# Fire Research and Building

Pettersson, Ove

1971

LUND INSTITUTE OF TECHNOLOGY · LUND · SWEDEN · 1971
DIVISION OF STRUCTURAL MECHANICS AND CONCRETE CONSTRUCTION · BULLETIN 22

OVE PETTERSSON

# FIRE RESEARCH AND BUILDING

C I B 5 T H C O N G R E S S

"Research into Practice, the Challenge of Application"
at Versailles, France from 22nd to 30th June 1971

# F I R E R E S E A R C H A N D B U I L D I N G

Response Paper

## SWEDISH STRUCTURAL FIRE ENGINEERING RESEARCH IN PROGRESS

by Prof. Dr. Ove Pettersson, Lund Institute of Technology, Sweden

Lund, 1971

SWEDISH STRUCTURAL FIRE ENGINEERING RESEARCH IN PROGRESS

To my regret, Sweden has not participated in the important work of the CIB Commission W 14 in such an extent as must be required with regard to the necessity of an international coordination of the fire engineering research. Possibly, this situation can be explained by the fact that the Swedish activities within the field of fire engineering research are of a comparatively young date and that most of the results of this research work has been published in Swedish only.

In order to improve in some degree this unsatisfactory situation I have thought it suitable to complete the excellent paper, presented by Mr. J. F. Fry, by a response paper giving a brief outline of fire engineering research in Sweden, recently published or in progress. With respect to the general theme for the actual CIB Congress, this outline will be introduced by a summary survey of some characteristics in modern Swedish fire engineering design of load-bearing and separating structures.

## 1. Some characteristics in modern Swedish fire engineering design

Generally it is prescribed for a fire engineering design of load-bearing and separating structures that it is to be proved that the structures during the fire action are able to fulfil the functional requirements stipulated. For a load-bearing structure that means a proof that the load-bearing capacity does not decrease below the design load (or some other prescribed load), multiplied by a required factor of safety, during neither the heating period nor the subsequent cooling period of the process of fire development. For a separating structure the requirements stipulated mean that it must be verified that during the complete process of fire development no flames or hot gases will pass through the structure and that the temperature increase on the unexposed face of the structure does not exceed a specified value.

As concerns basic characteristics for the process of fire development, the current Swedish Standard Specifications permit the structural engineer to choose between three alternatives leading to different degree of accuracy and different amount of fire engineering design work.

One alternative is related to the internationally prevalent standard heating curve for the gastemperature of the fire compartment combined with a cooling period, specified by a linear rate of temperature decrease of 10 deg C per minute.

A second, more differentiated alternative is characterized by a gastemperature-time curve ($\vartheta_t$-t) for the heating period, which depends on the opening factor $A\sqrt{h}/A_t$ of the fire compartment according to Figure 1, where $A_t$ = the total area of the surfaces bounding the compartment ($m^2$), A = the total area of the window and door openings ($m^2$), h = a mean value of the heights of window and door openings (m), weighed with respect to each individual opening, and $\vartheta_o$ = the gastemperature at the time t = 0. The length of the heating period or the fire duration T (min) is given by the relation

$$T = \frac{qA_t}{25A\sqrt{h}} \qquad (1)$$

where q = the fire load, defined as the corresponding heat value per unit area of the total surface bounding the compartment (Mcal per $m^2$). For a cooling period is specified, as in the first alternative, a linear rate of temperature decrease of 10 deg C per minute, if not some other characterization can be proved to be more correct. This second alternative is permitted to be applied when the fire load mainly is of wood fuel type.

Owing to studies, recently carried through by MAGNUSSON and THELANDERSSON [1], now a more differentiated state of knowledge exists for the gastemperature-time curves of the cooling period. This is exemplified by Figure 2 which shows theoretically determined gastemperature-time curves for the complete process of fire development at varying fire load q and opening factor $A\sqrt{h}/A_t$ for a fire compartment with surrounding structures, 20 cm in thickness and made of a material with a thermal conductivity $\lambda$ = 0.7 kcal per m per h per deg C and a heat capacity $\gamma c_p$ = 400 kcal per $m^3$ per deg C as representative average values within the temperature range associated with fires. The curves, which for the heating period are giving approximately the same temperature values as the curves in Figure 1, have been calculated over the heat and mass balance equations of the fire room on the basis of time curves for the burning rate, given as the quantity of released heat per unit of time and determined from the results of a great number of full-scale tests with wood fuel fires in enclosed spaces. The differentiated gastemperature-time curves, presented in Figure 2, constantly have been determined on the assumption of the fire to be ventilation controlled. For fuel bed controlled fires, such a simplifying assumption leads to a fire engineering design which will be on the safe side in practically every case - for a further discussion of this particular problem, cf. for instance [1] or [2].

As a third alternative, the current Swedish Standard Specifications permit a structural fire engineering design on the basis of a gas-temperature-time curve, calculated in the individual case over the heat and mass balance equations - or determined in some other way - - with regard taken to the thermal properties of the surrounding structures of the fire compartment.

Related to the second or third alternative, mentioned above, a differentiated fire engineering design of a load-bearing structure comprises the following main components [3] - [5].

(a) The choice, in each particular case, of representative combustion characteristics of the fire load.

(b) The determination for these combustion characteristics of the gas-temperature-time curve and the convection and radiation properties of the complete process of fire development, taking into account the geometry of compartment, the size and shape of window and door openings and the thermal characteristics of the structures, enclosing the compartment.

(c) The determination of the corresponding temperature-time fields in the structure or the structural element, exposed to fire.

(d) The determination - on the basis of data according to (c) and data on the strength and deformation properties of the structural materials in temperature range, associated with fires - of the point of time for collapse at prescribed loading or, alternatively, of the minimum load-bearing capacity of the structure or the structural element for the process of fire development valid.

In a differentiated fire engineering design of a separating structure or structural element the design component (d) usually is out of interest.

## 2. Swedish fire engineering research, recently published or in progress

The Swedish fire engineering research, recently published or in progress, has mainly been concentrated to problems which are of vital importance for making a differentiated structural fire engineering design according to the above practically applicable [6] - [8]. The problems have been chosen with a general programme for long-term fire engineering research [9] as a background. The object of this programme is twofold, viz., first, to facilitate the choice of research problems, and second, to stimulate and to intensify joint inter-Scandinavian research. The problems treated, on the whole can be divided into the following groups: the fire load, the process of fire development, the properties of structural materials in temperature range associated with fires, the temperature-time fields in structures exposed to fire and the corresponding static behaviour and load-bearing capacity of the structures.

### 2.1. Fire loads

In the current Swedish building codes and regulations the fire load q (Mcal per $m^2$) of a compartment is defined according to the relation

$$q = \frac{1}{A_t} \Sigma m_\nu H_\nu \qquad (2)$$

where $A_t$ = the total area of the surfaces bounding the compartment ($m^2$), $m_\nu$ = the total weight (kg) and $H_\nu$ = the effective heat value (Mcal per kg) for each individual material $\nu$.

With reference to such a definition, which is natural with respect to characteristics of the heat and mass balance of a fire compartment, statistical studies have been carried through of the fire loads in dwellings, offices, schools and hospitals [8], [10], [11]. The results obtained are examplified by Figure 3 [10] which refers some distribution curves, representative to dwellings in the suburbs and the central parts of Stockholm. In the figure the fire load is specified on one hand by a minimum value, which only includes the highly inflammable components, and on the other hand by a maximum value, corresponding to all combustible material in the compartment, excluding floor covering.

Fragmentary studies are in progress for a further development of the characterization of the fire load and as a first step of such a development a slightly modified definition has been put forward according to the following relation

$$q = \frac{1}{A_t} \quad \Sigma \mu_\nu m_\nu H_\nu \qquad (3)$$

in which $\mu_\nu$ denotes a coefficient between 0 and 1, giving the real degree of combustion for each individual component $\nu$ of the fire load. For some types of components then this coefficient can be dependent on the time of fire duration and of the gastemperature-time characteristics of the compartment.

## 2.2. Process of fire development

The research activities concerning the process of fire development can be divided with respect to full-scale tests, model tests and theoretical calculations. A determination of the characteristics of the complete process of fire development then is essential, irrespective of the method of investigation chosen.

During the last years fire development studies based on full-scale tests have been carried out in Sweden in test buildings, specially built for the purpose, in Stockholm, Rosersberg and Studsvik. In the first-mentioned test building, consisting of a half-cylindrical tunnel of reinforced concrete, systematically the gastemperature-time curves have been determined for a fire development in an enclosed space, under accurately controlled conditions, for fuels of wood and kerosene [12]. The parameters varied in the test series comprise the amount of fuel, the coefficient of dispersion of the fuel and the amount of air supplied for combustion per unit time. The results obtained are examplified in Figure 4 [12], giving experimentally determined gastemperature-time curves at different points of the test tunnel for a fire load of 68 kg kerosene fuel (full-line curves), compared with the corresponding temperature-time variation, calculated from the heat and mass balance equations of the fire compartment (dash and dotted-line curve). The test series made in the test house in Rosersberg primarily contain a detail study of the spread of fire and the fire development in rooms or flats with representative fire loads of furniture [13]. As a secondary purpose the test series have included a determination of the maximum distance between pieces of different types of furniture with regard to fire spread and the amount of fuel required for flash-over at varying geometry of the room or flat and varying ventilation. A fragmentary test result is refered in Figure 5 [13], dealing with experimentally obtained relationship, for some tests with a fire load of wooden cribs or furniture, between the maximum rate of combustion R for the active part of the fire and the air flow factor $A\sqrt{h}$. In the last-mentioned test building in Studsvik, finally, a study is going on concerning essential characteristics in connection with the fire and smoke spread along the outer wall and along a vertical ventilation duct during a fire in one distinct storey of a multistorey house [6] - [8], [14] - [16]. Figure 6 examplifies the test results by showing the temperature field outside of the outer wall of the test building, determined in a vertical symmetrical section at right angles to the wall and corresponding to the time for maximum temperature in the fire compartment. The curves refer to a fire test with an opening factor $A\sqrt{h}/A_t = 0.026\ m^{1/2}$ and a fire load q = 19.6 Mcal per $m^2$ total area of surfaces bounding the room.

As concerns fire development studies based on <u>model tests</u>, recently an investigation has been published on the composite influence on the rate of combustion of variations in the air flow factor $A\sqrt{h}$ of the compartment and the porosity factor $\phi$, according to GROSS, of the fire load [17]. The investigation comprises 175 tests on ventilation controlled as well as fire load controlled fires in cubic compartments of three different scales with the fire load composed of cribs of wooden sticks. For all experiments the magnitude of the fire load, the thickness of the wooden sticks and the thermal characteristics of the structures enclosing the compartment have been kept constant. Under these conditions the results of the investigation are summarized by approximate formulas for the average burning rate $R_{80-30}$ and the average gastemperature $\vartheta_{80-30}$ of the active part of the fire. An example of the results obtained is reproduced in Figure 7 [17], showing the average burning rate $R_{80-30}$ at varying opening factor $A\sqrt{h}/A_t$ and porosity factor $\phi$ for the largest fire compartment of the investigation. The studies will be continued by an extended experimental and theoretical analysis of the effect of variations in the magnitude of the fire load, the thickness of the wooden sticks and the properties of the structures bounding the compartment.

The field of fire development studies based on theoretical calculations, mainly is represented by a comprehensive study of wood fuel fires in compartments, recently presented by MAGNUSSON and THELANDERSSON [1]. In this work a systematized method is deduced for a calculation over the heat balance and mass balance equations of the gastemperature-time curve for the complete process of fire development. The design procedure, which can be seen as a generalization of the more limited methods previously presented by KAWAGOE-SEKINE [18] and ÖDEEN [19], contains a computer programme which enables a consideration of temperature dependent thermal properties and critical temperatures for decomposition of the materials entering into the surrounding structures, initial moisture content in the surrounding structures, effect of heat stored in structures enclosed in the compartment, and changes in size and shape of window and door openings during the process of fire development. The procedure is applicable to compartments, which contain up to three different types of surrounding structures with one of these structures composed of up to three different materials. On the basis of the method deduced and data from a great number of full-scale tests the authors have carried out in a systematic way very extensive calculations of the gastemperature-time curve of the complete process of fire development for varying assumptions concerning the geometrical and thermal characteristics of the room, the opening factor $A\sqrt{h}/A_t$ and the fire load q, defined as the corresponding heat value per unit area of the total surface bounding the fire room. Figure 2 examplifies the results of the study.

## 2.3. Material properties in temperature range associated with fires

For calculating the temperature field and the corresponding structural behaviour and load-bearing capacity of a structure or structural element due to an external thermal effect produced by a fire, it is required to know the thermal, strength and deformation properties of the structural materials in the temperature range associated with fires. Since a structure or a structural element has to fullfil its function during the heating period as well as the subsequent cooling phase, the properties mentioned must be known for each actual temperature level with connection to both an increase and a decrease of temperature.

Examples of current activities within this field of fire research are systematic experimental studies of the creep properties of steel [20] and of the temperature dependence of the thermal conductivity, the specific heat and the compressive, tensile and torsional strength of concrete with varying composition [21], [22] and fragmentary investigations of the thermal properties of different types of insulation materials. The results obtained are examplified in Figures 8 [8] and 9 [21], showing the temperature dependence of the thermal conductivity $\lambda$ for concrete and Limpet spray asbestos (density 200 kg per $m^3$) and the residual tensile strength $\sigma_t$ of concrete, determined by split test on cylinders, respectively.

## 2.4. Temperature fields in, and load-bearing capacity of, structures exposed to fires

Theoretical calculations of the temperature-time fields and the corresponding structural behaviour and load-bearing capacity of structures or structural elements exposed to fires have filled a large place in the Swedish fire engineering research during the last years. The work carried out and in progress comprises non-insulated and insulated steel structures [4], [5], [23] - [28], reinforced concrete slabs [29], [30], and ordinary reinforced and prestressed concrete beams [31], [32]. The results obtained are examplified by Figures 10 to 14.

In Figure 10 [5] then are reproduced some diagrams giving the maximum steel temperature $\vartheta_{s_{max}}$ for a steel section insulated with Vermiculite plaster Pyrodur (density 315 kg per $m^3$) exposed to fire for varying fire load q, relationship $A_i/V_s$ and insulation thickness $d_i$ and located in a fire compartment with opening factor $A\sqrt{h}/A_t$ = 0.04 $m^{1/2}$ and with characteristics for the gastemperature-time curve according to Figure 2. $A_i$ is the mean jacket surface of the insulation and $V_s$ the volume of the steel structure per unit of length. Figure 11 [25] illustrates the influence on the buckling stress $\sigma_k$ of a partial restraint to longitudinal expansion for an axially compressed steel column with a slenderness ratio $\lambda = 100$ and a quotient $i/d = 1$, where $i$ = the radius of gyration and $d$ = the distance from the gravity centre axis to the edge of the cross section with maximum compressive stress. The degree of restraint is characterized by the coefficient $\gamma$, giving the quotient between the possible longitudinal expansion and the completely free elongation of the fire exposed column. In Figure 12 [27] an experimentally determined time-deflection curve for a fire exposed, simply supported, insulated steel beam (full-line curve) is compared with two corresponding curves, calculated under different assumptions. The dash-line curve then refers to a calculation based on creep deformations for the lower flange of the beam only and at a constant bending stress. The dash and dotted line curve gives the result of a more accurate calculation taking into account the redistribution of the bending stresses during the fire exposure.

Figures 13 and 14 reproduce some results for fire exposed concrete beams. Figure 13 [31] then shows experimentally determined and calculated temperature distributions along the plane of symmetry (a) of a stem of a double T unit of prestressed concrete at different times in the course of the standard fire resistance test. Since some thermo-couples could have been displaced during the casting of the unit, the calculated temperature distributions along a section (b), situated at a distance of 2 cm from the plane of symmetry (a), are also shown in the graph for some portions of the stem. Figure 14 [32] presents the calculated relationship between the allowed fire load $q_{allow}$, the width of the cross section b and the distance t from the layer of the reinforcement to the underneath side of a rectangular, reinforced concrete beam exposed to a fire on three sides. The results refer to a critical temperature of the reinforcement $\vartheta_s = 510^\circ C$ and have been calculated on the basis of fire characteristics for a compartment with the opening factor $A\sqrt{h}/A_t = 0.04\ m^{1/2}$ according to Figure 2 with the influence of the cooling phase taken into account. The applicability of the results are marked in the diagram by horizontal arrows, connected to the ratio $\nu$ between the width b and the height h of the cross section.

A more extensive, experimental fire research activity is heavily difficult in Sweden at present as a consequence of the acute deficiences in permanent laboratory resources for fire engineering tests. This fact has limited the choice of research projects to such experimental investigations which in each individual case can be made in a test equipment built at a comparatively low cost. Examples of experimental investigations in progress are systematic studies of the structural behaviour and load-bearing capacity of statically indeterminate reinforced concrete slab strips (under the direction of ANDERBERG) [33], reinforced concrete beams in torsion (under the direction of THELANDERSSON) [22], and centrally compressed reinforced concrete columns (under the direction of ÖDEEN) [34]. The studies are carried out for varying gastemperature-time curves of the compartment with the influence of the cooling phase taken into account. A result illustration is shown in Figure 15 [34], giving the residual load-bearing capacity $P_u$ for centrally compressed reinforced concrete columns heated according to the standard fire resistance test with a time of fire duration T. The full-line curves refer experimentally determined values and the dash-line curves theoretically calculated results. The curves relate to columns which were not submitted to any load during the heating and cooling periods, and were tested to compressive failure without any buckling after slow cooling down to about $10^{\circ}C$.

## 3. Concluding remarks

In the survey, presented in the above, are given the principles of a functionally well-defined fire engineering design of structures or structural elements together with a fragmentary discussion of the essential components of such a design. Of reasons, introductory mentioned, the treatment mainly has been based on Swedish fire engineering research, recently published or in progress. The survey accentuates the importance of the concluding statement in the paper, presented by Mr. Fry, that the CIB Commission W 14 now has "to turn more of its attention to the application of its work to design problems, and to encourage the development of a truly fire engineering approach to building."

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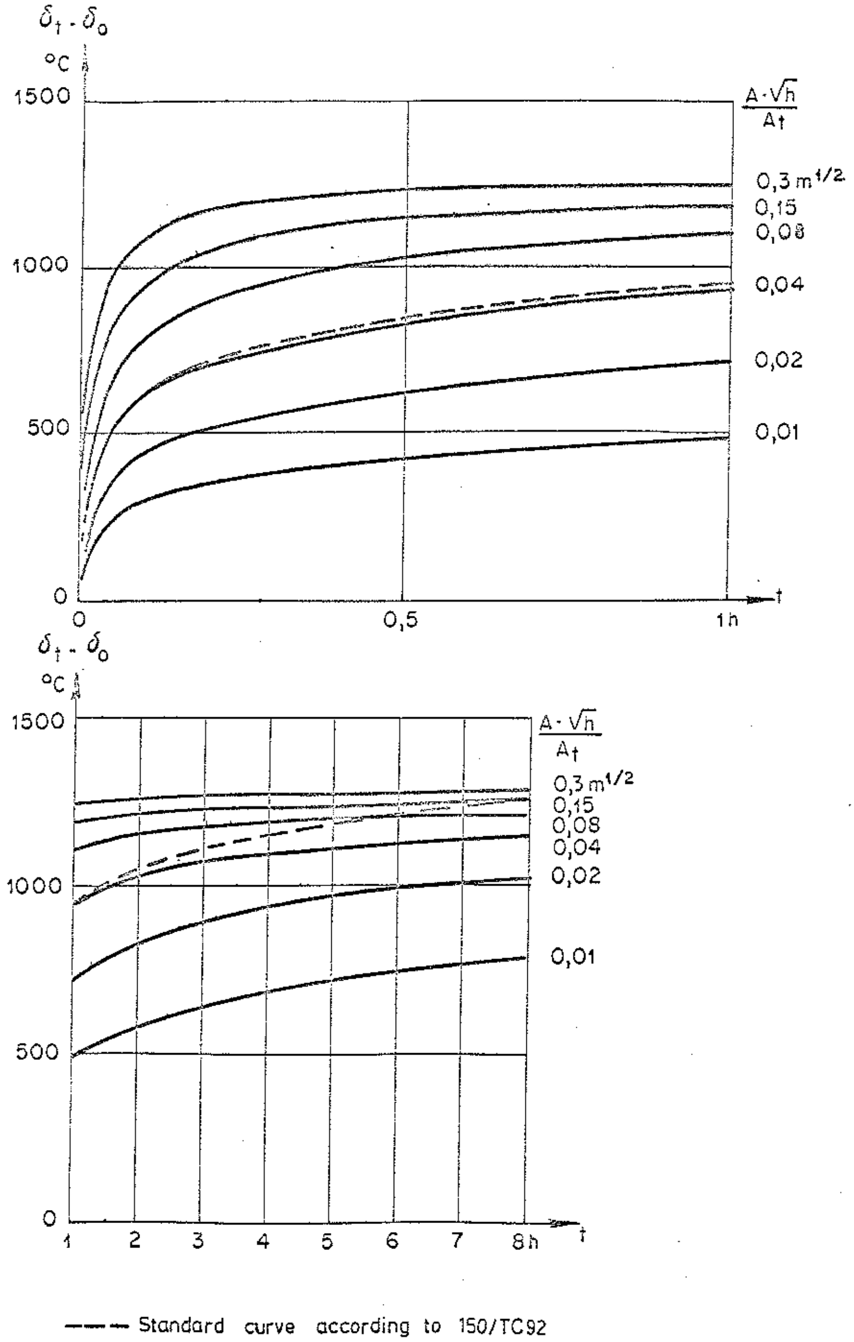

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Standard curve according to 150/TC92


Figure 1

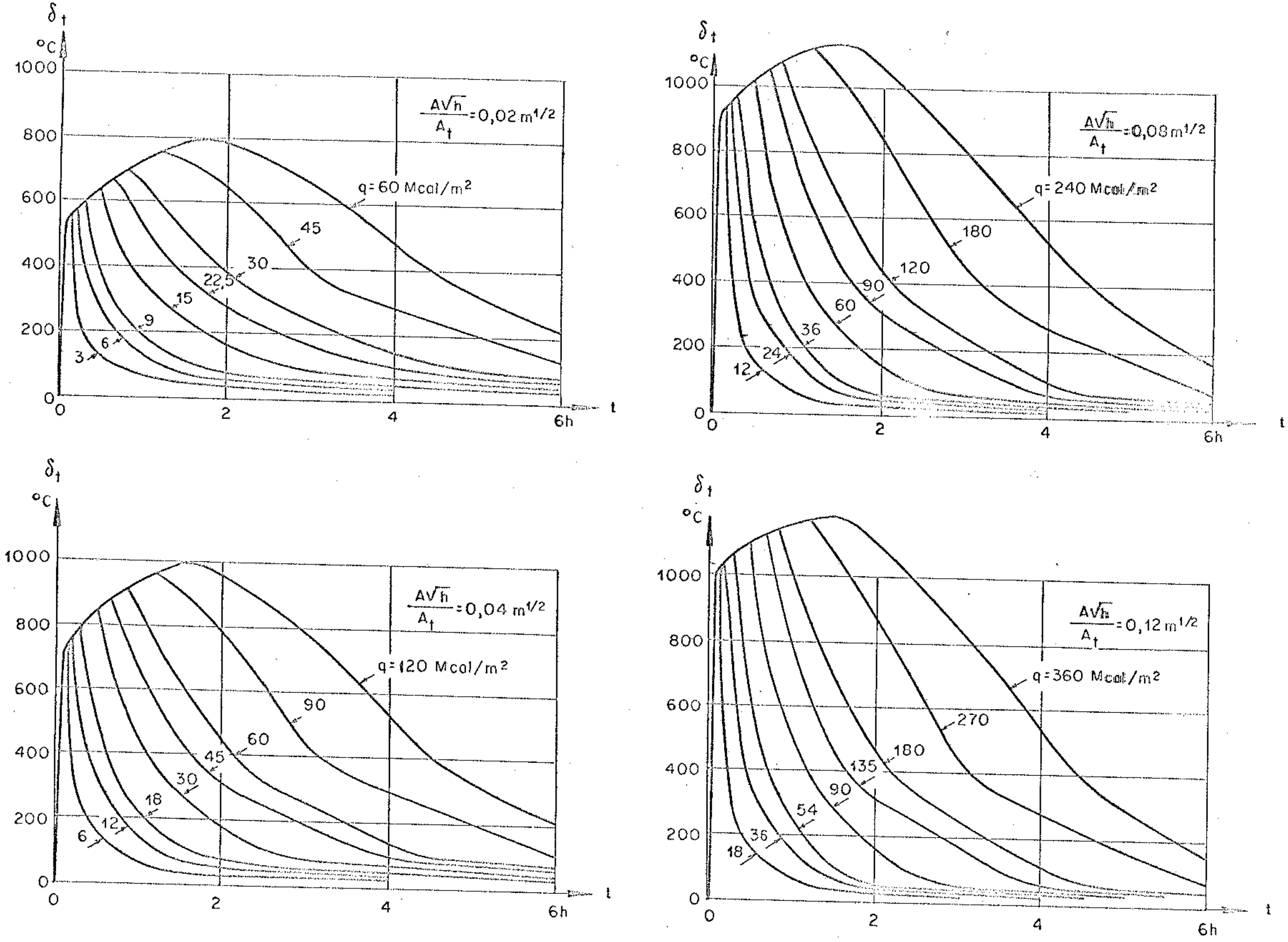

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Figure 2

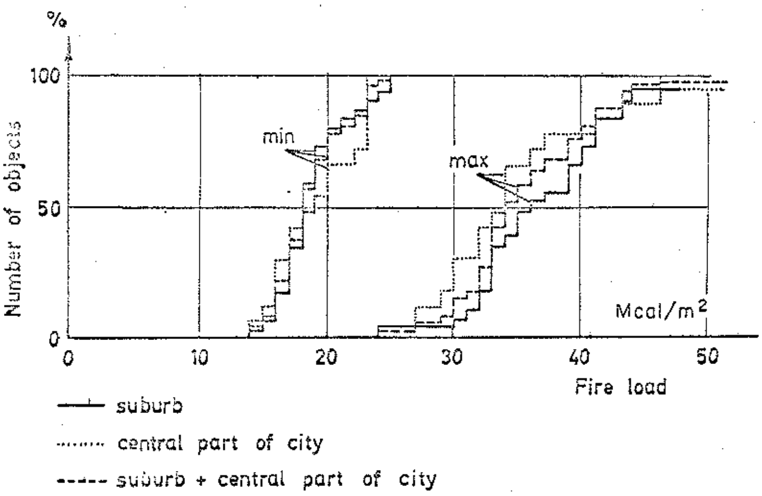



Figure 3

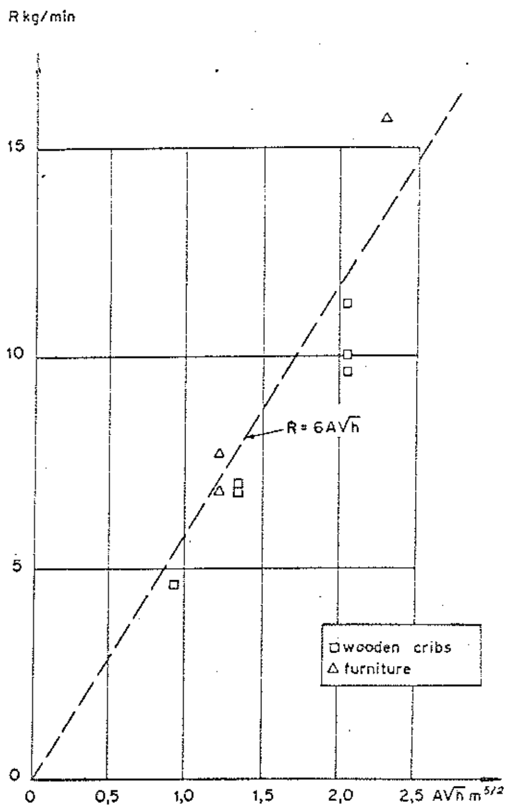
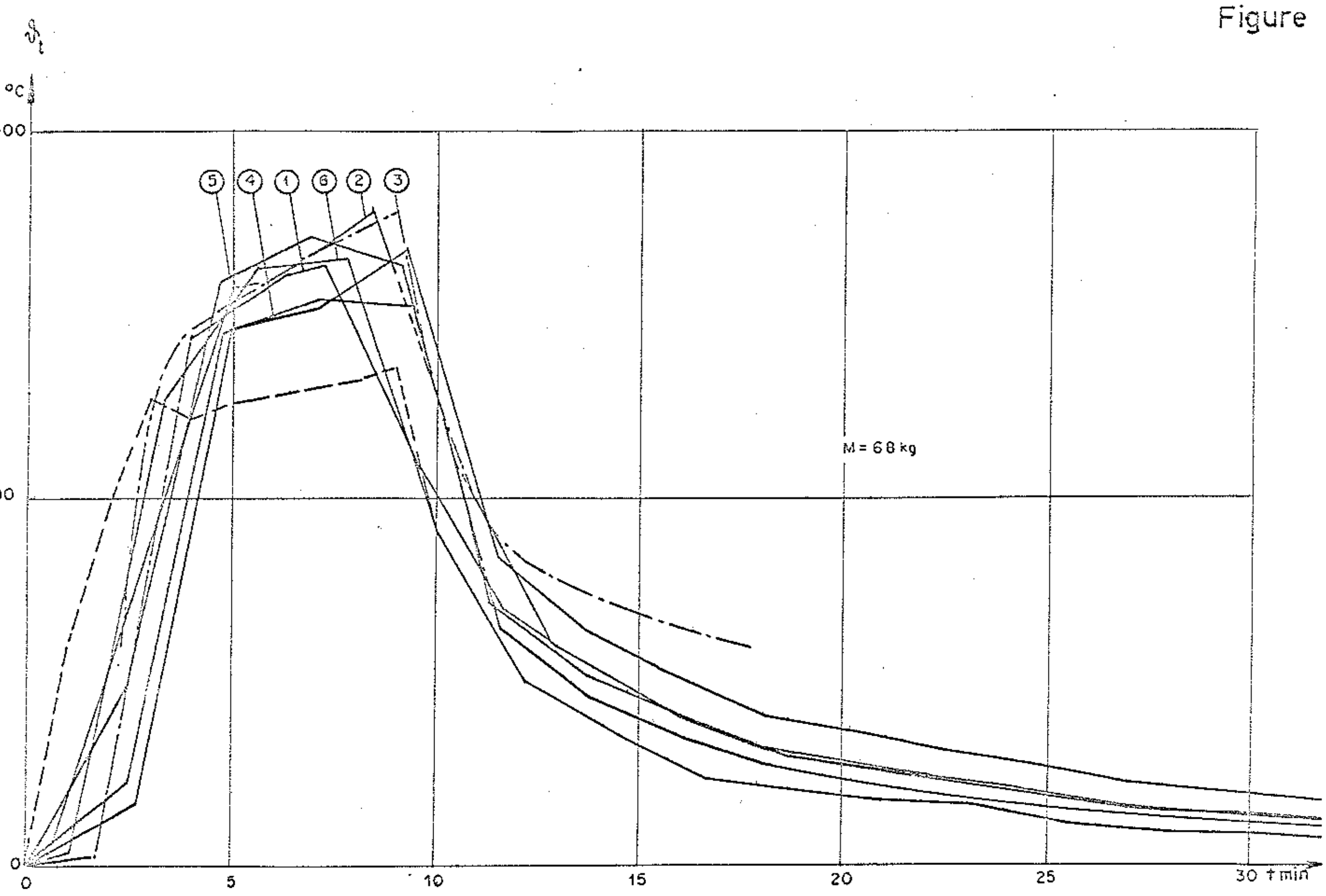



Figure 5

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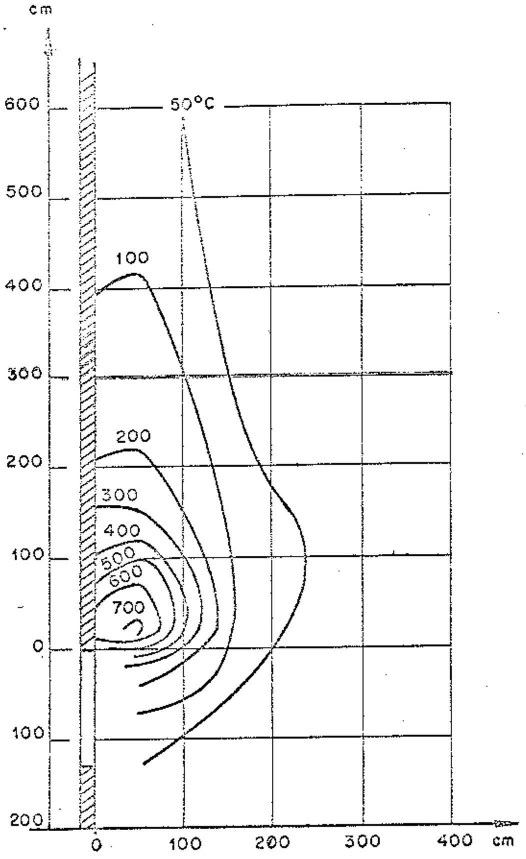


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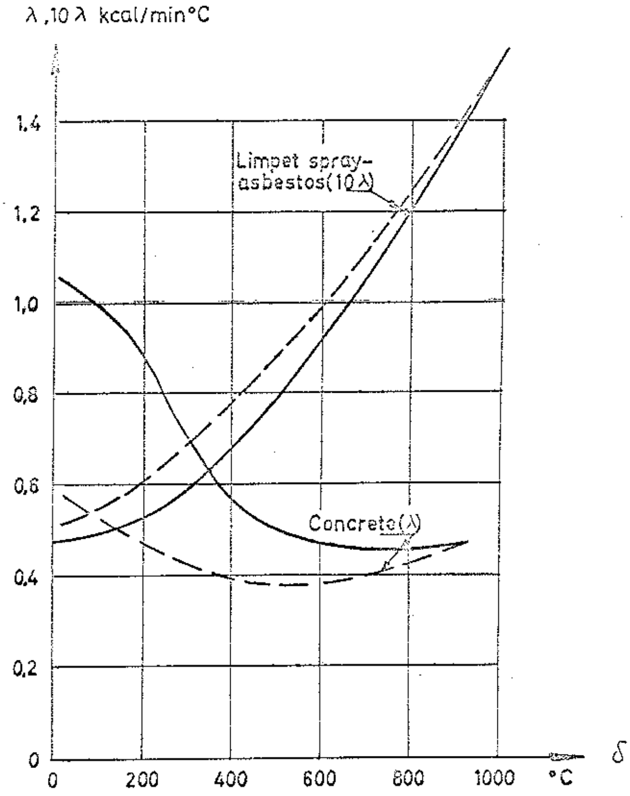



Figure 8

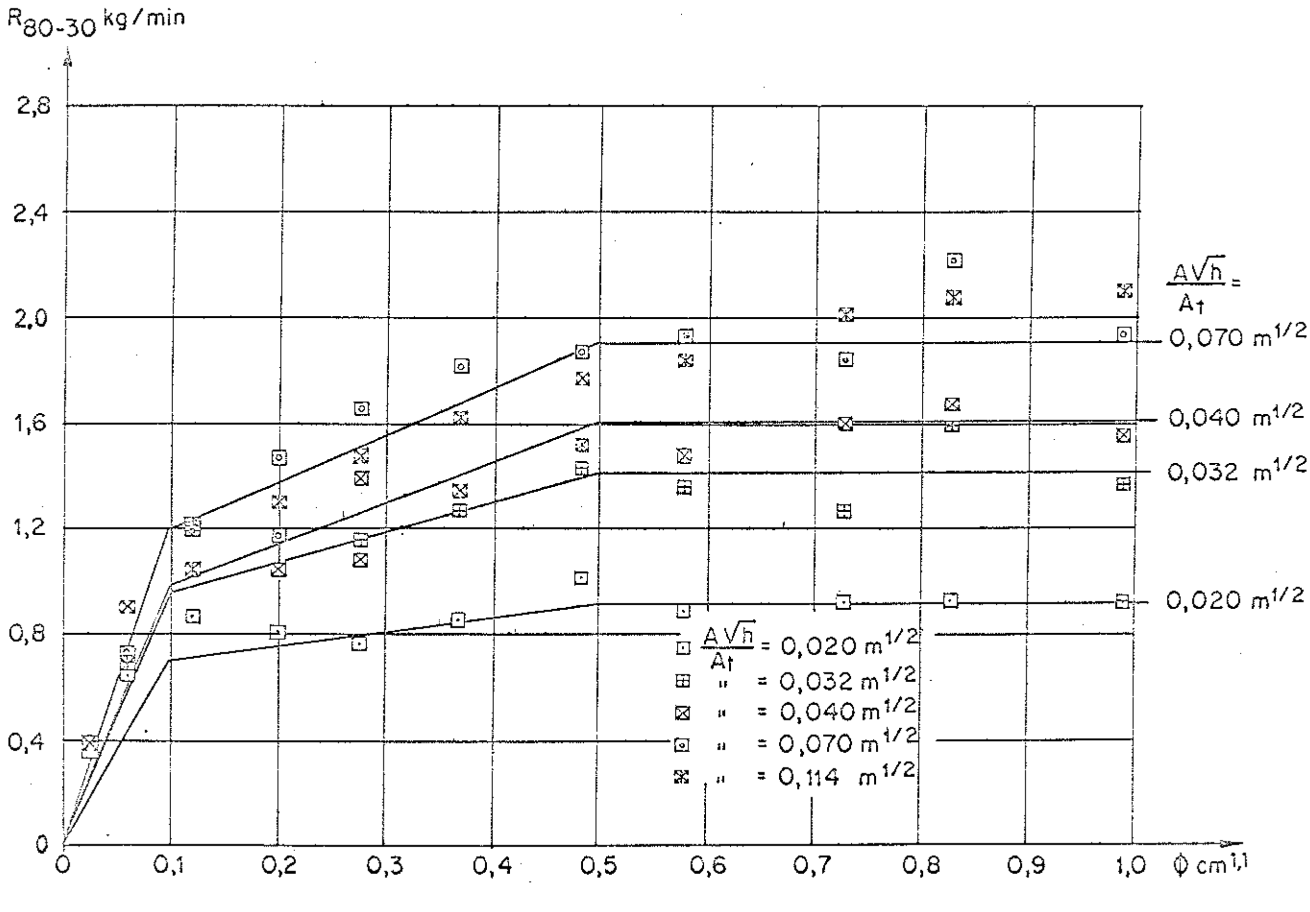



Figure 7

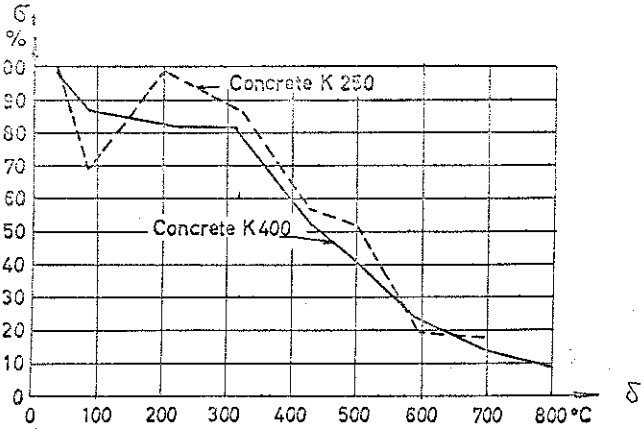



Figure 9

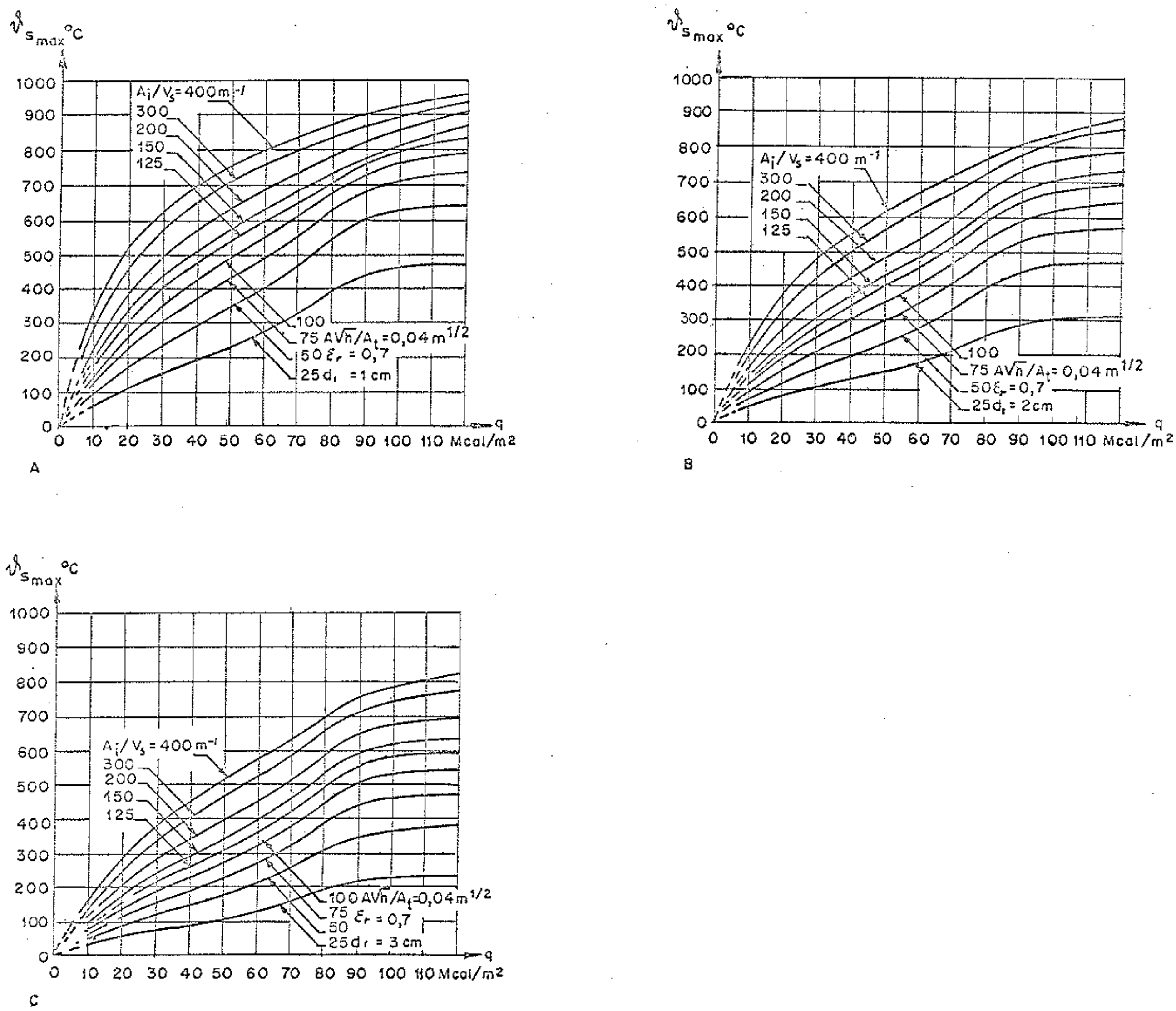



Figure 10

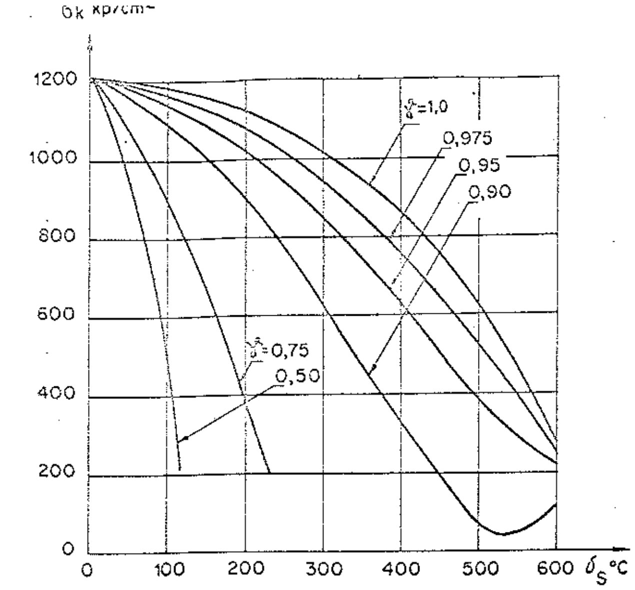



Figure 11

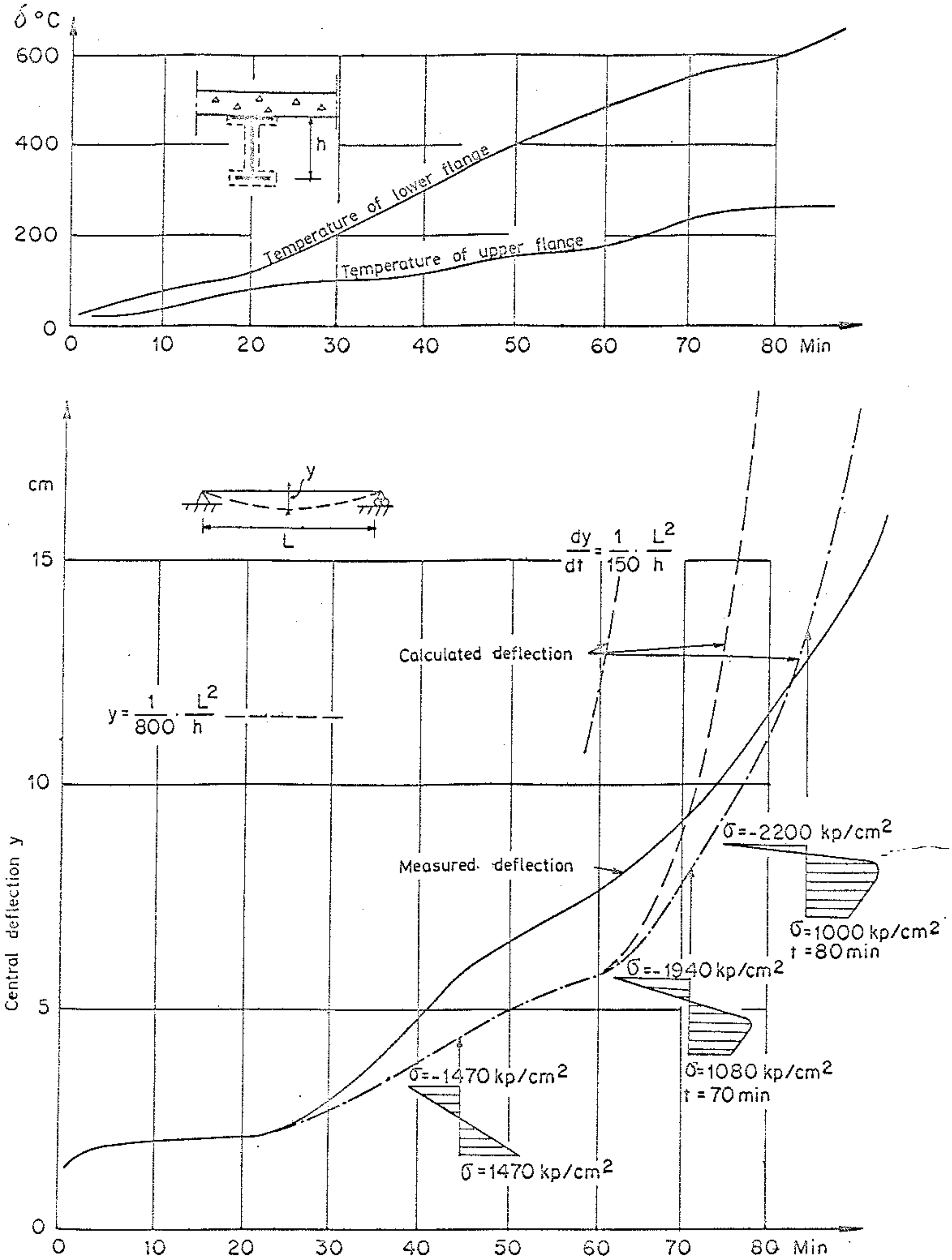
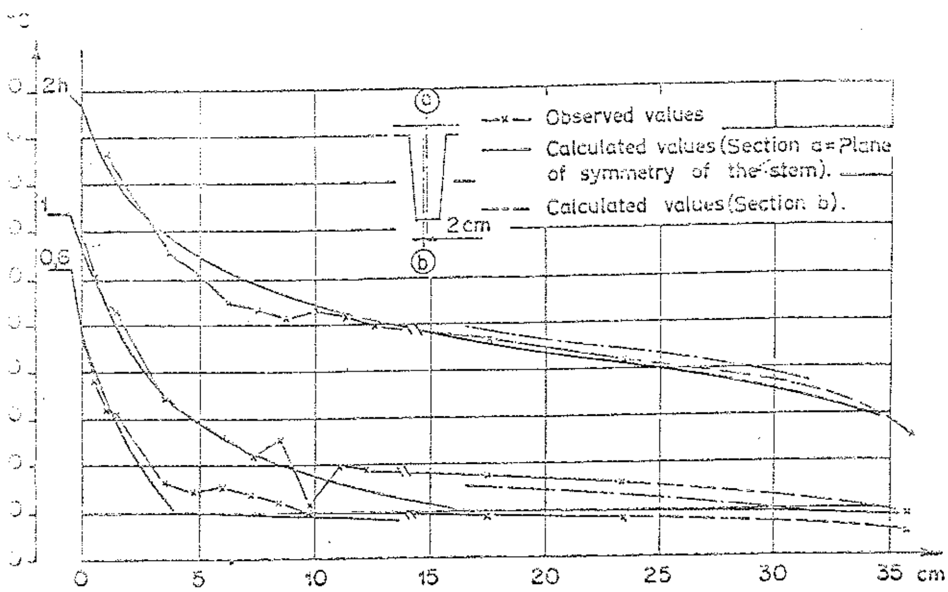



Figure 12



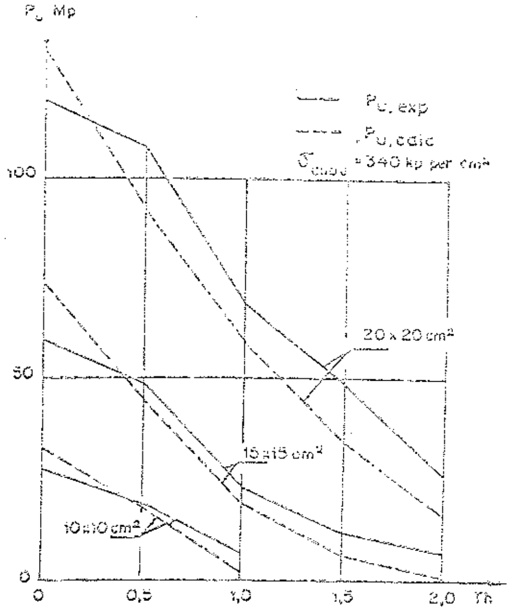




Figure 13

Figure 15

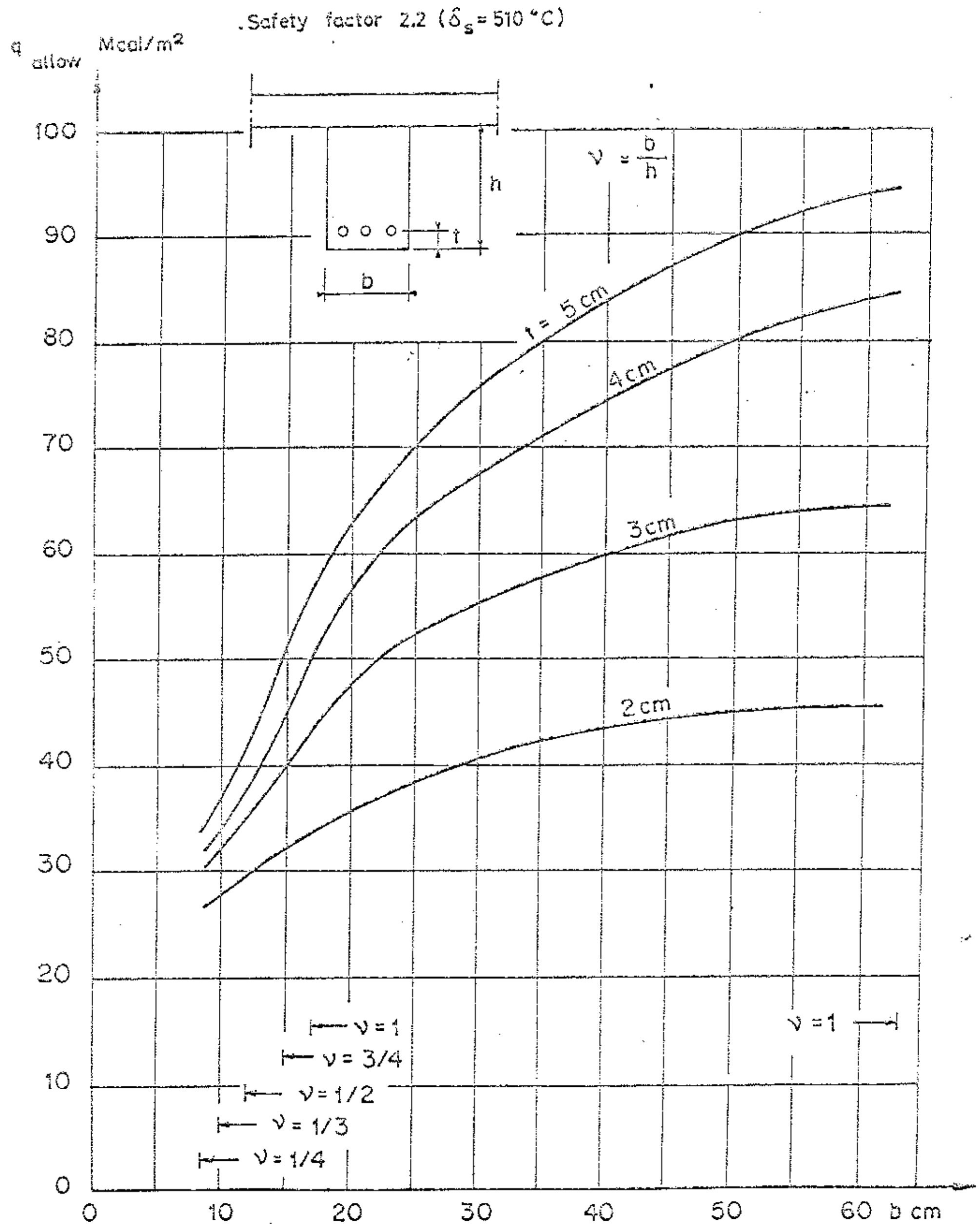



Figure 14