THE ROLLER KILN AND ITS INFLUENCE ON THE PLANARITY OF THE FINAL PRODUCT

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ABSTRACT

Producing quality also means knowing and controlling technological processes and the machines involved. The roller kiln is in current technology, the machine that has had the greatest influence on the quantity and quality of ceramic tile manufacture.

The planarity of the ware is also a function of the kiln used and its correct regulation.

Starting from elementary considerations of a theoretical nature, this study establishes an ideal path, leading from the need to fire a simple tile to modern industrial kilns. The different thermal, mechanical and dilatometric stresses are described together with their influence on the planarity of the final product.

1. INTRODUCTION

The subject of the Qualicer 94 Congress, ceramic product quality, is always of topical interest, and is currently of great importance for all producers of no matter what size, kind, or place.

The technical and technological revolution in the processes and machines used, widely confirmed in their fundamental principles and concepts, have allowed ever greater quantities to be manufactured, with high specific productivity in all the industrial centres. Rather than allowing this, it might be said that this **has obliged** the manufacturer to produce these quantities in order to fully exploit the production capacity of the facilities involved in the technological process.

Quality and quantity are, however, two quite different variables. Both modern and upgraded technologies and machines can be directly purchased, and they allow potential production yields resembling those of the best competitors to be obtained in a very short time, by using the experience of others. However, the opposite is usually the case when it comes to production efficiency, especially with regard to the constant quality of the final product. A great number of enterprises throughout the world are at present able to increase efficiencies and quality at their own new, well planned, but not such well run facilities (quantitative factor), at which process and technological variables (qualitative factor) are not suitably used.

We therefore propose to devote special attention to product quality, particularly with regard to one of the most important facilities involved in the cycle: **the roller kiln.**

This machine has undoubtedly been of the greatest influence in current production. Other units, have progressively been improved and upgraded in all aspects in function of their importance, but their conceptual characteristics have remained the same. The roller kiln, however, has completely changed the «firing concept», eliminating the typical defects inherent to the old firing systems and introducing a different system, which is however no simpler.

We shall deal with the roller kiln and the tiles that use it. We shall furthermore refer in detail to their flatness, a typical, specific characteristic of these heat-treatment facilities.

«Flat firing» a single piece involves taking into account the possibility of each square centimetre of surface area giving off and receiving heat, fast and conveniently.

However, it also means performing greater control over the geometric deformations that the single piece, without any further connections to a support, or involvement with any reciprocal influence of the setting, ends up developing more freely.

We shall attempt to do this using the simplest possible language, attaching more importance to the conceptual issues involved, rather than quantitative assessments, unless these are indispensable to the reciprocal comparison of the varying aspects that are being considered.

This is necessary because one of the main problems in our industry is certainly the existing gap between a highly detailed, basic, theoretical literature at higher education level (Spain being the main author), and an operational reality in most cases in countries far removed from the major centres, with clearly less preparation, and an empirical basis, directly oriented by local market situations to obtaining quick and easy, immediate economic results. Variations in these situations, a temporary excess in supply and the need for more exports eventually end up by considerably changing apparently correctly implemented production processes, showing basic approaches to be insufficiently oriented to an intrinsically better product quality.

The concept of quality does not represent, therefore, an absolute value, but is the expression of a relationship between the commodity being offered and its relative price.

$$\text{Quality} = K \frac{\text{use of what is offered}}{\text{price of the purchase}}$$

At a certain time, in a new marketplace, a certain production, based only on price, **may** represent the right quality.

It suffices to recall the concept of unpaid quality, expressing an absolute, unnecessary and therefore unpayable, qualitative value in these particular situations. At present, such commercial situations are subject to fast changes, especially in recently industrialized countries, often at speeds that exceed the companyís own ability to transform itself and perform differently, in function of the better qualities demanded.

Some years ago, an important car manufacturer sold cars of a certain value in Spain, and the corresponding service booklet had the following slogan written on the first page:

Quality is no accident

It is, on the contrary, a highly peculiar way of being, of «seeing» and caring for oneís own production.

2. DEVELOPMENT

Taking this as our premise, let us start by looking at Figure 1. It shows an unglazed tile, made of a uniform material, thermally inert and ponderally stable. We shall imagine it is suspended in space and subjected to heating at $\Delta t \rightarrow \supseteq$Zero (time = ∞).

The same temperature is found everywhere in it. Perfect and perfectly free of any stresses. It is, unfortunately, a rarely observed situation. Firing means destroying some balances and creating others. Let us examine some of these:

Figures 2a and 2b show the same tile on heating it only by convection, however no longer at tZero but at t which is finite and controlled. **Firing has commenced.**

In this case, making the above assumptions, the temperature at each point of the tile is a function of the heat received from the exterior through the interface, and the heat transmitted to its interior, in this case by thermal conductivity.

In a specific case, where:

λ = 1 kcal/m.h.°C

α = 15 kcal/m^2.h.°C

Specific heat = 0.25 kcal/kg °C

For size 30cm X 30cm having a thickness of 10 mm this yields:

corner temperature 294°C

surface temperature, at centre 254°C

temperature at tile centre 213°C

That is:

between surface and centre 41°C

between corners and centre 81°C

It is only an otherwise highly reductive example, because it assumes to be constant (which it is not), but it suffices to demonstrate how at finite t, temperature differences are **bound** to arise, owing to **thickness and shape of the piece, that is, the fact of being a slab or part of a slab.**

The thermodilatometric diagram in Figure 3 also shows how a specific geometric magnitude corresponds to each temperature, that is, a deformation (change) with regard to a nominal measurement, and it is well known that a hindered deformation involves a corresponding stress, where:

σ = (stress) = (f) δ = deformation

(f) Highly complex function for ceramic products, which is linear for products fired at ambient temperature, as well as for metals in an elastic field.

What we are saying is: Either the tile deforms or it is temporarily stressed.

In our case (drying), the tile is under stress. The edges, which are hotter, tend to lengthen, the central body hinders this to a certain extent, and compression of the edges arises. The greater resistance of the material to compression, rather than tensile strength, explains why tiles do not break all that easily during preheating.

However, a finite Δt demonstrates the form factor of the object to be heated with the corresponding arising stresses.

Figures 4a and 4b show a top view and a cross section of the same piece, heated this time only by radiation from above and below.

It is another purely theoretical case. It differs from the foregoing one in that only interface stresses are observed, which are functions solely of thickness and not of the form factor. The calculated differences, with the above assumptions are of the order of 40÷50°C.

These are indicative examples.

They aim to show the different ways of heating the same object. In practice there will not only be convection or radiation, but mixed heating, with either being predominant in function of the machine used and the targeted temperatures.

There will in reality also be noticeably higher temperature differences than the ones calculated previously.

All the computer programmes of this kind yield lower values than those observed directly.

The reason lies in having assumed that our tile had:

- uniform material
- was thermally inert
- ponderally stable

which represents a nice mathematics exercise, but is far removed from reality.

Figures 5 and 6 depict these considerations, reflecting thermal energy exchanges in the material and material loss of a certain interest in function, as already mentioned, of the different materials considered. These are well-known analyses.

Moreover, these new thermal equilibria will in these cases be determined by the heat the body receives through its own surface, and the heat it transfers into its interior not by conductivity but by **diffusion.**

The term **thermal diffusion** is found in an article by W.H.Holmes in 1969, where the author asked himself why fast firing was possible.

He considers **the joint effect** of conductivity, density and specific heat of the material not as a constant but as the expression of a ponderal and energy equilibrium, function of the material and the reactions taking place at each moment.

The value can be experimentally determined and this explains why practical temperature differences are not easy to calculate.

Figures 7-8-9-10-11-12-13, corresponding to different materials, show the thermodifferential and ponderal diagrams in the upper part, and the indicative variations in the differences in the lower part.

The values are self-explanatory. Notice in each case, the influence of calcium carbonate and kaolinite with regard to thermally more inert materials, which do not undergo significant weight loss.

We repeat, these are only indicative diagrams, without any quantitative pretensions at all.

We may, therefore, say in concluding that the simple fact of using real raw materials and trying to heat them gives rise to highly varying equilibrium situations that can only sometimes, not always, be achieved at the end of the whole heat-treatment cycle.

We are still far from the kiln that interests us. We have at present got a tile under stress, at different temperatures, but it is suspended in an ideal space.

It is in any case quite flat; if we wish to deform it, making it concave or convex, with almost uniform curvature, we only need to heat its top or bottom surfaces differently. When there is no plastic deformation, alternating different heating of the two surfaces would only entail transitory, recoverable deformations. Up to this point, planarity has not been a problem.

But we must also learn how to support it and transport it. Anyone that has had the opportunity of following the industryís evolution in recent years knows that the roller has been adopted as the means of transport after many experiences relating to other kilns and varying means of support.

Figure 14 (the drawing shows a motionless tile, undergoing cooling), shows our slab (because it is not yet a tile), without roller support. It lies close to them, but does not touch them.

This allows us to confirm the **GRID EFFECT** of the rollers on the slab, without considering the slabís weight. The **WEIGHT EFFECT** will subsequently be dealt with.

Figure 15 is only a schematic. An element of dissymmetry is now observed for the first time. The presence of the rollers introduces a highly disturbing, orienting factor.

They represent an obstacle for radiation and for the air streams as well, which are responsible for convection heating.

In other words, if they were not so indispensable, we would never use them.

Now let us examine what they do.

The schematic shows a slab «resting» on three little bars, of length L, height S, and width X. These are shown in red. The same can be imagined in the other direction; they are coloured green.

The slab is now heated from above and below. As far as the top is concerned, the situation resembles those described previously. Under the piece, however, lie the rollers, **the first dissymmetry**

The slab is no longer the same at both surfaces. Let us examine one sole bar, L.S.X. In this case, whether the bar promotes or hinders heating does not concern us. The bar tends to change in length to L ± L1-2 and its thickness changes as shown in the figure, which are small values but nevertheless always present.

We should remember that the slab is not touching the rollers. The differentiated deformation in length L ± L1-2 is mostly hindered by the remaining central part of the body, while the deformation arising in thickness can freely develop.

The same contrast, in length, affects the lengthwise deformations of the bars along their points «on» the rollers.

The result of all this is that the slab, whether differently heated or not at the two surfaces, **deforms more easily in the advancing than in the transverse direction.** The presence of the rollers therefore gives rise to dissymmetry in edge curvature, forming equal pairs of values for the sides, and the front and rear of the piece.

Figure 15 schematically shows these different deformations. Having the same dimensions, the sides will be more deformed than the front and rear of the slab.

We shall now let the rollers support the piece to see what happens. The actual kiln situation is thus approached ever more closely. To explain this further requires renouncing, in part, what the highest technical rigour would demand, and adopting simpler illustrative examples.

We shall not consider the slab as a small flat or curved piece, but as being almost rectilinear. Only a few slab-roller reciprocal positions will be examined. As stated in the foregoing, the important thing is to set out concepts.

The weight factor is taken into consideration.

Figure 16 illustrates, in this general case, that no sooner does the piece tend to deform for thermal reasons in a concave direction, do stresses appear that are capable of a certain self-straightening effect at those points where **the stresses exceed the ones required to plastically deform the material.**

The simplest case is that of the concave slab resting on the roller in its lengthwise direction. The induced stress and moment are greatest at the centre point. The value of the stress is - K L≤/S. **It increases with length squared and is inversely proportional to thickness.**

Please note the term: L^2/S, we shall be coming across it on several occasions.

Observe that for a tile of 15cm X 15cm X 0.5cm a relative value of 450 is found, whereas for a tile of 30cm X 30cm X 0.8cm the value obtained is 1125. The same figure also shows that the same curvature considered at the rollers, in the lengthwise direction of the kiln, arranged with a spacing p, yields two main values:

At the roller: $-K/S\ (L - p)^2$ (A)

At the central position: $K\ L/S\ (2p - L)$ (B)

As p is always positive, the value (A) will always be smaller than the foregoing case, while the stress at the central point will be proportional to (2p - L).

That is: when p = 0.5 L, the moment and the stress at the central point are null. The self-straightening effect is null. When L increases, with constant p, the value (2p - L) becomes negative and the effect is enhanced.

We can therefore say that the effect or capacity of self-correction is greater for the advancing sides than the other sides.

Remember too, that we have always been assuming a slab of equal sides.

It is quite interesting to see what happens in rectangular formats.

Let us look at a tile of 15cm X 20cm X 0.5cm. We will have:

Front - rear: 450k (Side 15)

At rollers: 450k (Side 20)

At rollers - centre: 400k (Side 20)
quite similar values.

Whereas a size 20 cm X 30 cm X 0.7 cm gives:

Front - rear: 571k (Side 20)

At rollers: 892k (Side 30)

At rollers - centre: 857 (Side 30).

The phenomenon is inverted. The correcting effect is now greater in the lengthwise direction of the kiln, as a consequence of considering a size with different side lengths.

On the other hand 20/15 = 1.33 and 30/20 = 1.5. The rectangular sizes, with a side ratio exceeding 1.33 are in fact those requiring most attention.

Figure 16 also shows the opposite case, when the slab, always for thermal reasons, tends to deform convexly.

Just as before, the correcting effect, with same side lengths, is greater in the advancing sides (front-rear).

The schematic in the figure exhibits a constant configuration for the advancing sides, always the same at each moment, while the drawing corresponding to the other sides shows one sole, very particular, position. The result is quite graphic.

A first conclusion is obligatory. (Always with same side lengths).

Whether it is because of the **GRID EFFECT** (as we have termed it) of the rollers, or as a result of the combined **weight-induced thermal deformation,** the sides parallel to the kiln are always more deformable than the transverse sides. However, it should be taken into account that the correcting effect, when it arises, because it may not occur when L is small, S large, and in materials with high porosity, **always gives rise to deformations having a different curvature radius.** The worst ones.

This is a prime reason for not exaggerating the use of different firing conditions above and below the setting plane.

We have rollers because we cannot do without them, so that the conditions should therefore be different but only to reduce to the utmost the unwanted presence of the required supports.

In the opposite case, the operational flexibility of the kiln (in the sense that it could be considered as two heat-treatment machines, one on top of the other), will end up by reducing, though never completely eliminating, defects that can be removed by other means. **An error should not be corrected with another error.**

We shall be coming back to this point later on.

Let us now examine cooling. Let us assume our slab has been suitably, uniformly fired, and has the targeted mechanical properties. Cooling takes place using the most common method, air-quenching. Quite easy. Is this really so? Let us have a closer look.

Figure 17 gives us the points of reference used in this new example, using the initial computer.

Figures 18 and 19 show the temperatures at each point in function of elapsed time (in seconds) for two slabs measuring 30cm X 30cm X 1cm and 30cm X 30cm X 1.5cm.

The conditions were as follows:

Density: 2100 kg/m^3

Specific heat: 0.25 kcal /K°C

λ = 1 kcal/m h °C at 600°C

λ = 1.5 kcal/m h °C at 1200°C

α = 40kcal/m≤ h °C

And in this case **without the previous assumptions,** the **suitably** fired material is:

Uniform

Thermally inert

Ponderally stable

and it is the calculation method that lies closest to the actual situation. Let us examine a slab of 30cm X 30cm X 1cm (Fig. 18). The temperature difference between body centre and surface centre is about 40˜50°C and keeps sufficiently constant.

The difference with regard to the edge is, however, already 140˜150°C just after 45 seconds, and remains like this at temperatures lying at half the initial temperatures.

These differences are quite striking, and it is easy to understand, on observing them, why tiles exhibit dark edges, like the frame of an imaginary painting, in the first step of the cooling stage. It is also clear why it is not difficult to break tiles during cooling. Contrary to the first example, in this case hindered edge deformation in respect of the centre, arises as a result of these **same tensile stresses.** Notice furthermore what the following expression means: when the piece is at 573°C cooling must be performed more carefully. 573°C? Where?

It should be mentioned that this slab has still been cooled alone. **We have up to this point been studying a single slab.** Why?

To more clearly demonstrate the great advantages to be had in preheating, firing, and especially in cooling, by placing the slabs next to each other. **As closely as possible.**

This is of much greater importance than might be imagined. Many many defects are amplified as a result of «carpets» of imperfect tiles that lack uniformity. On the other hand they are not easy to obtain, unless use is made of suitable roller movement, and extreme manoeuvrability. By doing this, the differences at the edges will decrease, except for the side edges at the ends of the setting.

The vertical air streams are only caused on these by the different conditions that have already been mentioned and criticised. It also happens because not only have we ideally arranged one slab next to another one, but also because we have closed it within a physical space. **Our kiln.** We have followed this imaginary route, in order to remind ourselves, whenever regulating an industrial kiln, of how we would do it in function of the elementary demands of the materials to be treated.

Until now, in one way or another, we have only fired biscuit or porcelain tile. We must now glaze our slab, on one surface only, the top.

Another dissymmetry is thus introduced; heating the top surface of our tile, (now it is a tile), **is also conditioned by a part of this new element: the glaze.**

And we all know how right and necessary it has been.

This has certainly been the case to date - whether it still is doubtful, at least to a certain extent. As we were saying: it is necessary to heat, above all, below the setting plane in order to reduce and/or contain the effects arising from the gases produced by firing, through the top surface of the tile and the glaze. This because the glaze starts fusing, that is, loses permeability, before these gas outflows cease.

We had agreed to stick to simple language. Nowadays, bodies are more or less the same, but glazes are however, quite different. Current glazes (and we are in a country that produces them), have initial fusion starting temperatures that are much higher, and the glazes remain porous and permeable up to these same values. Their correct use, accurate functioning of the body and firing cycle, reduce the need described above in its minimum terms, to the full advantage of firing uniformity, which is real and not fictitious, and final planarity. (Besides any considerations on the absolute value of maximum temperature).

Let us go back just a moment to Figure 9.

It is easy to imagine where any remainder of this material, which has not yet broken down, may be hidden in the thickness of the tile, preheated as described previously.

(We do not have enough time unfortunately to go into this interesting subject, since our main objective is to deal with the dilatometric aspects of this new glaze-body bilaminate.)

We said bilaminate. Our original slab has become more complex. To this body, which provides mechanical strength, has been applied a second layer of different material that contributes aesthetic characteristics and compactibility.

Each material, body and glaze, has its own dilatometric characteristics and temperature-time diagrams. **Which are not the same.** Because they cannot be, and if they were, it would not be correct.

Let us examine what happens in these bilaminates, keeping in mind that the objective is the final geometrical result.

Studies on the stresses and reciprocal influences of the two parts in firing and cooling have been developed in considerable detail on other occasions, even in former editions of this meeting. We refer any interested people to these for further information. We will examine what happens in our machine, the kiln, always in function of the planarity of the product.

Figure 20 shows the dilatometric aspects of a body (C) and a glaze (E). Point Ts represents the temperature at which the two parts of the bilaminate become one sole piece, which has been called the point of fit. **It simply means that the two different materials are bonded together.** The figure shows a final tile that would be perfectly flat. This is because independently of the form of the two expansion curves, the two points Ts and the abscissa-ordinate origin coincide. The theory says in this respect, that the deviation in a deformed tile (concave-convex), as a result of glaze-body fit, obeys the equation:

$$F = L^2/S \; Kr \; AC$$

Where Kr is a function of the thickness of the two components and the corresponding moduli of elasticity, AC is the difference between their free shrinkages until reaching ambient temperature. One could write:

$$F = KL^2/S \; AC$$

In the case shown, AC = Zero and therefore F = 0. **Flat tile.** Note that in this case as well, the term L≤/S appears. It is to be recalled that we are now talking about deviations whereas we were previously dealing with stresses.

Figure 21 exhibits the most common case. At temperature Ts, both parts have the same length, but at ambient temperature, the glaze would be longer than the AC value, the body being smaller than this value. This means a convex tile, which is obviously under stress and with a deviation evaluated by the above formula:

$$F = K \cdot L^2/S \cdot AC.$$

Figure 22 shows a different case. The two expansion curves are the same as in Figure 20, but the point of fit or bonding are obtained when the glaze and its interface are at temperature Ts, while the body has a higher temperature. This is a typical case resulting from fast cooling.

We can see how, for one reason or another, we have been examining flat or convex final products (not concave products for obvious reasons), with a deviation = $K \cdot L^2/S \cdot AC$ **but with constant curvature. With a single radius.**

However, actual industrial practice tells us that more complex deformations are often encountered, not having a single radius, but with composite curvatures, even contrary ones. A typical case is that of a tile with convex central curvature, and concave edges. A classic and quite common case.

¿What is the cause? The **principal** cause is not the grid effect of the rollers, or differing AC expansion of body and glaze. These two factors give rise to pieces with almost uniform curvature. The origin of differentiated curvature lies in **the self-correcting effect described previously and ... the cooling of Figs. 18-19, or the effect of both these causes.**

Looking at Figs. 18-19 again, let us imagine what happens from the point of view of temperature of fit Ts, taking into account the case of Figure 22. Obviously, very fast cooling, with large, rectangular tile sizes and limited thicknesses can give rise to, or increase deformations like those mentioned.

The conditions of fit are clearly different at the edges, near them, and at the centre of the body.

Getting back to the self-correcting effect. Is there any relationship with the glaze-body coefficients of expansion?

Quite likely. With the glaze, certainly.

Because without the glaze, without its «permeability type» needs, and dilatometric differences with regard to the body, **there would be no reason for it**. There would be no reason for such different heat-treatment conditions in firing under and above the setting plane.

What really happens, is that generally, it is attempted to control or reduce a defect caused by an AC giving rise to too much convexity, with a firing curve whose aim is to obtain more or less concave tiles, in the final firing stage, before cooling.

This is like saying: concave + convex = flat.
What happens however, if by:
Concave we mean: concave + self-correcting effect, and by
Convex we mean: convex with different curvatures owing to excessive cooling.

The result can easily be imagined.

There is now just one question we must ask ourselves. How can we decrease this kind of deformation?

By working in two directions. The manufacturer should use current facilities better, and the machinery producers should try to improve the machines even further.

The manufacturer should try to remember the imaginary route we have followed, and try to keep to it as closely as possible, according to the following guidelines:

- A set of tiles, forming the so-called «carpet of tile» must be formed, which are perfectly aligned. It is much more important than might be imagined, Figure 23 is quite indicative. It represents a tile in a row.

- The glaze-body fit must be studied in detail, and not just the dilatometric fit but the general fit. This is so as to allow the two surfaces of the tile to be heated, without any other effects than those arising as a result of the rollers. It is useless to refer here to the point of fit, as the factories only have available the coefficient 3 between 30°C and 300°C, and at times even this is not available. **It is perfectly useless, even conceptually.**

- Attention must be paid to size - thickness - roller spacing, product typology, remembering the expressions used and attempting to «reconstruct», moment by moment, the planarity of the glazed or unglazed tiles.

- A firing cycle must be chosen, which enables **all the material** to be perfectly fired, taking into account the effects of the different raw materials, and cooling, attempting not to give rise to stresses that will, sooner or later, tend to decrease by themselves, outside and/or inside the packing boxes, adding one defect to another. A 25 min cycle may be much more suitable than a 35 min one. It all depends on the materials involved.

- There should be a greater knowledge of the kiln, in all its details and possibilities. **And one should not be afraid of it. This happens all too frequently.**

- The machinery producers must, in turn, devote more attention to some points, which were referred to indirectly above.

- Symmetrical preheating must be provided, above and below the setting plane, except for certain specific cases. Minor differences are permitted, but sometimes these are exaggerated.

- The kiln must be fitted out with special burners, of one kind or another, capable of further improving temperature constancy in the relevant section. Kilns are becoming wider and wider. Probably already too much so for some typologies.

- The first stretch of the cooling section must be modified and/or reconsidered. My own opinion is that a conceptual revision in this respect would be required.

- And finally, we must all try and bridge that enormous (this is no exaggeration) gap, between what is said at meetings like QUALICER, and what is in fact found much too often at the actual factories.

It had been my intention to give an example concerning single-fired wall tile, but time does unfortunately not allow this. We shall leave it for another occasion. However, everyone can do this on his own. It is possible to do so by starting at Figure 3, paying particular attention to the last part of the diagram. Thank you for your attention.

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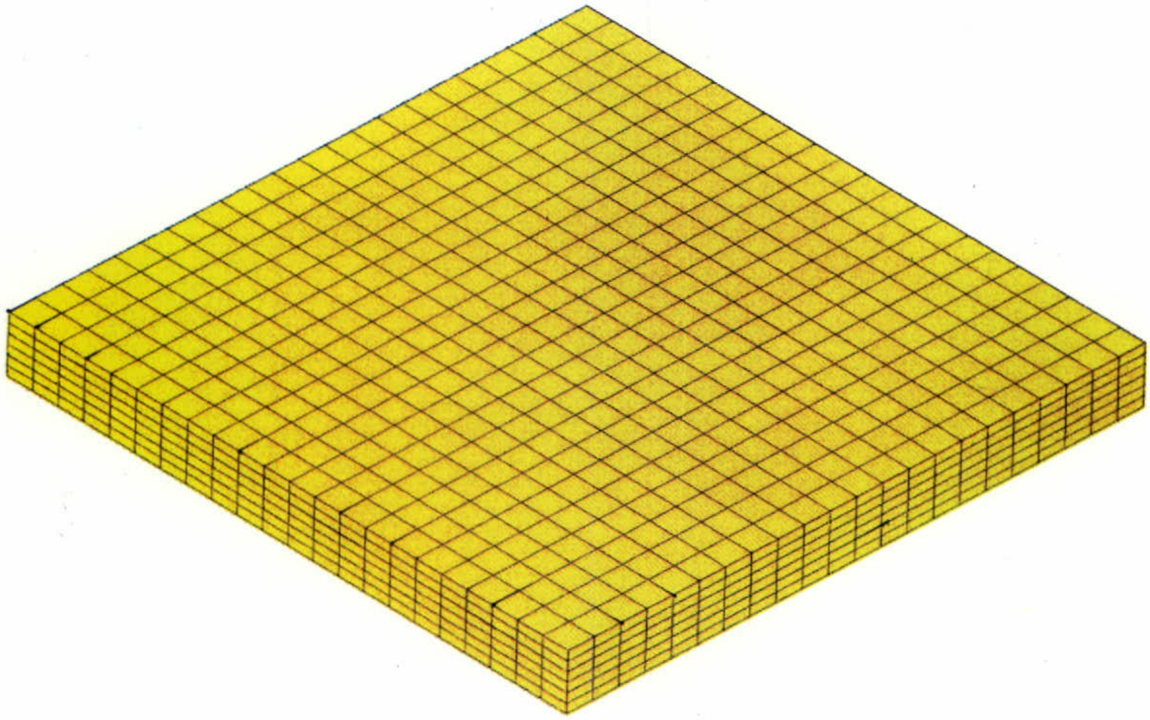

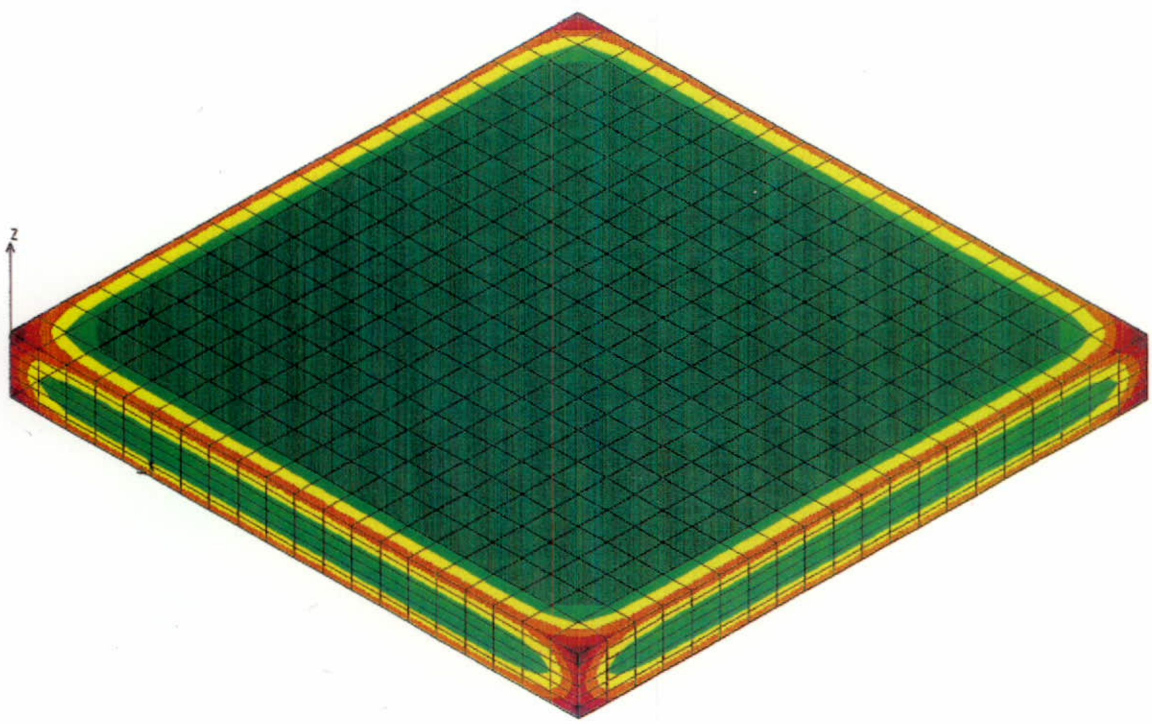
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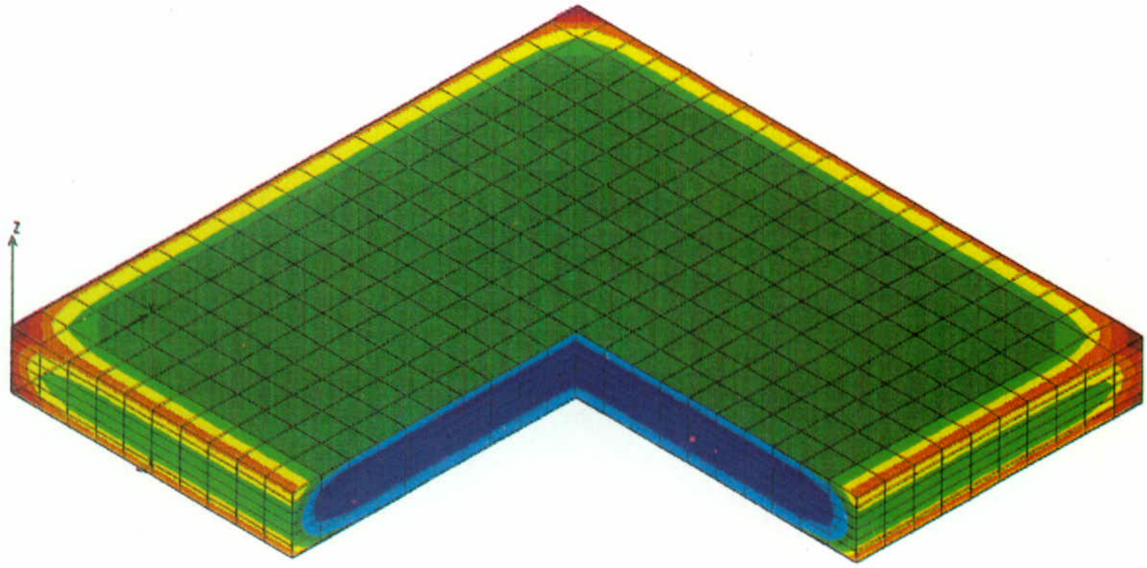

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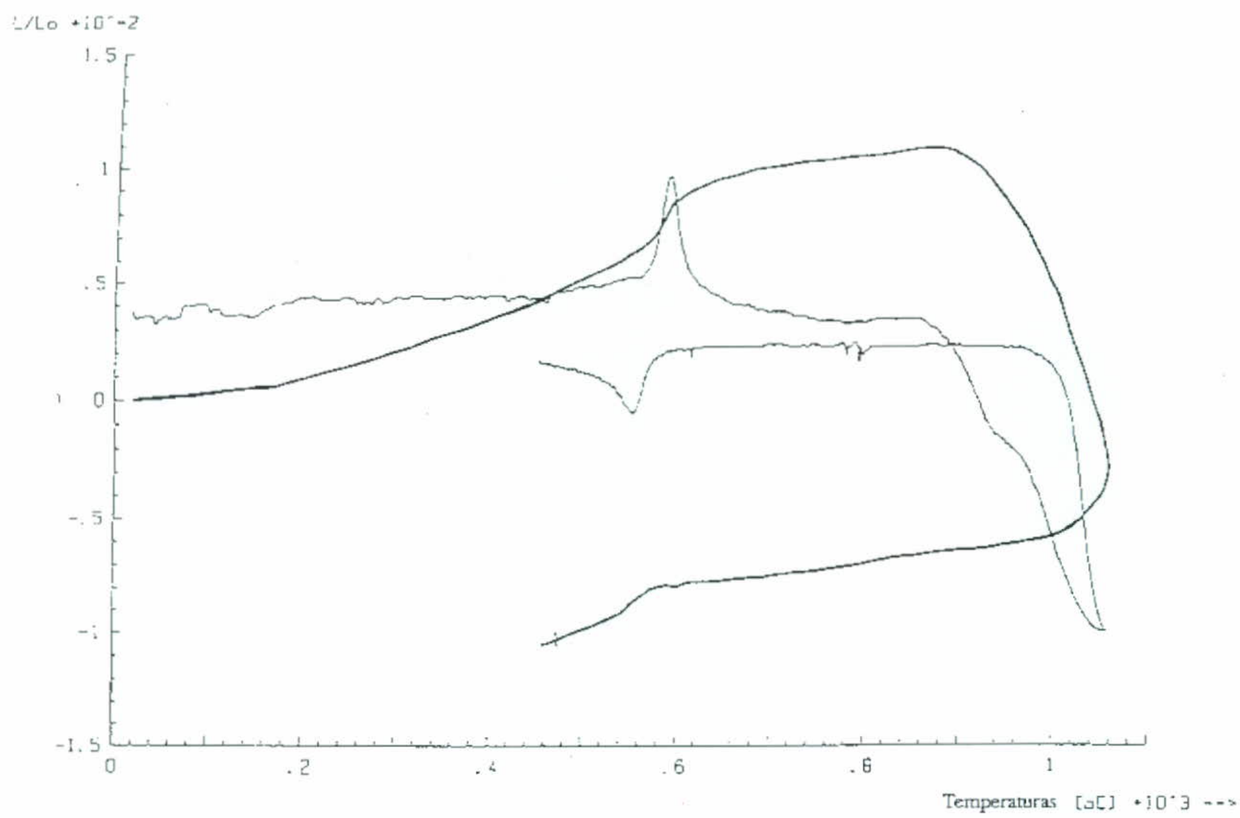

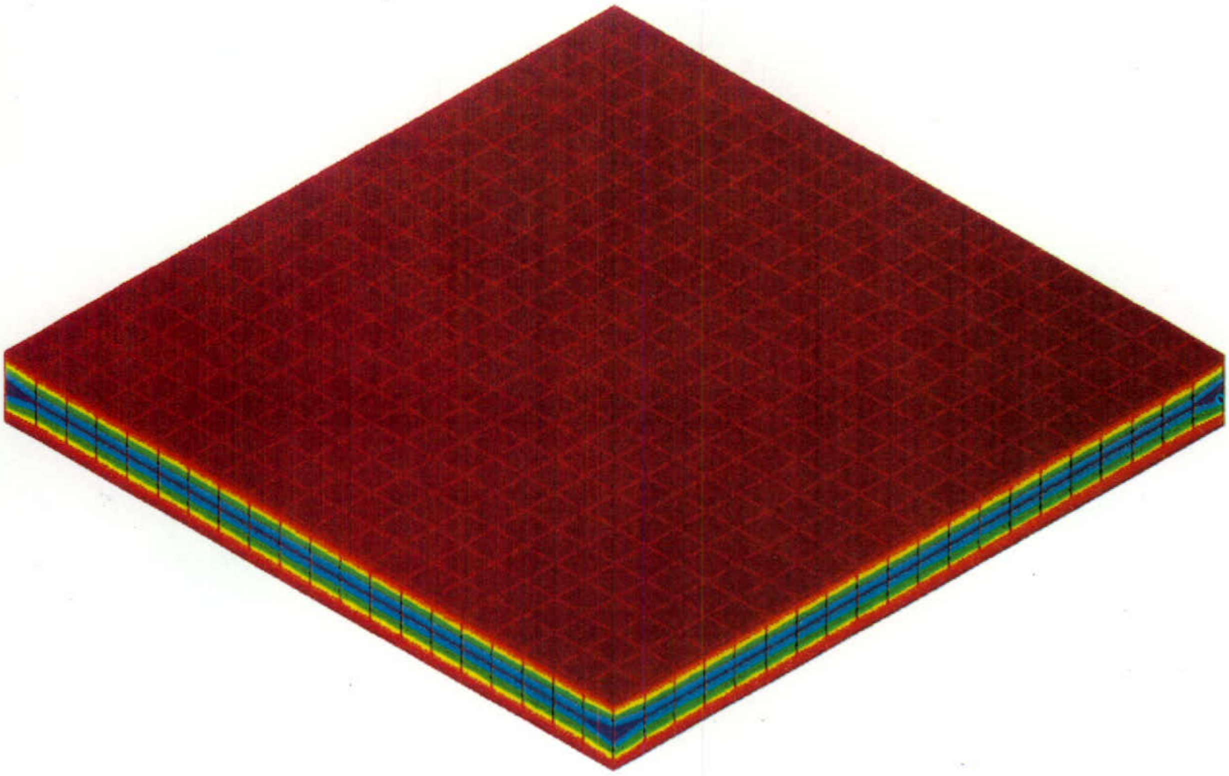

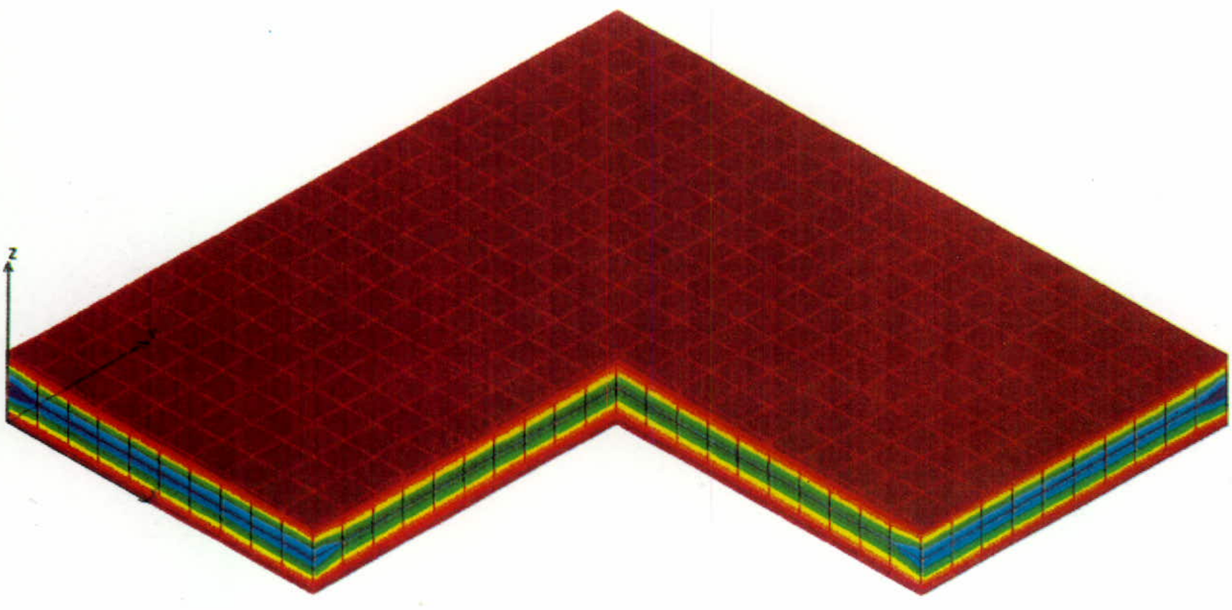
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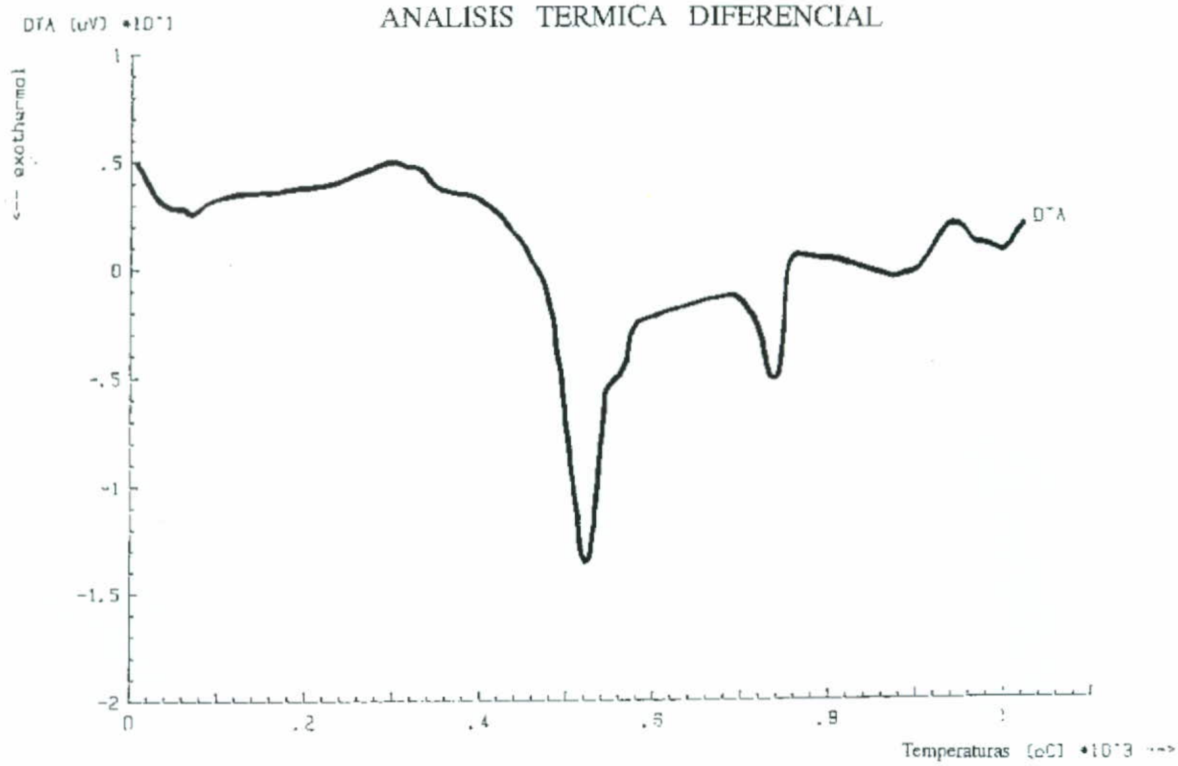

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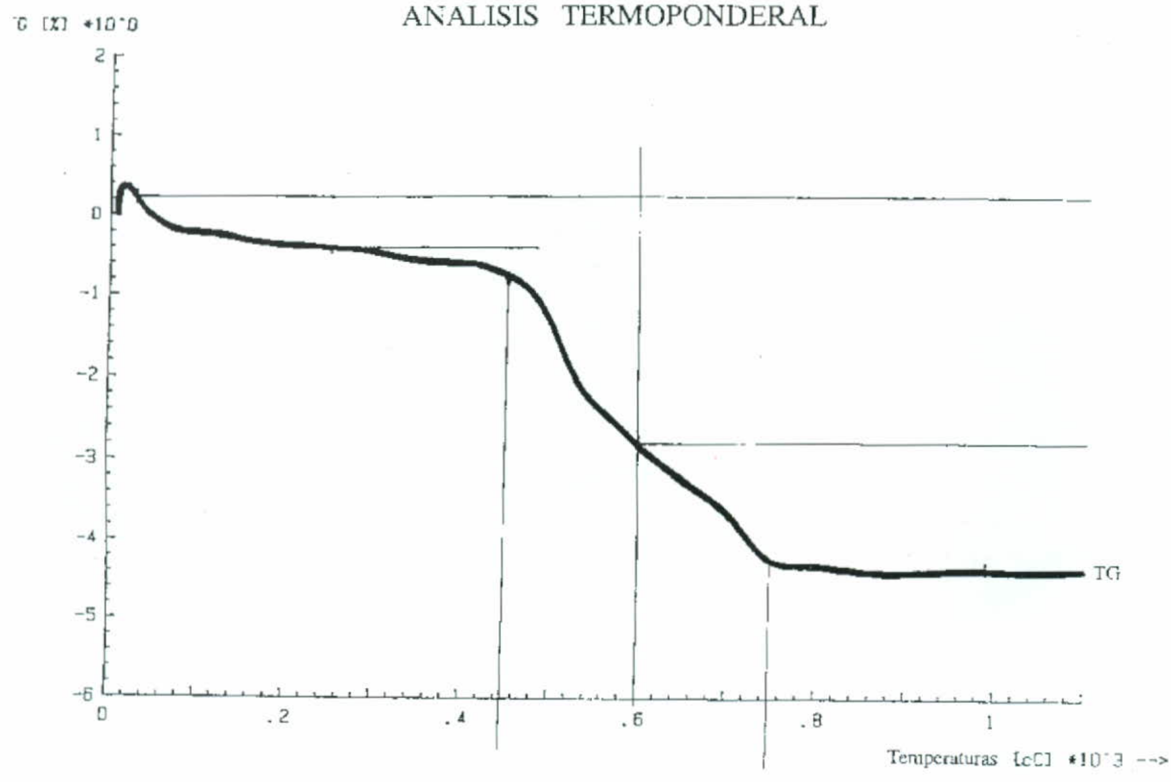
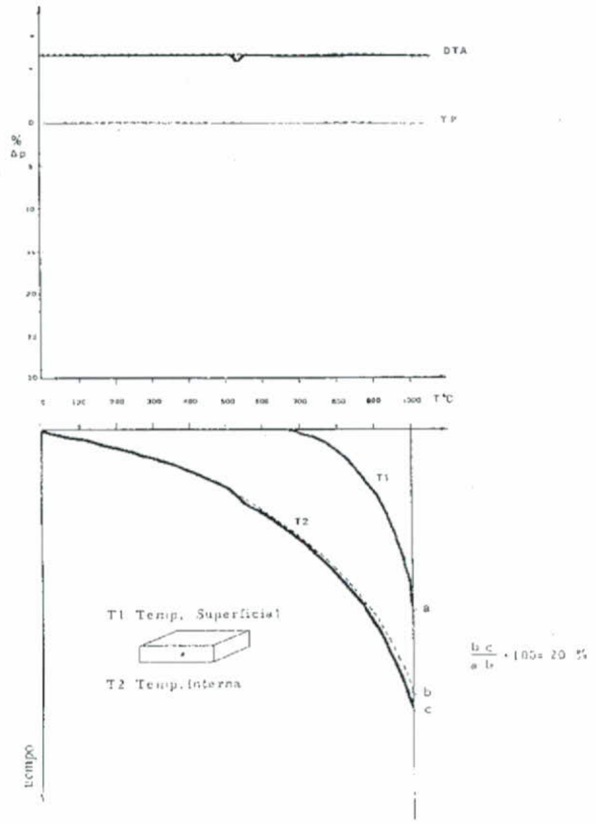


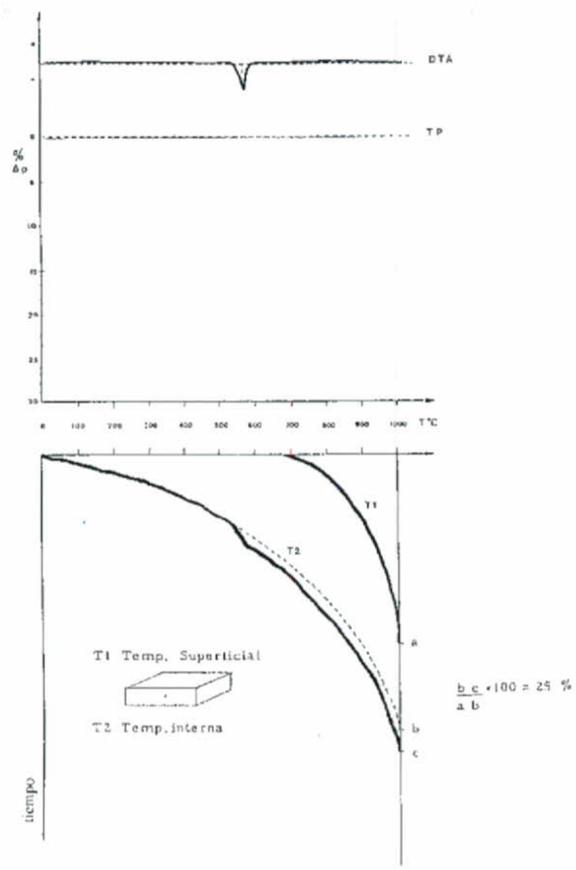
FELDESPATO

FIG.7



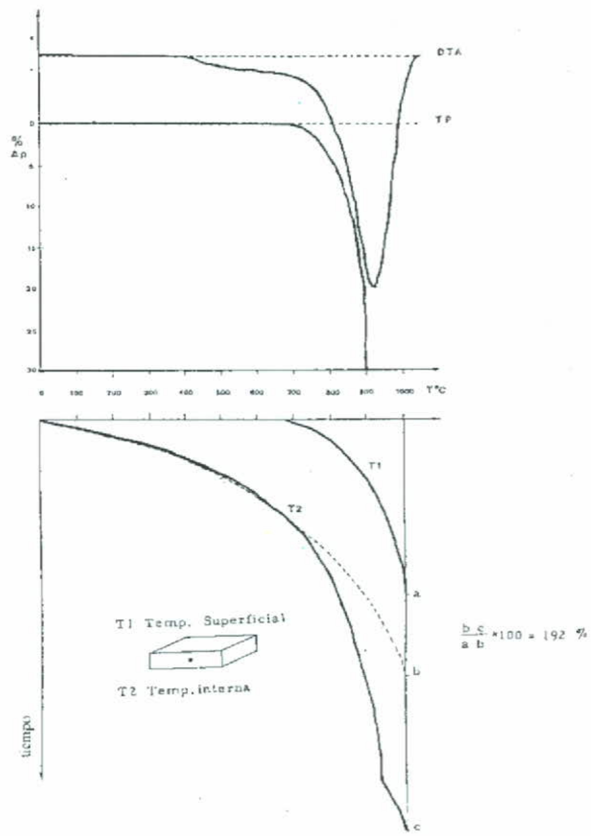
CUARZO

FIG.8



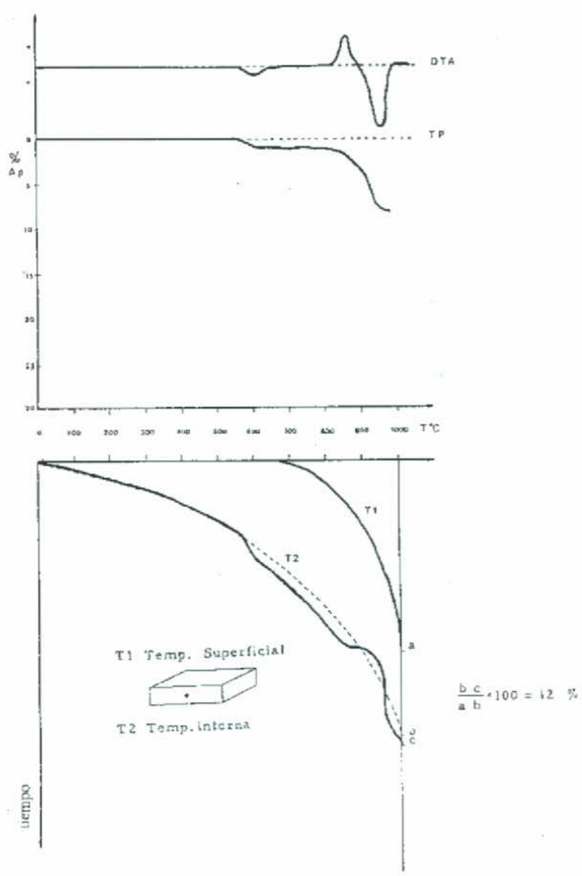
CARBONATO DE CALCIO

FIG.9



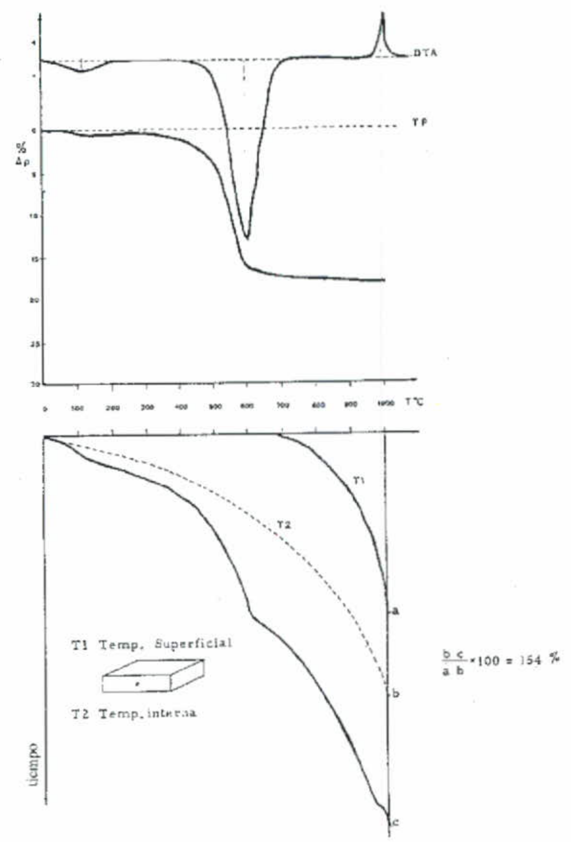
TALCO

FIG.10



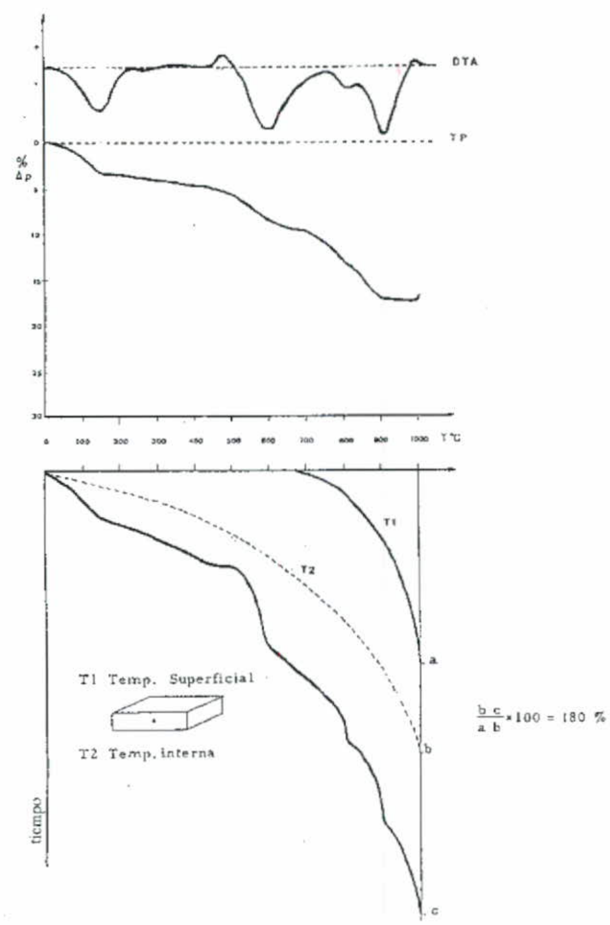
CAOLINITA

FIG.11



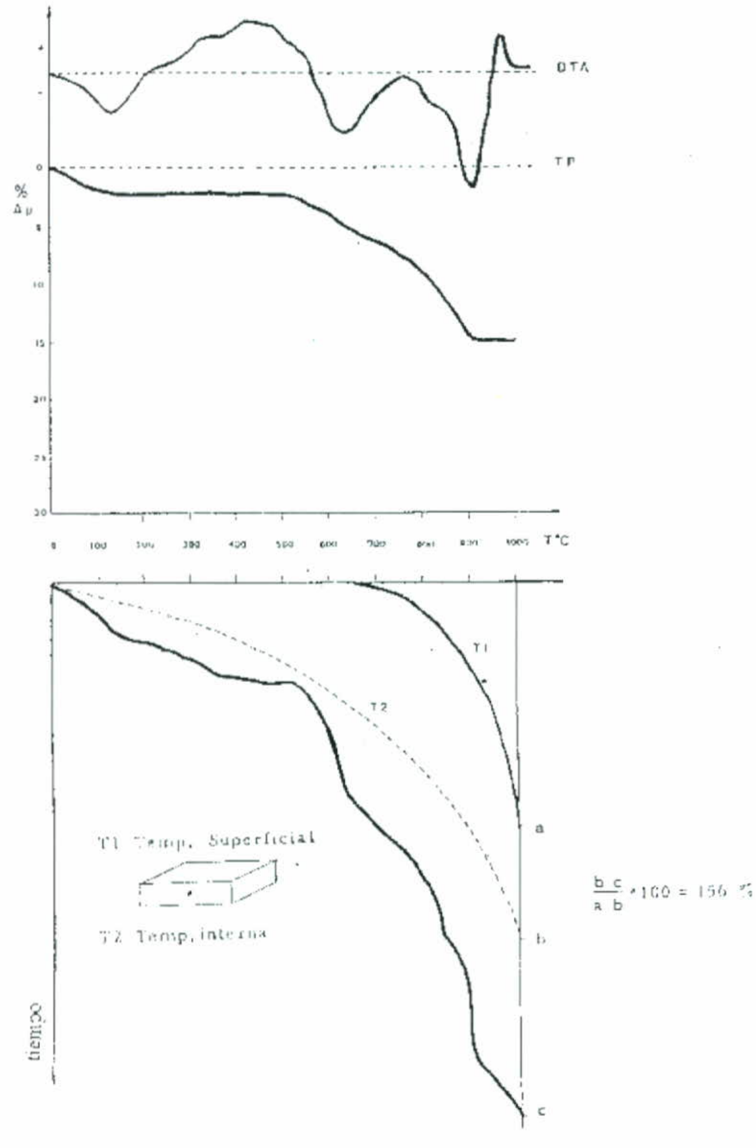
ARCILLA

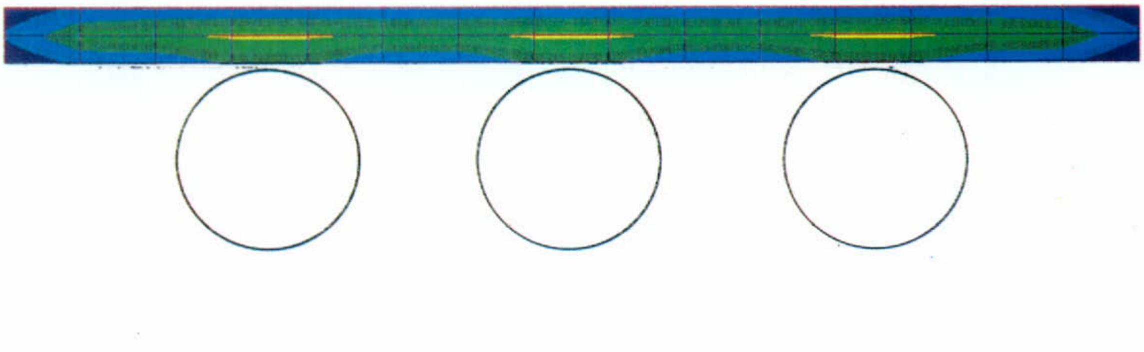
FIG.12



EMPASTE

FIG.13





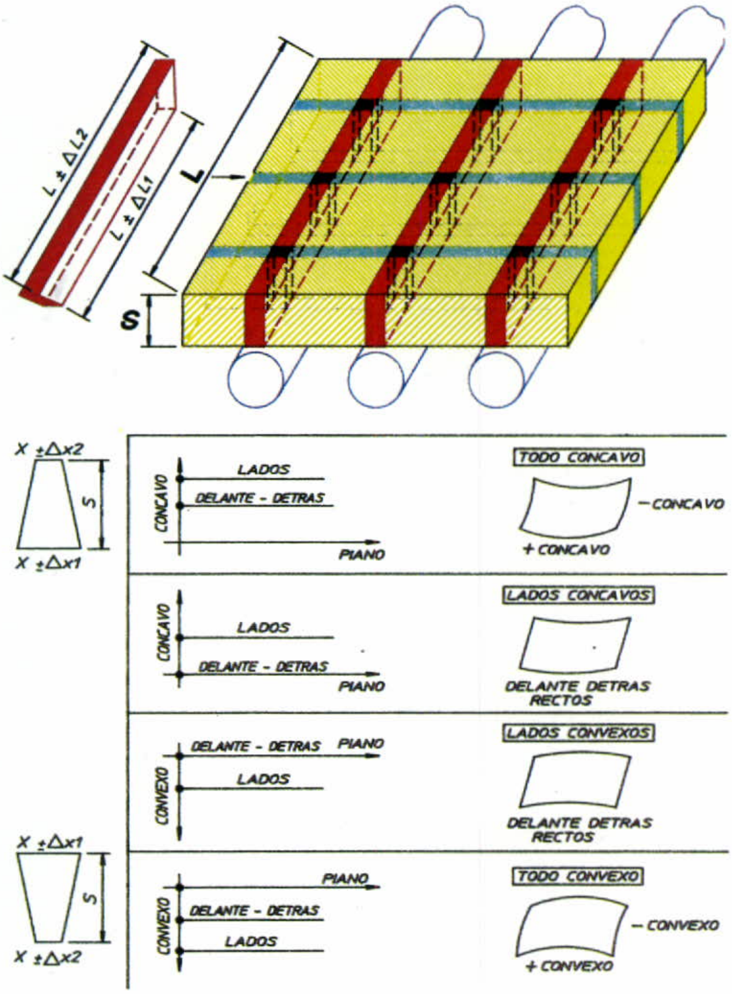
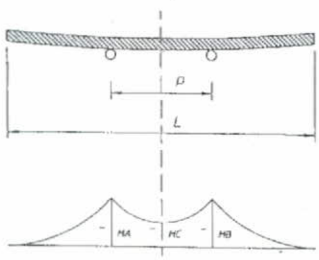


FIG. 16



PESO PLAQUETA = ESPESOR = S

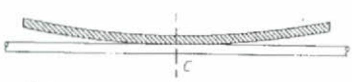
$$MA = MB = -\frac{S}{8}(L-p)^2$$

$$\sigma A = \sigma B = -K\frac{(L-p)^2}{S} \qquad (K = 6/8)$$

$$MC = \frac{S\,L}{8}(2p-L) \qquad \sigma c = \frac{K\,L}{S}(2p-L)$$

(LADOS PARALELOS)	15 cm x 15 cm x 0,5 cm	σAB = -200 K	σC = -150 K
EJEMPLOS : PLAQUETA	20 cm x 20 cm x 0,7 cm	σAB = -321 K	σC = -285 K
PASO = 5 cm	30 cm x 30 cm x 0,8 cm	σAB = -781 K	σC = -750 K

(LADOS DELANTE - DETRAS)

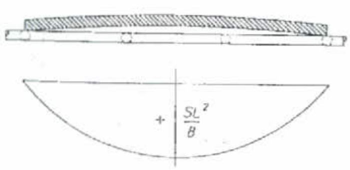


$$p = 0$$

$$MA = MB = MC = -\frac{S}{8}L^2$$

$$\sigma A = \sigma B = \sigma C = -K\frac{L^2}{S}$$

EJEMPLOS : PLAQUETA	15 cm x 15 cm x 0,5 cm	σ = 450 K
	20 cm x 20 cm x 0,7 cm	σ = 571 K
	30 cm x 30 cm x 0,8 cm	σ = 1125 K

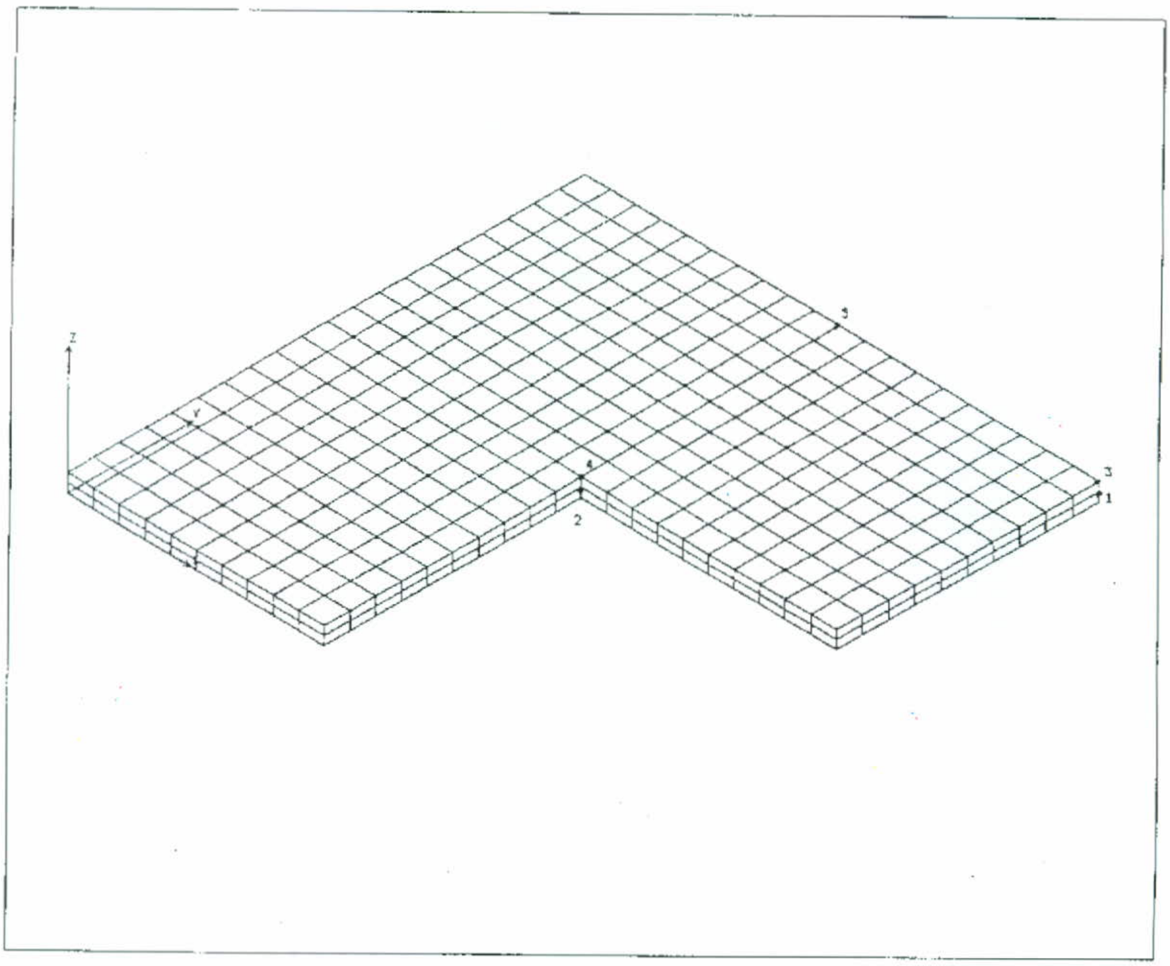


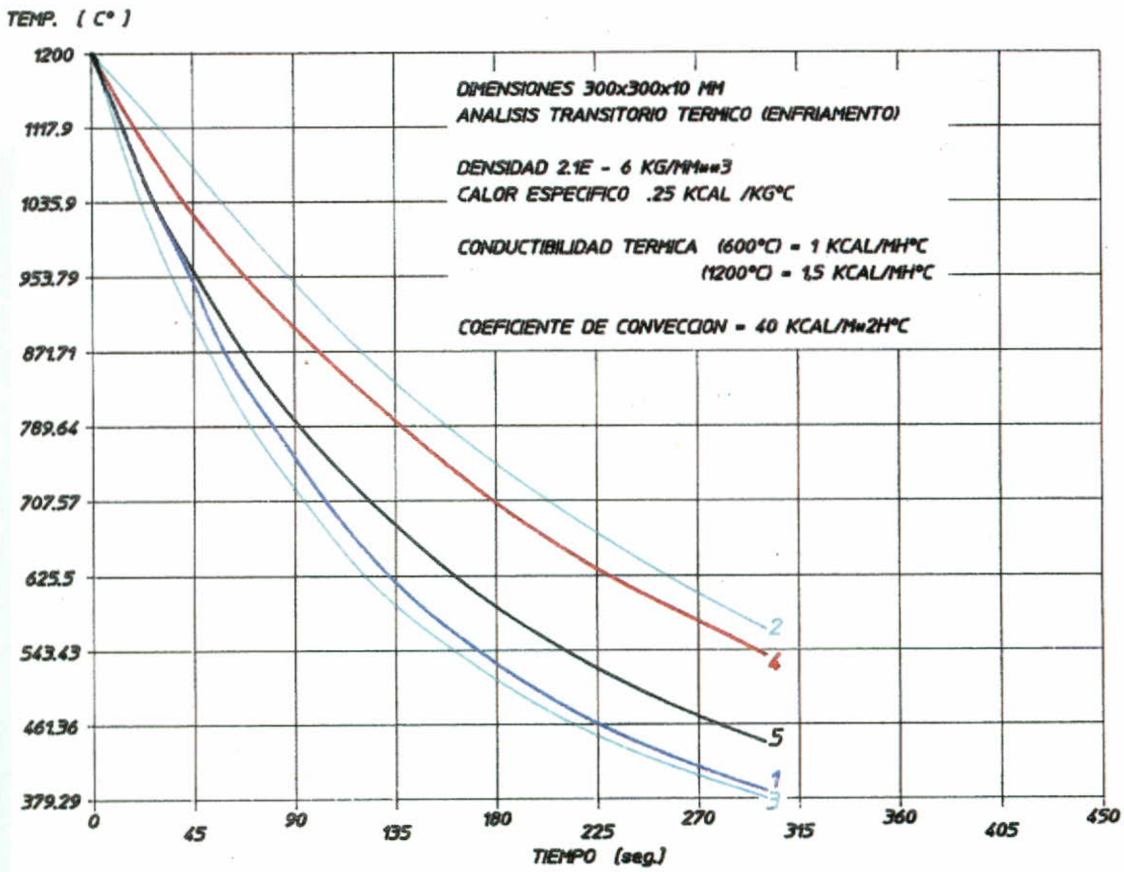
CASO $p = L$

$$MA = MB = ZERO \qquad \sigma A = \sigma B = ZERO$$

$$MC = \frac{SL^2}{8} \qquad \sigma C = \frac{KL^2}{S}$$

15 cm x 15 cm x 0,5 cm = 450 K
20 cm x 20 cm x 0,7 cm = 571 K
30 cm x 30 cm x 0,8 cm = 1125 K


Z
Y
X
1
2
3
4
5


TEMP. (C°)
1200
1117.9
1035.9
953.79
871.71
789.64
707.57
625.5
543.43
461.36
379.29
DIMENSIONES 300x300x10 MM
ANALISIS TRANSITORIO TERMICO (ENFRIAMENTO)
DENSIDAD 2.1E - 6 KG/MM**3
CALOR ESPECIFICO .25 KCAL /KG°C
CONDUCTIBILIDAD TERMICA (600°C) = 1 KCAL/MH°C
(1200°C) = 1.5 KCAL/MH°C
COEFICIENTE DE CONVECCION = 40 KCAL/M**2H°C
1
2
3
4
5
0
45
90
135
180
225
270
315
360
405
450
TIEMPO (seg.)

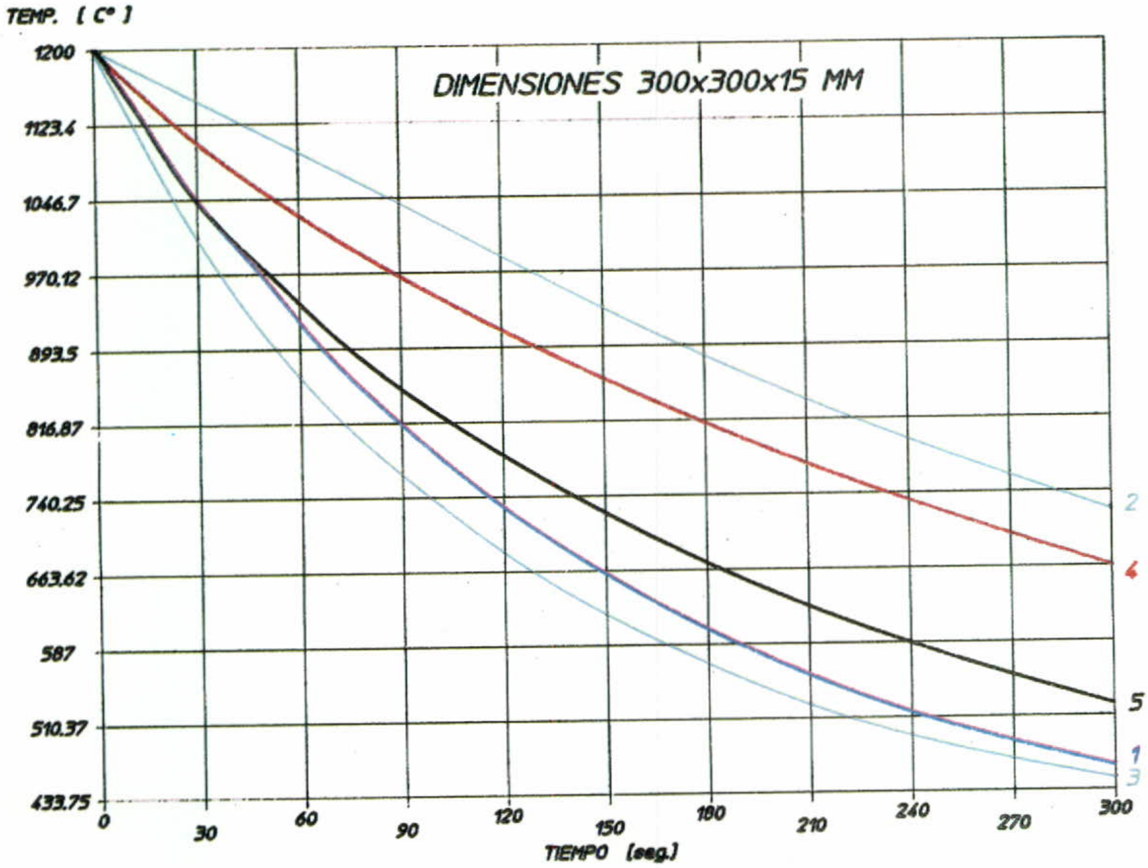

TEMP. [C°]
DIMENSIONES 300x300x15 MM
1200
1123.4
1046.7
970.12
893.5
816.87
740.25
663.62
587
510.37
433.75
0
30
60
90
120
150
180
210
240
270
300
TIEMPO [seg.]
2
4
5
1
3

FIG. 20

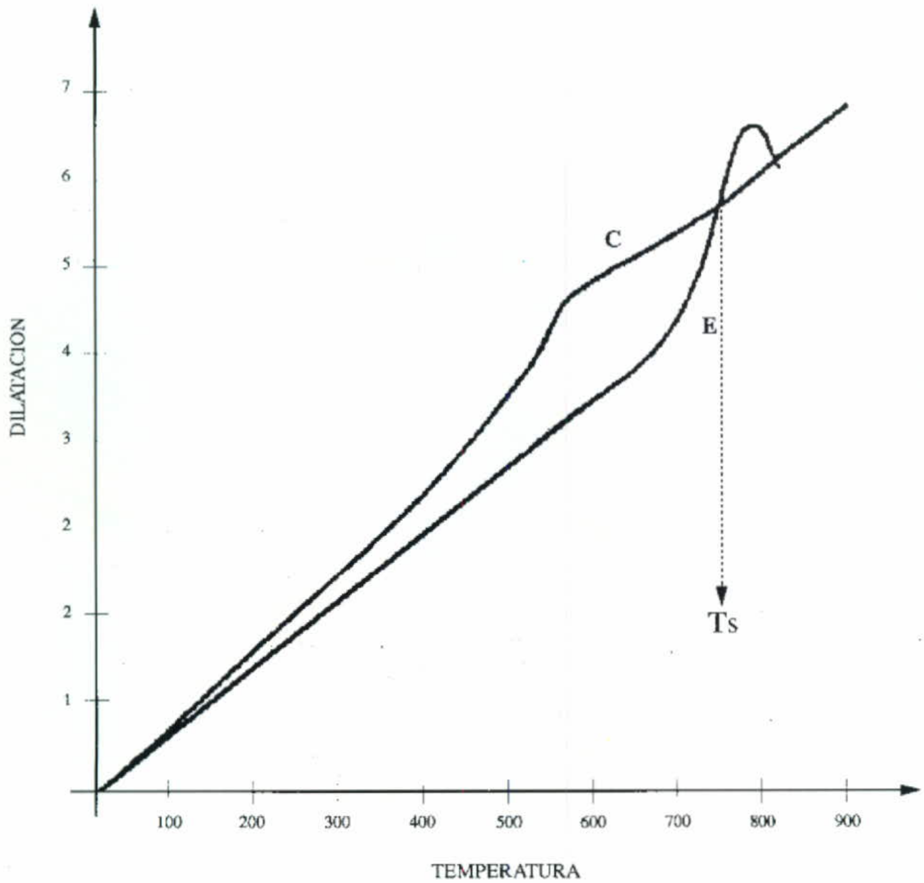
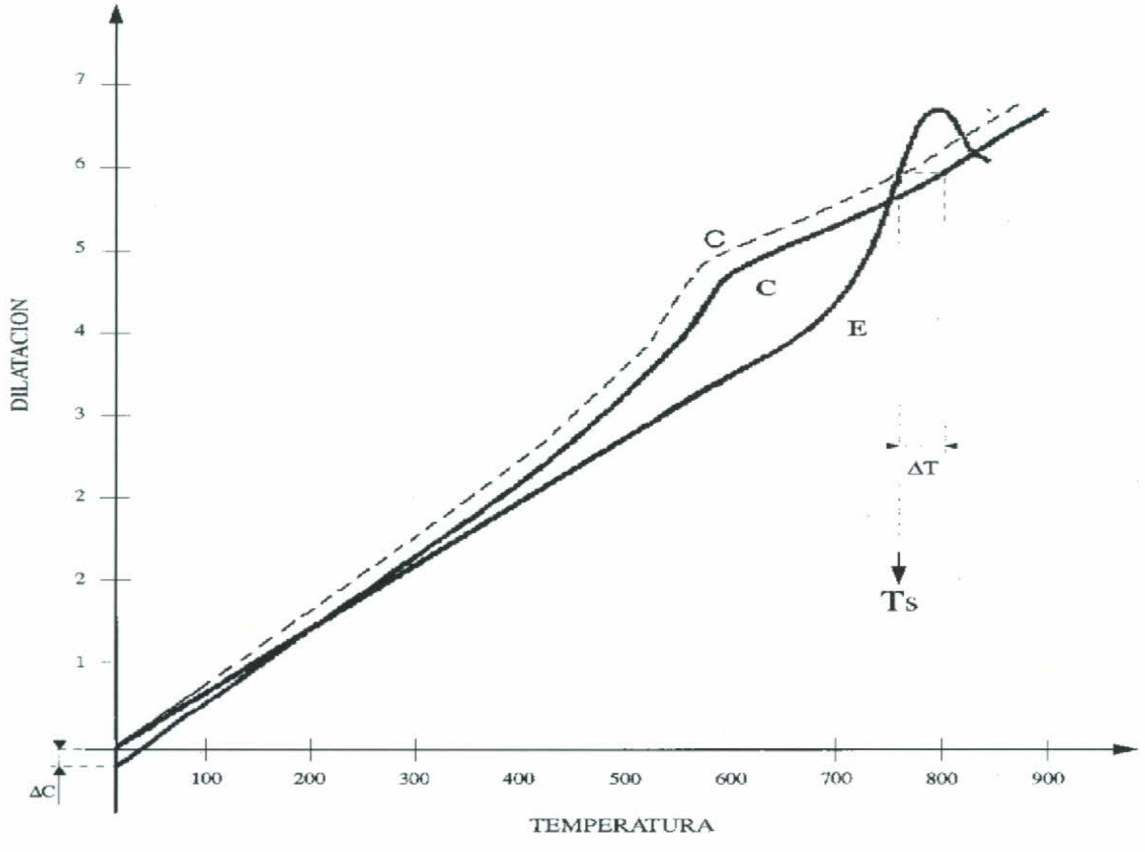

DILATACION
7
6
5
4
3
2
2
1
C
E
Ts
100
200
300
400
500
600
700
800
900
TEMPERATURA

FIG. 22


DILATACION
7
6
5
4
3
2
2
1
ΔC
C
C
E
ΔT
Ts
100
200
300
400
500
600
700
800
900
TEMPERATURA

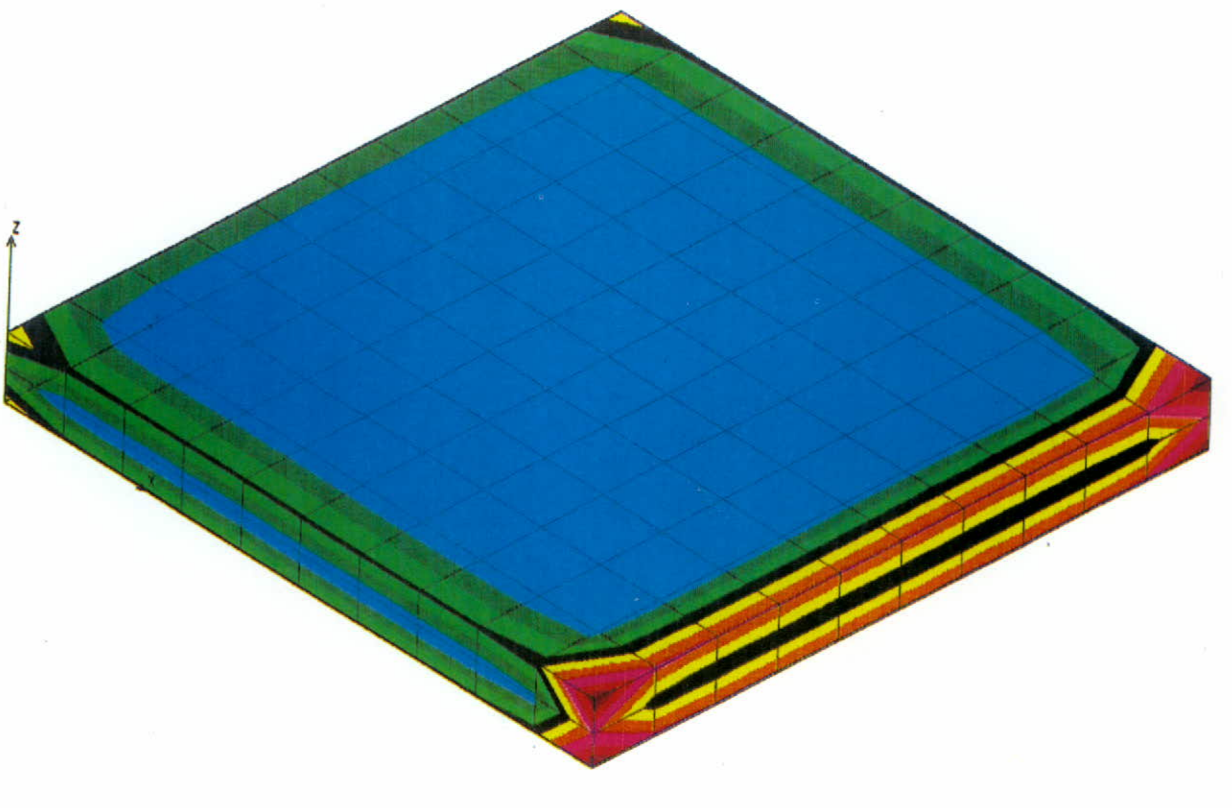


FIG. 21

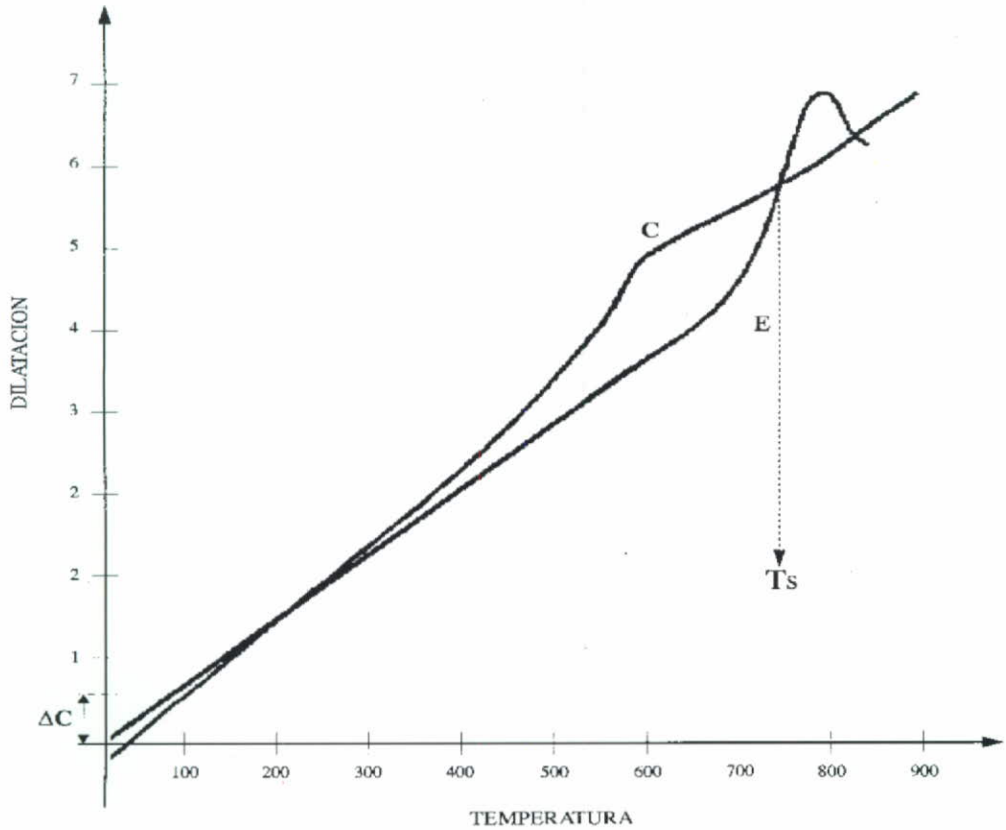
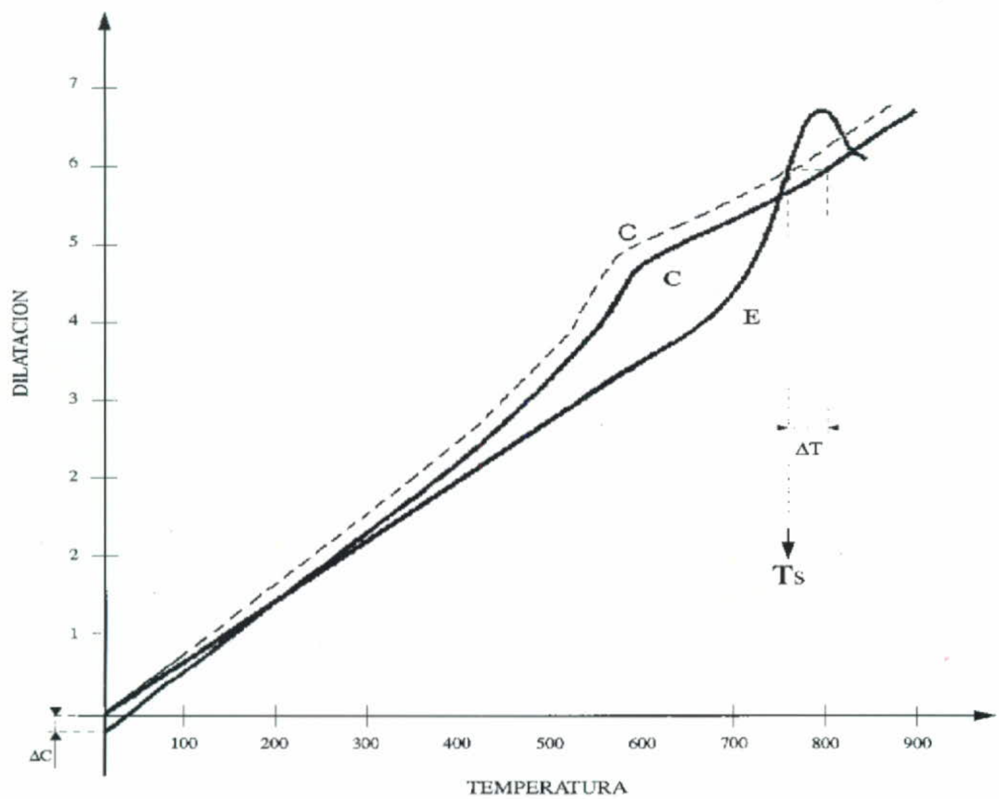

DILATACION
TEMPERATURA
7
6
5
4
3
2
2
1
ΔC
100
200
300
400
500
600
700
800
900
C
E
Ts

FIG. 22


DILATACION
TEMPERATURA
7
6
5
4
3
2
2
1
ΔC
100
200
300
400
500
600
700
800
900
C
C
E
ΔT
Ts