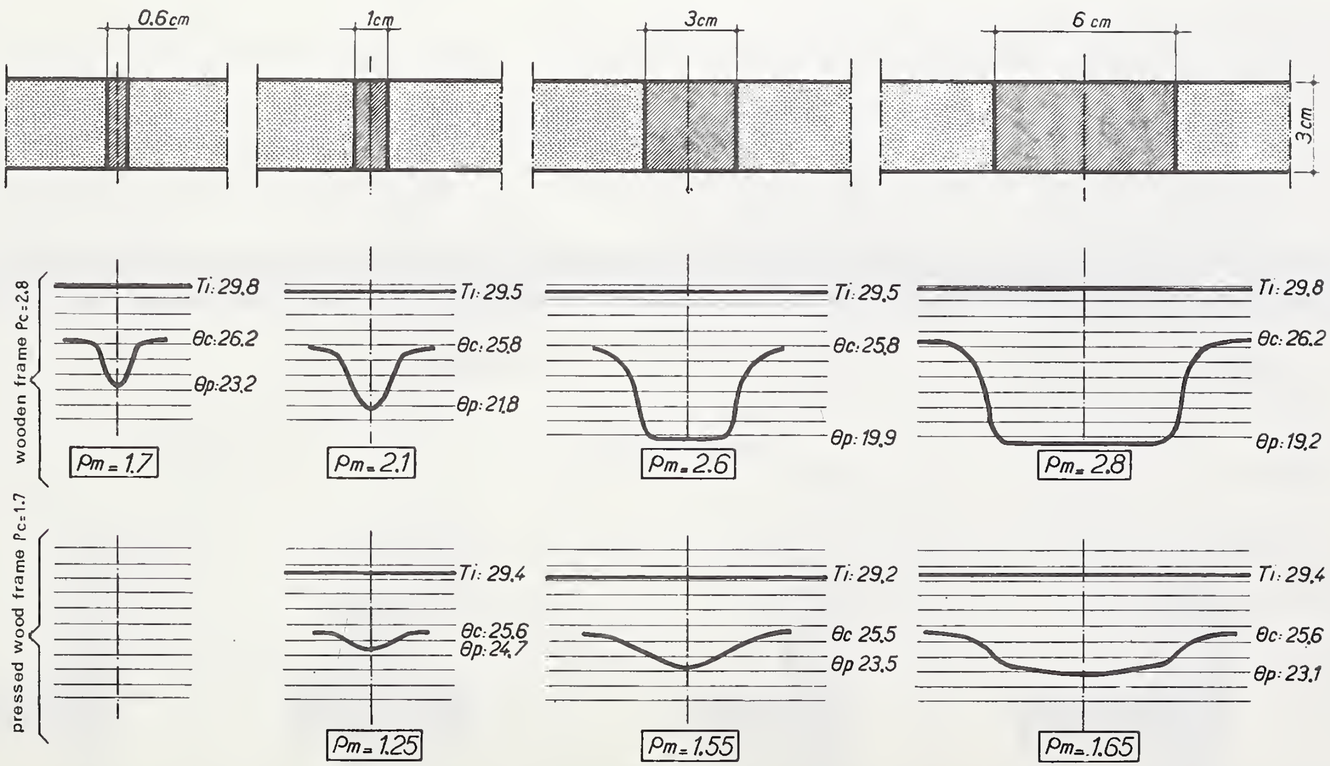


D₃



D₄

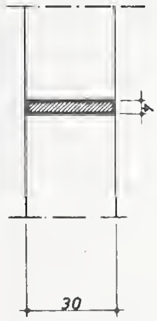
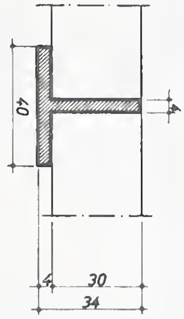
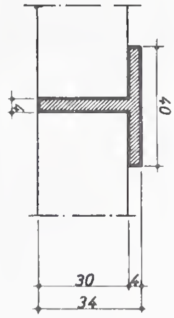
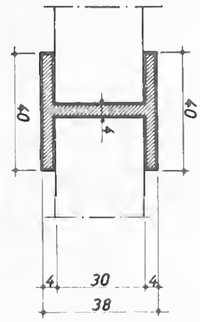
TABLE IV. – Light walls: Total bridges with wooden frame and pressed wood frame

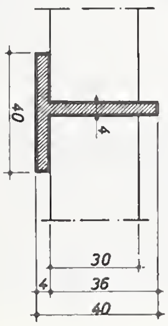
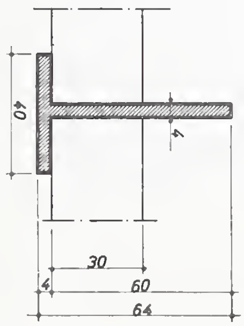
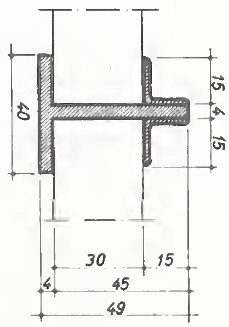


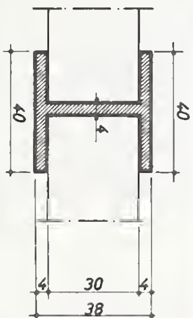
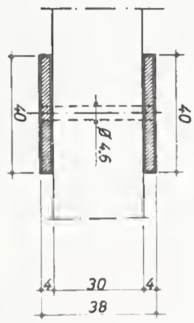
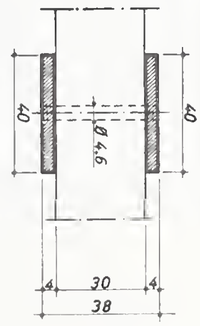
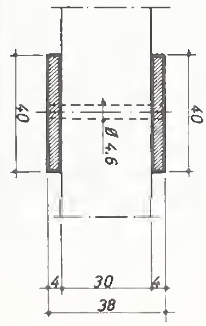
Polystyrene

Iron

TABLE V. – Light walls: Metal frame (interior space is to the left)

TOTAL BRIDGES				
ρ_m	5.4	3.1	7.2	4.9
μ	0.60	0.35	0.80	0.55

TOTAL BRIDGES WITH EXTERNAL FIN			
ρ_m	3.6	5.4	4.9
μ	0.40	0.60	0.55

INTERRUPTED BRIDGES				
	Uninterrupted web $\sigma = 40$ cm² per meter of section	1 screw every 4 cm $\sigma = 4$ cm²/m	1 screw every 8 cm $\sigma = 2$ cm²/m	1 screw every 16 cm $\sigma = 1$ cm²/m
ρ_m	4.9	3.9	3.4	3.1
μ	0.55	0.44	0.38	0.35

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

Uniformity of temperature on the internal face is one of the essential hygrothermal qualities for a wall.

Cold bridges, which are the cause of uneven temperatures, constitute a weakness which ought to be corrected.

The author describes a large number of tests carried out with various types of wall (dense walls and lightweight panels) in order to assess the importance of cold bridges and to determine the effectiveness of possible remedies; he shows that the accepted theory used in the calculation of U-coefficients is unsatisfactory when estimating surface temperatures. The results obtained can be explained, however, by means of two simple hypotheses; on the basis of these there are practical rules which can be used in establishing the importance of cold bridges, and recommendations for reducing them.

17. KEY WORDS (Alphabetical order, separated by semicolons)

Floors and panels; moisture condensation; thermal bridges; thermal insulation; U-values of walls.

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