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Principles of structural fire-engineering design with special regard to the connection between real fire exposure and the heating conditions of the standard fire-resistance test (ISO 834)

Principes d'ingénierie des structures compte tenu du feu, particulièrement en ce qui concerne le rapport entre l'exposition à un incendie réel et les conditions d'échauffement dans l'essai de résistance au feu normalisé (ISO 834)

FOREWORD

Technical Report 3956 was drawn up by Technical Committee ISO/TC 92, *Fire tests on building materials and structures*, and approved by the majority of its members. It is intended as useful background information to those using International Standard ISO 834, *Fire resistance tests – Elements of building construction*, and should be read in conjunction with that publication.

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0 INTRODUCTION

One of the fundamental aims of carrying out a fire-resistance test on elements of building construction is to obtain results that can be used as data for a structural fire-engineering design which takes into account real conditions. This Technical Report is intended to serve as guidance for facilitating the planning, performance and reporting of a fire-resistance test in conformity with this principle, especially with regard to the connection between real fire exposure and the heating conditions of a standard fire-resistance test according to ISO 834.

The present tendency of building codes and regulations towards more accurately defined functional requirements increases the need for the development of methods for a differentiated structural fire-engineering design. During recent years, several such design methods have been presented in the literature. These methods may generally be assigned to one of two groups according to the basic data on the process of fire development. The methods of the first group (see clause 3) are characterized by a design procedure which is directly based on gas temperature-time curves of the complete process of fire development, specified in detail with regard to the influence of the fire load and the geometrical, thermal and ventilation properties of the fire compartment. Characteristic of the methods of the second group (see clause 4) is a design procedure which takes into account the varying properties of the fire development over an "empirical" time of fire duration related to the standard temperature-time curve. In all methods, the effect of the cooling phase of the fire is included.

1 SCOPE AND FIELD OF APPLICATION

This Technical Report describes the basic characteristics of the process of fire development, and gives principles of structural fire-engineering design based on differentiated temperature-time curves and on an empirical time of fire duration.

2 BASIC CHARACTERISTICS OF THE PROCESS OF FIRE DEVELOPMENT

Irrespective of the group to which the method belongs, a structural fire-engineering design must be based on detailed knowledge of the characteristics of the process of fire development. Although numerous important investigations have been reported in the literature, the present state of knowledge is far from satisfactory in this respect.

In simple terms, fully developed compartment fires exhibit two types of behaviour (see [1]). For the first type, the combustion during the flame phase is controlled by the ventilation of the compartment; the burning rate is approximately proportional to the air supply through the openings of the compartment and is not in any decisive way dependent on the amount, porosity and particle shape of the fuel. For the second type, the combustion during the flame phase is controlled by the properties of the fuel bed; the burning rate is determined by the amount, porosity and particle shape of the fuel and is largely independent of the air supply through the openings. The boundary between the two kinds of fire behaviour is not sharply defined.

For ventilation-controlled fires, the average burning rate of the active part of the fire can be determined for different types of fire load, furniture included, with an accuracy which is sufficient in most practical cases for a structural design. For fuel bed-controlled fires with a more complicated behaviour, the present state of knowledge is too incomplete to permit a satisfactory calculation of the burning rate in practice when the fire load consists of furniture, the porosity properties of which are very difficult to define. In such a case, it seems reasonable at present to base a structural fire-engineering design on characteristics for the process of fire development which have been determined on the assumption that the fire is ventilation-controlled. For fuel bed-controlled fires, such an assumption leads to a fire-engineering design which will be on the safe side in practically every case, giving an over-estimation of the maximum gas temperature level, partly balanced by an under-estimation of the time of fire duration.

An extensive basis of gas temperature-time curves of a fire compartment, determined according to this philosophy, is given in [2] for the complete process of fire development, with varying assumptions concerning the geometrical and thermal characteristics of the room, the opening factor $A\sqrt{h}/A_t$ and the fire load q, where

A is the total area of the window and door openings of the fire room, in square metres;

A_t is the total area of the surfaces bounding the fire room, in square metres;

h is the mean value of the heights of the window and door openings of the fire room, in metres, weighted with respect to each individual opening;

q is the heat value per unit area of the total surface bounding the fire room, in megacalories[1] per square metre.[2]

A fragmentary illustration of the diagrams presented in [2] is given in figure 1.

The diagrams are valid for an opening factor $A\sqrt{h}/A_t = 0{,}04\ m^{1/2}$ and a fire compartment with surrounding structures 200 mm in thickness and made of a material with a thermal conductivity $\lambda = 0{,}7$ kcal/(h·m· °C)[3] as representative average values within the temperature range associated with fires.

3 PRINCIPLES OF STRUCTURAL FIRE-ENGINEERING DESIGN DIRECTLY BASED ON DIFFERENTIATED GAS TEMPERATURE-TIME CURVES

For a load-bearing structure, a fire-engineering design directly based on differentiated gas temperature-time curves comprises the following main components (see [3] and [4]) :

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 the 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 the temperature range, associated with fires — of the moment of collapse at prescribed loading or, alternatively, of the minimum load-bearing capacity of the structure or the structural element valid for the process of fire development.

In a differentiated fire-engineering design of a separating structure or structural element, the design component d), in most cases, is irrelevant.

To make such a differentiated fire-engineering design practically applicable for the structural engineer, it is necessary to complete the procedure with design diagrams for different types of structure or structural element (see, for instance, [4] and [5]).

Summarized, a structural fire-engineering design directly based on differentiated gas temperature-time curves is characterized by a mainly theoretical design procedure. The procedure is not related to any need for classification and gives low priority to the standard fire-resistance test on elements of building construction. In the design procedure, the results of such standard tests can be used either for confirmation, point by point, of the theoretical treatment or for obtaining basic information necessary for the calculations. Experimental investigations concerning gas temperature-time curves diverging from the standard temperature-time curve may be necessary in those cases where the basic information depends on the detailed characteristics of the process of fire development — for instance, basic data concerning the disintegration of structural materials, enlarged short-time effect of creep and shrinkage, effect of crack formation and spalling, behaviour and strength of fastening devices for different types of insulation, and rate of increase in the depth of the charred layer in timber structures. In most cases, the data required can be determined by less extensive experiments than the standard fire-resistance test.

1) 1 cal = 4,184 J

2) The corresponding fire load q_c, defined in a more conventional manner as the heat value per unit floor area A_f or as the equivalent amount of wood per unit floor area A_f, is then given by the formulae

$$q_c = \frac{A_t}{A_f} q \ \text{(Mcal/m}^2\text{)} \quad \text{and} \quad q_c = \frac{A_t}{4{,}5\,A_f} q \ \text{(kg/m}^2\text{)}$$

3) $1\ \text{kcal/(h·m·°C)} = \frac{1}{360}\ \text{cal/(s·cm·K)} = \frac{1}{360} \times 418{,}4\ \text{W/(m·K)}$.

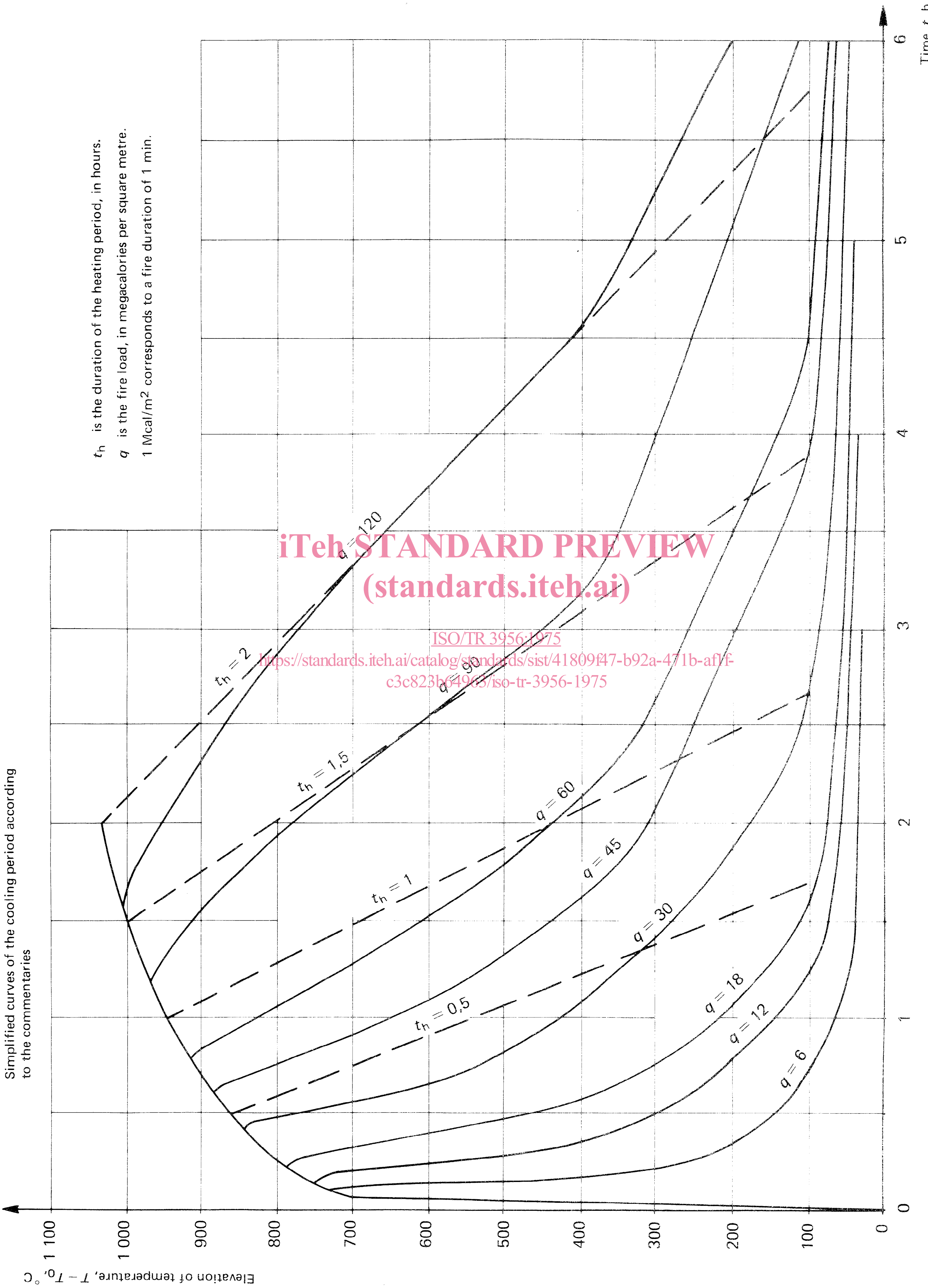

FIGURE 1 – Temperature-time curves for different values of fire load

4 PRINCIPLES OF STRUCTURAL FIRE-ENGINEERING DESIGN BASED ON AN EMPIRICAL TIME OF FIRE DURATION

The concept "empirical" or equivalent time of fire duration has been introduced to enable a direct translation to be made from a real fire exposure to a corresponding heating according to the standard temperature-time curve specified in 4.1.1 of ISO 834. Depending on the degree of accuracy required, the character of the concept will vary. So far, three different definitions of the empirical time of fire duration have been presented in the literature (see [4], [6] and [9]).

As shown by a non-insulated steel structure exposed to fire, one of the definitions given in [4] and [6] can, in principle, be explained according to figure 2, which shows by the continuous curves the time-variation of the gas temperature T_t and the steel temperature T_s corresponding to a real fire action, determined by the fire load q, the opening factor $A\sqrt{h}/A_t$, and the thermal properties of the structures bounding the compartment. The broken curves give the standard time-temperature variation T_t (S.C.[1]) and the corresponding time curve of the temperature T_s (S.C.[1]) of the steel structure. A transfer of the maximum steel temperature $T_{s\,max}$ for the real fire to the standard temperature-time curve for T_s (S.C.[1]) determines the empirical time of fire duration t_{hf}.

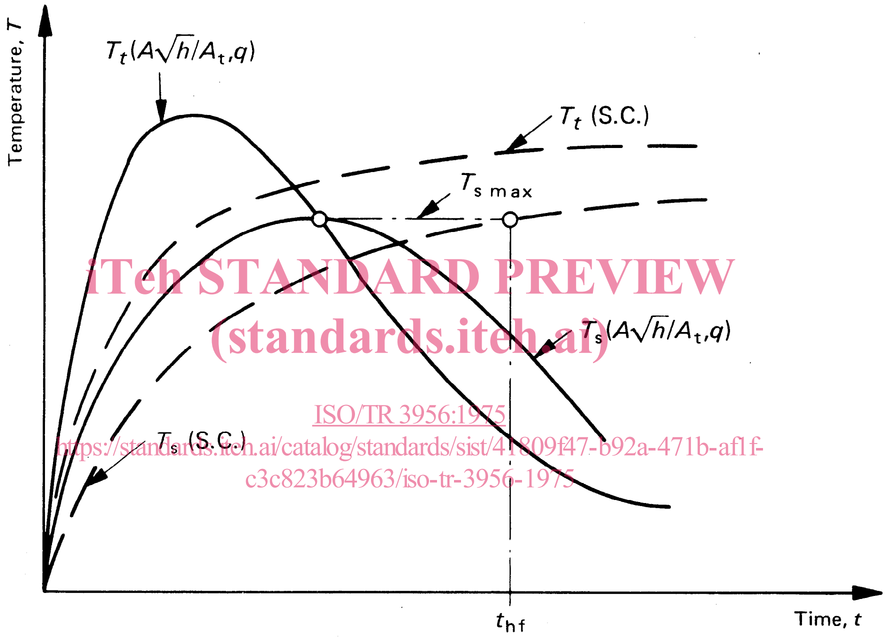

FIGURE 2 – **Determination of empirical time of fire duration from standard and real fire temperature-time curves for a non-insulated steel structure**

It is evident from a functional point of view that, defined in this way, t_{hf} is determined by the fire load q and the opening factor $A\sqrt{h}/A_t$, and must therefore depend on a great number of structural influences :

- for an insulated steel structure : the insulation material, the thickness of the insulation, the quotient A_i/V_s (A_i being the mean jacket surface of the insulation, and V_s the volume of the steel structure per unit length), and the resultant emissivity;

- for a reinforced concrete beam of rectangular cross-section : the height and the width of the cross-section, the distance from the layer of reinforcement to a fire-exposed surface, and the resultant emissivity.

A modified way of defining the empirical time of fire duration t_{hf} has been presented in [7] and [8] with special application to fire-exposed insulated steel structures. Among elements of construction having varying thermal characteristics with respect to fire exposure, that element is chosen which, for a given gas temperature-time curve of a real fire development, gives a maximum steel temperature of a fixed value. t_{hf} is then determined over the standard temperature-time curve for the same element and the same steel temperature. By repeating this procedure for different characteristics of real fires, a diagram can be constructed, applicable to a rough determination of an empirical time of fire duration t_{hf} for an insulated steel structure, irrespective of the detailed properties of the structure.

1) S.C. : Standard curve.

A third way of introducing the concept of empirical time of fire duration t_{hf} has been put forward in [9]. The principle is illustrated by figure 3, which shows by the continuous curve the time-variation of the gas temperature T_t corresponding to a real fire with a fire load q and an opening factor $A\sqrt{h}/A_t$ and by the broken curve the standard temperature-time variation T_t (S.C.). For a given type of structure, a temperature level $T_{t\ cr}$ is chosen which is critical with respect to the fire behaviour of the structure, and t_{hf} is then defined by a condition stipulating that the two areas between the respective gas temperature-time curves and the temperature level $T_{t\ cr}$ are to be equal.

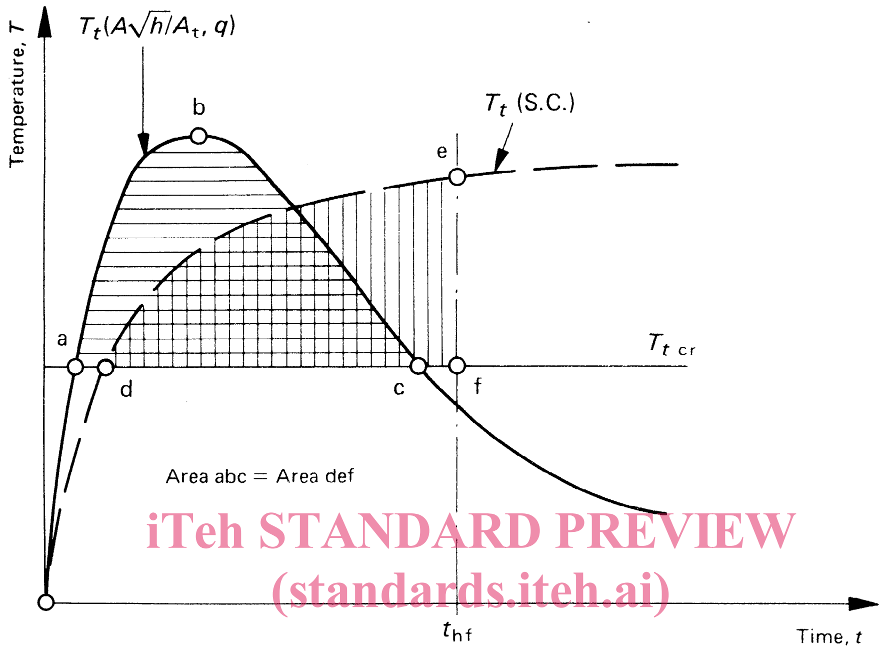

FIGURE 3 — **Determination of empirical time of fire duration by method of equal areas**

The determination of the empirical time of fire duration t_{hf} according to the second and the third definitions leads to results which are less accurate than those obtained from a determination based on the first definition of empirical time of fire duration. One advantage of such an approximate determination is that t_{hf} for a given type of structure will be independent of the detailed structural design. This is illustrated by figure 4 (see [8]), based on the results of a very comprehensive CIB model test investigation concerning the process of fire development and showing for insulated steel structures the empirical time of fire duration t_{hf} according to the second definition, as a function of the parameter $L/\sqrt{AA_t}$ where

L is the total fire load of the compartment, in kilograms, given as the equivalent quantity of wood;

A is the total area of the window and door openings, in square metres;

A_t is the area of the internal surfaces of the compartment over which heat is lost, in square metres.

Figure 4 gives a range of variation of t_{hf} with respect to varying porosity properties of the fire load, comprising wood cribs.

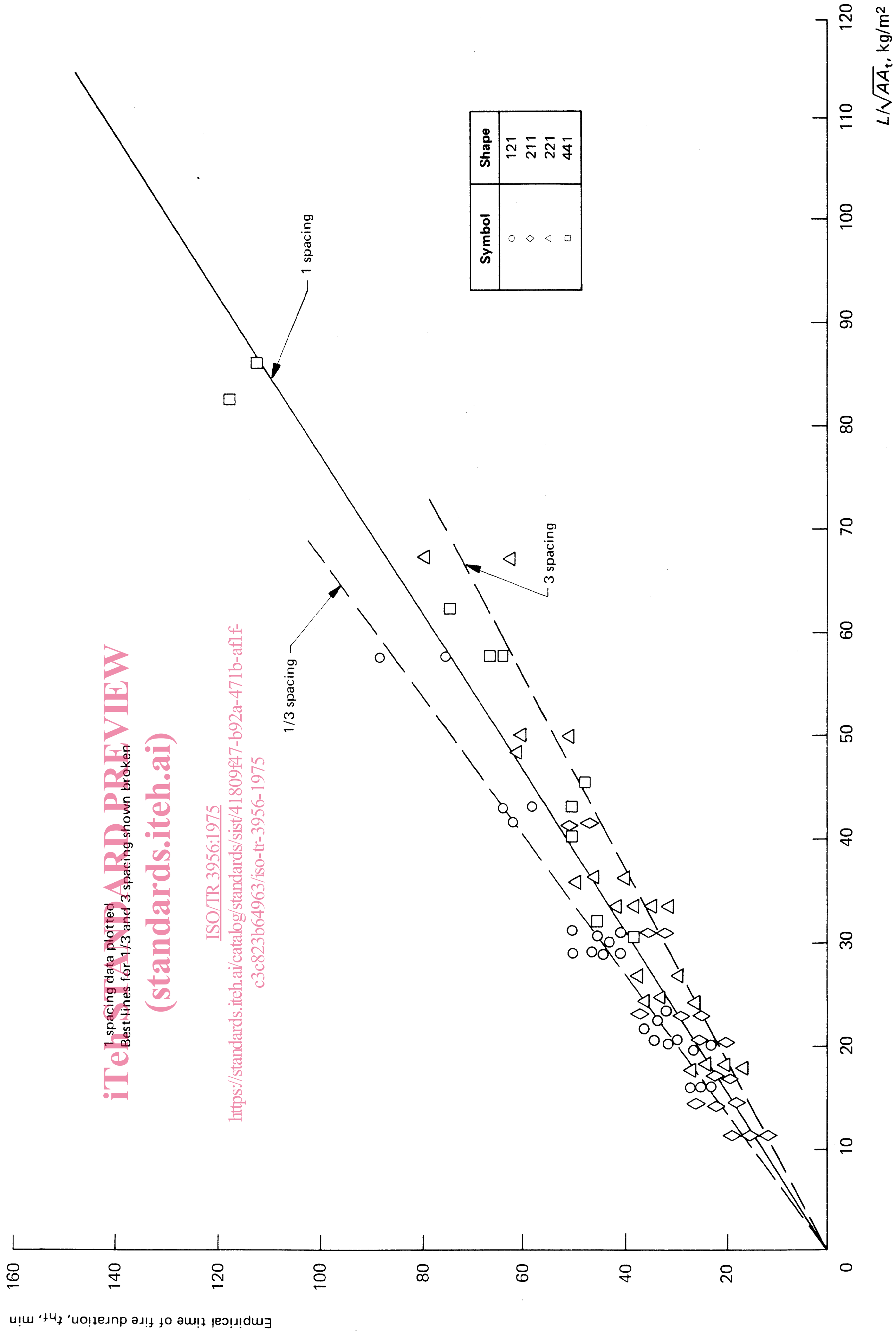

FIGURE 4 — **Graph of empirical time of fire duration for insulated steel structures as a function of $L/\sqrt{AA_t}$**

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