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## RESEARCH AND DEVELOPMENT:

**SESSION I**

**PAPER 4**

# STRUCTURAL STEEL AND FIRE

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## SYNOPSIS

During recent years there has been, both in this country and abroad, a reasonable volume of research and investigation into the behaviour of structural steel in fire. Much of the work carried out in the different countries is complementary but there is some need to draw together all the information now available. The areas where this can be done are indicated and the importance of much of the work is discussed. Lines along which future effort should be directed are suggested.

## INTRODUCTION

Photographs showing a twisted tangle of steelwork are not uncommon among the illustrations depicting the aftermath of a severe fire, when that steelwork has been unprotected. *Fig. 1* shows such a situation. No one would deny that under such conditions structural steel will soften and distort or collapse.

The temperature at the heart of a severe fire can reach a maximum value of some 1 200°C, and the energy released can be of the order of 25 kilowatts for every square foot of floor area; so it follows that steel will reach its critical temperature of 550°C at a fairly early stage when directly exposed in such an incident.

These facts are not in dispute and it is clear that if requirements were assessed on this basis only, then steel would always need heavy fire protection when used as the structural framework of a building.

It is the purpose of this paper to look at the situation in more detail in order to draw attention to those areas where present knowledge is sufficient to encourage the use of structural steel, and to identify the problems about which we still need information.

## RECENT RESEARCH

The features which have received, and continue to receive, critical study, are associated with:

1. The behaviour of a fire, that is to say, the factors which determine its severity, and from this to suggest the circumstance or position in which structural members can be safely used;
2. the behaviour of steel in fire conditions, again to identify the safer situations; and
3. to compare the standard fire resistance test with real fire situations to see if there is any scope for amending the statutory fire resistance requirements.

At the Fire Research Station a research programme which had these three aims was recently carried out. It was jointly sponsored by the steel industry (the then British Iron & Steel Federation) and the Joint Fire Research Organization of the Ministry of Technology and the Fire Offices' Committee.

In this work (1, 2), which was probably the largest and the most comprehensive yet undertaken, twenty-six fire tests were carried out in a specially constructed building using several conditions of ventilation and a variety of fire load densities typical of buildings in the low fire load class (e.g. residential and office buildings). *Fig. 2* shows one test in progress. Parameters known to affect fire severity were chosen as shown in Table 1. Unloaded structural steel members (29 steel beams and columns) were arranged in and outside the fire compart-

Fig. 1. Collapse of structural steelwork in severe fire.

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* Fire Research Station † BISRA, Inter-Group Laboratories of the British Steel Corporation

*References in parentheses are given at the end of the paper.*

## TABLE 1. PARAMETERS AFFECTING FIRE SEVERITY EXAMINED IN THE TEST PROGRAMME

| Parameter | Values used |
|---|---|
| Nature of fuel | Cribs using softwood sticks 45mm (1¾in.) square section in 1·1m (3ft 6in.) lengths.<br>Fibre insulating board linings to walls and ceiling.<br>Petrol and kerosine.<br>Domestic furniture:—mixed, medium and heavy. |
| Amount of fuel (fire load densities expressed as wood equivalent) | Cribs:—7·5, 15, 30 and 60kg/sq. m (1·55, 3·1, 6·2 and 12·4lb/sq. ft).<br>Fibre insulating board linings, petrol and kerosine:—7·5kg/sq. m (1·55lb/sq. ft).<br>Furniture:—15 and 25·5kg/sq. m (3 and 5·2lb/sq. ft). |
| Arrangement of fuel | Cribs:— covering ⅓ and ⅔ floor area.<br>Fibre insulating board:—uniformly disposed on walls and ceilings.<br>Petrol and kerosine:—eight trays each 0·9m (3ft) square.<br>Furniture:—typical of domestic occupancy. |
| Size and shape of room | 7·7m × 3·7m × 3m high (25ft 3in. × 12ft 2in. × 9ft 8in. high) single compartment or 7·7m (25ft 3in.) square (double) compartment. |
| Window area and shape | 2 openings, 3·05m × 1·83m (10ft × 6ft) in each of two opposite long walls such that single and double sided ventilation obtained with single and double compartments respectively. Each window width varied to give 1·3, 2·8 and 5·6sq. m (14, 30 and 60sq. ft) of opening corresponding to ⅛, ¼ and ½ ventilation. |
| Thermal insulation of room | 0·34m (13½in.) cavity brick external walls and lightweight concrete internal wall rendered with vermiculite plaster.<br>Concrete floor. Ceiling of refractory concrete.<br>With and without mineral wool slab 25mm (1in.) thick lining to walls and ceiling. |
| Glazing | Used only in some of the furniture tests. |

## TABLE 2. PARAMETERS AFFECTING BEHAVIOUR OF STEEL EXAMINED IN THE TEST PROGRAMME

| Parameter | Internal steelwork | External steelwork |
|---|---|---|
| Weight and shape of steel section | 37, 48, 52 and 107kg/m (25, 32, 35 and 72lb/ft)—I section.<br>18·75 and 43·8kg/m (12·6 and 29·4lb/ft)—Rectangular hollow section. | 37 and 52kg/m (25 and 35lb/ft)—I section. |
| Type and number of elements | 4 beams, 17 columns. | 3 beams, 5 columns. |
| Location of element | Columns:—built into wall, standing against wall and free-standing in compartment.<br>Beams:— built into wall, spanning compartment just below ceiling. | Columns:—against façade and 0·46m (18in.) away (unshielded column only).<br>Beams:— along top of window opening. |
| Area of element heated | Maximum (i.e. free-standing) to Minimum (fully built in). | Maximum (i.e. centre of window opening) to Minimum (shielded by brickwork). |
| Loading and restraint | None applied—concerned only with thermal behaviour. | |
| Protection (by encasement) | Nil.<br>13mm (½in.) mineral wool slab.<br>19mm (¾in.) asbestos insulating board.<br>25mm (1in.) tongued and grooved softwood. | Nil. |

Fig. 2. Fire test building with test in progress

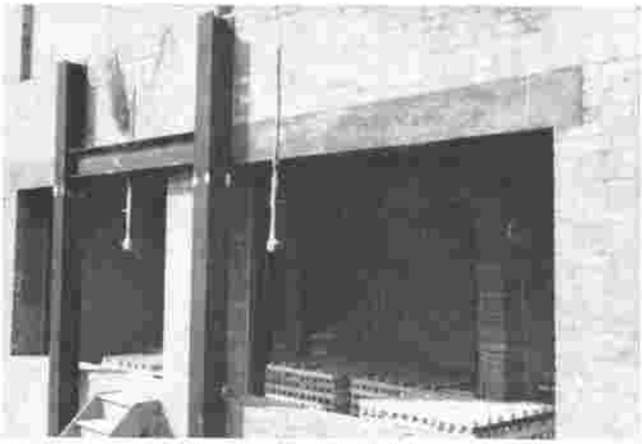


Fig. 4. Arrangement of wood cribs in test building

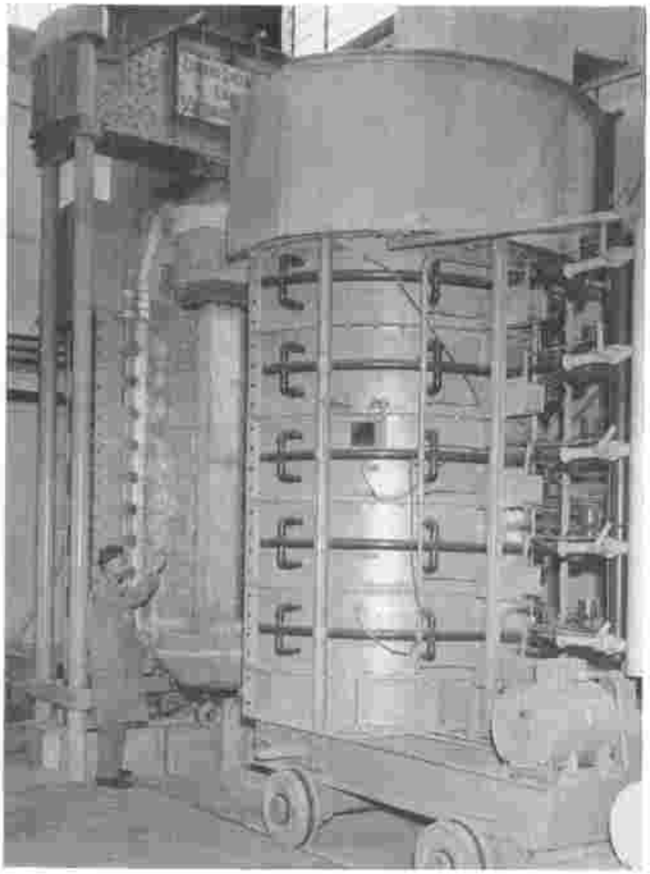


Fig. 3. Column testing furnace at Fire Research Station

Fig. 5. Domestic furniture in test building

ment to provide the data concerning a variety of situations (Table 2), and their behaviour (i.e. their temperature) was observed and compared with appropriate fire resistance test data. *Fig. 3* shows one such test in the column furnace of the Fire Research Station.

In most of this work the fuel used was wood sticks arranged as cribs but several tests were performed in which other fuels were used, for instance ordinary domestic furniture (3, 4). The arrangement of wood cribs in the test compartment seen in *Fig. 4* was that which gave the highest fire load in the tests carried out. *Fig. 5* shows the same compartment with domestic furniture in place. The time-temperature curves for the tests using furniture are compared in *Fig. 6* with those for the wood cribs using a similar fire load density and they indicate that the particular wood cribs, chosen as a convenient and easily reproducible fire load for test purposes, are also representative of furniture. The important comparison is the maximum temperatures reached, not the time taken to attain those temperatures since the latter will depend on experimental differences, all of which are not indicated on the diagram.

Investigations recently carried out in other countries (5 to 8) have, in the main, concentrated on the behaviour of steel members used in typical structural circumstances when exposed to the time-temperature conditions of the standard furnace test. The work carried out in Britain is therefore complementary to those investigations and all the results should be considered together in assessing the present position.

## FACTORS WHICH CONTROL FIRE SEVERITY

In general terms *Fig. 7* illustrates the story of fire severity. The important point to realize is that no single factor is predominant in determining the fire severity in a given circumstance and that considerable information is required about the building as well as the combustible contents.

In order to take this picture a stage further, the precise effect of the quantities listed needs to be quantified and part of the work in the programme of research has supplied valuable data in this respect which, when combined with the results of other investigations carried out at the Fire Research Station (9), and at other laboratories under the auspices of the Conseil International du Bâtiment, enable predictions of fire severity to be made for a large variety of circumstances.

Information on the combustible contents of modern buildings is scarce. This situation will be partly alleviated when a survey of modern offices in the United Kingdom is reported by the Fire Research Station within the next year.

It must be recognized, however, that certain factors affecting fire severity will never be predictable, and it is here that statistical techniques may possibly be applied. For example, it is difficult to account for the occupant who stores abnormally large amounts of combustibles. Again, the behaviour of glazing and hence pattern of ventilation depends on window design, weather conditions and the relative location of glazing and seat of fire.

## FACTORS AFFECTING BEHAVIOUR OF STEEL IN FIRE

Predicting the behaviour of steel under known fire conditions is, as a result of the work, now possible. *Fig. 8* illustrates diagrammatically the main factors affecting the behaviour of steel in fires, whilst *Fig. 9* shows the kind of data available from furnace tests. As a result of numerous furnace tests, much is known about the performance of different materials for fire protection and, in *Fig. 10*, data obtained in furnace tests carried out in Braunschweig and at the Fire Research Station are compared with predicted results based on furnace tests made in Holland. The results, for unprotected steel and for encased steel, show the importance of the steel mass and surface area, and the thickness of the encasement in determining the fire resistance time.

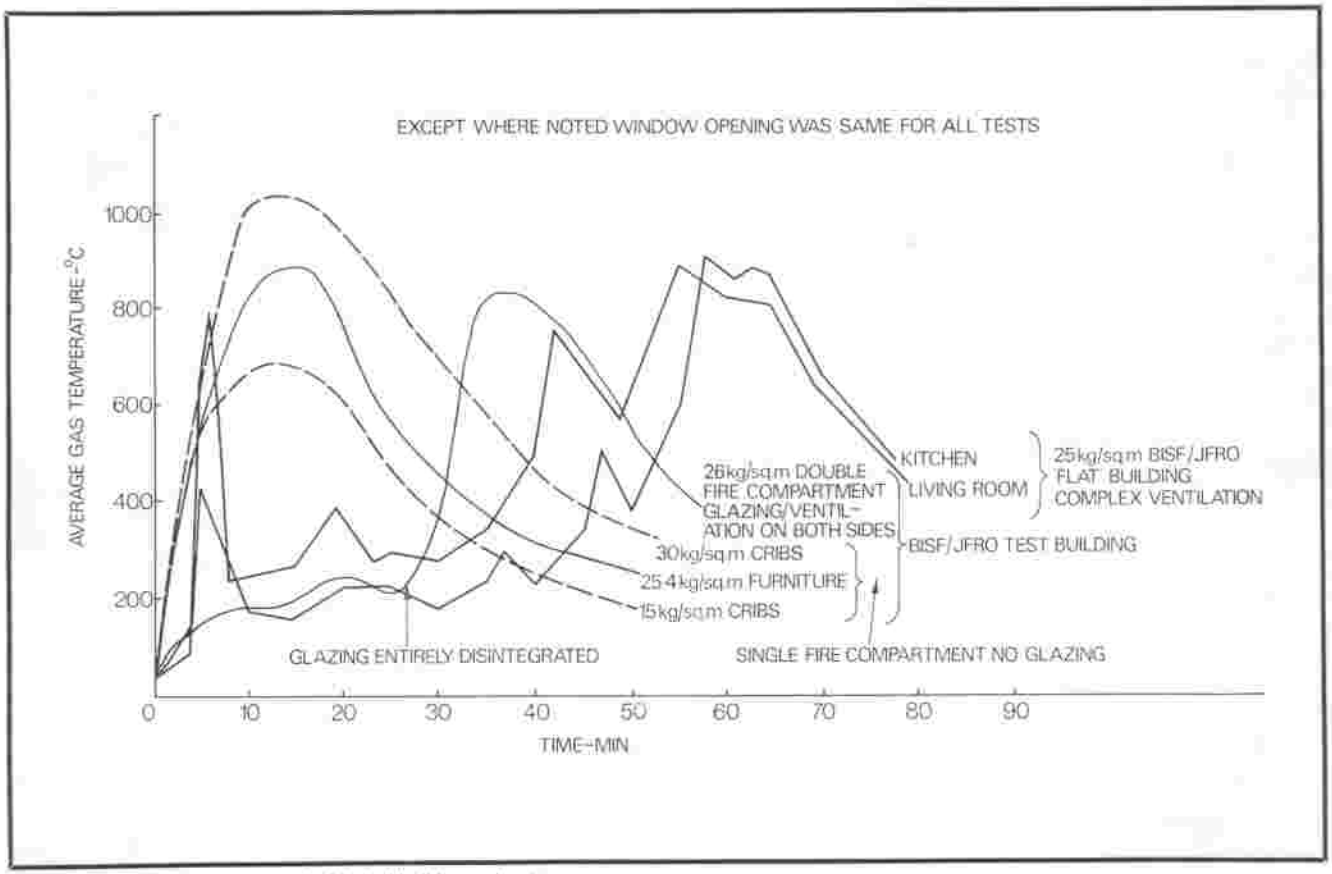


Fig. 6. Average gas temperatures inside test buildings showing
(i) correlation between fires using cribs and furniture, and
(ii) effect of glazing

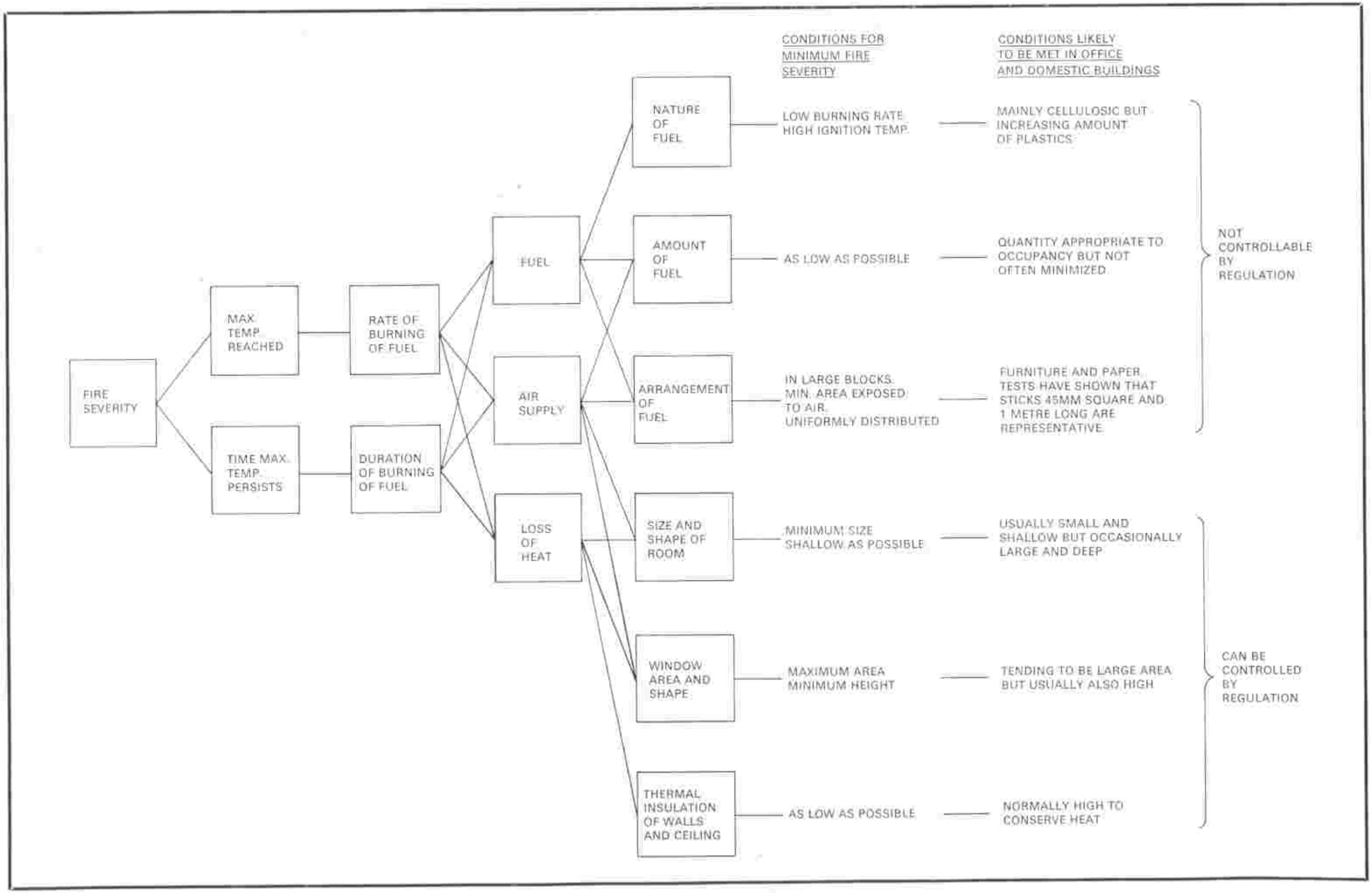


Fig. 7. Factors affecting fire severity

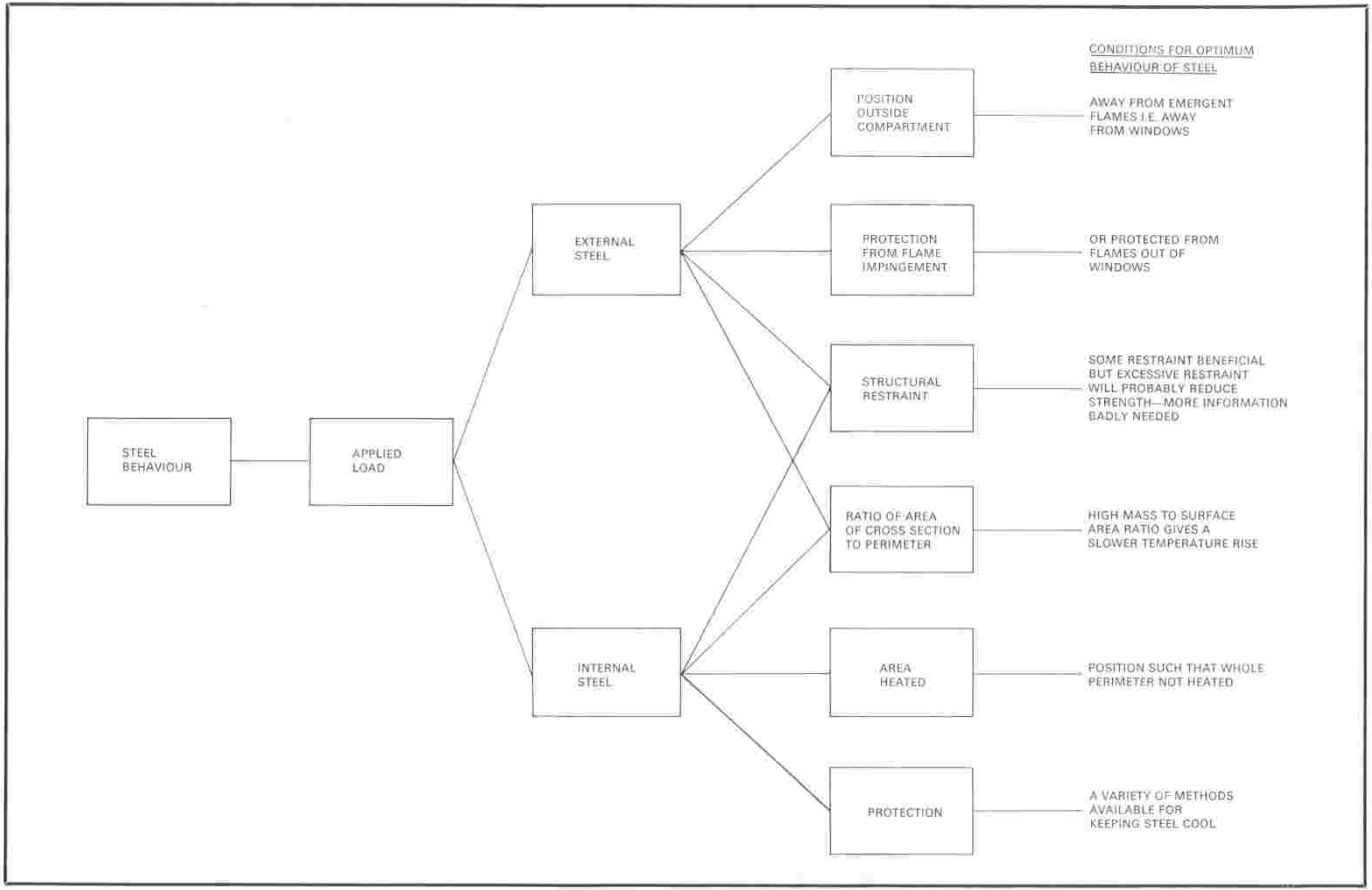


Fig. 8. Factors affecting behaviour of steel in fires

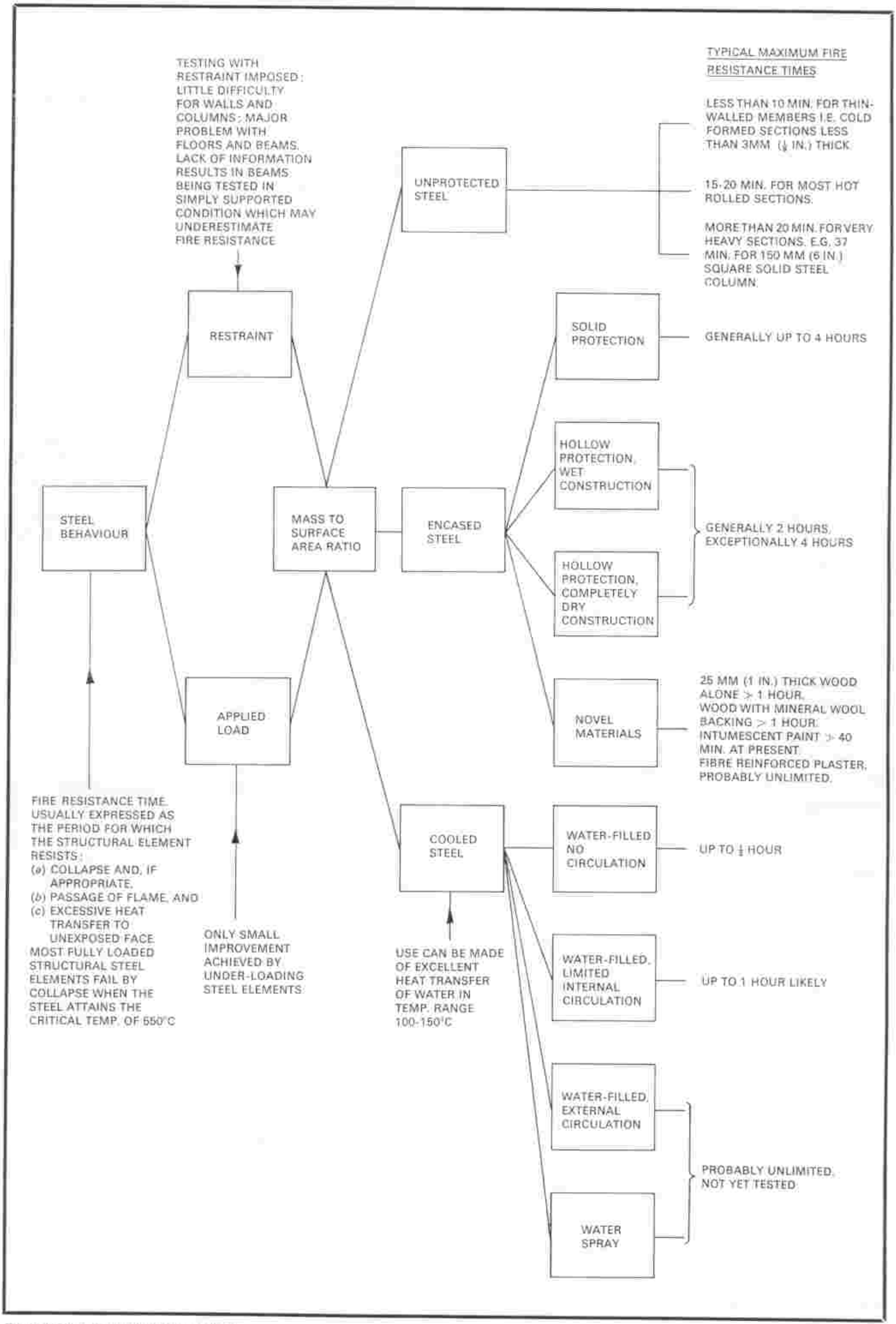
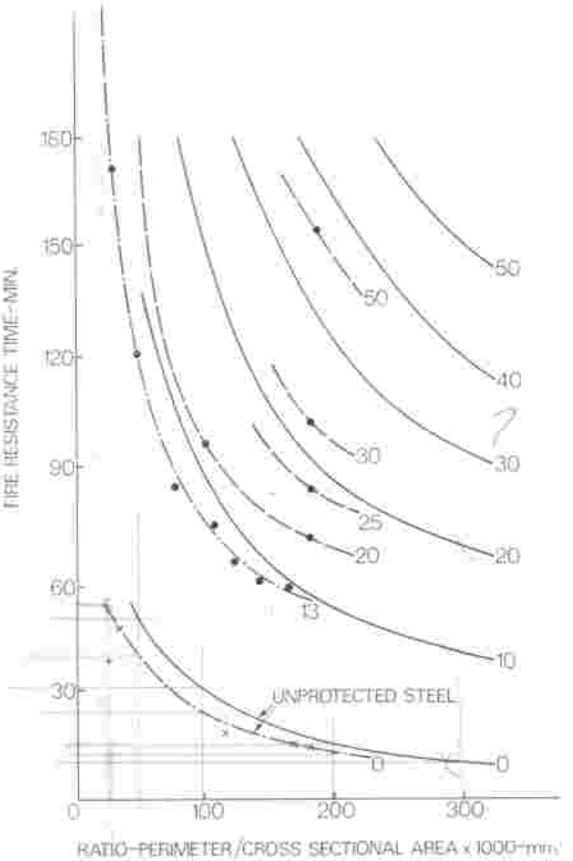


Fig. 9. Behaviour of steel in furnace test



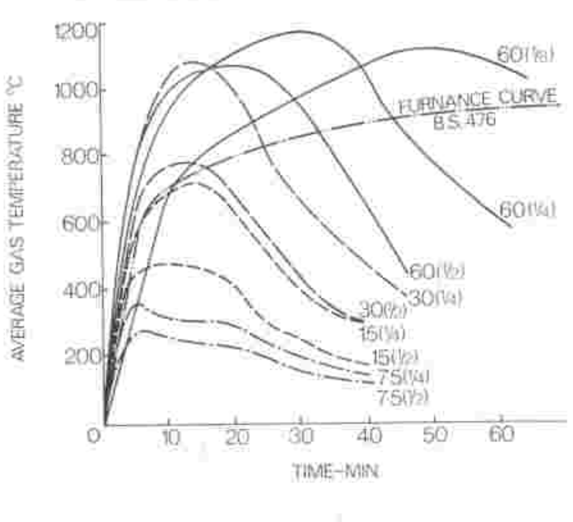
-·-·-·- Fire Research Station results. (Protection used: mineral wool slab).

— — — Braunschweig results. (Protection used: Vermiculite plaster).

——— TNO calculations (7).

Numbers against curves indicate thickness (mm) of protection used.

Fig. 10. Curves showing importance of steel geometry and thickness of protection



xample of curve notation:
30 (½) denotes a fire load density of 30kg/m² (6·2lb/sq. ft) with half of the area of the 7·7m (25ft 3in.) wall open as ventilation.

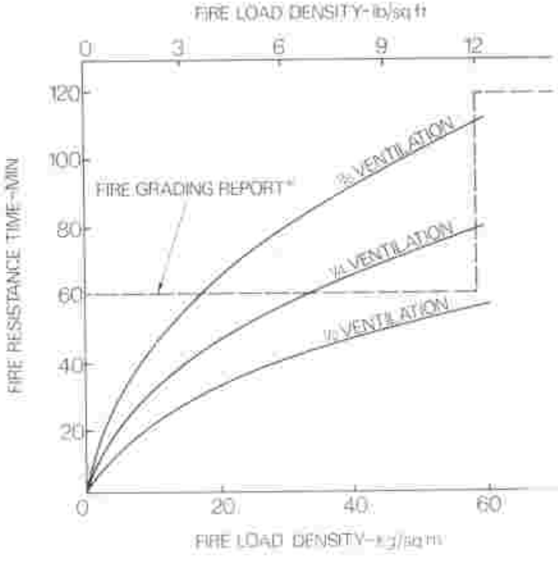
Fig. 11. Average gas temperatures inside single fire compartment using timber cribs compared with standard furnace test

## COMPARISON BETWEEN THE STANDARD FIRE RESISTANCE TEST AND REAL FIRE SITUATION

One of the most important aspects of the programme of research at the Fire Research Station has been the comparison that has been possible between real fire situations and the standard fire resistance test (*Fig. 11*). This comparison, based on a very large number of temperature measurements, shows that the heat transfer process in a real fire is different from that in the furnace test, the luminous flames of the fire giving greater heat transfer in the early stages. It follows therefore that, even if the time-temperature curves (fire and furnace) are similar, a condition that in practice is very rare indeed, it is not possible to equate fire duration to fire resistance time; consequently other means of comparison must be sought.

*Fig. 12* relates the results obtained in fire tests, presented as a function of the fire load density and of the window opening for tests carried out in one size and shape of compartment, to the fire resistance time. To obtain a final meaningful relation, however, the effect of the other factors controlling fire severity must be included. If the above curve can be extended to include higher fire load densities and other sizes and shapes of compartment, and then combined with the knowledge that is now available on fire severity, a basis for predicting the fire resistance required in any given building would be obtained.

This situation is nearly within reach and it will represent a means of rationalizing the specified fire requirements for buildings. Clearly, this must be regarded as one of the very definite benefits, albeit long term, which will accrue to the industry from the research it has sponsored.



*Fire grading of buildings. Part 1. General principles and structural precautions. Ministry of Works Post-War Building Studies No. 20. HMSO, London, 1946.

Fig. 12. Relationship between fire and furnace tests derived from results from protected columns

## UNPROTECTED STRUCTURAL STEEL

It would be of enormous economic benefit to the industry if situations could be identified where unprotected structural steel could be safely used in building structures. One such situation is when the steel members are placed outside the building (*Fig. 13*) but even so care must be taken with their placing.

The research has shown that, when exposed to a fire, unprotected steel columns external to the building will remain cool enough to continue to support design loads, provided they are positioned so that they are protected from direct attack by flames or from severe radiation through windows. Some reservation must be necessary here if the fire situation was very different from the experiment, for instance if the fire compartment had flammable linings or if more than one storey was involved.

*Fig. 14* demonstrates this. Column $C_2$ in this diagram remained below 300°C for all of the tests and was protected from the fire by the centre mullion between the windows, and the effect is shown to a lesser extent on another column ($C_1$) placed in a partly shielded position. Where columns ($C_3$, $C_{19}$ and $C_{20}$) were exposed to flame impingement, the critical temperature of 550°C was soon reached when the fire load densities were above 25kg/sq. m (5lb/sq. ft).

With the present trend in building design to make the whole of the building façade of glass or of curtain walling, the question immediately arises as to how simple can the protection to external steel be or how far must the steel be from the façade to be safe. In one of the later tests in the programme, fully exposed steel columns placed 0·46m (18in.) away from the building façade reached a temperature of only 300°C.

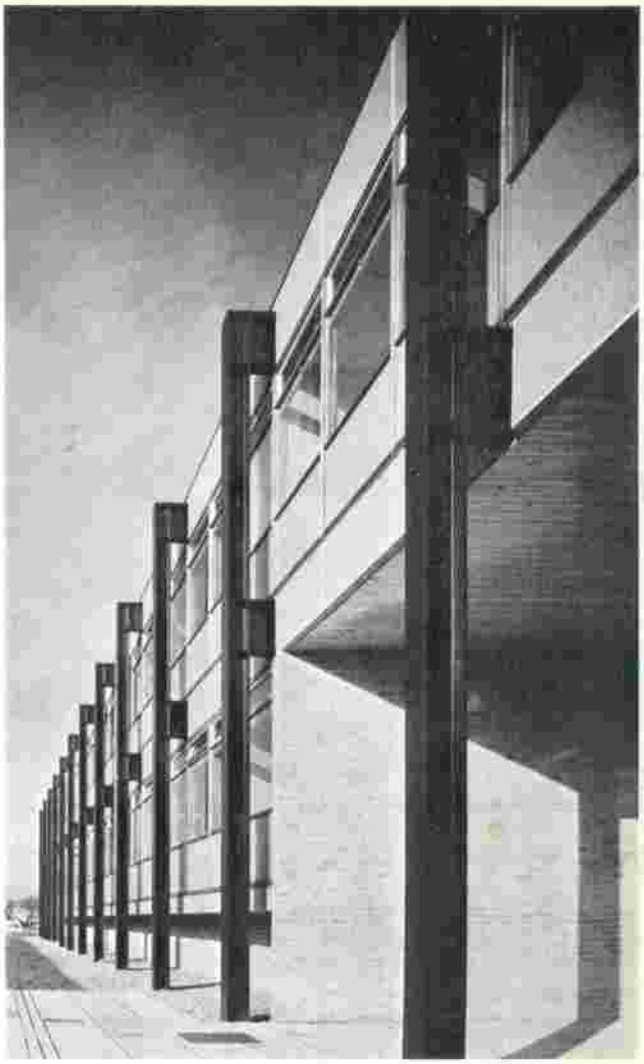
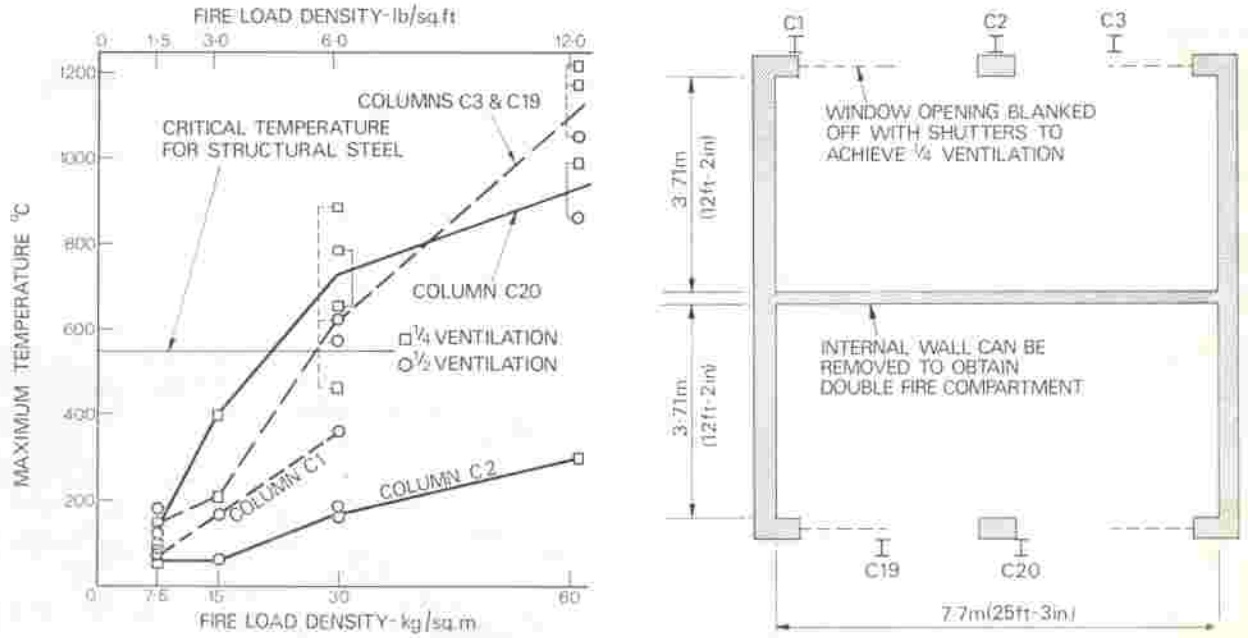


Fig. 13. Typical use of external unprotected steelwork



Horizontal section through walls of BISF/JFRO test building showing location of I section columns in relation to brickwork and shutters.

Fig. 14. Maximum temperatures reached by external unprotected columns in fires of various fire load densities

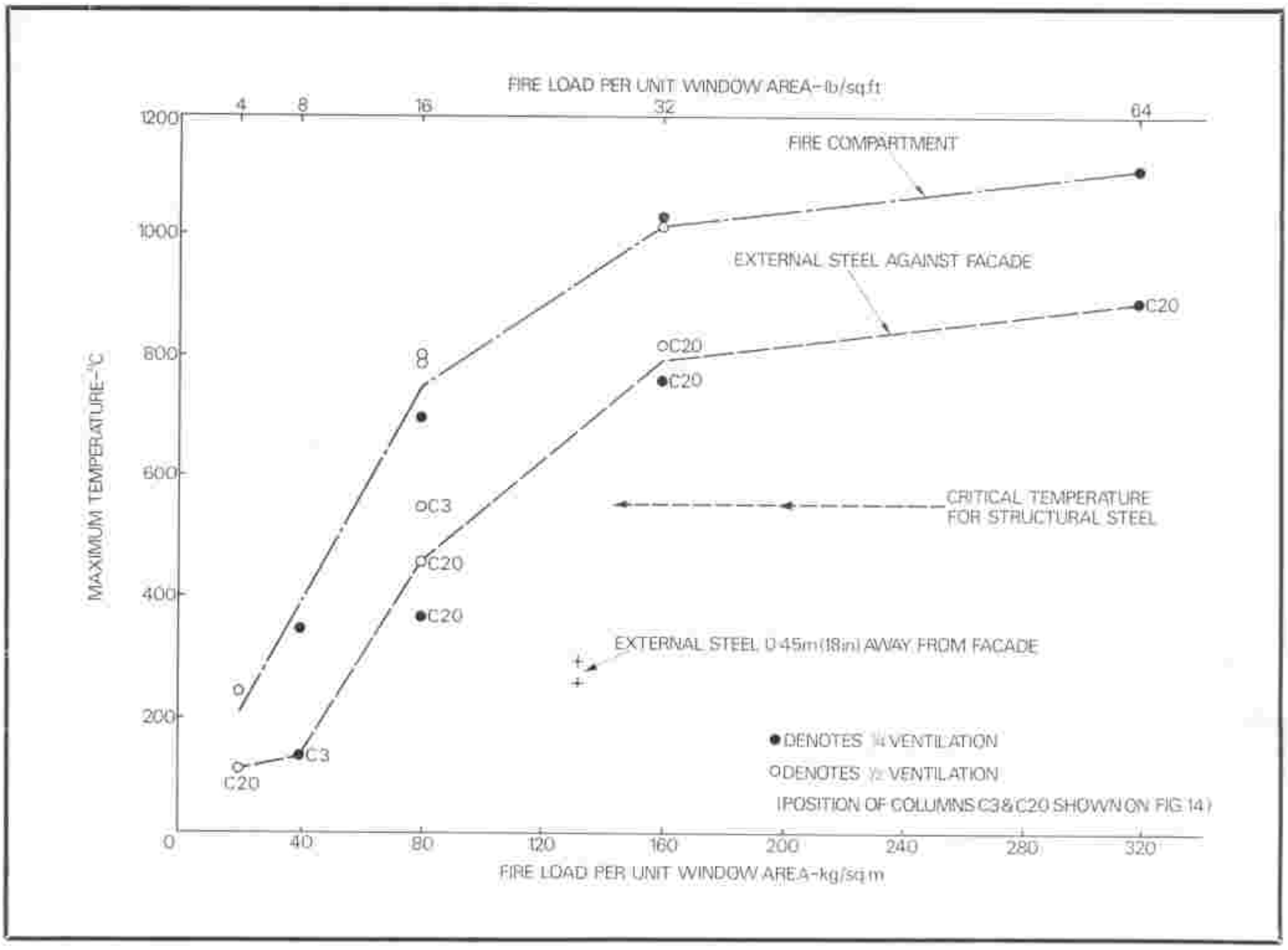


Fig. 15. Maximum temperatures for external unprotected steel columns against façade and away from it

*Fig. 15* shows this result and compares it with that for a column against the façade in a similar but not identical test. The comparison is, however, sufficiently good to illustrate the advantage of placing steelwork away from the façade. In this connexion, information from the work on fire severity is being studied so that criteria for the safe location of external steelwork may be established for all buildings.

The use of unprotected steel inside a building is more difficult to justify, but the work has shown (*Fig. 16*) that in fires with a low fire load density, particularly with large areas of window opening, structural steel would remain below its critical temperature. The size of such fire load densities is lower than those met in offices, housing, hotels, etc. but it was suggested that a car park might well be in this range. An analysis of the combustibles in an average car and the carrying out of additional tests (10) in which cars were ignited in a specially erected building, confirmed that the fire load density was likely to be in the range concerned. Moreover, the danger of spread of fire from one vehicle to another was not high. *Fig. 17* shows one of the fire tests in the simulated car park building.

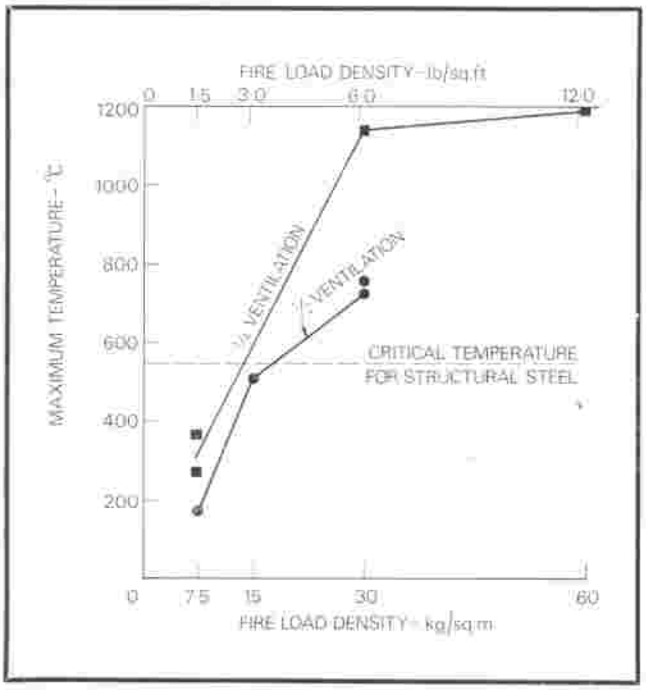


Fig. 16. Maximum temperatures reached by unprotected internal columns for fires of various fire load densities

Fig. 17. Car park fire test

As a direct result of this, the Ministry of Housing and Local Government has issued a circular (11) to Local Authorities which in effect allows unprotected steel to be used in the construction of multi-storey car parks provided they are above ground, open-sided, less than 50ft in height and satisfy certain space separation requirements.

This is an example of a direct benefit from the recent research work which has already become available to the industry. It also illustrates that the use of unprotected steel in building is more likely to be allowed when special categories of building with low fire potential can be identified than by a general relaxation.

Even though some parts of a building may have a fire load density which is in excess of that for which unprotected steel would be safe, there will be, nevertheless, considerable areas of that building where combustibles would not normally be found, or indeed, could not be placed if the law is to be satisfied. The possibility of siting the unprotected steel members so that they come within such areas has been suggested and might possibly be allowed if it can be shown that fire from the other parts of the building could not spread to these areas under any circumstances. Again, it may be advantageous for the building designer to separate with fire resisting construction those parts of a building performing less hazardous functions, thereby taking advantage of the lower fire resistance requirements pertaining. For example, an office attached to a factory may not need to possess the same fire resistance if the buildings are separated with a compartment wall.

## METHODS OF KEEPING STRUCTURAL STEEL COOL

### 1. Conventional casing

The protection of structural steel by encasement in conventional material, e.g. concrete, asbestos, etc, is a familiar and well established process. The Fire Research Station investigations did not include a comprehensive survey of the various materials and systems available, but it did confirm two important features; these were:

(a) that the size and shape of steel section inside the protection is an important factor in designing the protection needed and

(b) that the design of the protection needed can be satisfactorily achieved by calculation (12).

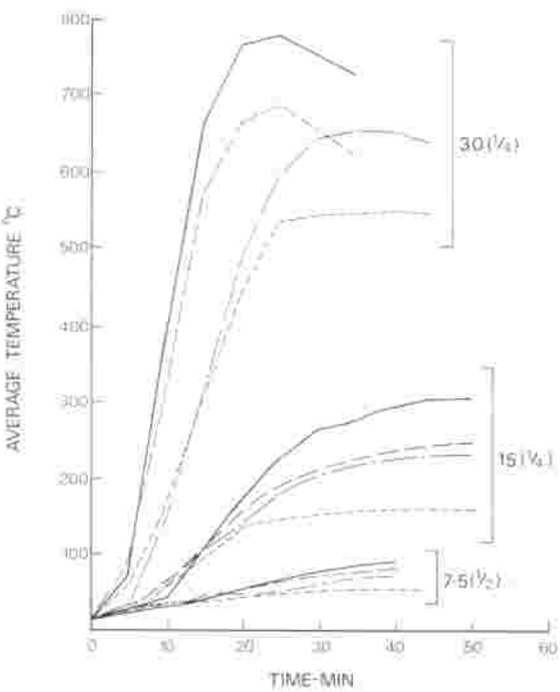
*Fig. 18* shows the important effect of the size of the steel section on the temperature reached by a variety of columns with the same protection.

*Fig. 9* shows diagrammatically the order of the periods of fire resistance obtainable with various forms of protection.

### 2. New materials

The economic pressure to avoid casing structural steel by any method (wet or dry) is well understood and accepted. Nevertheless, there will always be situations where steelwork must be protected and the use of new and more economical materials for this purpose must therefore be watched.

It has been suggested (13) that timber may be used as a protective casing in order to achieve fire resistance of up to one hour, and furnace tests have been reported which support this suggestion. Steel columns with 25mm (1in.) timber cladding were included in some of the fire tests at the Fire Research Station and subsequently a furnace test was carried out. These indicated that the method certainly had some promise, but that the manner of attaching the timber was critical. Partly to alleviate the problem, and to achieve fire ratings in excess of 1 hour, the steelwork may be clad with mineral wool before applying the timber. BISRA, Inter-Group Laboratories of the British Steel Corporation, the Timber Research and Development Association and the Fire Research Station are collaborating in these investigations which will, with the aid of further furnace tests, enable design criteria to be stated. It should be recognized, however, that such encasement may be inappropriate in certain buildings; for instance,



Example of curve notation:

30 (¼) denotes a fire load density of 30kg/m² (6·2lb/sq. ft) with a quarter of the area of 7·7m (25ft 3in.) wall open as ventilation.

——— Rectangular Hollow Section, 102mm × 102mm × 18·75kg/m.

— — — Rectangular Hollow Section, 203mm × 203mm × 43·8 kg/m.

-·—·— Universal Column, 206mm × 204mm × 52kg/m.

- - - - Universal Column, 267mm × 258mm × 107kg/m.

Fig. 18. Average temperatures reached by protected internal columns showing effect of size of section

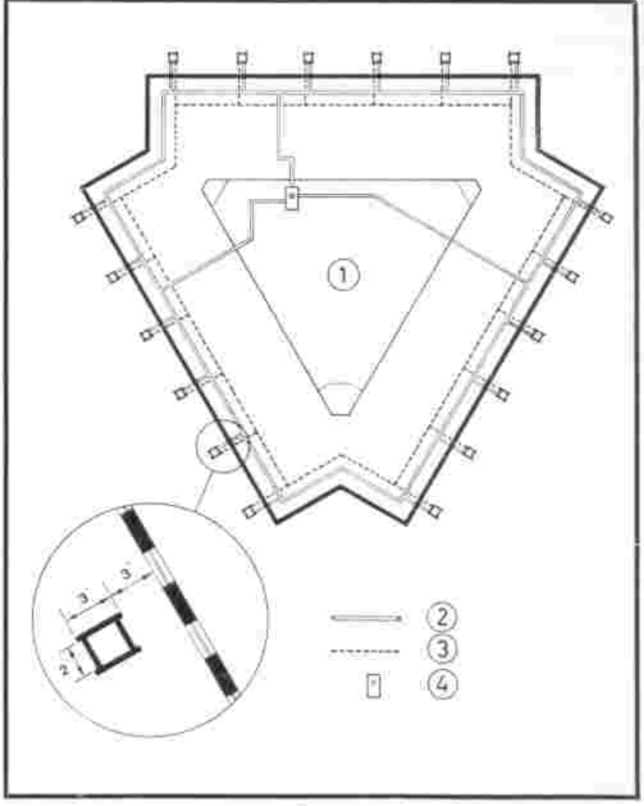


Fig. 19. USS Building, Pittsburgh. Plan showing arrangement for water cooling of external steelwork

where regulations require that combustible materials shall not be used in the construction of compartment floors and walls.

A new form of plasterboard (14) which contains glass reinforcing fibres is now passing through its development stages and this may possibly open the way to the use of plasterboard encasement for structural steel without the need for a secondary coating of plaster applied on the site as is now required. BISRA is extending this work by examining the use of a low cost composite material comprising plaster, sand as a filler, and slag-based mineral wool for reinforcement in fire conditions. It is intended that the material, combining the low cost and excellent insulation features of plasterboard with the integrity of asbestos insulating board, would be produced in board form or in a limited range of sections.

Other new materials which would be used because of their decorative value but which will also give fire resistance, must obviously be continuously sought.

### 3. Intumescent paint

At first sight, the use of a system such as a paint to give fire resistance to steel structural members seems attractive, but at present the materials available give only a short period of fire resistance, typically 30 to 40 minutes, and require several site applied coats to achieve it. An investigation sponsored by the Ministry of Public Building and Works is in hand in which new materials and methods of application are being examined in order to find a process which will give a reasonable period of fire resistance.

### 4. Water cooling

Perhaps one of the most interesting ways of protecting structural steel in fire is by the use of water as a coolant. A few furnace tests sponsored by the industry have been carried out at the Fire Research Station on water-filled columns (15) but otherwise there has been little experimental work on this method. Theoretical surveys of the possibilities have been produced (16, 17) together with the results of one test (18) and proposals for tests in the new furnace erected for Centre Technique Industriel de la Construction Métallique at Maizières-les-Metz are being considered. A multi-storey building over 800ft high is being erected in Pittsburgh for the American steel industry in which the external steel columns are water-cooled. *Fig. 19* is a plan showing the arrangement. It is believed that this is the only instance in which this method has actually been used, although it is understood that others are being planned.

The indications are that simple filling of the hollow members with water does not achieve any significant improvement and that a circulatory system in which the water is cooled outside the member affected by fire is likely to be necessary to obtain significant periods of fire resistance. Another method suggested (19) involves the use of sprinkler-like devices which spray water on to the surface of the steel members to cool them and this may have the advantage that the water is only in contact with the steel when and where it is needed. There are many difficulties associated with these methods, corrosion, freezing, additional pipework, etc, and the cost involved in these extra services may well make it difficult to produce an economically viable system.

## THE FUTURE

It is really only a recapitulation to say that if steel is to be more competitive as a structural material, then the methods of protecting it against fire must be as economical as possible.

To achieve the maximum use of structural steel the industry's thoughts should perhaps be directed towards the following:

1. to seek out the buildings, or the places inside and outside buildings, where unprotected steel can be safely used;
2. to explore economical methods, and if necessary assist in developing them, of keeping structural steel in buildings cool in case of fire; and
3. to collect as much information as possible about the design trends in buildings and the factors likely to affect their fire hazard so that information is available to assist in bringing up-to-date, from time to time, the fire resistance requirements for buildings.

The work which the industry has sponsored has produced a considerable amount of data which has increased knowledge of the factors associated with the problems which arise when fires occur and steel is attacked by them.

Some considerable benefits have already accrued, but much of the information still remains to be put to use, and this must be done by regarding it as being a very firm foundation from which can stem the ideas necessary to find and develop truly economical ways of keeping structural steel safe in fires.

## ACKNOWLEDGEMENT

This paper is contributed by permission of the Director of the Fire Research Station of the Ministry of Technology and Fire Offices' Committee and of the Director of BISRA, Inter-Group Laboratories of the British Steel Corporation. *Figs. 2, 3, 4, 5, 11, 12, 14, 16, 17* and *18* are Crown copyright and reproduced by permission of the Controller, H.M. Stationery Office.

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