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Timber structures and fire

A review of the existing state of knowledge and research requirements

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FOREWORD

Wood is a renewable natural material which has a long
tradition in building technology. From the point of view
of energy, it is superior to non-renewable building mat-
erials. The energy consumed in producing wood, for in-
stance, is only about 10% of that in producing steel.
Wood causes far less damage to the environment than most
other building materials, and residual products from wood
processing amount to only between a quarter and a half of
corresponding residual products from mining and mineral
processing.

About one half of Swedish wood production is utilised
in prefabricated houses, building components and glued
laminated timber - and to a dominant extent in differ-
ent types of loadbearing and separating constructions
and cladding materials. To this must be added a produc-
tion share for building joinery, amounting to about 15%.

Traditionally, wood and wood-based products have been
used to a large extent for private dwellinghouses, and
at present about 90% of private dwellinghouses in Sweden
are made of timber. Up to about 20 years ago the method
of construction was relatively uniform, with the build-
ing frame made in the form of a stud system in loose and
pre-cut timber, and, in some cases, prefabricated wall
blocks, often erected without any internal cladding or
insulation.

In recent decades the methods of building private dwell-
inghouses have increased in number in step with the in-
creased prefabrication of frame systems, and at present
there are about ten system groups ranging from pre-cut
timber to room units. The trend appears to be towards a
further increase in the number of systems.

Changed conditions relating to construction - primarily
problems relating to energy and the shortage of trained
labour on the construction sites - have provided the
initiative for new lines of development for buildings
and building components of which wood and wood-based
products form a part. Examples of these are thin and
composite structural elements of timber, composite con-
struction comprising timber and metal sheeting as load-
bearing elements, and sandwich construction comprising
loadbearing wood-based boards with an infill of foamed
plastics.

Wood and wood-based products, especially glued laminated
timber and sandwich units, are also well suited for
different types of larger structures for large-span and
multistorey buildings, etc. However, in Sweden timber
is not a traditional material in this field, and there
is only limited experience available. In countries such
as Canada, Switzerland, Germany and USA, on the other

large-span industrial, sports and exhibition buildings,
multistorey buildings of up to five storeys, churches
and bridges on rural roads.

Timber construction technology was for a long time an
area in which little research was done, and the amount
of expenditure on research was of very small extent
compared with that relating to steel and concrete con-
struction. Recently, however, the Swedish Board for
Technical Development (STU), together with the timber
industry, came to a decision to allocate considerable
funds for timber research and development over a five
year period, and timber construction technology was
considered to be one of the subject areas in which
development of capability and expansion of knowledge
were important. Two programme proposals, namely
JOHANESSON, C M, "Timber construction technology - re-
search and development needs",STU Information Bulletin
No 207/1981, and GIRHAMMAR, U A, "Large-span buildings
of timber - research and development in the field of
large timber structures", STU Information Bulletin No
293/1982, have been drawn up by commission of STU to
provide the background to this work. The object of
these publications is to initiate projects and to serve
as the basis for the planning of research in the field
of timber construction.

It is essential that fire protection should be given a
central place in future timber construction research.
This is emphasised in the national collective fire
research programme for 1982-84 which has been drawn up
by the Swedish Board for Fire Research (BRANDFORSK).
In order that a planning instrument may be created for
such nationally integrated fire research, BRANDFORSK
has commissioned the Division of Building Fire Safety and
Technology at Lund Institute of Technology to produce a
research programme for the subject area timber structures
and fire.

This report presents such a programme against the back-
ground of a brief review of existing knowledge in this
area. Chapter 1 examines design methods and related
performance requirements and criteria against an inter-
national present state and development perspective, and
draws certain conclusions regarding urgent research pro-
jects of an overriding character. Chapters 2-7 give
corresponding reviews of the state of the art in rela-
tion to the different stages of the design process, and
research projects of a more limited extent, formulated
on the basis of this review, are outlined. Finally,
Chapter 8 summarises the projects and gives brief de-
scriptions of these and the estimated staff requirement
and financial commitment. The interrelationship between
the projects is highlighted, and an outline strategic
plan is presented for an integrated and nationally
coordinated research effort.

Lund, May 1983

Robert Jönsson   Ove Pettersson

1. DESIGN PRINCIPLES, PERFORMANCE REQUIREMENTS AND CRITERIA

1.1 Introductory review

Methods for the design of loadbearing structures under fire exposure conditions, which are applied internationally, may be described in outline with reference to the matrix set out in FIG. 1.1 /1.1/. This is based on three types of thermal exposure (H_1, H_2 and H_3) and three types of loadbearing structure (S_1, S_2 and S_3). The following typical definitions apply.

Model for structure	S_1	S_2	S_3
Model for thermal exposure	Element	Substructure	Complete structure
H_1 ISO-834	test or calculation (deterministic)	calculation exceptionally testing (deterministic)	
H_2 ISO-834	test or calculation (probabilistic)	calculation, exceptionally testing (probabilistic)	calculation (probabilistic) should be avoided
H_3 real fire	calculation (probabilistic)	calculation (probabilistic)	calculation (probabilistic) in special cases and for research

FIG. 1.1. Schematic description of different methods for the design of loadbearing structures under fire exposure conditions.

S_1 - a simplification of a real loadbearing structure by breaking this down into individual elements such as beams and columns which are as a rule simply supported

S_3 - a real loadbearing structure.

H_1 - thermal exposure according to ISO 834 or national
standards corresponding to this /1.2/. This expos-
ure is predominant internationally in practical
design and is based on the results of standardised
fire tests and associated classification. In some
countries it is permissible for such a classifica-
tion to be alternatively based on the results of
analytical calculations. The exposure is defined
by the expression

$$T - T_o = 345 \ \log_{10} \ (8t + 1) \tag{1.1}$$

where

t = time in minutes
T = furnace temperature at time t (°C)
T_o = furnace temperature at time t = 0 (°C)

The time t_{fd} specified for thermal exposure in a
test or corresponding calculation varies according
to the situation concerned, and is laid down in
e.g. the Swedish Building Code (SBN).

H_2 - the same thermal exposure as that according to H_1,
Equation (1.1). The time t_e of thermal exposure is
determined in each individual case by the real fire
process in the fire compartment. In practice, this
is carried out on the basis of the equivalent fire
duration t_e which is defined as the time required
for thermal exposure according to ISO 834 which
produces the same critical effect on the structure
concerned as a real fire. For steelwork, the follow-
ing approximate formula can be used /1.3/:

$$t_e = 0.067 \ \frac{f}{(\frac{A\sqrt{h}}{A_{tot}})^{1/2}} \quad \text{(min)} \tag{1.2}$$

where

f = fire load intensity in the fire compartment in
    MJ/m^2 of enclosing surface
A = total area of window and door openings, m^2
h = mean value of the height of openings, weighted
    with respect to the area of the opening con-
    cerned, m
A_{tot} = total internal enclosing surface of the
        fire compartment inclusive of openings, m^2.

H_3 - exposure due to a real fire. The exposure can be
described in terms of a time curve relating either

be determined on the basis of the heat and mass
balance equations of the fire compartment, or from
available manuals. FIG. 1.2 gives an example of
such data, taken from the Commentary to the Swed-
ish Building Code 1976:1.

To these typical definitions must be added the following
comments regarding the models for thermal exposure, the
H models.

Loadbearing and separating constructions of combustible
material may themselves provide considerable additional
input in the event of fire. This is not taken into con-
sideration in furnace tests according to ISO 834, in
which the input power of the furnace is regulated in
such a way that the prescribed curve of the furnace tem-
perature T as a function of time t conforms to Equation
(1.1). In a given furnace, this requires an input power
which is considerably less in a test on a structure of
combustible material than in a test on a non-combustible
material, particularly if the latter absorbs a large
amount of the input power.

From the point of view of thermal exposure, the time
curve for the heat flow rate supplied to the structure
is critical with regard to the fire behaviour of a struc-
ture. International discussions are therefore taking
place within ISO concerning a possible change to con-
trolling thermal exposure in a furnace test so that it
conforms to such a time curve for the rate of heat flow
towards the element of construction being tested. How-
ever, it is at present difficult to predict whether such
a change is probable.

In order to simplify description of the thermal exposure
on a loadbearing and/or separating construction of non-
combustible material in the event of fire, Harmathy has
introduced the concept of normalized heat load which is
defined by the expression /1.4, 1.5/

$$H_n = \frac{1}{\sqrt{(k\rho C)}} \int_0^\tau q \, dt \qquad (s^{1/2} \, {}^\circ C) \qquad\qquad (1.3)$$

where

q = the heat flow rate towards the constructions enclos-
ing the fire compartment, at time t (W/m^2)
τ = duration of fire exposure (s)
$\sqrt{(k\rho C)}$ = the thermal inertia of the enclosing construc-
tions (J/m^{2}s$^{1/2}$ $^\circ$C), where k = thermal conducti-
vity, ρ = density, and C = specific heat capacity

This concept can be used to quantify the thermal expos-
ure potential, both in conjunction with exposure accord-

The gas temperature-time curves for a real fire, which are exemplified in FIG. 1.2, presuppose a fire compartment of a size applicable to e.g. dwellings, ordinary offices, schools, hospitals, hotels and libraries. In the case of fire compartments of very large volume - e.g. industrial and sports premises - the curves do not give a good representation of the actual fire exposure. This is also true for the gas temperature-time curve (H_1) which is applied in standard fire tests.

In the event of a fire in large premises, a loadbearing structure may be subject to local exposure which is more intense than that described by the gas temperature-time curve according to FIG. 1.2. This may occur mainly in the case of loadbearing structures or elements which are placed in a corner of the premises or which, owing to their great height, form "screens" with intermediate spaces. It is known from real fires - e.g. from the fire at the Star Dust Club discotheque in Dublin on 14 February 1981 - that loadbearing and separating structures may in such an event be subjected to very high levels of exposure, up to 250 kW/m^2.

At present there is no analytical simulation model available which describes in a satisfactory manner the fire process in a fire compartment of large volume. Research in this area is therefore of high priority. This is also emphasised, for instance, in the fire research programme for the period 1982-84, adopted by the Swedish Board for Fire Research (BRANDFORSK), which contains a project B.17 "Fire spread and fire process in large premises", the primary object of which is to collate and evaluate the present state of knowledge in the field of fire physics, identify the need for research, and propose suitable projects. From the point of view of fire physics, work on such a programme consists of two parts. The first relates to the propagation and growth process of the fire, and is mainly based on a combustion technology approach. The second is based on a more refined fluid mechanics approach, and comprises determination of mass flows, temperature and velocity profiles in fire plumes, and gas flows below the ceiling.

In the light of these comments concerning the thermal exposure models, this introductory review is finally summarised by way of some views on the practical relevance of different combinations of H and S models.

As mentioned in the foregoing, the internationally dominant design procedure is based on thermal exposure according to Type H_1. The fire resistance t_{fr} of the loadbearing structure is normally determined by furnace tests according to ISO 834, but analytical calculation of t_{fr} is beginning to be accepted in an increasing number of countries as an alternative. See /1.6/ - /1.11/. The ISO standard has limited application for elements of construction such as beams, columns, walls, floors
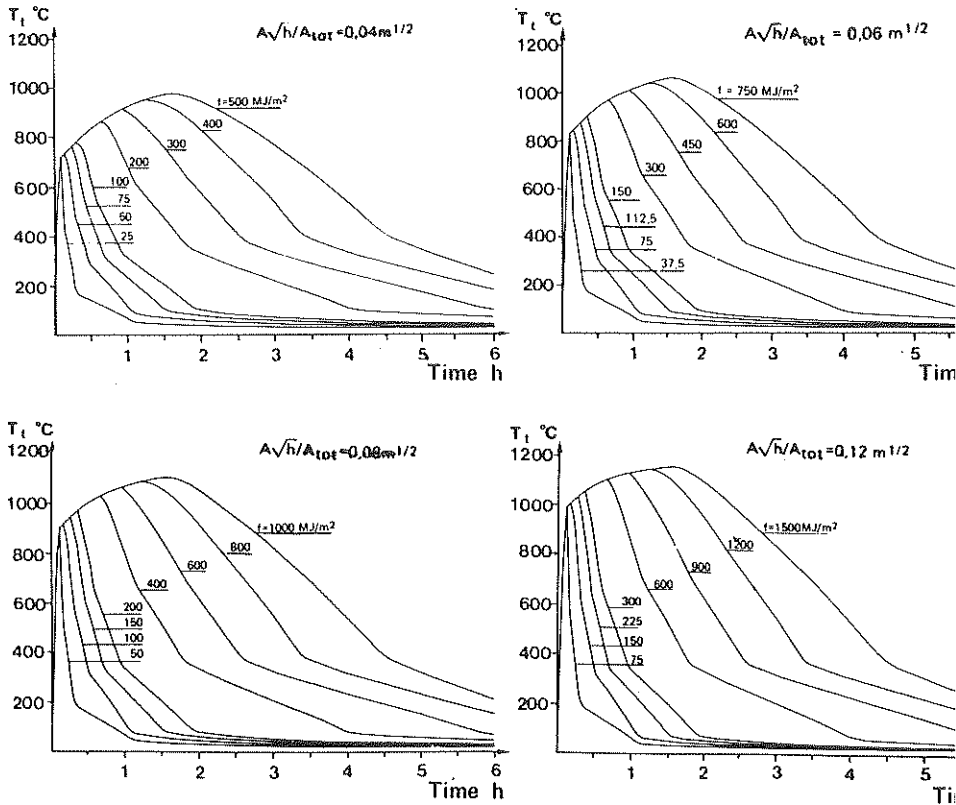
FIG. 1.2. Examples of gas temperature-time curves for a
real fire as a function of the fire load in-
tensity f and the opening factor $A\sqrt{h}/A_{tot}$ of
the fire compartment. According to Commentary
to the Swedish Building Code 1976:1, Fire Com-
partment Type A.

In a few countries, however, application of the proced-
ure has been extended to the combination $H_1 - S_2$, prim-
arily in association with analytical determination of
the fire resistance. The combination $H_1 - S_3$ involves
far too large an imbalance in the description of ther-
mal exposure and loadbearing systems to be acceptable
in practice.

A design based on natural fire exposure - exposure Type
H_3 - is generally characterised by analytical treatment.
For rapid practical application, it is necessary for
systematised design data in the form of e.g. manuals to
be available. In such cases it is usually the combina-
tion $H_3 - S_2$ which is used, and in certain cases the
combination $H_3 - S_1$. Design according to the combination
$H_3 - S_3$ generally demands access to a computer to be

Design for thermal exposure of the H_2 type is based in-
directly on a real fire, described by the temperature-
time curve according to ISO 834, Equation (1.1), with
reference to the concept of equivalent fire duration t_e.
The behaviour of a loadbearing structure, calculated for
such an exposure, is different from its behaviour in a
real fire situation in cases where the heating history
is of significance. In the combination H_2 - S_1 design
can be performed either analytically or on the basis
of a furnace test according to ISO 834. In the combina-
tion H_2 - S_2 analytical design is the normal procedure,
and experimental verification is an exception. The com-
bination H_2 - S_3 is really a roundabout way of approach-
ing a design according to the combination H_3 - S_3, and
should therefore be avoided.

1.2   Internationally accepted conventional design

The internationally accepted conventional design method
of fire design for loadbearing and separating structures
may be summed up by the flow chart in FIG. 1.3.

The fire resistance t_{fr} of the element of construction
is determined by the standardised Nordic test method
NORDTEST FIRE 005 which is identical to ISO 834. The
element of construction is subjected in a furnace test
to thermal exposure according to Equation (1.1) - Type
H_1 - within prescribed tolerances. Heating continues
until the element of construction ceases to comply with
the specified performance requirements, and the time at
which this occurs defines the fire resistance t_{fr} of
the element of construction.

For a loadbearing element of construction, the perform-
ance requirement implies that it shall not collapse at
a time $t \leq t_{fr}$ for the actual load, selected according
to Subclause 21:234 of the Swedish Building Code SBN
1980. For a separating construction the performance
requirement implies that it shall be capable of prevent-
ing the spread of fire to the adjoining fire compart-
ment for a time $t \leq t_{fr}$. As far as the test procedure
is concerned, the performance requirement contains a
sub-requirement concerning resistance to the penetra-
tion of flames and hot gases (the integrity requirement),
and a sub-requirement concerning limitation of tempera-
ture rise on the face of the element of construction
remote from the fire (the insulation requirement).

For an element of construction which has a dual load-
bearing and separating function, all three performance
requirements - the loadbearing, integrity and insula-
tion requirements - must be complied with for $t \leq t_{fr}$.
During design, according to FIG. 1.3, the fire resist-

$$t_{fr} \geq t_{fd} \qquad\qquad (1.4)$$

For loadbearing elements of construction, the prescribed fire resistance classes are set out in Clause 37:32 of SBN 1980. These requirements are differentiated with respect to

o   the type of building

o   the magnitude of fire load

o   the number of storeys and the vertical position of the element of construction in the building

o   the consequence of the failure of the element of construction.

Similarly, for elements of construction with a separating function, the prescribed fire resistance classes are set out in Subclause 37:422 of SBN 1980.
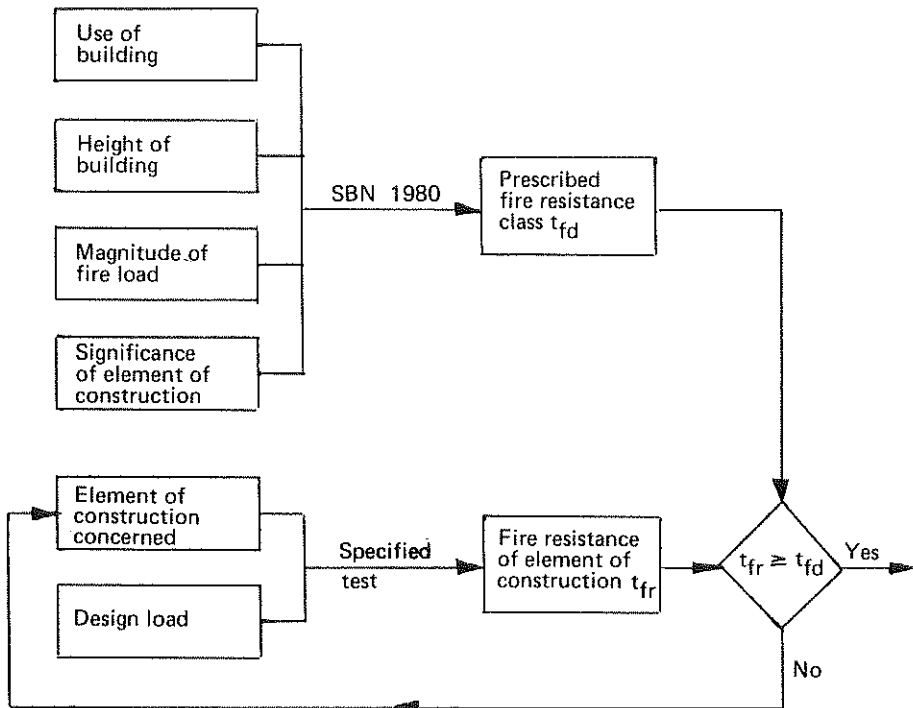
FIG. 1.3. Internationally accepted conventional design

1.3   Analytical design based on real fire exposure

In the last few decades, great advances have been made
in the field of analytical fire design of loadbearing
structures. The aim is to devise a design procedure
which is based on the properties of the real fire pro-
cess - exposure Type H_3 - the structure of which agrees
with the design technique normally applied for the mode
of action and loadbearing capacity of structures at
ordinary temperatures.

FIG. 1.4 gives an outline of the calculation procedure.
During design the least loadbearing capacity R_d of the
structure during a fire is calculated, and this is com-
pared with the design load effect S_d during the fire.

The design thermal exposure to which a loadbearing struc-
ture is subjected in the event of fire in a fire compart-
ment is determined partly by the design fire load inten-
sity f and partly by the properties of the fire compart-
ment. The critical influence exerted by the fire com-
partment is due partly to the opening factor which is
a function of the height and area of window and door
openings, and partly to the thermal properties of the
constructions enclosing the fire compartment, i.e. the
type of fire compartment. See FIG. 1.2.

For a loadbearing structure whose properties are speci-
fied, the design fire exposure, together with data con-
cerning the thermal properties of the material contained
in the loadbearing structure and the surface heat trans-
fer conditions relating to the free surfaces of the load-
bearing structure, provides the basis required for deter-
mination of the temperature field of the loadbearing
structure as a function of time. When the mechanical pro-
perties of the loadbearing material at elevated tempe-
ratures are known, this temperature field can be con-
verted by calculation into the stress-strain curve at
varying temperature and load levels of the loadbearing
structure when this is exposed to fire. If this is then
related to a failure criterion, the variation in time
of the loadbearing capacity of the structure can be cal-
culated.

The least value of this during the fire defines the
design loadbearing capacity R_d which is to be compared
with the design load effect S_d in the event of fire.
The design requirement is that

$$R_d \geq S_d \qquad\qquad (1.5)$$

In general, SBN 1980 permits analytical fire design of
loadbearing structures according to the procedure set
out in FIG. 1.4 as an alternative to the conventional
international design according to Section 1.2. The de-

associated regulations for fire load intensity, loads
and loadbearing capacity are given in Subclauses 21:234
and 37:332 b of SBN.

Practical application of the design method is made easier
by manuals granted type approval by the Swedish Board of
Physical Planning and Building /1.12/, /1.13/.
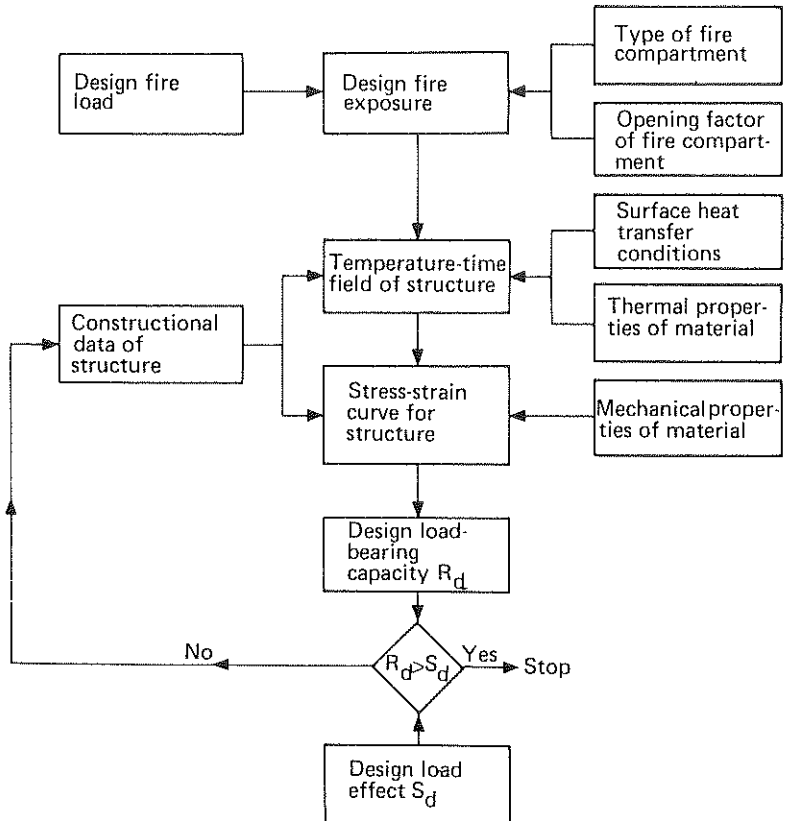
FIG. 1.4. Flow chart for analytical fire design of load-
bearing structures on the basis of real fire
exposure.

1.4   Design based on the concept of equivalent
        fire duration

As described in detail in Section 1.3, the Swedish Build-
ing Code permits analytical design of loadbearing and

which is based on the results of fire tests according
to ISO 834. In the as yet rare cases where similar ana-
lytical design is accepted in other countries, this is
as a rule associated with the concept of equivalent
fire duration - thermal exposure Type H_2. The equivalence
is defined with reference to the criterion that the real
fire and a thermal exposure according to ISO 834, Equa-
tion (1.1), shall produce the same critical effect with
respect to the relevant limit state in the structure
concerned.

For design based on the concept of equivalent fire dura-
tion t_e, the general requirement is that

$$t_{fr} \geq t_e \qquad\qquad (1.6)$$

where t_{fr} is the fire resistance of the element of con-
struction, determined in a fire test according to ISO
834 or by corresponding calculation.

This requirement holds for both loadbearing and separat-
ing elements of construction.

In an accurate treatment, the equivalent fire duration
t_e depends both on the parameters of the fire and on
the constructional details of the element of construc-
tion /1.3/. For a more approximate treatment, formulae
of the type exemplified by Equation (1.2), which are
independent of the constructional details of the load-
bearing structure, can be used. Approximate formulae of
this type which are available have been verified as
reasonable for loadbearing structures of steel and for
reinforced concrete beams in which flexural failure is
initiated by yield of the reinforcement. For other types
of loadbearing structure and for elements of construc-
tion with a separating function, the concept of equi-
valent fire duration is as yet incomplete or has not
been studied at all.

1.5 Fire design of loadbearing structures according to probabilistic methods

For some years, work has been carried out on existing
design methods for loadbearing structures exposed to
fire so that they may be adapted to modern safety theory
methods of the type which has begun to be applied for
the design of loadbearing structures in ordinary tempe-
rature conditions /1.14/ - /1.20/.

In order that such a development may be meaningful, the
design method must be made up of functionally well de-

procedure based on the results of fire tests according
to ISO 834 or on corresponding calculation results -
the H_1 method - does not meet this fundamental require-
ment. On the other hand, the methods described in Sec-
tions 1.3 and 1.4, which are directly or indirectly
based on the characteristics of real fires - the H_3 and
H_2 methods - lend themselves to further development in
this respect.

For methods which are to be used in normal practical
application, the natural aspiration level is thus to
aim for the development of probabilistic methods in
which the statistical influences are taken into consi-
deration by means of characteristic values and partial
safety coefficients specified for the quantities in-
volved - loads, fire load, geometrical quantities, ther-
mal properties, strength properties. For the derivation
of the values of the partial safety factors, a probabi-
listic analysis based on some first order reliability
method (FORM) is needed.

In such an analysis, the design criterion is that in the
event of fire exposure a specified least safety margin
shall be maintained with respect to the least loadbear-
ing capacity of a loadbearing structure, and with respect
to the highest temperature on the side of a separating
construction remote from the fire. Expressed in terms
of a safety index - defined as the ratio of the mean
value of the safety margin to its standard deviation -
the design criterion has the form

$$\beta_{fm} - \beta_r \geq 0 \qquad\qquad\qquad (1.7)$$

where β_{fm} is the least value of the safety index during
the fire sequence involved, and β_r the specified value
of the safety index.

Exemplified for a loadbearing structure of timber which
is exposed to fire and which is designed according to
the H_3 method (FIG. 1.4), a safety index analysis can
be described in outline by FIG. 1.5.

On the basis of the magnitude and properties of the fire
load and the geometry, ventilation and thermal charac-
teristics of the fire compartment, the fire exposure is
determined - described, for instance, in terms of the
combustion gas temperature-time curve. In the next step,
the reduced cross section of the loadbearing structure
and the associated transient temperature and moisture
conditions are calculated for this fire exposure on the
basis of data relating to the configuration of the load-
bearing structure and the thermal, moisture mechanics
and combustion properties of the material of the load-
bearing structure as input quantities. Using the strength
and deformation properties of the loadbearing material

e.g. the bending moment $M_R(t)$ at a critical section of the loadbearing structure.

The load which is statistically representative of the fire situation produces a maximum load effect with an associated bending moment $M_S(t)$ at the section where $M_R(t)$ is applied. This permits definition of the safety margin

$$Z(t) = M_R(t) - M_S(t) \tag{1.8}$$

the risk of failure

$$P(t) = \int_{-\infty}^{0} f_Z \{Z(t)\} \, dZ \tag{1.9}$$

and the safety index

$$\beta_f(t) = \phi^{-1}\{1 - P(t)\} \tag{1.10}$$

where

$f_Z \{Z(t)\}$ = the distribution function for the safety margin $Z(t)$
ϕ^{-1} = the inverse of the standardised normal distribution.

In determining $Z(t)$, $P(t)$ and $\beta_f(t)$, the following factors must be taken into consideration:

o   the uncertainty in specifying the fire load

o   the uncertainty in describing the ventilation properties of the fire compartment and the thermal characteristics of the constructions enclosing the fire compartment

o   the uncertainty in the analytical model for determination of the fire process and its thermal effect on the structure

o   the uncertainty in specifying the geometry and imperfections of the structure

o   the uncertainty in specifying the thermal, moisture mechanics, combustion and mechanical properties of the structural material at elevated temperatures

o   the uncertainty in the analytical models for determination of the transient temperature and moisture states and the loadbearing capacity of the structure

o   the uncertainty in specifying the load

Fire load intensity f

Properties of fire compartment

Fire exposure T - t

Thermal, moisture mechanics and combustion properties of timber

Constructional data of structure

Size of reduced cross section and associated temperature and moisture states

Surface heat transfer conditions

Loadbearing capacity $M_R(t)$

Strength and deformation properties

Load

Safety margin $Z(t) = M_R(t) - M_S(t)$

Risk of failure $P(t)$

Safety index $\beta_f(t)$

Maximum load effect $M_S(t)$

Minimum value of safety index βfm

$\beta_{fm} \geq \beta_r$

Required value of safety index β_r

FIG. 1.5. Derivation of partial safety factors for a timber structure under fire exposure conditions on the basis of a safety index analysis.

The required value of the safety index β_r depends on
the consequences of failure in the structure, the pro-
bability of occurrence of a fully developed fire, the
attendance time of the fire brigade, and the effect of
an automatic fire extinguishing system.

For design according to one of the H_2 methods, a proce-
dure based on partial safety factors may be summarised
in terms of the design criterion

$$\frac{t_f}{\gamma_f} \geq \gamma_n \gamma_e t_e \tag{1.11}$$

where t_f is the fire resistance of the loadbearing or
separating construction, determined experimentally in
accordance with ISO 834 or by a corresponding calcula-
tion, and t_e is the equivalent fire duration determined,
for instance, from Equation (1.2). γ_f, γ_n and γ_e are
partial safety factors which together allow for all the
uncertainties inherent in the design process.

The partial safety factor γ_e obviously refers to the
uncertainties due to specification of the characteris-
tics of the fire load and fire compartment, and to the
uncertainties in the analytical model for the determi-
nation of the associated fire exposure. The partial
safety factor γ_f allows for uncertainties in specifying
the load and the thermal, moisture mechanics, combustion
and mechanical properties of the structural material,
and the uncertainties in the analytical models which
determine the load effect, the transient temperature
and moisture processes, and the loadbearing capacity of
the structure. The partial safety factor γ_n takes into
consideration the consequences of failure and the pro-
bability of occurrence of a fully developed fire, and
the effect on this of the attendance time of the fire
brigade and, if installed, an automatic fire extinguish-
ing system.

1.6   Urgent research projects within the over-
         riding area relating to loadbearing and sepa-
         rating constructions in the event of fire

It will be evident from the above

o   that fire classification of elements of construct-
        ion based on analytical treatment instead of the
        results of furnace tests according to ISO 834 -
        FIG. 1.3 - is gradually being permitted in an in-
        creasing number of countries,

o   that, in Sweden, analytical fire design of load-

minant design procedure based on standardised ther-
mal exposure according to ISO 834, FIG. 1.4, with
the fire exposure exemplified by FIG. 1.2. This
method is now beginning to gain a foothold in other
Nordic countries, and is part of the instruction at
a number of foreign universities,

o   that international development is in progress to
     adapt these analytical design methods, based on a
     real fire sequence, to modern safety philosophy -
     FIG. 1.4 and 1.5 in combination,

o   that development in Sweden in this respect is related
     to a direct design procedure according to the flow
     chart in FIG. 1.4, while in some non-Nordic countries
     development is taking place in association with an
     indirect design method in which a real fire sequence
     and thermal exposure according to ISO 834 are coupled
     by means of the concept of equivalent fire duration.

Analytical determination of the behaviour and loadbearing
capacity in the event of fire of loadbearing elements
of construction is today a practical possibility - as
a rule with relatively little labour - for most types
of steel structure. For loadbearing structures of re-
inforced and prestressed concrete the present design
data are obviously inadequate. However, at the Division of
Building Fire Safety and Technology, Lund Institute of
Technology, design and development work has been taking
place for some years on the production of a manual for
analytical design of fire-exposed concrete structures,
and it is expected that this will be ready in 1983.
The manual gives systematic data both for determination
of the fire resistance of elements of construction in
conjunction with thermal exposure according to ISO 834,
and for analytical design of a loadbearing structure
on the basis of a real fire, adapted to modern loading
and safety regulations /1.21/. For similar adaptation
of the manual for fire design of steel structures, pub-
lished in 1976 /1.12/, the Swedish Institute of Steel
Construction has been allocated funds by BRANDFORSK.
With regard to design calculations for loadbearing and
separating structures in large premises, reference is
to be made to the comments given in Section 1.1.

With regard to the concept of equivalent fire duration,
the present state of knowledge verifies practical app-
lication of this only for steel structures and rein-
forced concrete beams subject to certain modes of fail-
ure.

For timber structures exposed to fire, fire resistance
and loadbearing capacity can at present be calculated
approximately for beams and columns of solid cross sec-
tion. For lightweight and composite timber structures,
even this is impossible. Probabilistic fire design and
the concept of equivalent fire duration are research
areas which are at present practically untouched as

It is of urgent necessity that knowledge concerning the behaviour and design of timber structures under fire exposure conditions should be developed to a level similar to that for steel and concrete structures. This is essential in order that steel, concrete and timber may in the future be able to compete on equal terms as materials for loadbearing and separating constructions.

With regard to types of problem, development towards such a balanced state of knowledge may be broken down into the following overriding research projects:

(1) Development of methods for analytical determination of the fire resistance of elements of construction of timber in conjunction with thermal exposure according to ISO 834.

(2) Development of methods for fire design of loadbearing and separating timber constructions on the basis of a real fire.

(3) Production of data for determination of the equivalent fire duration for elements of construction of timber.

(4) Further development of the design method according to (2) with a view to adapting this to modern loading and safety regulations based on probabilistic methods.

Projects (1) and (2) comprise broadly related research projects and should therefore be treated in parallel. Project (3) is based on the results of Projects (1) and (2). Project (4) necessitates as its basis a design method made up of functionally well defined and verified analytical models of the type applicable to Project (3).

On the basis of an international assessment, all four research projects are of great urgency. Nationally, Project (3) has a lower degree of priority than the others as a result of the fire design philosophy decided on in the Swedish Building Code.

The overriding research projects (1), (2) and (3) each contain a number of subprojects with well defined areas. In the order in which they are encountered in a design process according to FIG. 1.4, these are

o   Development of an analytical model for calculation of the rate of charring under variable thermal exposure, and production of material data for such a model,

o   development of an analytical model for calculation of transient temperature and moisture states for uncharred portions of the cross section, and production of material data with respect to heat and moisture transfer for such a model,

o   analysis of the physical and chemical mechanisms
           involved in the action of flame retardants, and
           determination of the possibilities of optimum inter-
           action between different mechanisms,

o   development of an analytical model for calculation
           of the behaviour and loadbearing capacity under
           fire exposure conditions of solid, lightweight and
           composite timber structures with the above models
           for rate of charring, heat and moisture transfer
           and the mechanical behaviour of timber as the com-
           ponents,

o   development of analytical models for the thermal
           and mechanical behaviour of joints and connections
           under fire exposure conditions.

Most of these projects can be dealt with as independent
research tasks. If this is done, it is essential that
the individual tasks should be planned in view of the
fact that, in practical application, they are to be in-
tegrated components of a total design process. All pro-
jects include experimental verification at model or full
scale as an essential and obvious element. It is impor-
tant in this connection that the possibility of making
use of published experimental results for such verifi-
cation should be fully examined.

The overriding design project No (4) contains, as part
of a process of deriving partial safety factors for
timber structures, an analysis of

o   the uncertainties in the analytical models for cal-
           culation of the rate of charring, heat and moisture
           transfer, and mechanical behaviour and loadbearing
           capacity,

o   the uncertainty in specifying the combustion, ther-
           mal, moisture mechanics and structure mechanics
           material properties,

o   the mutual significance of the uncertainties in the
           various design components, with a view to ascertain-
           ing the parts of the design process on which research
           should concentrate.

The research tasks comprised in these overriding research
projects are described in greater detail in the following
chapters.

REFERENCES

/1.1/   WITTEVEEN, J, "A Systematic Approach Towards
         Improved Methods of Structural Fire Engineer-
         ing Design". ISO/TC92/SC2/WG2 Document N37,
         1982.

/1.2/   ISO 834 "Fire Resistance Tests - Elements of
         Building Construction". Geneva, 1975-11-01.

/1.3/   PETTERSSON, O, "The Connection Between a Real
         Fire Exposure and the Heating Conditions accord-
         ing to Standard Fire Resistance Tests". Euro-
         pean Convention for Structural Steelwork, Chap-
         ter II, CECM-III-74-2E.

/1.4/   HARMATHY, T Z, "The Fire Resistance Test and
         Its Relation to Real-World Fires". Fire and
         Materials, Vol. 5, No 3, 1981.

/1.5/   MEHAFFEY, J R, HARMATHY, T Z, "Assessment of
         Fire Resistance Requirements". Fire Technology,
         Vol. 17, No 4, 1980.

/1.6/   BARTHÉLÉMY, B, KRUPPA, J,"Resistance au Feu des
         Structures - Béton, Acier, Bois". Édition
         Eyrolles, Paris, 1979.

/1.7/   CSTB, "Méthode de Prevision par le Calcul du
         Comportement au Feu des Structures en Béton".
         Document Téchnique Unifié, Paris, 1980.

/1.8/   TWILT, L, WITTEVEEN, J, "Brandveiligheid Staal-
         constructies". Staalcentrum Nederland, 1980.

/1.9/   ACI, "Guide for Determining the Fire Endurance
         of Concrete Elements". Concrete International,
         February 1981.

/1.10/   ECCS, "European Recommendations for the Fire
         Safety of Steel Structures - Level 1: Calcula-
         tion of the Fire Resistance of Load Bearing
         Elements and Structural Assemblies Exposed to
         the Standard Fire". Elsevier, 1982.

/1.11/   CEB, "Design of Concrete Structures for Fire
         Resistance". Appendix to the CEB Model Code,
         Bulletin d'Information No 145, Paris, 1982.

/1.12/   MAGNUSSON, S E, PETTERSSON, O, THOR, J, "Fire
         Engineering Design of Steel Structures".
         Manual, Swedish Institute of Steel Construction,
         Stockholm 1976.

/1.13/   PETTERSSON, O, ÖDEEN, K, "Brandteknisk dimen-
         sionering - principer, underlag, exempel" (In
         Swedish). (Fire engineering design - principles,
         data, examples). Liber förlag, Stockholm 1978.

/1.14/   MAGNUSSON, S E, PETTERSSON, O, "Functional
         Approaches - An Outline". CIB Symposium on Fire
         Safety in Buildings: Needs and Criteria, held
         in Amsterdam 1977-06-02/03, Publication 48,

/1.16/   MAGNUSSON, S E, PETTERSSON, O, "Rational Design
         Methodology for Fire Exposed Load Bearing Struc-
         tures". Fire Safety Journal, Vol. 3, No 4,
         March 1981.

/1.17/   PETTERSSON, O, "Reliability Based Design of
         Fire Exposed Concrete Structures". Contemporary
         European Concrete Research, Stockholm, June
         9-11, 1981.

/1.18/   CIB W14, "A Conceptual Approach Towards a Pro-
         bability Based Design Guide on Structural Fire
         Safety". CIB W14 Workshop "Structural Fire
         Safety", to be published in Fire Safety Journal.

/1.19/   BROZZETTI, J, LAW, M, PETTERSSON, O, WITTEVEEN,
         J, "Safety Concept and Design for Fire Resist-
         ance of Steel Structures". IABSE Surveys
         S-22/83, Zurich, February 1983.

/1.20/   PETTERSSON, O, JÖNSSON, R, "Fire Design of
         Wooden Structures". International Seminar
         "Three Decades of Structural Fire Safety",
         held at the Fire Research Station, Boreham-
         wood, Herts, UK, 22/23 February 1983, pp.
         229-246.

/1.21/   ANDERBERG, Y, PETTERSSON, O, THELANDERSSON,
         S, WICKSTRÖM, U, "Brandteknisk dimensionering
         av betongkonstruktioner". (In Swedish). (Fire
         design of concrete structures). Manual, in
         the course of preparation.

2.   IGNITION

2.1   Introduction

Prediction of whether or not ignition will occur due to
different external thermal exposures is a very complex
problem. A large number of factors influence the processes
leading up to ignition, and it is impossible to devise
unambiguous ignition criteria which are valid in all
cases. In addition, the definition of ignition varies
between different investigations, and this makes com-
parison of experimental data difficult. NBS defines the
ignition temperature as the lowest temperature from which,
under favourable conditions, a material spontaneously
heats up until glowing or flaming occurs. According to
Graff /2.1/, ignition is defined as "when the rate of
heating in the substrate exceeds the rate of external
heating and has visible flaming or glowing as a result".
There are also other definitions.

The most important aim of studies of the ignition pro-
cess is to develop verified theories and methods which
permit determination of whether ignition will take
place as a result of a specific exposure, and whether,
after ignition, the material will continue to burn (sus-
tained flaming). Experiments which have been carried out
had the object of ascertaining the time to ignition for
materials subject to external thermal exposure. The in-
fluence of various factors on ignition time was studied,
and an endeavour was also made to determine a specific
ignition temperature. Ignition theories have been pre-
sented, but owing to the high degree of complexity of
the problem these have produced complicated results with
many factors of uncertainty. The foremost reason for
this is that wood under thermal exposure constantly
changes. The theories have been found most useful for
the study of flame spread expressed in terms of a series
of successive ignitions. The ignition temperatures es-
tablished for wood based materials are mainly useful for
purposes of classification. On the other hand, they cannot
be used for precise prediction of the behaviour of a mate-
rial in a real fire situation.

2.2   Different types of ignition

In determining ignition criteria, a distinction can be
made between two types of ignition, one with and one
without a pilot. In the pilot case, a small flame is
placed immediately in front and above the material un-
der test. Ignition occurs when a flammable gaseous mix-
ture of decomposition products and air reaches the flame.
The flame may also be in direct contact with the surface,

a developed fire. Ignition without a pilot is designated
spontaneous ignition, and occurs when the gaseous mixture
itself has attained a high enough temperature to ignite.
Spontaneous ignition can be further broken down into two
cases depending on the time of exposure. These different
types of ignition are set out in FIG. 2.1. Spontaneous
ignition is of the greatest importance for the study of
flame spread between separated objects. Ignition both
with and without a pilot occurs in a similar manner.

```
┌──────────────────┐        ┌──────────────────────┐
│ Pilot ignition   │        │ Spontaneous ignition │
│                  │        └──────────────────────┘
│                  │              ╱        ╲
│                  │        ┌───────────┐  ┌──────────────────┐
│ Surface ignition │        │ Fire      │  │ Non fire         │
└──────────────────┘        │ condition │  │ condition        │
                            └───────────┘  └──────────────────┘
                                 │              │
                        ┌──────────────────┐ ┌────────────────────┐
                        │ Spontaneous      │ │ Self-ignition,spon-│
                        │ ignition         │ │ taneous combustion │
                        └──────────────────┘ └────────────────────┘
                             │
                    ┌──────────────────┐
                    │ Flash pyrolysis  │
                    │                  │
                    └──────────────────┘
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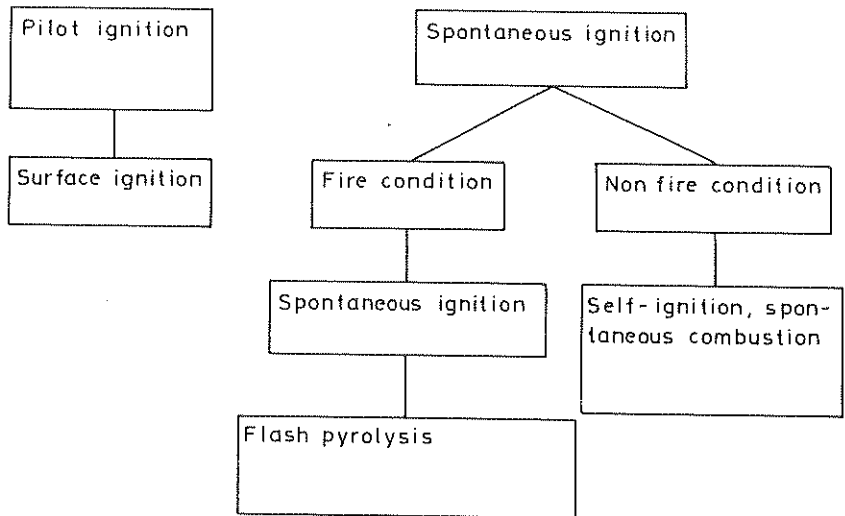
FIG. 2.1. Different types of ignition.

2.3   Factors which influence ignition

FIG. 2.2 illustrates schematically the different events
during the ignition process for a solid body exposed to
external heat radiation on one side. That part of the
radiation which is absorbed heats the wood next to the
surface. This heating causes thermal breakdown of the
wood and the emission of flammable gases. The quantity
of energy absorbed depends on the level of radiation
and on the transparency of the wood to radiation, i.e.
on the diathermancy of the wood. Transparency is deter-
mined by the spectral distribution of radiation, the
reflectance of the surface and the wavelength dependent
absorption of the wood. If the effective absorption co-
efficient is large, most of the external radiant energy
will be absorbed in a thin layer at the surface. The tem-
perature in such a case rapidly increases to levels re-

radiation level required for ignition are therefore
governed by the properties of the wood and the spectral
distribution of radiation.

Solid phase   Gaseous phase

Heat

External radiation

Heat

Diffusion
of fuel   Diffusion
                                     of oxygen

{ Exothermic
  reaction in
  gaseous phase }

Heat   Heat

Backscatter
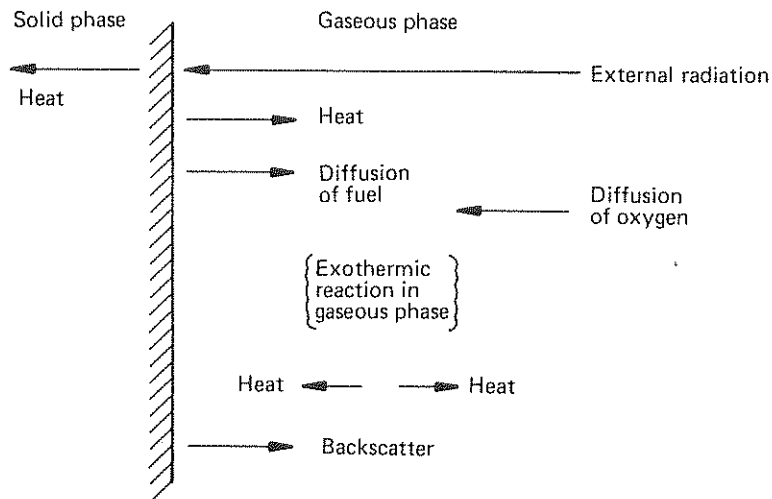
FIG. 2.2. Ignition scenario for solid fuel subject to
          external heat radiation /2.2/

When the wood breaks down, gases are emitted from the
surface, and by diffusion and convection these are mixed
with the oxygen in the air. Exothermic reactions are set
up. Simultaneously, the gases next to the surface are
heated up by convection from the hot wood surface and
by absorption of the external radiant energy.

The gases can reach a temperature higher than the sur-
face temperature. As these processes are taking place,
the number of exothermic reactions and thus chemical
production of heat increases. This causes further ther-
mal decomposition of the wood and increased emission of
gases, which in turn accelerates the rate of reaction,
and finally these processes result in ignition.

The parameters normally studied in ignition tests are
the ignition time, surface temperature, temperature dis-
tribution in the material, loss of weight, absorption of
radiant energy, moisture ratio, and convective effects.
These parameters are governed both by material properties
and the test and measurement technique selected. The
essential factors which govern ignition are

(1) the heat source

(3) surface structure and absorption

(4) size of test specimen

(5) the ignition flame

(6) density and thermal properties of the material

(7) initial moisture ratio of the material

(8) thermal decomposition of the material.

Comments will now be made regarding these factors.

(1) The most important form of heat transfer in a fully
developed fire is radiation, and for this reason
radiation has been the most common heat source in
ignition tests. Ignition owing to convective heat
and conduction of heat from hot plates has also been
studied /2.3/. The latter is of interest in conjunc-
tion with the study of splices and connections. The
influence of convective heating is also significant
for the ignition of e.g. wood in roof structures.

Examples of radiant panels which have been used are
gas fired radiators, electric radiant panels, arc
discharge lamps, tungsten filament lamps, and flames
from liquid fuel burners. A gas fired radiator has
a surface temperature of about 1000 K and a radia-
tion level < 50 kW/m^2. Arc discharge lamps have
been used to simulate radiation from nuclear explo-
sions, and have a radiation level < 4200 kW/m^2. For
exposure of larger test specimens, tungsten filament
lamps which have a surface temperature of about
2500 K are used. (A comparison of these radiant pan-
els is given in Simms /2.4, 2.5/). Flames from
liquid fuel burners have been used for radiation
levels < 130 kW/m^2 /2.6/.

At the same radiation level, the different radiant
panels give rise to different ignition times. This
is partly explained by the fact that spectral dist-
ribution of the emitted energy is different, and
the material which receives the radiation absorbs
different quantities of energy. Furthermore, certain
types of radiant panel cause disturbances in flow
conditions at the material surface. Another impor-
tant factor is that backscatter from the material
towards the radiant panel and the surroundings varies
between different test arrangements.

(2) One of the conditions necessary for ignition to
occur is that the flammable gases which leave the
material must become mixed with the air, so that an
ignitable gas may be formed. This can take place
either through turbulent mixing or through diffusion
under laminar conditions. Ignition then occurs when
the gas mixture has the correct concentration and
temperature. Ignition may occur either with the aid
of a flame (pilot ignition) or within the gas mix-

height is necessary, and for radiation intensities
less than a certain value the ignition time depends
on the height of the specimen up to a critical
height. For specimens of greater height the igni-
tion time is influenced by free convection. (These
conditions are described in Alvares et al /2.7/).
At low intensities, a moderate artificial draught
produces a reduction in ignition time. This does
not hold for higher radiation intensities. There
are also indications that a strong draught increases
the ignition temperature irrespective of radiation
intensity /2.1/. Furthermore, ignition time decreases
if the concentration of oxygen increases. As a cer-
tain least radiation intensity is always required
in order that ignition may occur, this minimum level
may be affected by the presence of a draught /2.3/.

(3) In Strömdahl /2.8/ there is a description of an ex-
perimental investigation which contains a study of
the effect of different types of surface treatment.
An example of the results is given in FIG. 2.3.
The investigation shows, inter alia, that wrought
timber has a lower ignition time than sawn timber,
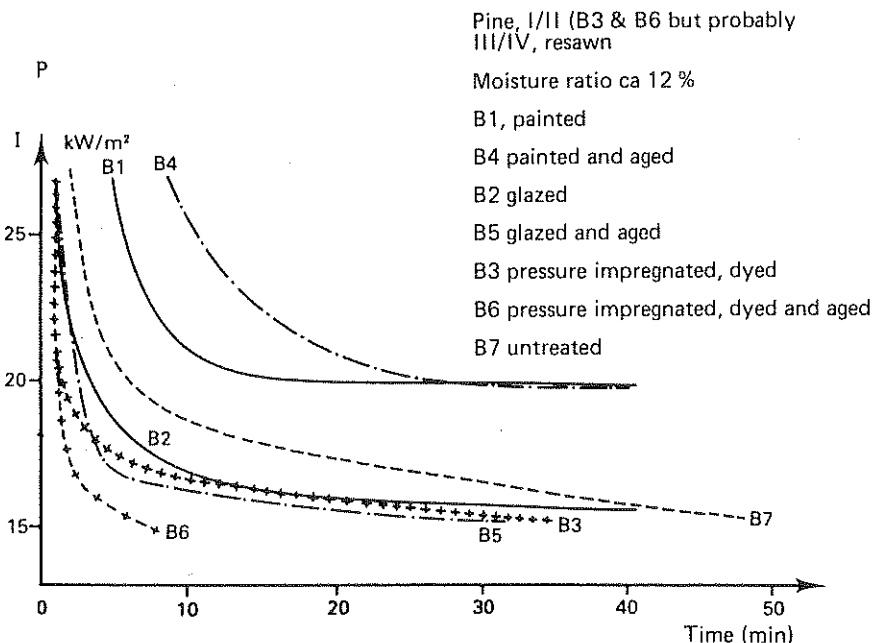and that a higher resin content tends to reduce
ignition time.

FIG. 2.3. Relationship between ignition time t_{ig} and
the level of constant radiation intensity P

Wood is to some extent diathermic (transparent to thermal radiation), and a diathermic material ignites at a lower surface temperature than one which is not diathermic. This diathermic effect decreases and becomes negligible when thermal decomposition of the wood begins /2.5/. Investigations show that absorptivity (the ratio of the intensity required for ignition of a sooty surface to that required for ignition of a non-sooty surface for one and the same ignition time) increases with the time of exposure, and gradually reaches a constant value.

(4) Small surfaces (< 10 cm^2) require a higher least radiation intensity than larger surfaces in order to ignite /2.3/, and in most cases the small surface will glow while the larger one will produce a flame. The size of the surface also affects flow conditions, as described under (2) above. This state of affairs shows the difficulties involved in directly converting small scale results into full scale results. Some works indicate that for radiation intensities > 130 kW/m^2 the ignition time at small scale should be reduced by multiplication by a factor of 0.8 in order that good agreement with full scale conditions may be obtained. Radiation of such high levels is primarily of interest in connection with civil defence.

Wood is regarded as thermally "thick" - i.e. thermal exposure of one side of a panel produces negligible effect on the unexposed side - for thicknesses of 10-20 mm, depending on the level of radiation. For thicknesses greater than these values, ignition time is not affected by variations in thickness. For smaller thicknesses the ignition time decreases in direct proportion to the thickness /2.4, 2.9/.

(5) In order that the pilot flame configuration should not exert an influence on the ignition time, the pilot flame must be placed in such a way that it transmits a negligible amount of energy to the material. Its size shall further be such that it covers an uneven mixture of pyrolysis products and air. This means that the pilot flame should be placed immediately in front and above the upper front edge of the test specimen.

(6) For a short time at the commencement of thermal exposure, the diathermic properties of wood are important with regard to the quantity of energy transmitted to the wood. This effect then vanishes owing to thermal decomposition of the wood, and convection becomes the dominant transport term /2.10/. A higher density and a higher thermal conductivity increase the ignition time /2.11, 2.12/.

(7) The time to ignition and the minimum radiation inten-

pilot, moisture ratios less than 20% have little
influence on ignition time, and for moisture ratios
less than 40%, variations in moisture ratio have
little effect on the required minimum radiation in-
tensity. The influence of moisture is considerably
greater in conjunction with spontaneous ignition.
As the moisture content rises, the ignition time
increases owing to the rise in thermal conductivity,
transfer of heat due to diffusion of water, and
vaporisation of water /2.12/.

(8) When wood is heated, a number of chemical reactions
occur which break wood down into simpler components.
Depending on the temperature distribution, differ-
ent reactions take place, and this affects the type
of pyrolysis product which leaves the surface of
the material. It also influences the mixing ratio
between air and flammable gases which is required
for ignition. Wood is therefore classified into
characteristic zones depending on the temperature.
Detailed descriptions of these are given in Chap-
ter 4.

2.4 Mathematical models

Existing mathematical models have been developed bearing
in mind the requirement that they should be easy to app-
ly. Because of this, the number of variables in these
models is small. The variables included vary between
authors, as a result of differences in opinion as to the
factors which are of the greatest importance and those
which can be ignored. Furthermore, the models have in
most cases been developed in conjunction with an experi-
mental series, and this also affects the number of vari-
ables.

Taken together, the various models should eventually
result in a model which describes events from the time
external thermal exposure begins until the time ignition
occurs. Ideally, such a model should be capable of handl-
ing an arbitrarily selected heat source and should also
take into consideration each change which occurs in the
material up to ignition. Our imperfect knowledge at pre-
sent with regard to identification of the reactions
which take place in the material will probably make it
very difficult to formulate such a "complete" model.

Research at present concentrates on studies of indivi-
dual variables with the object of finding critical
levels of these in a more perfect mathematical model.

In conjunction with studies of spontaneous ignition in
fire conditions, knowledge of the heat balance in the

pletely evaluated. Simms /2.10/ mentions the following
variables which should be included in studies of the
heat balance for ignition of dry wood:

(1) The external heat source, usually radiation, which
    is absorbed in the surface layer if the material is
    opaque, or inside the material if this is diathermic,

(2) thermal conduction perpendicular to the surface,

(3) heat capacity,

(4) convective heat transfer in the material owing to
    gas transport,

(5) heating due to thermal decomposition,

(6) cooling of the surface.

The reason why treatment has been confined to dry wood
is that further difficulties are encountered when mois-
ture dependent effects are to be taken into considera-
tion. This simplification is fully acceptable, since
it is the most critical case which is studied /2.12/.

In solving the heat balance, Simms ignores the diather-
mic properties and the heat increment owing to the che-
mical reactions. Since a number of heat transfer vari-
ables are included and it is also difficult to decide
which of these dominate, a large number of simplifica-
tions are made.

When a model of the heat balance has been constructed
in this way, this shall be coupled to an ignition crite-
rion. It is usual to choose a specific temperature, or
a least emission of pyrolysis products, or a critical
concentration of flammable gases and air /2.3/. There
are further proposals regarding ignition criteria, and
different formulae have also been proposed for determi-
nation of the time to ignition on the basis of a certain
exposure. Lawson and Simms /2.13/ present a formula for
qualitative assessment of the time to ignition.

Jentzsch /2.14/ is of the opinion that spontaneous igni-
tion takes place if the following three conditions are
simultaneously satisfied:

(1) A certain least temperature,

(2) sufficient production of pyrolysis products,

(3) sufficient concentration of oxygen at this tempera-
    ture for the formation of a flammable gas mixture.

When a pilot is present, this replaces condition (1)
above.

Ignition with a pilot differs from spontaneous ignition
only as regards the ignition criteria. The pilot ignites
the products of pyrolysis earlier, and otherwise has no
influence. When the pilot is in contact with the surface

At different gas concentrations it has been found that
a gas mixture temperature of 350°C is commensurate with
ignition in the presence of a pilot /2.15, 2.16/.

In studies of ignition with a pilot, use can be made of
a theory developed in order to describe extinguishment
of liquid fires by cooling. This theory defines a criti-
cal surface temperature, the fire point, which is suffi-
cient to ignite the material and to sustain a flame
after the ignition source has been removed. This tempe-
rature is higher than the flame point of a liquid.

Previous work has shown that when liquid fires are ex-
tinguished with water by cooling these down to the fire
point, this is the reverse of the process of ignition
with a pilot /2.17/. Rasbash /2.18/ has developed this
theory further so that it can also be used for solid
materials, and it is therefore easier to study the con-
ditions under which a material ignites. Apart from a
critical surface temperature, the following three con-
ditions must also be satisfied in order that ignition
may take place:

(1) Sufficient convective heat transfer from the flame
    to the surface,
(2) sufficient production of pyrolysis products,
(3) sufficient flame temperature.

There are other ignition criteria.

Application of a critical least radiation intensity has
little relevance in a fire situation in which surface
ignition is in most cases dominant. Unfortunately, stu-
dies of ignition have concentrated on sponteneous igni-
tion to the detriment of other forms of ignition.

2.5   Conclusions

A large number of experimental investigations have been
reported in which most of the factors which influence
ignition of wood have been studied. Comparative analysis
of the available data is difficult, due, among other
things,to the fact that different test techniques have
been used in these investigations and different defini-
tions of ignition have been applied.

Mathematical models have been developed from which the
time to ignition can be calculated as a function of a
temporally constant level of radiation. In real fire
situations, exposure of a material to fire varies in
time, and a pilot flame can reach the exposed surface
at different times during a heating sequence. It is
therefore difficult directly to predict the ignition
time in actual fire conditions on the basis of calcu-

pendent thermal conditions into time-dependent ones.
Application of this in this context presupposes partly
that ignition is governed by the surface temperature,
and partly that all thermal data required for calcula-
tion are known.

In the light of this, development of simplified models
which can translate a radiation-ignition time curve,
determined either experimentally or analytically for
constant levels of radiation, into an ignition criterion
for a fire environment which is variable in time, appears
to be a research project of great urgency. A proposal for
such a model is presented in /2.19/.

REFERENCES

/2.1/   GRAF, S H, "Ignition Temperatures of Various
          Papers, Woods and Fabrics". Oregon State
          College, Engineering Experiment Station, Bulle-
          tin No 26, 1949, p. 69.

/2.2/   KASHIWAGI, T, "Radiative Ignition Mechanism of
          Solid Fuels". Fire Safety Journal, 3(1981),
          pp. 185-200.

/2.3/   FANG, J B, "Ignition Properties of Cellulose
          Materials". A survey of the literature on wood,
          fire behaviour and fire retardant treatment.
          Canadian Wood Council, 1966, p. 25.

/2.4/   SIMMS, D L, "Ignition of Cellulosic Materials
          by Radiation". Combustion and Flame $\underline{4}$(4),
          1960, pp. 293-300.

/2.5/   SIMMS, D L, "Experiments on the Ignition of
          Cellulosic Materials by Radiation ". Combust-
          ion and Flame $\underline{5}$(4), 1961, pp. 369-75.

/2.6/   KOOHYAR, A N, WELKER, J R, SLIEPOVICH, C M,
          "The Irradiation and Ignition of Wood by Flame".
          Fire Technology, Vol. 4, No 4, 1968.

/2.7/   ALVARES, N J, BLACKSHEAR, P L, MURTY KANURY, A,
          "The Influence of Free Convection on the Igni-
          tion of Vertical Cellulosic Panels by Thermal
          Radiation". Combustion Science and Technology
          $\underline{1}$(6), 1970, pp. 407-13.

/2.8/   STRÖMDAHL, I, "Träpanelers motståndsförmåga
          mot värmestrålning".(In Swedish).(The resistance
          of wooden panels to thermal radiation). Swedish
          Fire Protection Association, Stockholm, 1972.

/2.9/   WESSON, H R, WELKER, J R, SLIEPOVICH, C M,
          "The Piloted Ignition of Wood by Thermal Radi-
          ation". Combustion and Flame $\underline{16}$(3), 1971, pp.
          303-10.

/2.11/   KOLLMAN, F, COTE, W, "Principles of Wood
          Science and Technology in Solid Wood". 1968,
          pp. 149-157.

/2.12/   SIMMS, D L, LAW, M, "The Ignition of Wet and
          Dry Wood by Radiation". Combustion and Flame
          11 (5), 1967, pp. 377-88.

/2.13/   SIMMS, D L, "The Ignition of Wood by Radiation".
          British Journal of Applied Physics 3(9), 1952,
          pp. 288-92.

/2.14/   JELLITO, K, "Ignition of Wood. Tests with the
          Ignition Value Method". Diploma, Reisbek (cited
          by Jentzsch 1959, Ref No 79), 1953.

/2.15/   SIMMS, D L, "On the Pilot Ignition of Wood by
          Radiation". Combustion and Flame 7(3), 1963,
          pp. 235-61.

/2.16/   AKITA, K, "Studies on the Mechanism of Ignition
          of Wood". Report of Fire Research Institute of
          Japan 9(1-2), 1959, pp. 1-44, 51-54, 77-83,
          99-105.

/2.17/   RASBASH, D J, ROGOWSKY, Z W, Combustion and
          Flame 1, 1957, p. 453.

/2.18/   RASBASH, D J, "Relevance of Fire Point Theory
          to the Assessment of Fire Behaviour of Combus-
          tible Materials". International Symposium.
          Fire Safety of Combustible Materials, Edin-
          burgh, 1975, pp. 169-178.

/2.19/   FREDLUND, B, MAGNUSSON, S E, NILSSON, L,
          PETTERSSON, O, STARNDBERG, S, THELANDERSSON,
          S, "Skydd mot brandspridning inom småhusbe-
          byggelse i lättbetong". (In Swedish). (Preven-
          tion of the spread of fire between private
          dwellinghouses of lightweight concrete).
          Swedish Fire Protection Association, Stockholm,
          1977.

3. THERMAL PROPERTIES

3.1 Introduction

Accurate knowledge of the thermal properties of charred
layers and of uncharred wood is necessary for calcula-
tion of the non-steady temperature field of timber struc-
tures under fire exposure conditions. Complications arise
in this respect due to the anisotropy of wood, its biolo-
gical variation within a structure, and the not insigni-
ficant variation of thermal properties with temperature
and moisture ratio. This explains the present incomplete
state of knowledge concerning the thermal properties of
wood, in spite of a large number of reported investiga-
tions. These thermal properties are as follows:

Specific heat capacity C_p (J/kgK)

Thermal conductivity k (W/mK)

Enthalpy rise ΔH (J/kg)

Phase transition energy Q_L (J/kg)

3.2 Specific heat capacity

The specific heat capacity can be determined experimen-
tally by the following methods:

Ordinary calorimeter

Bunsen ice calorimeter

Vacuum calorimeter

Heat flow methods

Differential scanning calorimetry (DSC).

Reference is to be made to the literature for more
detailed descriptions of these methods. Only some of
the data obtained by the various methods are given here.

For oven dry wood, the following values apply at tempe-
rature $T^{\circ}C$:

Reference	C_p kJ/kgK	temperature range	method
Dunlap /3.1/	1.11 + 0.0049 T	0 - 112	Bunsen
Koch /3.2/	1.11 + 0.0042 T	60 - 140	DSC

and for wood of moisture ratio m%

Reference	C_p kJ/kgK	temperature range	method
Vohlbehr /3.3/	1.08 + 0.0041 m + 0.0025 T + 0.00006 mT	0 - 100	Bunsen

Measurement of heat capacity does not normally involve any major difficulty.

Few values exist for the specific heat capacity of carbon, and those that are available have considerable scatter.

Buller /3.4/ uses   C = 0.50 kJ/kgK

Perry /3.5/ uses   C = 1.01 kJ/kgK

For the flammable gases, Bullen /3.4/ uses C = 1.8 kJ/kgK.

3.3   Thermal conductivity

Thermal conductivity can be experimentally determined by the following methods:

Lee's disc method

Hot wire method

Differential scanning calorimetry (DSC).

McLean /3.6/ gives the following equation for wood of moisture ratio m % and density ρ kg/m^3 radially to the grain:

k = (2.0 + 0.0406m) ρ × 10^{-4} + 0.0238 W/mK   m < 40%

k = (2.0 + 0.0544m) ρ × 10^{-4} + 0.0238 W/mK   m ≥ 40%

Thermal conductivity is also temperature dependent, and Kollman /3.7/ has found that in the temperature range 0 - 100°C the thermal conductivity is approximately directly proportional to absolute temperature.

According to Griffiths and Kaye /3.8/, thermal conductivity in the tangential direction is 0.9 - 0.95 times that in the radial direction, and in the longitudinal direction it is 1.75 - 2.25 times that in the radial

For carbon, values of k between 0.076 and 0.94 W/mK
have been reported, but no information is given as to
what temperature and density they refer to. Hadvig /3.9/
found in his experiments that for carbon layers thicker
than 6 mm, k = 0.38 W/mK is an acceptable value.

3.4   Enthalpy and energy of phase transition

Enthalpy is usually measured in a bomb calorimeter.
Information concerning the enthalpy of wood is given in
Harmathy /3.10/, Roberts /3.11/ and Thomas and Nilsson
/3.12/, the value for dry wood being between 18 and 19
MJ/kg.

Thomas /3.13/ has developed a model for the calculation
of the enthalpy of the gases when the enthalpies of wood
and carbon are known together with the temperature, heat
capacities and the proportion of wood which has been
vaporised.

There is a coupling between the energy of phase transi-
tion, which varies between 0.4 and 0.5 MJ/kg, and the
enthalpy, but this is complicated.

The following examples are taken from Böhm /3.14/ and
refer to dry wood:

Energy of phase transition MJ/kg   5.4   2.7   1.35

Enthalpy of flammable gases   24.2   21.5   20.15

During a fire, the thermal properties and the proportion
of wood which is pyrolysed per unit time both change,
which makes calculation of the enthalpy of the flammable
gases difficult.

3.5   Conclusions

Expansion of the present state of knowledge concerning
the thermal properties of wood should focus primarily
on the thermal conductivity and specific heat capacity
of both charred and uncharred wood within the tempera-
ture range above 100°C. Priority should also be given
to development of the relationship required for calcu-
lation of the heat of reaction of wood in real fire
conditions on the basis of data regarding enthalpy and
phase transition energy.

REFERENCES

/3.1/   DUNLAP, F, "The Specific Heat of Wood". US
          Department of Agriculture, Bulletin 110, 1912.

/3.2/   KOCH, P, "Specific Heat of Ovendry Spruce
          Pine Wood and Bark". Wood Science 1(1), 203,
          1969.

/3.3/   VOLBEHR, B, "Swelling of Wood Fibres". Doctoral
          Thesis, Kiel, 1896.

/3.4/   BULLEN, M L, "The Burning Rate of Wood Dowels
          in Small Scale Arrays". Fire Research Station,
          Note N159/76, 1976.

/3.5/   PERRY, J H, "Chemical Engineers Handbook".
          4th Edition, McGraw-Hill, 1963.

/3.6/   MACLEAN, J D, "Thermal Conductivity of Wood".
          Heating, Piping, Air Conditioning, Vol. 13,
          No 6, 1941.

/3.7/   KOLLMAN, F, COTÉ, W, "Principles of Wood
          Science and Technology in Solid Wood". 1968,
          pp. 149-157.

/3.8/   GRIFFITHS, E, KAYE, G W C, "The Measurement
          of Thermal Conductivity". Proceedings Royal
          Society (London), Series A, 104:71-98, London,
          1923.

/3.9/   HADVIG, S, "Charring of Wood in Building Fires".
          Laboratory of Heating and Air Conditioning,
          Technical University of Denmark, 1981.

/3.10/   HARMATHY, T Z, "A New Look at Compartment
          Fires". Fire Technology, Vol. 8, Nos 3 and 4,
          1972.

/3.11/   ROBERTS, A F, "Comments on a Letter by J.J.
          Brenden". Combustion and Flame, 1967.

/3.12/   THOMAS, P H, NILSSON, L, "Fully Developed
          Compartment Fires. New Correlations of Burning
          Rates". Fire Research Station, Fire Research
          Note 979, 1973.

/3.13/   See HADVIG /3.9/, p. 101.

/3.14/   BÖHM, B, "Fully Developed Polyethylene and
          Wood Compartment Fires". Laboratory of Heating
          and Air Conditioning, Technical University of
          Denmark, 1977.

4.   RATE OF CHARRING, TEMPERATURE AND
            MOISTURE STATES

4.1   Introduction

In fire design of loadbearing and separating construc-
tions of timber, knowledge of the non-steady temperature,
moisture and density-time fields relating to the con-
struction is essential information. From the density-time
field, a reduced cross section at any elapsed time can be
determined. This reduced cross section, the temperature
and moisture-time fields and the associated changes in
the mechanical properties of wood then form the basis
for determination of the structural behaviour and load-
bearing capacity of the construction under fire exposure
conditions.

The behaviour of wood subject to thermal exposure is
governed by a large number of physical and chemical
mechanisms, the most important of which are

o   the internal convective heat flow due partly to
     gases and water which are formed during pyrolysis
     and which are transported both further into the
     wood and towards the exposed surface, and partly to
     transport of initial water,

o   thermal conduction and its modification by variable
     temperature and moisture content,

o   storage of heat,

o   exchange of heat at the material surface in the form
     of radiation and convection, inclusive of the effects
     of mass transport,

o   vaporisation of water, and

o   the chemical reactions which take place at varying
     temperatures and moisture contents in the wood.

The problem is complicated by biological variation of
the wood.

Derivation of accurate mathematical models for determi-
nation of the rate of charring and the temperature and
moisture gradients which fully allow for all these com-
plex physical and chemical mechanisms, is a task of awe-
some complexity. In addition, the task is also meaning-
less in practice since there is no information available
concerning most of the material parameters. Effort has
so far been directed instead at the development of app-
roximate one-dimensional models for initially dry wood.
These models have been verified experimentally. Applica-
tion of the models excludes thin-walled timber struc-
tures. The following may be mentioned among published
models: Fredlund /4.1/, Roberts /4.2/, Kansa-Perlee-

for calculation of the rate of charring in timber struc-
tures exposed to a real fire characterised by the curves
in FIG. 1.2. The models reported in /4.1/ and /4.4/ in-
clude determination of the temperature field within the
uncharred portion of the structure. Reference /4.1/ also
outlines an approach for treatment of the transient mois-
ture state.

Temperature (°C)

—·— 13mm from exposed surface
———— 25mm   "
– – – 38mm   "
— — 51mm   "
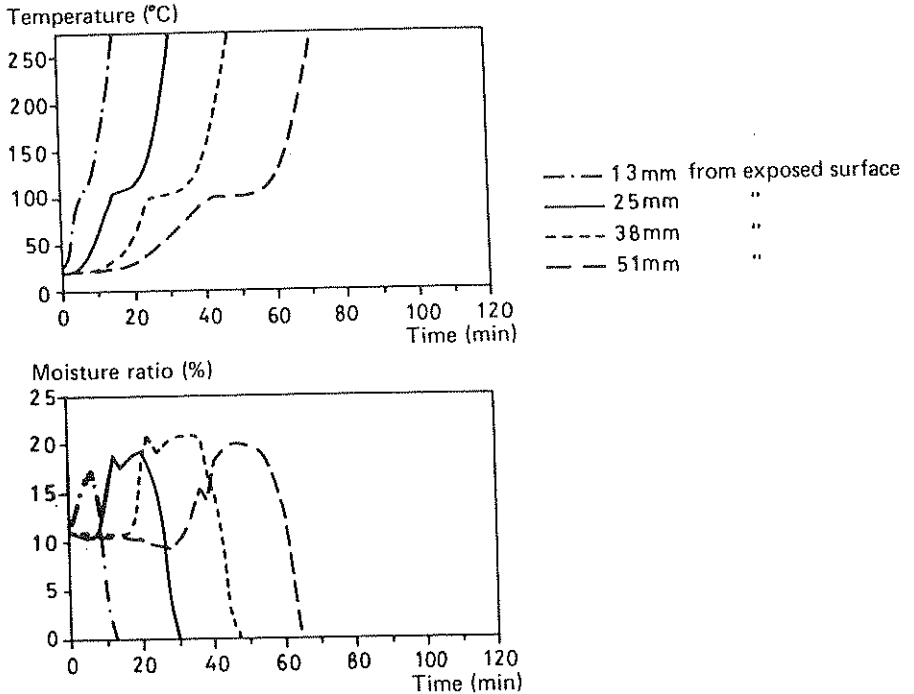
Moisture ratio (%)

FIG. 4.1. Temperature-time and moisture ratio-time curves
for redwood panel exposed to fire according to
ISO 834 on one side /4.6/.

The most detailed experimental investigations have been
reported by Hadvig /4.5/ and White-Schaffer /4.6/. The
latter report presents accurate moisture gradient measure-
ments which illustrate, inter alia, the steep rise in
moisture which occurs at different points of the cross
section of a timber structure exposed to fire, and which
reaches its maximum at each point when the 100°C isotherm
is passed. See FIG. 4.1.

4.2   Thermal decomposition

Wood is an organic material made of a number of compo-
nents of individual chemical properties. Analytical simu-
lation of the behaviour of wood by combining these com-
ponents results in complex treatment which is made yet
more difficult by "defects" in the form of variations
in the biological structure of wood etc.
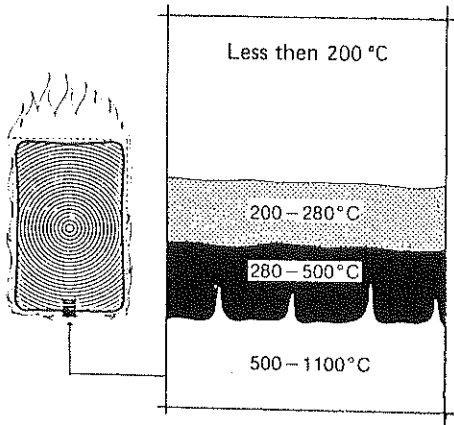
FIG. 4.2. Characteristic zones in wood during pyrolysis.

Studies of wood at elevated temperatures (pyrolysis)
have given the result that, during pyrolysis of wood,
four characteristic zones can be distinguished parallel
to the heated surface. See FIG. 4.2. The following de-
scription is based on /4.7/.

Zone A. Temperature less than 200°C

The gases formed during a very slow pyrolysis are not
ignitable. Wood is subject to a slow loss of weight. In
certain cases, wood may begin to char above 95°C. There
is oxidation of the charred layer which is exothermic
and which, in circumstances when the heat is stored, can
result in self ignition. However, sound wood - without
e.g. decay - does not ignite in Zone A.

Zone B. 200° - 280°C

Even though the gases emitted are not ignitable, an exo-
thermic state is reached during pyrolysis. The tempera-
ture at which the net result of all pyrolytic reactions

until temperatures which are higher than those applicable
to Zone B are reached.

Zone C, 280° - 500°C

The gas mixture which is emitted in large quantities in
Zone C initially contains far too much carbon dioxide
and water vapour to be ignitable. Gradually, however,
flammability increases due to another and more rapid
pyrolysis. At this stage combustion with a flame occurs
only in the gas phase outside the wood, the reason being
that there must be time for the rapidly emitted gases to
become mixed with suitable proportions of atmospheric
oxygen. Self sustaining diffusion flames from organic
fuels burn at a temperature of about 1100°C. The char-
coal formed cannot burn but is accumulated so long as
production of gas is sufficiently large to isolate the
surface of the wood from oxygen. As charcoal has lower
thermal conductivity than wood, the layer of charcoal
retards penetration of heat and the occurrence of an
exothermic state in parts of the wood further inside.

Zone D, above 500°C

At 500°C charcoal glows and is oxidised. When the surface
temperature attains a value just over 1100°C, charcoal
is consumed at the surface just as fast as the penetra-
tion of the reactive zones.

When the reactive zones have penetrated so long that all
original wood has been burned, the luminous diffusion
flames cease, and only the non-luminous flames of burn-
ing carbon monoxide and hydrogen remain.

If we wish to mark approximately the boundary between
charcoal and wood which has more or less escaped mecha-
nical destruction, some investigations indicate that a
temperature of 300°C is a usable criterion.

4.3   Charring processes

Two distinct processes govern the rate of charring, namely
reaction kinetic processes and transport processes. The
kinetic processes describe the rate at which chemical
reactions occur at a certain temperature, and the trans-
port processes the way and the time at which this tempe-
rature is reached. Which of these dominates is governed
by the thickness of the material. It is a satisfactory
rule of thumb that a thin material is governed by the

When solution is carried out with reference to a pyro-
lysis model, extensive simplifications are made at pre-
sent by analysing pyrolytic data with the aid of a first
order Arrhenius function which can be written

$$\frac{d\rho}{dt} = -\rho b e^{-(E_A/RT)} \tag{4.1}$$

where

ρ = density of the material at time t
R = universal gas constant
T = temperature in K
b, E_A = constants where E_A denotes the activation energy

These two constants are obtained by thermogravimetric
measurements on small test specimens or by measurements
of density and temperature at different points on small
or large test specimens. Determination of these constant
presents great difficulties, since the constants must
reflect all pyrolytic reactions, each of which has a
separate process at different temperatures. The variable
biological, chemical and physical structure of the wood
sample also exerts an influence.

Another difficulty is presented by measurement of the
heat of reaction, which for wood varies within wide
limits depending on the conditions which obtain during
pyrolysis. The heat of reaction can be determined by
differential calorimetric measurements on small speci-
mens or by means of energy balance calculations in com-
bination with tests on large specimens.

In determining the constants b and E_A and the heat of
reaction, correction for moisture has so far been made
only for the heat of reaction.

A more detailed description of the combustion mechanisms
of wood is given in Fredlund /4.1/.

The transport processes contain the following components

-    conduction of heat

-    diffusion of oxygen through wood and carbon

-    transfer of gas inclusive of water vapour through
     wood and carbon.

The rate of combustion of wood is probably mainly govern
by four parameters, namely density, permeability along t
grain, moisture ratio, and thickness. Thermal conductivi
is also important, but this is largely determined by den
sity. In experiments on different wood species, thick-
nesses, moisture ratios and radiation intensities, it
has been found that the loss of weight is proportional

The effect due to the thickness of the charcoal layer
is negligible for thicknesses greater than 6 mm /4.8,
4.9/. As permeability along the grain is 10,000 times
as high as perpendicular to the grain, the test specimen
must be carefully sealed. The water and the gases formed
during combustion further complicate the processes by
virtue of the fact that some of these leave the specimen
and some are transported further into the material and
condense there, perhaps to be vaporised again at a later
stage. This transport, condensation and vaporisation has
a pronounced effect on the temperature-time relationship
inside the specimen. This has been verified in tests on
wooden cylinders /4.10/.

The following material parameters should be taken into
consideration in a study of the rate of charring in a
timber structure exposed to fire: density, thermal con-
ductivity and moisture ratio of the uncharred wood, the
temperature at the base of the charcoal layer, the quan-
tity of flammable gases, and the characteristics of the
charcoal layer (thickness, crack size, permeability and
thermal conductivity). Variables in the environment such
as fire compartment temperature and the type of heat
source also affect the rate of charring.

A flow chart which describes the influence of these para-
meters in outline is given in FIG. 4.3. It will be seen
from this figure that the interacting physical and che-
mical processes exert a great influence, and that the
sequence of events can be divided into two parts. One
of these parts is associated with the inside of the
material and consists of determination of the reaction
products which are generated for a given thermal expos-
ure, and for the temperature history of the specimen.
The other part refers to the surface of the material and
to the boundary layer situated outside this. This part
consists of determination of the size and intensity of
the flame at the boundary layer and of the heat trans-
ferred by the flame to the surface of the material for
a given quantity and composition of the pyrolytic pro-
ducts which enter the boundary layer.

This problem can be solved comparatively easily in the
case of a liquid fuel, since in this case vaporisation
(pyrolysis) is confined to a thin layer near the surface,
and only the external conditions need then be deter-
mined. The problem is more complicated in the case of
solid fuels which char, since in this case the internal
conditions play a critical role.

Since we know far more about dealing with heat and mass
transfer problems than about dealing with chemical pro-
cesses, it is natural for the rate of charring and the
temperature states to be studied by solving the heat
and mass balance equations, and for the influence of
the chemical processes to be taken into consideration
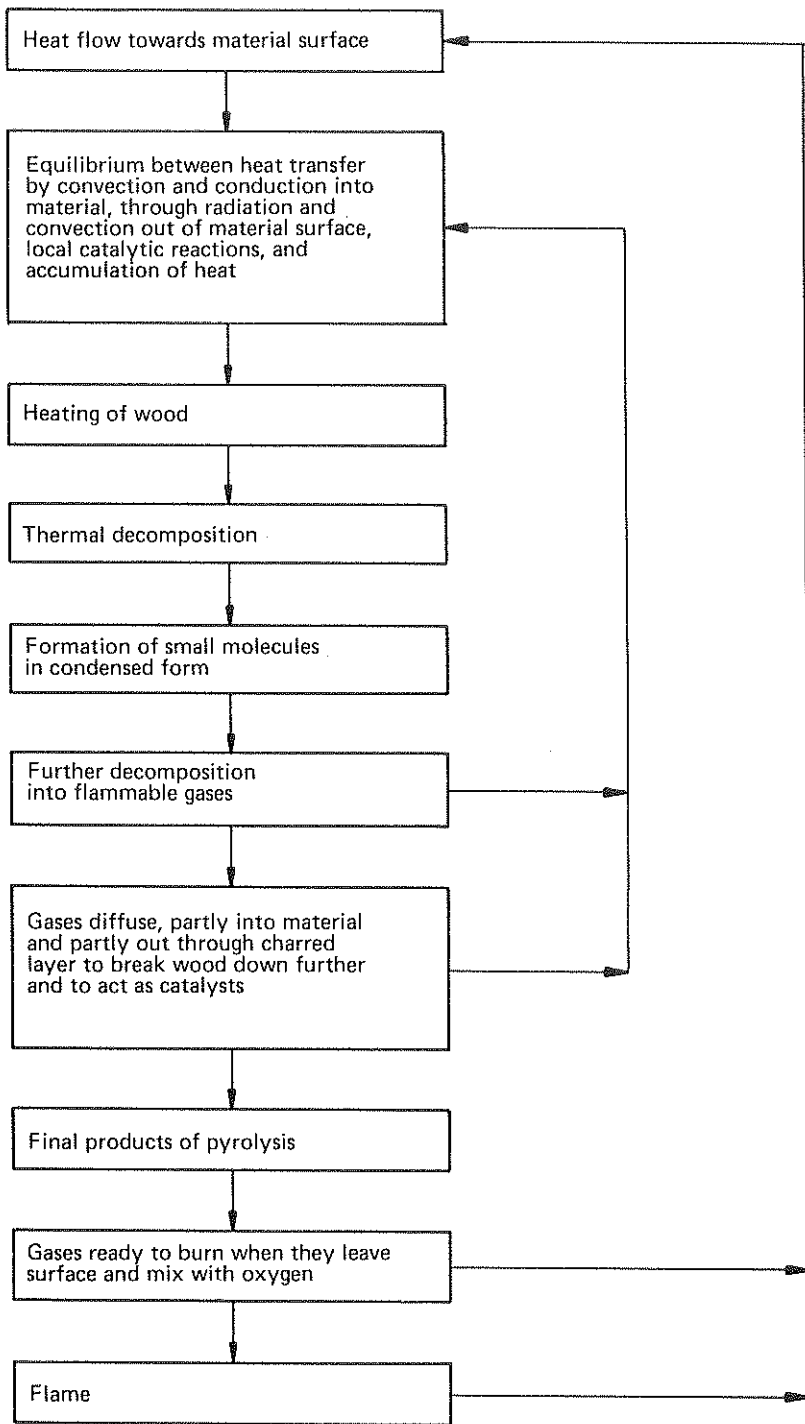as "point sources". In studying these point sources, it

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┌─────────────────────────────────────────────┐
│ Heat flow towards material surface           │◄──────┐
└─────────────────────────────────────────────┘       │
                      │                                 │
                      ▼                                 │
┌─────────────────────────────────────────────┐       │
│ Equilibrium between heat transfer            │       │
│ by convection and conduction into            │       │
│ material, through radiation and              │◄──┐   │
│ convection out of material surface,          │   │   │
│ local catalytic reactions, and               │   │   │
│ accumulation of heat                         │   │   │
└─────────────────────────────────────────────┘   │   │
                      │                             │   │
                      ▼                             │   │
┌─────────────────────────────────────────────┐   │   │
│ Heating of wood                              │   │   │
└─────────────────────────────────────────────┘   │   │
                      │                             │   │
                      ▼                             │   │
┌─────────────────────────────────────────────┐   │   │
│ Thermal decomposition                        │   │   │
└─────────────────────────────────────────────┘   │   │
                      │                             │   │
                      ▼                             │   │
┌─────────────────────────────────────────────┐   │   │
│ Formation of small molecules                 │   │   │
│ in condensed form                            │   │   │
└─────────────────────────────────────────────┘   │   │
                      │                             │   │
                      ▼                             │   │
┌─────────────────────────────────────────────┐   │   │
│ Further decomposition                        │───┼──►│
│ into flammable gases                         │   │   │
└─────────────────────────────────────────────┘   │   │
                      │                             │   │
                      ▼                             │   │
┌─────────────────────────────────────────────┐   │   │
│ Gases diffuse, partly into material          │   │   │
│ and partly out through charred               │───┘   │
│ layer to break wood down further             │       │
│ and to act as catalysts                      │       │
└─────────────────────────────────────────────┘       │
                      │                                 │
                      ▼                                 │
┌─────────────────────────────────────────────┐       │
│ Final products of pyrolysis                  │       │
└─────────────────────────────────────────────┘       │
                      │                                 │
                      ▼                                 │
┌─────────────────────────────────────────────┐       │
│ Gases ready to burn when they leave          │──────►│
│ surface and mix with oxygen                  │       │
└─────────────────────────────────────────────┘       │
                      │                                 │
                      ▼                                 │
┌─────────────────────────────────────────────┐       │
│ Flame                                        │──────►┘
└─────────────────────────────────────────────┘
```

a) As the charred layer increases in thickness all the
   time, it will be more difficult for the products of
   pyrolysis to pass through the layer.

b) As a result of this increased resistance, it is poss-
   ible for the flammable gases to contribute to further
   decomposition of the material and for them also to
   act as catalysts.

c) A network of cracks of a depth which increases in step
   with the expansion of the pyrolytic zone develops at
   the surface. Exchange of heat between the external
   heat source and the cracked zone then no longer takes
   place across a plane surface, but the radiant and con-
   vective heat can now be transferred directly to the
   uncharred wood by way of these cracks. If the grain
   is parallel to the irradiated surface, gases will
   mainly exit through the cracks, since flammable gases
   can be transferred most easily along the grain. This
   is illustrated in FIG. 4.4. The effect of these cracks
   reduces the effects due to a) and b) above.

d) The simultaneous and interacting chemical processes
   are extremely complicated, and very little is known
   about them at present.

e) Heating of the wood varies with temperature level and
   time. This means that the kinetic constants will also
   vary.
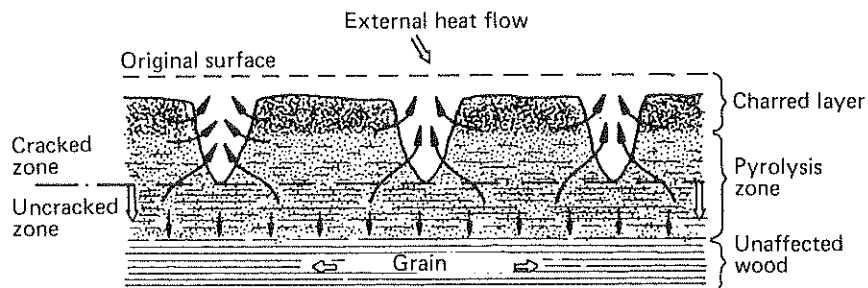
Full arrows show probable direction of flow of flammable gases

FIG. 4.4. Section of wood subject to pyrolysis /4.2/.

f) In the uncracked zone the flammable gases will build
   up to an internal excess pressure which at first in-
   creases in direct proportion to the distance from
   the exposed surface and then diminishes to the value
   applicable to the unaffected wood. As a consequence
   of this pressure, most of the flammable gases will
   flow towards the exposed surface, but a smaller por-
   tion is transported further into the wood where it

g) The coupling between heat and mass transport reduces
   the rate of heating inside the material /4.11/.

4.4   Mathematical models

An outline description is given in the following of the
structure of a mathematical model which is intended for
calculation of the non-steady temperature, moisture and
density-time fields for a timber structure exposed to
fire, in which the flow of heat inside the material is
divided into a conductive part and a convective part,
and exchange of heat at the surface of the material con-
sists of a radiant component and a convective component.
Such a model comprises the following constituents /4.1/:

a) Equations of continuity for the fundamental variables
energy, moisture, gas components and mass.

b) Relations between the variables of state of the prob-
lem which, in addition to the fundamental variables
according to a), comprise temperature, vapour pressure,
relative humidity, saturation pressure at a given tem-
perature, the pressure of condensed water, and pore vol-
ume.

The fundamental assumption made is that thermodynamic
equilibrium exists locally at each point during the dyna-
mic process. This implies that the gas phase, liquid
phase and solid phase assume the same temperature in the
immediate vicinity of the point. In addition, the whole
liquid phase assumes the same pore water pressure in the
immediate vicinity of the point, and all gas phases ass-
ume the appropriate gas pressure and vapour pressure in
this confined region. It is further assumed that the
pressure differences due to the flammable gases are neg-
ligible, so that the flammable gases are free to move
out of the pore system, i.e. there is no change in pyro-
lytic concentration.

c) Expressions for the flows of energy, moisture and
flammable gases. These expressions must be formulated
in such a way that the flows at an arbitrarily selected
point in time can be calculated from the distribution
of temperature, moisture etc in the wood.

The flow of energy is complicated by the mass flow which,
in addition to thermal conduction, contributes to the
total flow of energy. The total flow can be described
as a convective component which defines the energy con-
tent per unit mass of flammable gases and moisture, and
a conductive component for which the thermal conductivity
is a function of temperature, moisture content and densi-
ty. Treatment of moisture flow is very complicated owing

lysis of wood is particularly complicated, and this may
explain why it has been the subject of only a few studies.
Fredlund /4.1/ presents a mathematical model which has
not, however, been verified experimentally, and in other
investigations only the distribution of moisture in test
specimens exposed to fire has been measured /4.6, 4.13,
4.14/. If it is further assumed that the pressure differ-
ences due to the flammable gases are negligible, the rate
of flow of these is given by the rate of production of
flammable gases.

d) Expressions for the production terms which describe
the energy released per unit time, and the change of
phase which occurs during pyrolysis. This change of phase
is usually assumed to mean decomposition of the wood into
flammable gases and water. The production terms are rela-
ted to the rate at which wood undergoes pyrolysis. Pyro-
lysis is governed by complicated chemical reactions. On
the assumption that most of the chemical reactions in the
wood consist of decomposition of molecules independently
of the presence of other molecules, and that the chemical
reactions are affected to the same extent by the tempera-
ture, a "mean reaction" for the pyrolysis of wood may be
considered to conform to an Arrhenius function. If the
heat of reaction of wood is known, the energy released
during pyrolysis can also be given.

e) Boundary and initial conditions which have been dis-
cussed briefly in the foregoing.

As a complement to a more complete mathematical model
of the character described above, it is desirable to
have access to a simplified model which can be used for
rapid estimation of the rate of charring of a material.
Such a model has recently been presented by Delichatsios
and de Ris /4.15/. This model comprises a simple analy-
tical solution for calculation of the asymptotic rate of
pyrolysis for charring materials which are exposed to a
constant external radiation. Together with the results
of a few laboratory experiments, this model provides a
satisfactory basis for the simple approximate prediction
of the rate of charring of a material in a real fire
environment.

The analytical solution assumes that heat transfer in
the charred layer and in the flammable gases can be ig-
nored in relation to heat transfer in the unaffected
material. It is further assumed that the process of pyro-
lysis can be described in terms of constant temperature
and heat of reaction, i.e. without application of an
Arrhenius function. This assumption has been verified by
long experience of simple homogeneous materials.For wood
and wood based materials which are characterised during
a fire by the formation of a permanent charred layer
which gradually reduces the rate of pyrolysis, this
assumption represents a crude approximation.

4.5   Conclusions

From the above, the following appear as urgent research projects:

1) For thin walled timber structures

Development of a simplified one-dimensional model for calculation of the rate of charring and temperature distribution. Consideration must be given in this context to the reaction kinetics parameters of wood, which requires extensive experimental studies.

2) For timber structures comprising solid sections

Development of a simplified one-dimensional model for calculation of the rate of charring, temperature gradient and moisture distribution. This task can be solved without recourse to complicated combustion equations. Treatment must include transfer processes, and this requires a simplified model for moisture transfer in the material, and experimental determination of a number of material constants.

In a second stage, it is natural to develop such a model into a two and three dimensional one, so that it may have practical application for beams and different types of splices and connections.Such a process must take account of the anisotropic properties of wood.

REFERENCES

/4.1/   FREDLUND, B, "Modell för beräkning av temperatur samt reducerad tvärsnitt i brandpåverkade träkonstruktioner". (In Swedish).(Model for calculation of temperatures and reduced cross section in timber structures exposed to fire). Internal Report IR79-2, Department of Structural Mechanics and Concrete Construction, Lund Institute of Technology, 1979.

/4.2/   ROBERTS, A F, "Problems Associated with the Theoretical Analysis of the Burning of Wood". Thirteenth Symposium on Combustion, August 1970.

/4.3/   KANSA, E, PERLEE, H, CHAIKEN, R, "Mathematical Model of Wood Pyrolysis Including Internal Forced Convection". Combustion and Flame 29, 1977, pp. 311-324.

/4.4/   WHITE, R H, SCHAFFER, E L, "Application of CMA

/4.5/   HADVIG, S, "Charring of Wood in Building Fires".
          Laboratory of Heating and Air Conditioning,
          Technical University of Denmark, 1981.

/4.6/   WHITE, R H, SCHAFFER, E L, "Transient Moisture
          Gradient in Fire-Exposed Wood Slab". Wood and
          Fiber 13(1), 1981.

/4.7/   FREDLUND, B, "Träets antändnings- och förbränn-
          ingsmekanism". (In Swedish). (The ignition and
          combustion mechanism of wood). Internal Report
          IR79-3, Department of Structural Mechanics and
          Concrete Construction, Lund Institute of Tech-
          nology, 1979.

/4.8/   Great Britain Ministry of Technology and Fire
          Offices' Committee, Joint Fire Research Organ-
          isation 1964. Fire Research 1963; Report of
          the Fire Research Board with the Report of the
          Director of Fire Research, London.

/4.9/   AKITA, K, "Studies of the Mechanism of Ignition
          of Wood". Report of the Fire Research Institute
          of Japan, 9(1, 2), 1959, p. 98,

/4.10/   BLACKSHEAR, P L, KANURY, M A, "Heat and Mass
          Transfer to, from and within Cellulosic Solids
          Burning in Air". Tenth Symposium on Combustion,
          1965, pp. 911-23.

/4.11/   HENRY, P H S, Proceedings, Royal Society (Lon-
          don), Series A171, 1939, p. 215.

/4.12/   CLAESSON, J, GAFFNER, D, "Fukt i porösa bygg-
          nadsmaterial". (In Swedish). (Moisture in porous
          building materials). Report 1977:1, Department
          of Building Science, Lund Institute of Techno-
          logy, 1977.

/4.13/   "Fire Resistance of Wood Structures". Symposium
          VTT, Finland, 1980.

/4.14/   DORN, H, EGNER, K, "Fire Tests on Glued Lamina-
          ted Structural Timbers". Holz-Zentralblatt, 28,
          Stuttgart, 1961.

/4.15/   DELICHATSIOS, M A, DE RIS, J, "An Analytical
          Model for the Pyrolysis of Charring Materials".
          Presented at the CIB W14 Workshop, Borås,
          Sweden, May 1983.

5.   MECHANICAL PROPERTIES

5.1   Introduction

Optimum design of loadbearing timber structures which
are exposed to fire requires methods which take into
consideration the assumptions made concerning loading
and thermal exposure. Section 6.1 describes existing
design methods for beams and columns which - depending
on the degree of thermal exposure selected - provide a
more or less rough estimate of loadbearing capacity and
real fire resistance. These methods normally yield re-
sults which are probably very considerably on the safe
side. Application of these methods is confined to calcu-
lation of limiting bending moments and critical loads
for certain types of instability phenomena. Calculation
of deformations is not possible by means of these methods.

Methods which are to be of more general application and
also form the foundation of optimum design must be based
on experimentally verified analytical models which give
a functionally correct description of the different pro-
cesses involved in the thermal and mechanical behaviour
of the structure in the event of fire. For optimum de-
sign, the design method must further be coupled to a
probabilistic analysis according to Section 1.5.

One of the requirements for advanced calculation of the
loadbearing capacity of a structure under fire exposure
conditions is an experimentally verified material model
in which the mechanical properties of wood are described
as functions of the transient stress, temperature and
moisture states. When such a material model is available,
a structural calculation can be carried out concerning
the behaviour of the construction at any time during the
fire with respect, inter alia, to temporal variations in
forces, moments and stresses due to internal and exter-
nal constraints.

5.2   Strength and deformation properties

Existing knowledge concerning the mechanical properties
of wood derives mainly from tests on small specimens.
However, a large body of information obtained by exten-
sive tests of this type provides only a limited basis
for practical design, since in these tests the strength
properties are determined on wood without any defects.
It has been shown with regard to bending resistance that
the stresses in the compression zone are critical for
small specimens without defects, while it is the stresses
in the tension zone which are crucial for structural ele-

more in line with a Weibull distribution, which shows
that the strength of structural timber is governed by
brittle failure.

Existing knowledge of the mechanical properties of wood
is mainly derived from investigations carried out at
constant temperature and moisture, either at constant
stress levels or at stresses subject to different tem-
poral variation patterns, while in a real fire situation
temperatures and moisture contents are transient. These
investigations thus provide information concerning the
variation in strength and deformation properties for
different combinations of steady temperature and moisture
levels.

Wood has a very complex anisotropic structure, is subject
to wide variation in quality within the same species of
timber, and has different types of defect. This makes it
difficult to summarise variation in mechanical properties
due to different types of exposure.

The instantaneous moduli of elasticity and strength val-
ues relating to different loading directions increase
both when the moisture ratio decreases below the fibre
saturation point and when the temperature drops. This
is shown for wood loaded parallel to the grain in FIG.
5.1, 5.2, 5.3 and 5.4, taken from Gerhards /5.1/. The
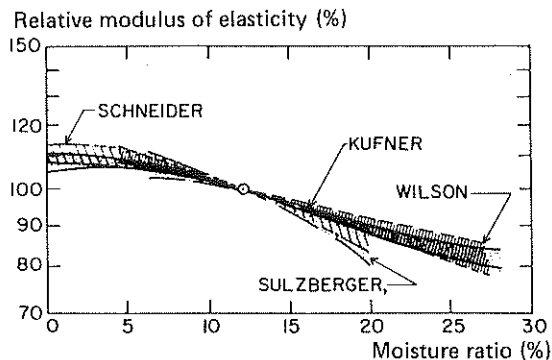captions refer to the sources from which the results
are taken.

Relative modulus of elasticity (%)

FIG. 5.1. Effect of variable moisture ratio on the modu-
          lus of elasticity parallel to the grain at
          20°C. The value at 12°C is taken to be 100%.
          /5.1/.

It will be seen from the figures that for temperature
levels above 100°C there are no results concerning bend-

tures, but these results are taken from investigations
on cellulosic fibres heated over periods of only a few
seconds.

The periods of exposure which are of interest for a tim-
ber structure exposed to fire are 1-2 hours. This means
that the long-term effect given in the literature, creep
up to failure, is not relevant for timber structures
under fire exposure conditions at normal stress levels.
In such cases the stress level chiefly influences the
proportionality of the creep curve, the magnitude of
creep and the modulus of elasticity of wood. Other im-
portant factors which govern deformations are tempera-
ture and moisture ratio. It is clear from reported tran-
sient tests that the deformation which occurs in a spe-
cimen for a defined combination of stress and tempera-
ture is dependent on the stress and temperature history
/5.2, 5.7/.

At a given stress level, higher temperatures and higher
moisture ratios generally result in greater deformation
/5.3, 5.4/. A change in moisture ratio at a load likely
to occur under fire exposure conditions has a consider-
able effect on deformation, as shown, inter alia, by
Armstrong and Kingston /5.5/. Perkitny claims that
changes in moisture ratio as small as 1% exert an appre-
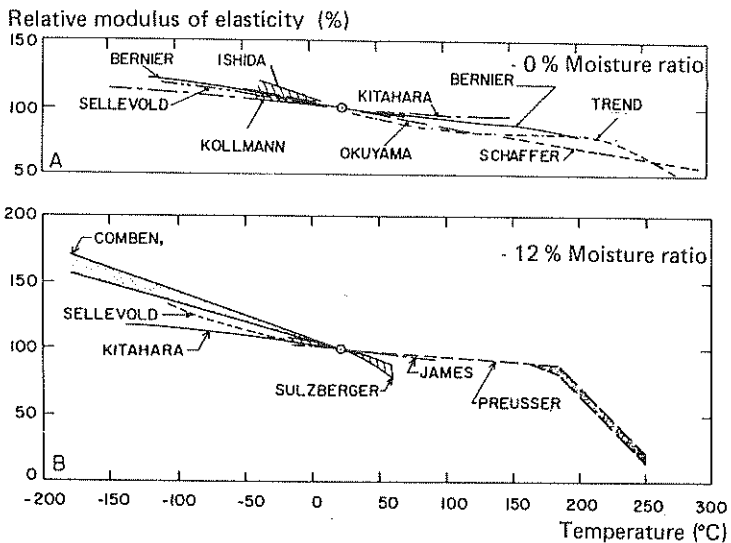ciable effect on creep /5.6/.

Relative modulus of elasticity (%)

FIG. 5.2. Effect of variable temperature on the modulus
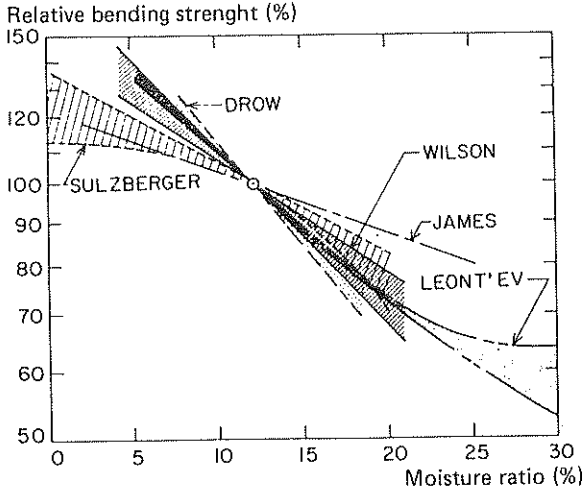of elasticity parallel to the grain. A: Mois-

FIG. 5.3. Effect of variable moisture ratio on bending resistance at 20°C. The value at 12% moisture content is taken to be 100% /5.1/.
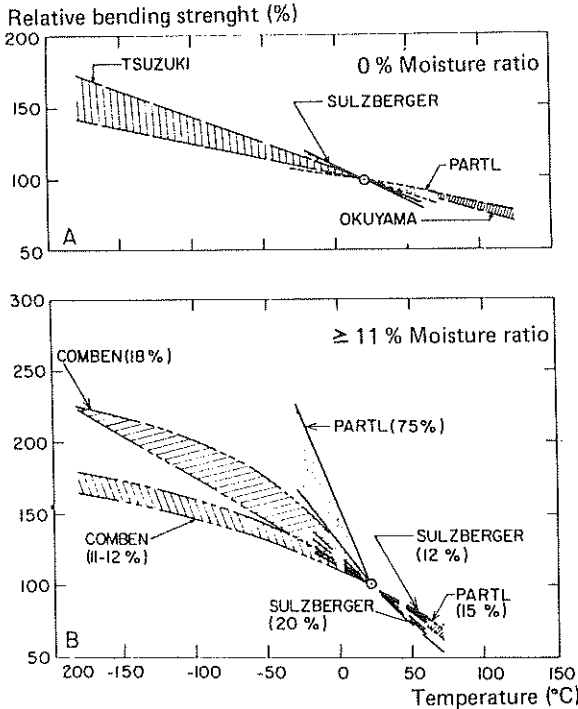

FIG. 5.4. Effect of variable temperature on bending re-sistance. A: Moisture ratio 0%, B: Moisture

Summaries of test results relating to the mechanical
properties of wood at different temperature and moisture
levels are consistently characterised by wide scatter.
This is due to the fact that a large number of different
timber species have been used in the investigations, and
to the difficulties encountered in measuring temperature
and moisture ratio. The fact that in wood the moisture
ratio changes with temperature makes precise definition
of state difficult.

5.3   Conclusions

Reference has been made in the foregoing to the differ-
ences in data obtained concerning the mechanical proper-
ties of wood in tests on small defect-free specimens and
in tests on structural elements of timber of ordinary
dimensions. Future codes for timber structures will in-
creasingly take these factors into consideration in con-
junction with design at normal temperatures. It is essen-
tial that when data for these codes are produced, the
specific problems associated with design methods for
timber structures exposed to fire should be included.

On the basis of the experimental investigations on small
specimens at variable temperature and moisture conditions
a number of crude material models have been developed for
the mechanical behaviour of wood, but there is none in
which consideration is given to the deformations due to
transient stresses and temperatures and the simultaneous
presence of moisture. It is therefore essential that
such an analytical model, suitable for advanced calcula-
tions, should be developed. This model must be capable
of use for practical calculations of the deformations
and instability loads in timber structures exposed to
fire. Validity of this model must be verified by experi-
mental studies on small specimens and, finally, also on
some larger specimens such as beams in flexure and col-
umns under axial compression.

Nothing has been published as to why temperature and
moisture modify the mechanical properties, only the way
in which these change. It is therefore important to
ascertain whether the biological differences between
different species or within the same species can pheno-
menologically explain some of the great scatter in result
relating to the mechanical properties of wood at defined
combinations of temperature and moisture ratio. Such an
investigation should include development of a simplified
analytical model which takes into consideration the
growth ring structure of wood and the relationship be-
tween cellulose and lignin.

REFERENCES

/5.1/   GERHARDS, C C, "Effects of Moisture Content
         and Temperature on the Mechanical Properties
         of Wood: An Analysis of Immediate Effects".
         Wood and Fiber 1, 1982.

/5.2/   KITAHARA, K, YUKAWA, K, "The Influence of the
         Change of Temperature on Creep in Bending".
         Journal of Japan Wood Research Society, Vol.
         10, No 5, 1964, pp. 169-175.

/5.3/   NEMETH, L L J, "The Influence of Moisture on
         Creep in Wood". M.S. Thesis, University of
         California, Berkely, 1964.

/5.4/   TAKEMURA, T, "Plastic Properties of Wood in
         Relation to the Non-Equilibrium States of
         Moisture Content". Journal of Japan Wood
         Research Society, Vol. 13, No 3, 1967, pp.
         77-81.

/5.5/   ARMSTRONG, L D, KINGSTON, R S, "Effect of
         Moisture Changes on Creep in Wood". Nature
         (London), Vol. 185, No 4716, 1960, pp. 862-863.

/5.6/   PERKITNY, T, "Über Wechselbeziehungen zwischen
         Sorption, Desorption und Rheologie von Holz".
         Holz als Roh- und Werkstoff, Vol. 23, No 5,
         1965, pp. 173-182.

/5.7/   SCHAFFER, E L, "Elevated Temperature Effect
         on the Longitudinal Mechanical Properties of
         Wood". Thesis, Engineering Mechanics, Univer-
         sity of Wisconsin, 1971.

6. FIRE BEHAVIOUR OF STRUCTURAL ELEMENTS AND STRUCTURES

The overriding object of advanced design of loadbearing and separating constructions must be that the design is based on realistic assumptions concerning fire exposure and loading, and that it produces structures which have a uniform and reasonable level of safety in combination with satisfactory overall economy.

The methods which are normally applied at present for the determination of the behaviour and limit states of a timber structure exposed to fire permit only rough assessments. The inescapable consequence of this in practical design if the production of design solutions of greatly variable safety level at a cost which can be very far from the optimum.

In Sweden, extensive research has been carried out concerning the fire behaviour and design of steel and concrete structures. In conjunction with this, an entirely new design procedure has been developed. For steel structures exposed to fire, the research results have been summarised in a manual which has been granted type approval by the Swedish Board of Physical Planning and Building /1.12, 1.13/. As regards concrete structures under fire exposure conditions, research and development is in progress at the Division of Building Fire Safety and Technology, Lund Institute of Technology with the aim of producing a similar design manual /1.21/. The design procedure is based on conditions during real fires and is well suited for adaptation to modern loading and safety principles. The method also results in a more uniform safety level and reduced costs in relation to those obtained by means of the highly schematic methods which are internationally predominant.

Research which may result in a similar functionally based design procedure for timber structures exposed to fire is of urgent necessity, and is essential if steel, concrete and timber are to compete in the future on equal terms as materials for loadbearing and separating constructions.

In Section 6.1, a description is given of the calculation procedure for a functionally based design method related to actual fire conditions. The present state of knowledge and the practical conditions for application of this method are touched upon in outline with reference to structures of solid section, for instance glued laminated structures. In Section 6.2 a similar assessment is made concerning lightweight and composite timber structures with a loadbearing and/or separating function. Finally, in Section 6.3, the problems which are specific to fire design of splices, attachments and connections are dealt with.

6.1   Timber structures of solid section

The characteristics applicable to fire in a fire com-
partment are of fundamental importance for analytical
fire design of loadbearing and separating structures.
The critical input parameters are as follows /6.1/ -
see FIG. 6.1.

(1) The design value of the fire load intensity,

(2) the combustion properties of the fire load,

(3) the size and geometry of the fire compartment,

(4) the ventilation conditions in the fire compartment,

(5) the thermal properties of the constructions enclos-
    ing the fire compartment.

These parameters together determine the rate of combus-
tion and the energy released per unit time, and the
design gas temperature-time curve of the fire compart-
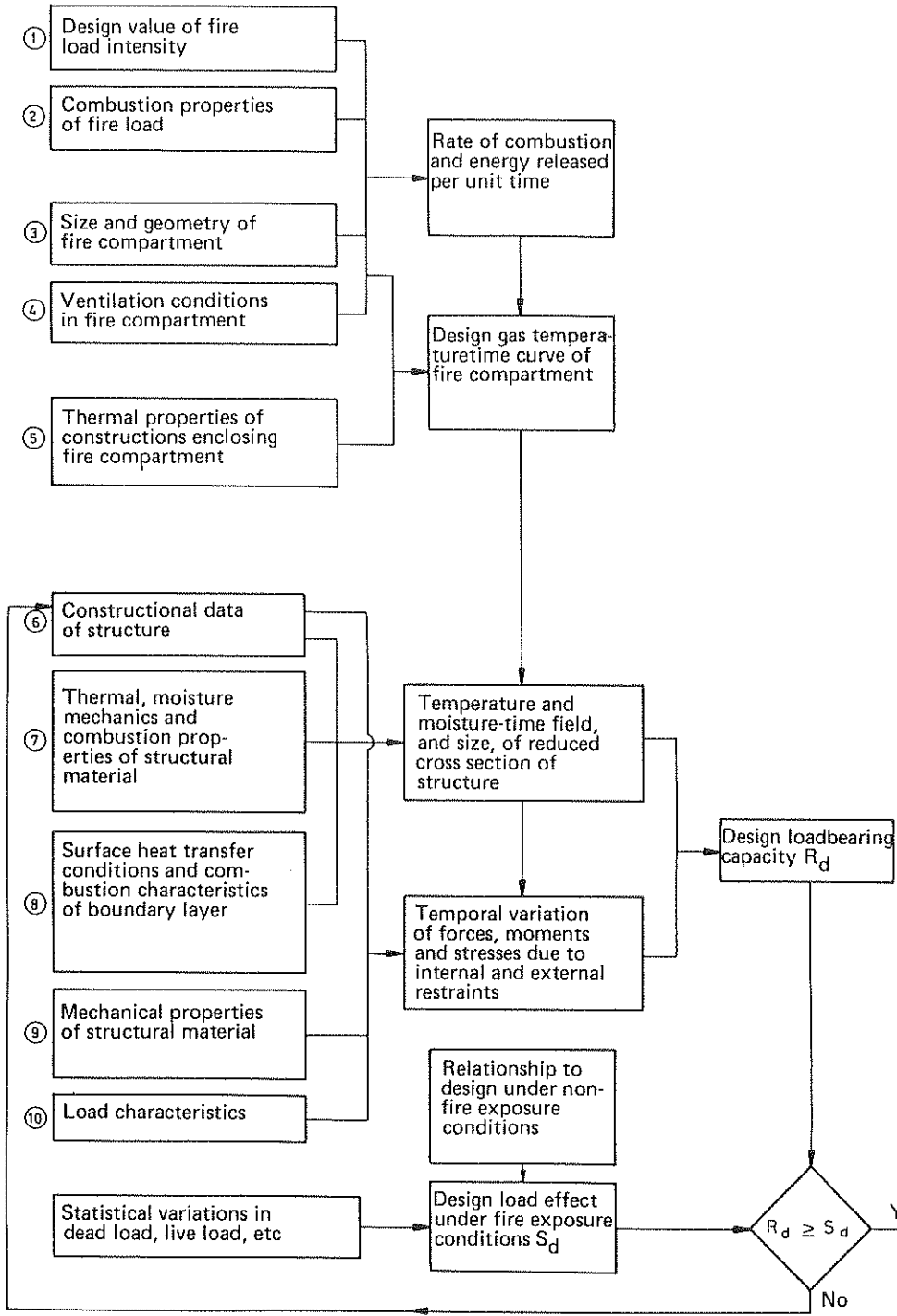ment for an undisturbed fire sequence.

Together with

(6) the structural data of the structure,

(7) the thermal, moisture mechanics and combustion pro-
    perties of the structural material,

(8) the surface heat transfer conditions and the combus-
    tion characteristics for the boundary layer,

this curve defines, for a structure of combustible mat-
erial, the temperature and moisture fields and the red-
uced cross section of the fire-exposed structure and
its components at every point in time of the fire se-
quence. With

(9) the mechanical properties of the structural material

(10) load characteristics

as further input parameters, the forces, moments and
stresses which occur in the fire-exposed structure due
to internal and external restraints on deformation which
may be present, and the temporal variation of the load-
bearing capacity of the structure, can be determined.
The smallest value of this loadbearing capacity during
the complete fire sequence defines the design loadbearing
capacity R_d of the structure.

On the basis of characteristic values, partial coeffi-
cients and load reduction factors relating to dead load,
live load etc, selected in view of the fact that fire
exposure is to be regarded as an accidental load, the
design load effect in the event of fire, S_d, is defined
/6.2/. Direct comparison of the design loadbearing capa-

```
┌─────────────────────┐
① │ Design value of fire │
  │ load intensity      │────────┐
  └─────────────────────┘        │
┌─────────────────────┐          │      ┌─────────────────────┐
② │ Combustion properties│─────────┼─────▶│ Rate of combustion  │
  │ of fire load        │         │      │ and energy released │
  └─────────────────────┘         │      │ per unit time       │
                                  │      └─────────────────────┘
┌─────────────────────┐          │                 │
③ │ Size and geometry of │─────────┤                 ▼
  │ fire compartment    │         │      ┌─────────────────────┐
  └─────────────────────┘         │      │ Design gas tempera- │
┌─────────────────────┐          │      │ turetime curve of   │
④ │ Ventilation conditions│────────┼─────▶│ fire compartment    │
  │ in fire compartment │         │      └─────────────────────┘
  └─────────────────────┘         │                 │
┌─────────────────────┐          │                 │
⑤ │ Thermal properties of│─────────┘                 │
  │ constructions enclosing                          │
  │ fire compartment    │                            │
  └─────────────────────┘                            │
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```
┌─────────────────────┐                             │
⑥ │ Constructional data  │──────┐                    │
  │ of structure        │      │                    ▼
  └─────────────────────┘      │     ┌─────────────────────┐
┌─────────────────────┐       │     │ Temperature and     │     ┌─────────────────────┐
  │ Thermal, moisture    │      │     │ moisture-time field,│     │ Design loadbearing  │
⑦ │ mechanics and        │──────┼────▶│ and size, of reduced│────▶│ capacity Rd         │
  │ combustion prop-     │      │     │ cross section of    │     └─────────────────────┘
  │ erties of structural │      │     │ structure           │                │
  │ material            │      │     └─────────────────────┘                │
  └─────────────────────┘      │                │                           │
┌─────────────────────┐       │                ▼                           │
  │ Surface heat transfer│      │     ┌─────────────────────┐                │
⑧ │ conditions and com-  │──────┤     │ Temporal variation  │                │
  │ bustion characteristics     │     │ of forces, moments  │                │
  │ of boundary layer   │      │     │ and stresses due to │                │
  └─────────────────────┘      │     │ internal and external                │
┌─────────────────────┐       │     │ restraints          │                │
⑨ │ Mechanical properties│──────┤     └─────────────────────┘                │
  │ of structural material      │                                           │
  └─────────────────────┘      │     ┌─────────────────────┐                │
┌─────────────────────┐       │     │ Relationship to     │                │
⑩ │ Load characteristics │──────┘     │ design under non-   │                │
  └─────────────────────┘            │ fire exposure       │                │
                                     │ conditions          │                │
                                     └─────────────────────┘                │
┌─────────────────────┐                        │                           ▼
  │ Statistical variations│            ┌─────────────────────┐          ╱╲       Y
  │ in dead load, live   │───────────▶│ Design load effect  │         ╱Rd ≥╲───────
  │ load, etc           │            │ under fire exposure │────────▶╲ Sd  ╱
  └─────────────────────┘            │ conditions Sd       │         ╲  ╱
                                     └─────────────────────┘          ╲╱
                                                                        No
```

For purposes of design, the gas temperature-time curve
of the fire compartment can be selected either accord-
ing to /6.1/, Section 3.2 (Method I) - as exemplified
in FIG. 1.2 - or it can be determined in each individual
case on the basis of the energy and mass balance equa-
tions of the fire compartment or in some other equivalent
manner, for instance experimentally or by a combined ex-
perimental and theoretical method (Method II). The fire
characteristics according to Method I assume a fire com-
partment of a size applicable,for instance, to dwellings,
ordinary offices, schools, hospitals, hotels and libra-
ries. For fire compartments of very large volume - for
instance industrial and sports premises - the data pro-
duced by Method I provide a very poor representation of
a real fire exposure.This also applies for the gas tem-
perature-time curve which is used in conjunction with
standardised fire tests according to ISO 834. At present
there is no well substantiated body of data available
which permits more accurate fire design of fire compart-
ments of large volume - see also the comments on p. 11

The design fire load and the characteristics of the fire
compartment thus form the basis for determination of the
design fire exposure, expressed in terms of the design
gas temperature-time curve of the fire compartment,
which is used as input in the flow chart in FIG. 6.1.
Depending on practical application, the design load-
bearing capacity may be required for

a) a complete fire sequence

b) part of the fire sequence, t_{ext},
   determined with respect to the
   time needed for fire fighting
   in unfavourable conditions

c) part of the fire sequence, limi-
   ted by the design escape time
   t_{esc} from the building.
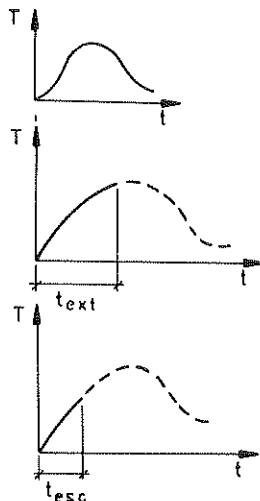
The provision of an automatic fire extinguishing system
can be taken into consideration in selecting the design
fire load. This is also affected, for instance, by the
consequences of failure in the loadbearing structure
with respect to injuries to persons or damage to pro-
perty.

The time for which retention of loadbearing capacity is
to be specified must be judged in each case. It is quite

tive a), results in comparatively large savings in cost
owing to the smaller dimensions of the loadbearing sys-
tem. Apart from the requirements specified in the regu-
lations,one of the factors which are critical for the
choice of the alternative to be used as the basis of
design are the economic judgments made by the owner of
the building. The value of the building, the value of
its contents, the costs due to loss of production, the
clearance and repair costs etc are all relevant to such
a judgment.

The feasibility of applying the design method described
in FIG. 6.1 is commented on in the following with refer-
ence to a timber structure of solid section such as a
glued laminated structure.

6.1.1   Rate of charring

Design may, for instance, be based on experimentally
determined relationships between the thickness of the
charred layer and the duration of fire exposure. FIG.
6.2 illustrates such a relationship for the thermal ex-
posure applicable for standardised fire tests according
to ISO 834 - Equation (1.1).
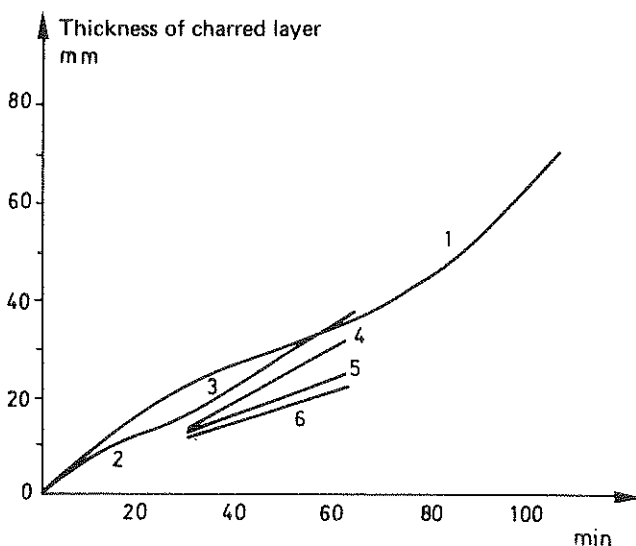
FIG. 6.2. Experimentally determined relationship between
the thickness of the charred layer and the

On the basis of the curves in FIG. 6.2 and the results
of similar investigations, the rate of charring which
is representative for thermal exposure according to ISO
834 is often taken to be 0.6 mm/min. /6.18 and 6.19/
quote corresponding figures which are appreciably more
conservative. The rate of charring applied for columns
is 0.7 mm/min, and for beams it is 0.8 mm/min for the
vertical and upper horizontal surfaces, and 1.1 mm/min
for the soffit. These figures have been adopted in DIN
4102, Part 2.

For fire design of timber structures for a differentiated
fire sequence, with the gas temperature-time curves in
accordance with FIG. 1.2, the Commentary to SBN 1976:1
recommends the curve in FIG. 6.3 as the provisional basis
for the rate of charring - see also /6.7/ and /6.13/. This
approximate curve has been drawn on the basis of a study
of investigations reported by Knublauch /6.8/. The dura-
tion of fire is estimated to be the time up to the point
where the downward branch of the appropriate gas tempe-
rature-time curve has dropped to 300°C.
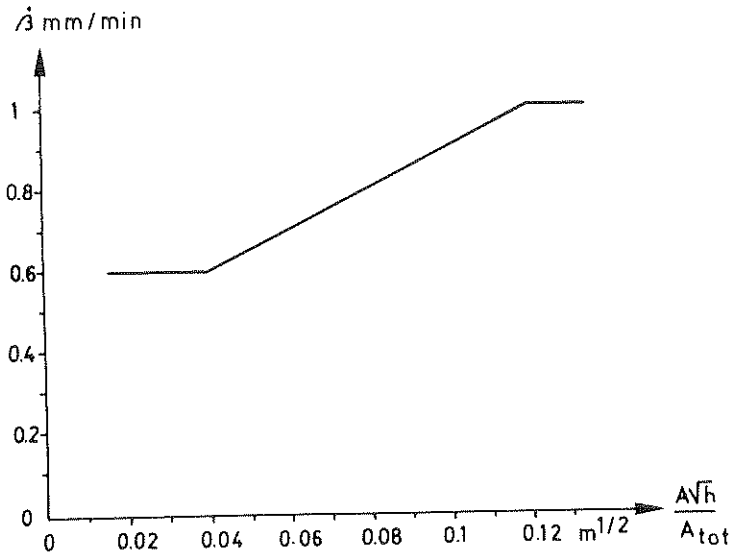
FIG. 6.3. Approximate relationship constructed on the
basis of simplified considerations for the
rate of charring β of solid or laminated tim-
ber beams of pine or spruce as a function of
the opening factor $A\sqrt{h}/A_{tot}$ of the fire com-
partment /6.1, 6.7, 6.13/.

A simplified analytical model for calculation of the
depth of the charred layer under variable thermal expos-

diagrams and approximate formulae for calculation of the
depth (mm) of the charred layer in laminated structures
exposed to fire in conformity with the gas temperature-
time curve according to FIG. 1.2. The following approx-
imate formulae apply:

$$\theta = \frac{0.0175f}{\dfrac{A\sqrt{h}}{A_{tot}}} \tag{6.1}$$

$$\beta_o = 1.25 - \frac{0.035}{\dfrac{A\sqrt{h}}{A_{tot}} + 0.021} \tag{6.2}$$

$$\left.
\begin{aligned}
\beta &= \beta_o t && \text{for } 0 \le t \le \tfrac{\theta}{3} \\[2mm]
\beta &= \beta_o \left(-\tfrac{\theta}{12} + \tfrac{3t}{2} - \tfrac{3t^2}{4\theta}\right) && \text{for } \tfrac{\theta}{3} \le t \le \theta
\end{aligned}
\right\} \tag{6.3}$$

where

f = fire load intensity, MJ/m^2 of enclosing surface
$A\sqrt{h}/A_{tot}$ = opening factor of fire compartment, $m^{1/2}$
θ = time in minutes at which maximum charring rate
     occurs for the fire load intensity and opening
     factor concerned
β_o = initial value, mm/min, of the rate of charring
t = elapsed time in minutes.

The model in /6.9/ provides no information concerning
temperature and moisture distribution in the uncharred
portion of the timber section.

Fredlund /6.11/ gives a model for the pyrolysis of wood
which is of more general application and is also func-
tionally superior to the models given in the literature.
This model provides data for calculation of the rate of
charring under variable real conditions during the early
stages of a fire and for a fully developed fire. The
publication also outlines methods for approximate deter-
mination of the temperature and moisture states in tim-
ber structures. Further development is however needed
before this method is easy to apply in practice.
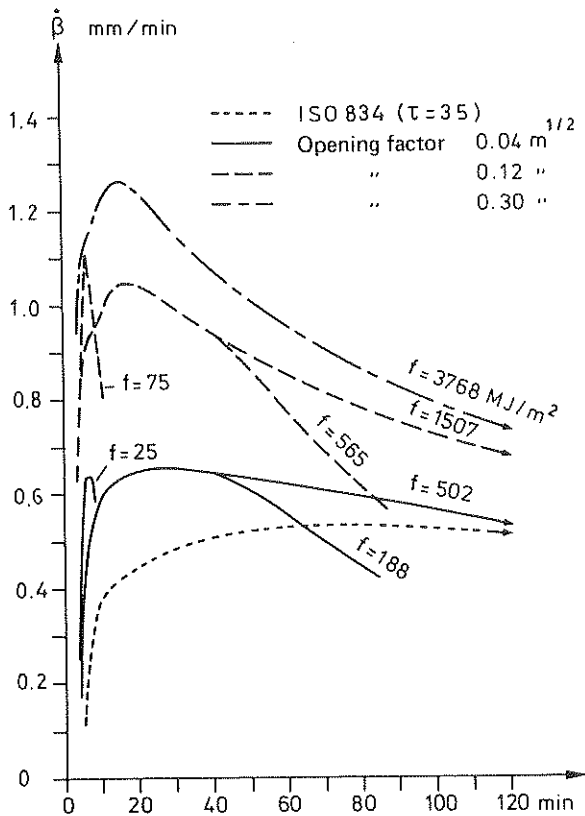
FIG. 6.4. Mean rate of charring $\dot{\beta}$ as a function of fire
duration for thermal exposure according to
the standard fire curve (ISO 834), corrected
for a furnace with the characteristic time
$\tau = 35$ minutes, for different gas temperature-
time relationships expressed in terms of the
fire load intensity f and the opening factor

6.1.2   Beams in a limit state in the form of
flexural failure

On the assumption that the thickness β of a charred layer
during the relevant part of the fire sequence can be de-
termined according to Equations (6.1) - (6.3), and that
the change in mechanical properties of the uncharred mat-
erial under fire exposure conditions can be described as
a reduction of ultimate stress by a factor μ, relation-
ships can be derived for the loadbearing capacity of a
cross section exposed to fire on three or four sides.

FIG. 6.5 and 6.6 set out such curves for fire exposure
on four and three sides respectively. The curves give
the value of the ratio β/B corresponding to flexural

the cross section with respect to failure in pure bend-
ing prior to fire exposure. For the region β/B > 0.25
the curves are shown dashed, as for this region the de-
sign assumptions have not been sufficiently verified
experimentally. The factor μ which describes the reduced
loadbearing capacity of the uncharred part of the cross
section with respect to elevated temperature and in-
creased moisture content during the fire has been given
the value 0.8.
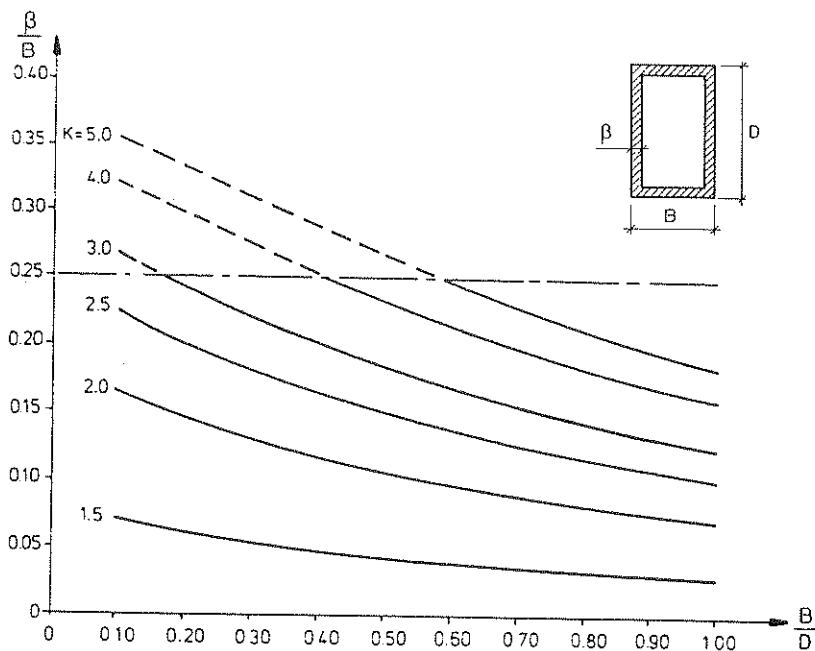
FIG. 6.5. Curves showing the relationship between the
ratio β/B and the width/depth ratio B/D of
the cross section for a solid or laminated
timber beam of rectangular cross section
which is exposed to fire on four sides. The
curves are drawn on the assumption of flexural
failure. K is the factor of safety of the
cross section prior to fire exposure /6.13/.
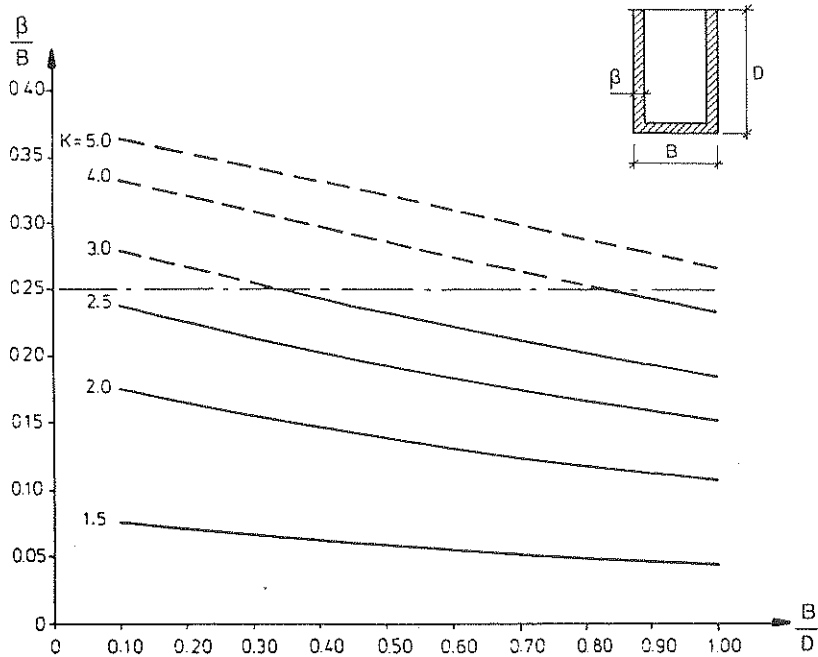
FIG. 6.6. Curves showing the relationship between the
ratio β/B and the width/depth ratio B/D of
the cross section for a solid or laminated
timber beam of rectangular cross section
which is exposed to fire on three sides. The
curves are drawn on the assumption of flexural
failure. K is the factor of safety of the
cross section prior to fire exposure /6.13/.

6.1.3 Beams in a limit state in the form of instability failure

If the risk of lateral torsional instability must be con-
sidered, the problem is complicated by the fact that the
critical load gradually diminishes during the fire owing
to progressive reduction of the cross section and the
consequent increase in slenderness ratio. The risk is
further accentuated if lateral stiffeners collapse or
vanish during the fire.

/6.12/ gives an extensive body of data for the design
of rectangular timber beams under fire exposure condi-
tions with respect to the risk of lateral torsional in-
stability. To sum up, this design comprises the follow-
ing stages:

The unburned part of the cross section is determined in

section. The time up to failure is defined as the time
that elapses until the stresses attain a certain value,
depending on slenderness, which is defined by the for-
mula

$$\alpha = \sqrt{\{\frac{\sigma_{bk}}{\sigma_E}\}} \tag{6.4}$$

where σ_{bk} is a characteristic value of the ultimate
flexural stress calculated on the assumption of linear
stress distribution. The Swedish Building Code SBN 1980
specifies the value $\sigma_{bk} = 3\sigma_{ma}$, where σ_{ma} is the permiss-
ible compressive stress in bending. σ_E is the maximum
compressive stress in bending due to the critical lateral
torsional load calculated according to the elastic theo-
ry. The permissible compressive stress in bending, σ_{ma},
is reduced with respect to lateral torsional failure
by multiplication by the factor $\kappa_v(\alpha)$ which has the
following values:

$$
\begin{aligned}
\kappa_v(\alpha) &= 1 && \text{when } \alpha \leq 0.6 \\
\kappa_v(\alpha) &= 1.37 - 0.61\alpha && \text{when } 0.6 < \alpha \leq 1.4 \\
\kappa_v(\alpha) &= 1/\alpha^2 && \text{when } \alpha > 1.4
\end{aligned} \tag{6.5}
$$

A subsidiary condition is that the least lateral dimen-
sion of the beam should not, initially, be less than 4
times the maximum depth of penetration of the charred
layer.

Once the value of the thickness β of the charred layer
is known during the relevant part of the fire sequence,
then, according to the technique described above, an
expression can be derived for the critical value of the
ratio β/B as a function of K, B/D and a parameter η
which expresses the sensitivity to lateral torsional
failure of a beam which is not exposed to fire. This
parameter is defined as

$$\eta = \sqrt{\frac{LD}{mB^2}} \tag{6.6}$$

where L is the length of the beam and m is a coefficient
which depends on the load on the beam and its end re-
straint conditions and which, for normal practical app-
lications, can be obtained from manuals.

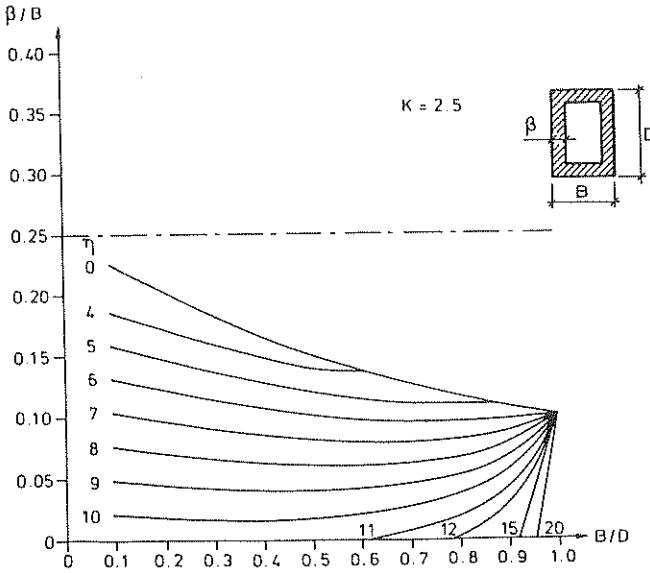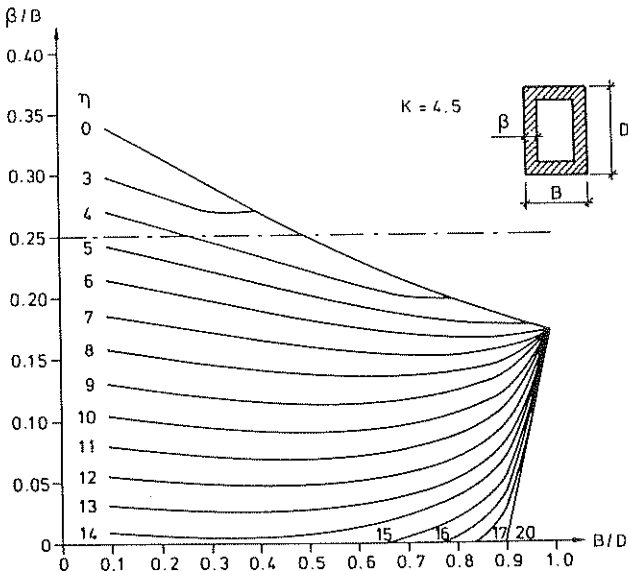FIG. 6.7 and 6.8 give examples of solutions for the case

FIG. 6.7. The ratio β/B as a function of the width/depth ratio B/D for beams exposed to fire on four sides, for different values of the parameter η and for K = 2.5 where K is the factor of safety with respect to flexural failure prior to the fire /6.12/.

FIG. 6.8. The ratio β/B as a function of the width/depth ratio B/D for beams exposed to fire on four sides, for different values of the parameter η and for K = 4.5

6.1.4 Columns in a limit state in the form of buckling

In designing columns where there is no risk of buckling, the same procedure can be applied as for beams. If the risk of buckling must be taken into consideration, the problem is complicated by the fact that this risk increases during the entire fire sequence owing to the progressive reduction in cross section and the consequent increase in slenderness ratio.

The unburned part of the cross section is determined in the same way as for beams according to Subsection 6.1.1. The slenderness ratio and the stresses are calculated for the reduced cross section. The time up to failure is defined as the time that elapses until the stresses have attained a certain value which depends on the slenderness ratio. According to /6.13/, this value can be permitted to attain twice the value permissible for the stress for an ordinary combination of loads. A subsidiary condition is that the slenderness ratio shall not exceed 170, and that the least initial lateral dimension of the cross section shall not be smaller than four times the maximum depth of charring.
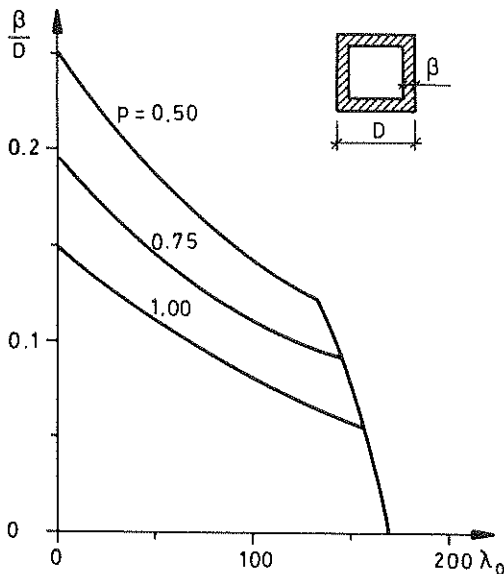
FIG. 6.9. Curves for determination of the thickness β of the charred layer corresponding to buckling for different values of the initial slenderness
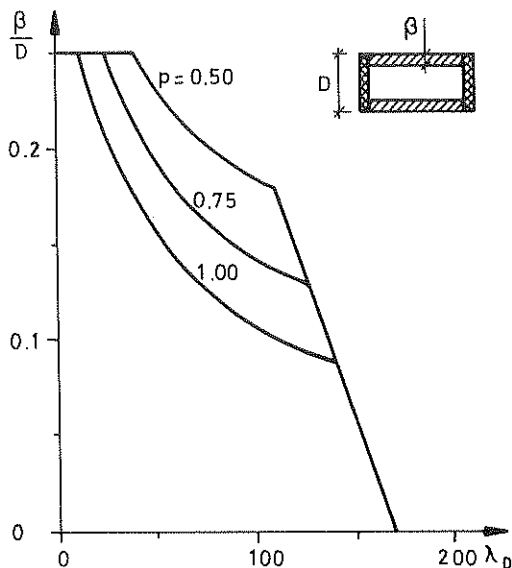
FIG. 6.10.The same curves as in FIG. 6.9, but appli-
cable to the case where the fire can attack
the section only on two opposed sides. It is
assumed that buckling occurs at right angles
to the surfaces exposed to fire /6.13/.

When the thickness β of the charred layer has been deter-
mined according to Equations (6.1) - (6.3), the relation-
ships according to FIG. 6.9 and 6.10 can be calculated
on the basis of these assumptions. From FIG. 6.9, the
thickness of the charred layer corresponding to failure
can be determined for a column of square cross section
which is exposed to fire on all four sides as a function
of the initial slenderness ratio λ_0 and the ratio p of
the applied load to the load permitted for an ordinary
combination of loads. FIG. 6.10 presents the same curves
for the case when fire can attack the cross section only
on two opposed sides, buckling being assumed to occur
at right angles to the sides exposed to fire.

6.1.5   Conclusions

The design method described for laminated timber struc-
tures exposed to fire is based on simplified assumptions
for all the components of the method. In consequence,
applicability of the method is confined to approximate
calculations, which however represents considerable pro-
gress in relation to conventional design based on fire
classification and the results of standard fire tests.

perties, temperature and moisture conditions, and mecha-
nical properties. Improved knowledge of these components
will permit a more meaningful and substantiated theore-
tical analysis of the behaviour and loadbearing capacity
of different types of loadbearing timber structures under
fire exposure conditions. These structures may be either
directly exposed to fire, or exposed only after a certain
time has elapsed since the outbreak of fire. The modes of
failure which are of interest are bending, shearing, tor-
sion, buckling, lateral torsional buckling. Analysis of
the behaviour of nailed and bolted connections should be
included, together with design which will give these the
same strength as the rest of the fire-exposed structure.
This is commented in greater detail in Section 6.3.

The structural analysis described above is made easier
by the existence of software for high temperature struc-
tural mechanical calculations, primarily developed for
concrete and steel structures.

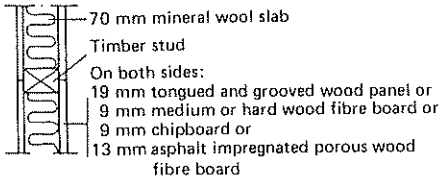## 6.2   Lightweight and composite timber structures

With regard to lightweight and composite timber struc-
tures with a loadbearing and/or separating function,
subject to the action of fire, the present state of know-
ledge is mainly confined to the results of standard fire
tests and summaries of such tests in the literature. In
Sweden, type approved structures for different fire
classes are listed in Approval List B published by the
Swedish Board of Physical Planning and Building. An ex-
tract from this is given in /6.15/ with regard to type
approved wall and floor structures of timber and/or wood
based materials - FIG. 6.11 and 6.12. The most compre-
hensive international summaries of the results of stand-
ard fire tests and associated fire classifications are
given in /6.14/ and /6.19/.

All the results published with regard to the behaviour
and loadbearing capacity during a fire of lightweight
and composite structures of timber relate to thermal ex-
posure in conformity with a standard fire test - ISO
834, Equation (1.1). There are no experimental results
available which illustrate the behaviour and loadbearing
capacity in relation to exposure more representative of
a natural fire. Nor have any analytical methods been de-
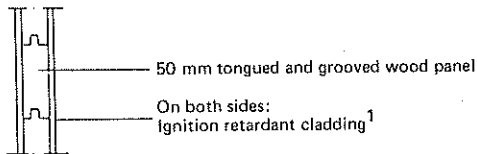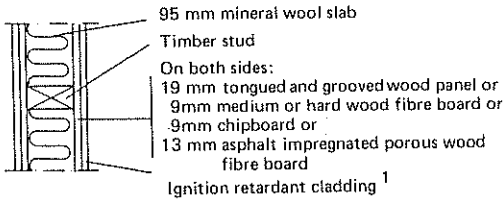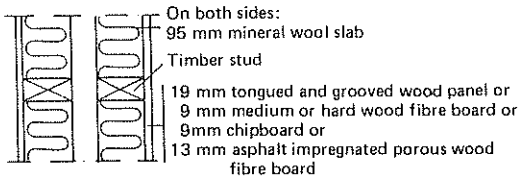veloped for the fire design of these types of structure.

Research which may result in the development of such
analytical methods is therefore of great urgency. This
applies both for thermal exposure according to ISO 834
and for real exposure, described, for instance, by the
gas temperature-time curves given in FIG. 1.2. Such a
development would include experimental studies at full
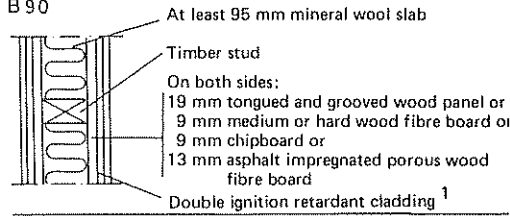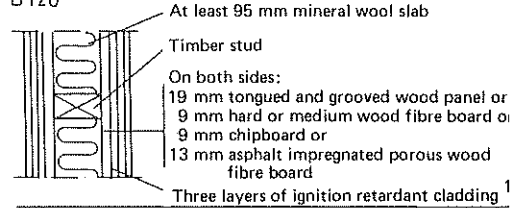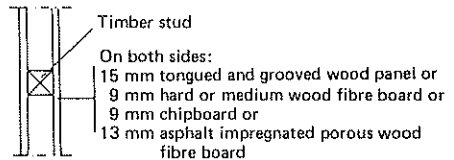
Loadbearing and separating walls

B 30

70 mm mineral wool slab

Timber stud

On both sides:
19 mm tongued and grooved wood panel or
9 mm medium or hard wood fibre board or
9 mm chipboard or
13 mm asphalt impregnated porous wood
       fibre board

70 mm mineral wool slab

Timber stud

On both sides:
Ignition retardant cladding [1]

B 60

On both sides:
95 mm mineral wool slab

Timber stud

19 mm tongued and grooved wood panel or
9 mm medium or hard wood fibre board or
9mm chipboard or
13 mm asphalt impregnated porous wood
       fibre board

95 mm mineral wool slab

Timber stud

On both sides:
19 mm tongued and grooved wood panel or
9mm medium or hard wood fibre board or
9mm chipboard or
13 mm asphalt impregnated porous wood
       fibre board
Ignition retardant cladding [1]

50 mm tongued and grooved wood panel

On both sides:
Ignition retardant cladding [1]

B 90

At least 95 mm mineral wool slab

Timber stud

On both sides:
19 mm tongued and grooved wood panel or
9 mm medium or hard wood fibre board or
9 mm chipboard or
13 mm asphalt impregnated porous wood
       fibre board
Double ignition retardant cladding [1]

B 120

At least 95 mm mineral wool slab

Timber stud

On both sides:
19 mm tongued and grooved wood panel or
9 mm hard or medium wood fibre board or
9 mm chipboard or
13 mm asphalt impregnated porous wood
       fibre board
Three layers of ignition retardant cladding [1]

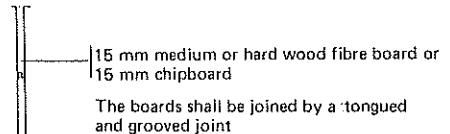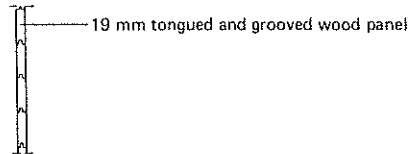## Walls of only separating function

B 15

19 mm tongued and grooved wood panel

15 mm medium or hard wood fibre board or
15 mm chipboard

The boards shall be joined by a tongued
and grooved joint

Timber stud

On both sides:
15 mm tongued and grooved wood panel or
9 mm hard or medium wood fibre board or
9 mm chipboard or
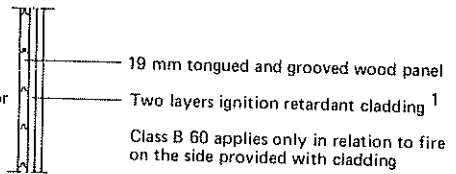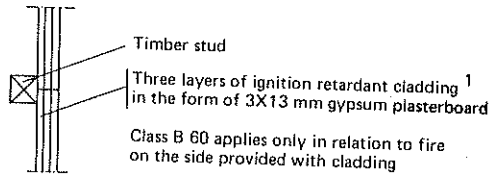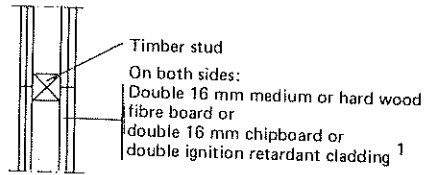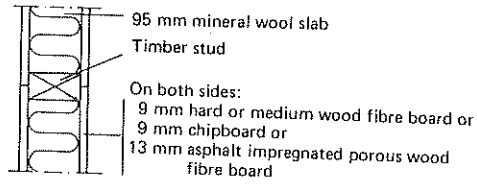13 mm asphalt impregnated porous wood
       fibre board

---

[1] Ignition retardant cladding may be 10-13 mm
gypsum plasterboard or 12 mm wood fibre board
with a mineral surface layer of approved type
"approved as cladding on internal wall and
ceiling surfaces which is equivalent to cladding
of non-combustible material". See also Approval
List B published by the Swedish Board of
Physical Planning and Building.

FIG. 6.11. Walls of timber and/or wood based materials
granted type approval for different fire classes. For
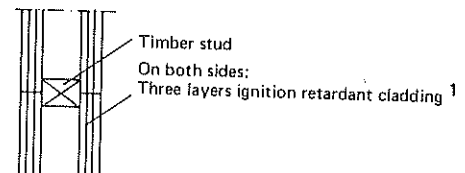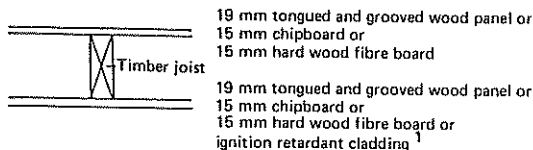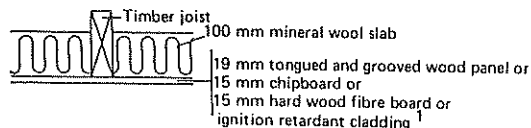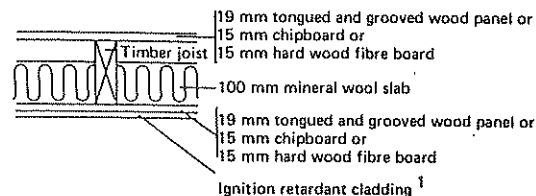further constructional details, reference should be made
to /6.15/.

B 30

50 mm tongued and grooved wood panel

24 mm medium or hard wood fibre board or
24 mm chipboard

The boards shall be joined by a tongued
and grooved joint

Timber stud

On both sides:
Ignition retardant cladding [1]

Timber stud

On both sides:
Double 9 mm hard or medium wood fibre board or
double shipboard at least 9 mm thick

Timber stud

Double ignition retardant cladding in the
form of 13 mm gypsum plasterboard (Class
B 30 applies only in relation to fire on the
side provided with the cladding)

B 60

95 mm mineral wool slab

Timber stud

On both sides:
9 mm hard or medium wood fibre board or
9 mm chipboard or
13 mm asphalt impregnated porous wood
fibre board

Timber stud

On both sides:
Double 16 mm medium or hard wood
fibre board or
double 16 mm chipboard or
double ignition retardant cladding [1]

Timber stud

Three layers of ignition retardant cladding [1]
in the form of 3X13 mm gypsum plasterboard

Class B 60 applies only in relation to fire
on the side provided with cladding

19 mm tongued and grooved wood panel

Two layers ignition retardant cladding [1]

Class B 60 applies only in relation to fire
on the side provided with cladding

B 90

Timber stud

On both sides:
Three layers ignition retardant cladding [1]

FIG. 6.11 (continued)

B 15

Timber joist
100 mm mineral wool slab

19 mm tongued and grooved wood panel or
15 mm chipboard or
15 mm hard wood fibre board or
ignition retardant cladding [1]

19 mm tongued and grooved wood panel or
15 mm chipboard or
15 mm hard wood fibre board

Timber joist

19 mm tongued and grooved wood panel or
15 mm chipboard or
15 mm hard wood fibre board or
ignition retardant cladding [1]

B 30

Timber joist
100 mm mineral wool slab

19 mm tongued and grooved wood panel or
15 mm chipboard or
15 mm hard wood fibre board

Ignition retardant cladding [1]

19 mm tongued and grooved wood panel or
15 mm chipboard or
15 mm hard wood fibre board

Timber joist

19 mm tongued and grooved wood panel or
15 mm chipboard or
15 mm hard wood fibre board

Ignition retardant cladding [1]

19 mm tongued and grooved wood panel or
15 mm chipboard or
15 mm hard wood fibre board

Timber joist
100 mm mineral wool slab

19 mm tongued and grooved wood panel or
15 mm chipboard or
15 mm hard wood fibre board

B 60

Timber joist
100 mm mineral wool slab

19 mm tongued and grooved wood panel or
15 mm chipboard or
15 mm hard wood fibre board

Double ignition retardant cladding [1]

19 mm tongued and grooved wood panel or
15 mm chipboard or
15 mm hard wood fibre board

Timber joist
100 mm mineral wool slab

19 mm tongued and grooved wood panel or
15 mm chipboard or
15 mm hard wood fibre board

Ignition retardant cladding [1]

19 mm tongued and grooved wood panel or
15 mm chipboard or
15 mm hard wood fibre board

Timber joist

19 mm tongued and grooved wood panel or
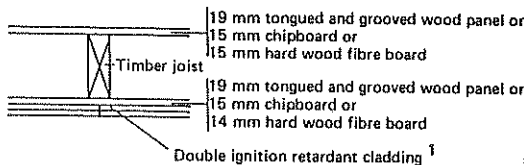15 mm chipboard or
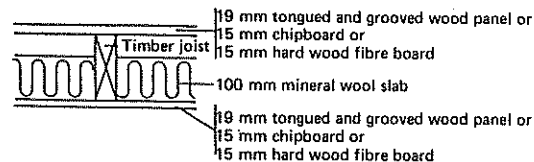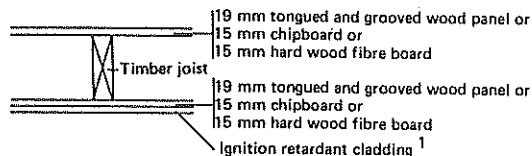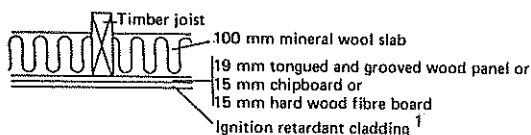14 mm hard wood fibre board

Double ignition retardant cladding [1]

[1] Ignition retardant cladding may be 10-13 mm gypsum plasterboard or 12 mm wood fibre board with a mineral surface layer of approved type "approved as cladding on internal wall and ceiling surfaces which is equivalent to cladding of non-combustible material". See also Approval List B published by the Swedish Board of Physical Planning and Building.

FIG. 6.12. Floor constructions of timber and/or wood based materials granted type approval for different fire classes. For further constructional details, reference should be made to /6.15/.

thin panels of wood and wood based materials under diff-
erent kinds of thermal exposure - FIG. 6.13 /6.14/.
Another important and urgent research project in this
field is theoretical and experimental study of the poss-
ibility of increasing the fire resistance of lightweight
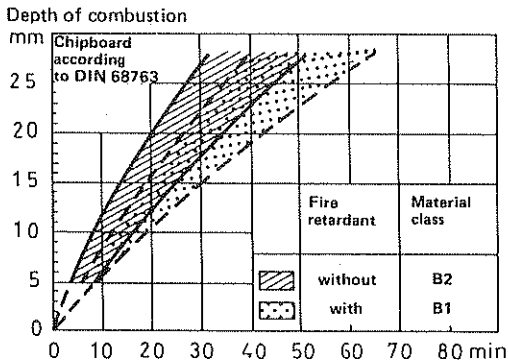and composite timber structures by means of fire retard-
ant finishes.

Depth of combustion

FIG. 6.13.Range of variation of experimentally deter-
mined depth of combustion for chipboard of
density $\geq$ 600 kg/m³ when subject to thermal
exposure according to a standard fire test,
ISO 834 /6.14/.

6.3   Splices,attachments and connections

In loadbearing timber structures, splices, attachments
and connections are critical details which demand par-
ticular attention in conjunction with design and sizing
for fire exposure. The overriding requirement in this
respect which is specified in Finnish building regula-
tions reads: "Metal components which constitute a load-
bearing element in timber structures shall be protected
in such a way that they have at least the same fire re-
sistance as the rest of the structure. In order that
this degree of protection may be achieved, wood, chip-
board or mineral wool etc of sufficient thickness may
be used. Metallic materials in direct contact with the
timber shall be insulated in such a way that their tem-
perature does not exceed 300°C during the specified fire
resistance period". There are proposals for the intro-
duction of this structural regulation in Norwegian stan-
dards for calculation of the fire resistance of timber
structures /6.20/.

6.19 and 6.21/. A fragmentary illustration of the results
is given in FIG. 6.14 which shows the increase in fire
resistance of bolted and nailed connections in shear
owing to wooden cover sheets glued or nailed over the
connection. /6.20/ gives the results of some preliminary
studies, with thermal exposure according to ISO 834, con-
cerning the possibility of increasing the fire resistance
of timber connections by insulating the steel details
with a fire retardant finish (3 coats of Unitherm) or
a mortar (20 mm Pyrocrete 102).

Failure of splices, attachments and connections in the
event of fire usually occurs due to large local defor-
mations within the timber/steel contact area. This is
verified in the few experimental investigations which
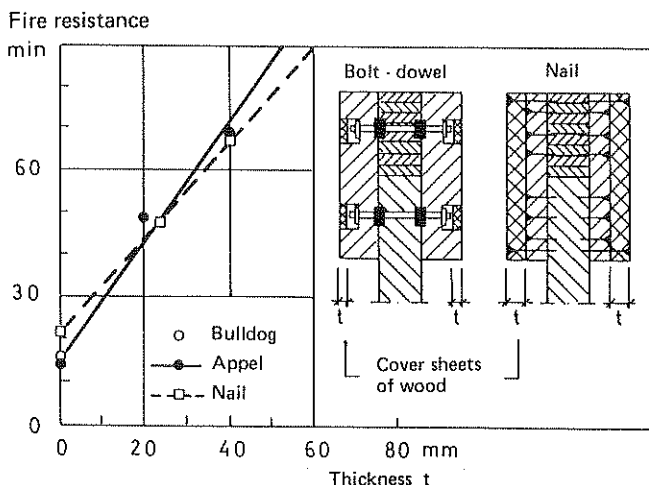have been published /6.21/ - /6.24/.

FIG. 6.14.Fire resistance of bolted and nailed connec-
tions in shear as a function of the thickness
t of wooden cover sheets glued or nailed over
the connection /6.14/.

There is no analytical model available which makes poss-
ible the calculation of the behaviour and loadbearing
capacity of e.g. a nailed or bolted connection in the
event of fire. On the other hand, models are in exist-
ence for similar conditions at ordinary room tempera-
tures. These models are eminently suitable to form a
phenomenological point of departure for the development
of models which also cover fire conditions. Such a deve-
lopment would include the following components:

o   A two or three dimensional model for calculation of
    the rate of charring, temperature gradient and mois-
    ture distribution for the wood around a heated nail
    or bolt.

erent charred layer, temperature and moisture con-
ditions and for variable pin diameters, wood thick-
nesses and angles between the grain and the direction
of force,

o   similar experimental investigation for bolts in
    single and double shear for supplementary determina-
    tion of the effect of friction in the connection,

o   application - for variable thermal exposure - of the
    data obtained in these investigations to available
    models for the behaviour and loadbearing capacity
    of connections - see, for instance, /6.25/ in which
    a similar application is described for bolted connec-
    tions in steel structures exposed to fire,

o   experimental verification of the theory at model or
    full scale.

A research project of the structure described has a
high degree of urgency. This also applies for a project
of more limited character for the production of design
data for determination of the required thickness of
cover sheets and other types of insulation for bolted
or nailed connections for real fire exposures, described,
for instance,by the gas temperature-time curves accord-
ing to FIG. 1.2.

REFERENCES

/6.1/   Swedish Board of Physical Planning and Build-
          ing, "Commentary to SBN 1976:1". (In Swedish).
          Liber Förlag, Stockholm, 1976.

/6.2/   Swedish Board of Physical Planning and Build-
          ing, SBN Section 2A, "Loadbearing Structures:
          Safety Regulations Based on Probabilistic Prin-
          ciples and the Method of Partial Coefficients".

/6.3/   Swedish Board of Physical Planning and Build-
          ing, "Svensk Byggnorm 1980". (Swedish Build-
          ing Code 1980, in the process of being trans-
          lated into English). Liber Förlag, Stockholm
          1980.

/6.4/   ÖDEEN, K, "Fire Resistance of Glued Laminated
          Timber Structures". Symposium No 3, "Fire and
          Structural Use of Timber in Buildings", held
          at the Fire Research Station, Borehamwood,
          Herts, UK, October 25, 1967, London 1970.

/6.5/   TENNING, K, "Limmade träbalkar, brandförsök
          och erfarenheter". (In Swedish). (Glued lami-
          nated timber beams, fire tests and experiences).
          "The Fire Stability of Timber Structures", Sym-
          posium at Chalmers University of Technology,
          18 June 1962, CTH Publication No 274, Gothen-
          burg 1963.

ings", held at the Fire Research Station, Borehamwood, Herts, UK, October 25, 1967, London 1970.

/6.7/ PETTERSSON, O, "Differentierad, brandteknisk dimensionering av träkonstruktioner". (In Swedish). (Differentiated fire design of timber structures). "Tre i tiden", Timber Information Council, Oslo, 1975, p. 93.

/6.8/ KNUBLAUCH, E, "Über Ausführung und Aussagefähigkeit des Normbrandversuches nach DIN 4102, Blatt 2 im Hinblick auf die Nachbildung natürlicher Schadenfeuer". BAM-Berichte Nr. 16, Berlin 1972.

/6.9/ HADVIK, S, "Charring of Wood in Building Fires - Practice, Theory, Instrumentation, Measurements". Laboratory of Heating and Air Conditioning, Technical University of Denmark, Lyngby 1981.

/6.10/ HADVIG, S, "Indbraending og temperaturforhold i trae under brand". (In Danish). (Depth of penetration and temperature conditions in wood exposed to fire). Nordic Timber Symposium, Aalborg, 28-30 May 1979, Nordisk trätidskrift, No 6, 1979, pp. 115-124.

/6.11/ FREDLUND, B, "Modell för beräkning av temperatur och fuktfördelning samt reducerad tvärsnitt i brandpåverkade träkonstruktioner". (In Swedish). (Model for calculation of temperature and moisture distribution and reduced cross section in timber structures exposed to fire). Internal Report IR79-2, Department of Structural Mechanics, Lund Institute of Technology, 1979.

/6.12/ FREDLUND, B, "Structural Design of Fire Exposed Rectangular Laminated Wood Beams with respect to Lateral Buckling". Report No 79-5, Department of Structural Mechanics, Lund Institute of Technology, 1979.

/6.13/ PETTERSSON, O, ÖDEEN, K, "Brandteknisk dimensionering av byggnadskonstruktioner - principer, underlag, exempel". (In Swedish). (Fire design of building structures - principles, data, examples). Liber Förlag, Stockholm 1977.

/6.14/ KORDINA, K, MEYER-OTTENS, C, "Brandverhalten von Holzkonstruktionen". Informationsdienst Holz, EGH, Munich 1977.

/6.15/ TRÄINFORMATION, "Trä och brand". (In Swedish). (Timber and fire). Stockholm 1974.

/6.16/ LIE, T T, "A Method for Assessing the Fire Resistance of Laminated Timber Beams and Columns". Canadian Journal of Civil Engineering 2, 1977.

/6.17/ PETTERSSON, O, JÖNSSON, R, "Fire Design of Wooden Structures". International Seminar

/6.18/   MEYER-OTTENS, C, "Junctions in Wood Structures Total Construction". International Seminar "Three Decades of Structural Fire Safety", held at the Fire Research Station, Borehamwood, Herts, UK, 22/23 February 1983, pp. 247-259.

/6.19/   KORDINA, K, MEYER-OTTENS, C, "Holz - Brand-schutz - Handbuch". Holzwirtschaftlicher Verlag, Düsseldorf, 1983.

/6.20/   RIMSTAD, N O, "Ståldeler i limtrekonstruksjoner beskyttelsemetoder". (In Norwegian). (Steel components in laminated timber structures - methods of fire protection). Nordic Timber Symposium, Aalborg, 28-30 May 1979, Nordisk trätidskrift No 6, 1979, pp. 129-133.

/6.21/   INSTITUT FÜR BAUSTOFFKUNDE UND STAHLBETONBAU DER TECHNISCHEN UNIVERSITÄT BRAUNSCHWEIG, "Untersuchungsbericht Nr. 77 169 über die Prüfung von Verbindungen zwischen brettschichts-verleimten Holzbauteilen auf Brandverhalten in zwei Versuchsabschnitten: Teil I - Bestimmung der Feuerwiderstanddauer von auf Abscheren beanspruchten Anschlüssen von Trägern an Stützen. Teil II - Bestimmung der Feuerwider-standsdauer von auf Abscheren beanspruchten Anschlüssen von Zuggliedern". Aufgestellt für die Entwicklungsgemeinschaft Holz (EGH), Munich 1977.

/6.22/   PERCIVAL, D H, SUDDARTH, S K, "An Investigation of the Mechanical Characteristics of Truss Plates on Fire-Retardant Treated Wood". Forest Products Journal, Vol. 21, No 1, January 1971.

/6.23/   JOHNSON, J W, "Tests on Fire-Retardant Treated and Untreated Lumber-Plywood Nailed and Stapled Joints". Forest Products Journal, Vol. 29, No 4, April 1979.

/6.24/   AHLÉN, B, MÅNSSON, L, "Experimentell undersök-ning av ståldetaljers inverkan på brandmot-ståndet hos limträ". (In Swedish). (Experimental investigation of the effect of steel detail on the fire resistance of glued laminated timber). Swedish Council for Building Research, Report No R48:1979.

/6.25/   PLEM, E, "Theoretical and Experimental Investigation of Point Set Structures". Swedish Council for Building Research, Document No D9:1975.

7.   THE EFFECT OF FIRE RETARDANT ADDITIVES

7.1   Introduction

By means of flame retardants, the fire behaviour of tim-
ber structures during the different stages of a fire
sequence - slow pyrolysis during the heating stage, ig-
nition of the flammable gases formed, active pyrolysis
and combustion with flaming, and smouldering, i.e. oxi-
dation of the charcoal formed - can be altered in various
respects. The mechanisms involved in the action of the
flame retardants can be roughly broken down into mecha-
nisms with a physical or chemical mode of action - FIG.
7.1 /7.1/. The effect of flame retardants of physical
action includes energy absorption, release of non-flamm-
able gases, and formation of diffusion resistant radia-
tion protection layers on the surface of the material.
For the chemical mechanisms, a distinction is made between
action in the solid phase and action in the gaseous phase
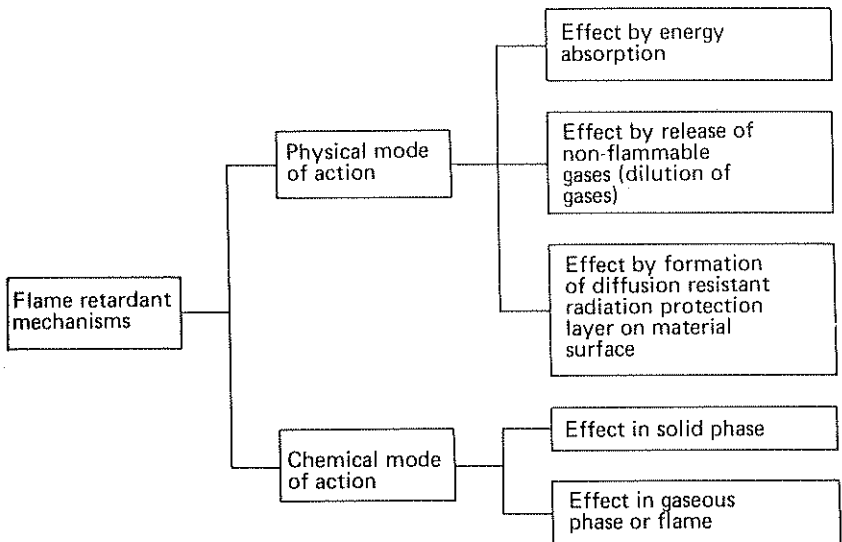or flame.

FIG. 7.1. Mechanisms of action of flame retardants.

In the case of many chemicals, the flame retardant effect
is obtained by interaction between several physical mecha-
nisms, or between physical and chemical mechanisms. The
effect can be controlled by mixing the flame retardant
chemicals, for instance in such a way that they comple-
ment one another during a complete fire sequence. The
physical and chemical properties relevant to the differ-

melt, vapour pressure and latent heat of vaporisation, water solubility.

In the following, the effect of these mechanisms and their interrelationship is further developed according to a scheme presented in /7.2/.

7.2   Chemical mechanisms

In conjunction with action in the solid phase, the chemical flame retardant theory for wood and other cellulosic materials is based on a change of the rapid pyrolysis to a slow pyrolysis. If pyrolysis of cellulose could be steered towards the ideal complete dehydration into water and carbon, according to

$$(C_6H_{10}O_5)_n \rightarrow 6nC + 5nH_2O$$
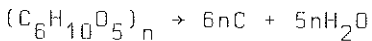
then no flammable gases would be formed from the principal wood component until the temperature became high enough to initiate the water-gas reaction. Many flame retardants also steer decomposition in this direction. Even though the ideal reaction cannot be achieved, there is increased formation of charcoal, and the volatile components are richer in oxygen and thus have a lower heat of combustion. Formation of tar is also reduced. This has the effect that the initial stage involving slow pyrolysis is prolonged. According to the theory of chemical action in the solid phase, effective flame retardants prevent formation of laevoglucosane by blocking or removing the hydroxyl group on carbon atom No 6.

It is also possible during heating of lignocellulosic materials to bring about crosslinking of adjacent cellulose chains by elimination of water. The rate at which these crosslinks are formed is considerably affected by the presence of certain inorganic salts such as aluminium sulphate, ferric nitrate and copper nitrate.

In conjunction with action in the gas phase, flame retardants do not affect the formation of combustible products, but influence their later reactions. The flame retardant acts as an inhibitor in the chain reactions between free radicals in the flame by releasing gaseous products. This means that the protective effect is obtained mainly during the ignition phase and active pyrolysis, while the initial slow pyrolysis is unaffected. Flame retardants which modify the combustion process by means of this mechanism should have a high vapour pressure and be dissociated rapidly at the temperatures which prevail in the event of fire.

7.3   Physical mechanisms

(a) Absorption of energy

Energy absorption provides a flame retardant effect by
virtue of the fact that the chemicals absorb large
amounts of heat during heating. This can be achieved by
giving the substance a high heat capacity or by making
it subject to phase transitions or reactions which re-
quire large quantities of energy, such as fusion, sub-
limation, decomposition and dehydration. This mechanism
exerts the greatest influence during the early slow pyro-
lysis.

(b) Dilution of gases

Many flame retardants decompose when heated and give off
non-flammable gases such as water vapour, nitrogen or
carbon dioxide. It is assumed that these gases protect
the material in two ways. They both dilute the gas
mixture and in this way render it non-flammable, and
they shield the material from oxygen and in this way
prevent combustion of this.

(c) Formation of protective layer

A flame retardant effect by the formation of a protect-
ive layer can be accomplished in three ways. One way is
to spray or brush onto the surface a film which excludes
oxygen from the surface of the material and prevents the
escape of flammable gases. Such a layer must be very
elastic, otherwise it is rapidly destroyed in the event
of fire. Another way is melting of the added chemical
and consequent formation of a film on the surface of
the material. The protective effect is obtained in this
case by reflection of heat, thermal insulation, exclus-
ion of atmospheric oxygen, and prevention of the escape
of flammable gases. Finally, protection can be obtained
by the provision of a layer which intumesces under the
action of heat to form a porous, thermally insulating
coat similar to charcoal.

7.4   Interaction between different mechanisms

The flame retardant effect of many chemicals is due to
interaction between several physical mechanisms or be-
tween physical and chemical mechanisms. A flame retard-
ant chemical may have the following mode of action.

releases an inert gas and also forms an acid residue
which has an action in the solid phase. The inert gas
may have the dual function of diluting the gas mixture
and of forming bubbles in the surface layer, thus in-
creasing its thermal insulation capacity. Energy is also
consumed during fusion and the decomposition reaction.
In this instance interaction occurs between five differ-
ent mechanisms /7.1/.

7.5   Different types of flame retardant

The technique of protecting wood by means of flame
retardant additives has been used for a long time.
Lyons /7.3/ states that reference to flame retardants
extend over more than 200 years. The earliest reference
to a flame retardant for wood in Chemical Abstracts is
found in Volume 1 from 1905, and concerns a mixture of
ammonium phosphate and boric acid, a preparation still
often used at present. At about the same time there is
discussion of sodium silicate, tungsten, borates and
aluminium hydroxide, and chlorides of calcium, magne-
sium, zinc and tin. A British Patent dating from 1912
specifies as flame retardant a mixture of zinc, mercury
and copper salts which are applied to the timber by sub-
jecting it to a vacuum prior to impregnation. In 1914
the American Wood Preservers Association recommends
NH_4Cl, $(NH_4)_2SO_4$ and NH_4 phosphates as particularly
suitable preparations, and a publication of the same
Association in 1944 quotes $Na_2Cr_2O_7$, $(NH_4)_2HPO_4$,
$NH_2H_2PO_4$, $Na_2B_4O_7$, H_3BO_3, $ZnCl_2$, and chromated $ZnCl_2$,
as suitable agents. References /7.2, 7.3/ tabulate a
large number of flame retardants and associated methods
of application.

Table 7.1 lists some flame retardants in common commer-
cial use at present and their recommended chemical com-
positions.

Sellman et at /7.1/ has collated physical and thermal
data for some inorganic flame retardant chemicals, bro-
ken down into borates, phosphates and silicates. The
following conclusions can be drawn from this:

o   In the case of borates the flame retardant effect is
    considered to be due to a combination of chemical
    action in the solid phase, energy absorption, develop-
    ment of diluent gases, and formation of a protective
    film on the surface of the material.

o   In the case of ammonium phosphates, chemical action
    in the solid phase dominates, but release of diluent
    gases and energy absorption should provide additive

o In the case of sodium silicates, the protective me-
chanisms are more difficult to evaluate, but the
protective film formation mechanism is probably the
dominant one.

o The modes of action of the different groups are simi-
lar, and they act at about the same stage of the fire
sequence. Combinations of these are therefore not
likely to produce an appreciable increase in flame
retardant effect.

Table 7.1 (according to /7.3/)

Chemicals	Proportion	Specification
$(NH_4)_2SO_4$	78	Type 1[a]
$NH_4H_2PO_4$ or $(NH_4)_2HPO_4$	19	
$(NH_4)_2SO_4$	60	
H_3BO_3	20	
$(NH_4)_2HPO_4$	10	Type 2
$Na_2B_4O_7$	10	Minalith
$Na_2B_4O_7$	60	Type 3
H_3BO_3	40	
$ZnCl_2$	77.5	Type 4
$Na_2Cr_2O_7.2H_2O$	17.5	CZC
$ZnCl_2$	62	
$Na_2Cr_2O_7.2H_2O$	15.5	Type 4
$(NH_4)_2SO_4$	10	CZC(FR)
H_3BO_3	10	
$Na_2B_4O_7$	67-70	
$NH_4H_2PO_4$	33-30	
$ZnCl_2$	54	
$NH_4H_2PO_4$	46	
$ZnCl_2$	35	
$(NH_4)_2SO_4$	35	Protexol Class D
H_3BO_3	25	Pyresote
$Na_2Cr_2O_7.2H_2O$	5	

7.6   Conclusions

In relation to the behaviour and design for fire expos-
ure conditions of loadbearing and separating construc-
tions of timber, the above description of the effect of
fire retardant additives points to the following re-
search projects:

(1) A review of the existing state of knowledge and
    further analysis of the physical and chemical
    mechanisms involved in the action of flame retard-
    ants, and study of the possibilities of achieving
    an optimum interaction between different mechanisms
    at the different stages of a fire - slow pyrolysis
    during the heating phase, ignition of the flammable
    gases formed, active pyrolysis and combustion with
    a flame, and smouldering. In conjunction with cer-
    tain applications, e.g. calculation of the rate of
    charring, it should be possible to study by means
    of analytical pyrolysis models the effect of fire
    retardants which are based on physical action in
    the solid state.

(2) A review of the existing state of knowledge and
    preparation of a detailed programme for further
    research concerning the effect of flame retardant
    additives on phenomena and properties which are
    critical in fire design of loadbearing and separat-
    ing timber constructions - rate of charring, thermal
    properties, mechanical properties, the behaviour
    of splices and connections /7.4/ - /7.11/.

REFERENCES

/7.1/   SELLMAN, L G, ÖSTMAN, B, BACK, E, Fysikaliska
           och termiska data för några oorganiska flam-
           skyddskemikalier". (In Swedish). (Physical
           and chemical data for some inorganic flame
           retardants). Swedish Forest Products Research
           Laboratory, Stockholm 1974.

/7.2/   FREDLUND, B, "Träets antändnings- och för-
           bränningsmekanism". (In Swedish). (The igni-
           tion and combustion mechanism of wood). Depart-
           ment of Structural Mechanics, Lund Institute
           of Technology, Internal Report IR79-3, Lund
           1979.

/7.3/   LYONS, J W, "The Chemistry and Uses of Fire
           Retardants". John Wiley and Sons, USA, 1976.

/7.4/   PERCIVAL, D H, Suddarth, S K, "An Investigat-
           ion of the Mechanical Characteristics of Truss
           Plates on Fire Retardant Treated Wood". Forest
           Products Journal, Vol. 21, No 1, January 1971.

/7.6/   HOLMES, C A, "Effect of Fire Retardant Treat-
          ments on Performance Properties of Wood".
          Forest Products Laboratory, US Dept of Agri-
          culture,Madison, Wis., 1977.

/7.7/   SAWKO, P M,"Structural Wood Panels with Im-
          proved Fire Resistance". NASA CASE No.
          ARC-11174-1, Serial No 929.086, July 1978.

/7.8/   NARAHARA, T, "Today's Choices in Fire Retard-
          ant Coatings for Wood". The Construction Spe-
          cifier, July 1978.

/7.9/   NANASSY, A J, "Flame Ratardant Effects on
          Thermal Properties of Wood-Char Studied by
          the Transient Method". Wood Science, Vol. 11,
          No 2, October 1978.

/7.10/   ADAMS, E H, MOORE, G L, BRAZIER, J D, "The
          Effect of Flame Retardant Treatments on Some
          Mechanical Properties of Wood". Building
          Research Establishment, Department of Environ-
          ment,CP 8/79, September 1979.

/7.11/   JOHNSON, J W, "Tests of Fire Retardant Treated
          and Untreated Lumber-Plywood Nailed and Stapled
          Joints". Forest Products Journal, Vol. 29, No
          4, April 1979.

8.   SUMMARY OF THE PROPOSED PROJECTS. PRIORITIES

In the final section of each of the previous chapters,
conclusions have been drawn concerning research projects
of urgent necessity on the basis of the review of exist-
ing knowledge presented in that chapter. Research pro-
jects of an overriding character are described in Sec-
tion 1.6. This section also lists a number of projects
which relate to narrower subject areas. These projects
are directly related to the different stages of fire
design of loadbearing and separating timber construc-
tions. The projects are described in greater detail in
Sections 2.5, 3.5, 4.5, 5.3, 6.1.5, 6.2, 6.3 and 7.6
in the order in which they are encountered in the course
of design.

In the following, brief descriptions are given of these
projects, accompanied by an estimate of the staff re-
quirement and the overall financial commitment. The
estimate of the financial requirement has been based on
the representative costs of university research. A de-
scription is first given of the projects which have a
direct relation to the stages of the design process and
are thus more limited in scope (Section 8.1), and the
projects of more overriding character which concern the
entire design process are then described (Section 8.2).
In Section 8.3, finally, the interrelationship of the
different projects is illustrated, and an overall stra-
tegic plan is given with regard to the necessary research
effort.

8.1   Projects associated with the different
           stages of the design process

A   Development of a simplified model for translation
     of the relationship between radiation level and the
     time to ignition into an ignition criterion for a
     temporally variable fire environment (Section 2.5).

     Existing relationships between radiation and time
     to ignition have been determined experimentally or
     analytically for different materials and material
     combinations on the assumption of radiation levels
     constant in time. FIG. 2.3 gives examples of these
     relationships. In real fires, a material or material
     combination is subject to radiation exposure which
     varies in time. It is therefore of urgent necessity
     to develop a simplified model and an associated ig-
     nition criterion in order that real fire exposure
     and constant radiation level-ignition time curves
     may be interrelated, enabling a prediction to be

This is a combined experimental and theoretical project which requires access to equipment incorporating a radiant panel. The staff requirement is 1 researcher and assistants for about six months. Financial commitment: SEK. 250,000.

B   Expansion of knowledge regarding the thermal properties of charred and uncharred wood (Section 3.5).

Such expansion of knowledge is needed in order to enhance the possibility of analytically calculating the rate of charring and the temperature and moisture distributions in the uncharred portions of timber structures exposed to fire. Attention should be primarily focused on thermal conductivity and specific heat capacity of both charred and uncharred wood at temperatures above 100°C.

The task comprises both critical appraisal of information in the literature and additional experimental determinations. Access is needed to equipment for determination of the thermal conductivity and specific heat capacity at varying moisture ratios and varying elevated temperatures, up to about 300°C for uncharred wood and up to about 500°C for charred wood. The staff requirement is approximately 1 researcher and assistants for about six months. Financial commitment: SEK. 300,000.

C   Further work on existing relationships for calculation of the heat of reaction of wood in real fire conditions (Section 3.5).

Calculation of the heat of reaction of wood on the basis of data concerning enthalpy rise and phase transition energy is an important component of a mathematical model for analytical determination of the rate of charring and the temperature, moisture and density-time fields for a timber structure subject to variable fire exposure.

The task is predominantly a theoretical one, but must also comprise experimental verification studies at laboratory scale. Staff requirement is 1 theoretician and 1 experimentalist and assistants for about nine months. Financial commitment: SEK. 400,000.

D   Development of a simplified model for calculation of the rate of charring and temperature distribution in thin-walled timber structures exposed to fire (Sections 4.5 and 6.2).

The rate of charring in a timber structure exposed to fire is governed partly by reaction kinetic pro-

timber structures the rate of charring is mainly
governed by the transport processes.

Existing models for calculation of the rate of charr-
ing have been developed for solid timber structures
and therefore they are not applicable for thin-walled
timber structures. A combined theoretical and experi-
mental research project which will produce data for
prediction of the depth of penetration of fire for
thin panels of wood and wood-based materials under
the action of different thermal processes is there-
fore of urgent necessity. It is expected that the
experimental studies will be extensive.

Information provided by Project C is a component of
the theoretical part of this research task. Coordi-
nation or integration of Projects C and D is there-
fore essential. Staff requirement for Project D -
exclusive of the extraction of necessary information
from Project C - is 1 theoretician and 1 experimen-
talist, and assistants, for about 1 year. Financial
commitment: SEK. 700,000.

For an initial investigation associated with the
above project, the Swedish Forest Products Research
Laboratory has been allocated SEK. 100,000 by BRAND-
FORSK for the period 1982-84.

E   Further work on a simplified model for calculation
     of the rate of charring, temperature and moisture
     distribution in fire-exposed timber structures of
     solid section (Section 4.5).

     A simplified analytical model for determination of
     the depth of charring in solid timber structures
     subjected to variable thermal exposure is presented
     in /4.5, 6.9/ - see Subsection 6.1.1. This model can
     be used for calculation of a systematic basis for
     practical design of loadbearing structures in rela-
     tion to a real fire exposure. The model has been
     developed for the one-dimensional case, assumes dry
     wood, and provides no information concerning tempe-
     rature and moisture distribution in the uncharred
     portion of the structure. Reference /4.4/ presents
     an alternative one-dimensional model which also in-
     cludes description of the temperature distribution
     in the uncharred portion of the cross section. Ref-
     erences /4.1, 6.11/ describe a more general one-
     dimensional model for the pyrolysis of wood which,
     in addition to calculation of the rate of charring,
     also gives a method for approximate determination of
     the temperature and moisture condition in the timber
     structure. Further development, particularly with
     respect to the effect of moisture, is however needed
     in order that the method may be capable of easy prac-
     tical application

For the effect of moisture, development work may
alternatively be associated with the following
aspiration levels:

(a) Moisture transfer is ignored, and initial mois-
ture and that produced during pyrolysis is vapor-
ised at the original point in the cross section.

(b) A partial model for moisture transfer is in-
cluded.

It is further important that existing and developed
models should be extended so as to be valid for two
and possibly three dimensional cases for practical
application to beams and to different types of
splices and connections (Section 6.3). The aniso-
tropic properties of wood must be taken into consi-
deration.

The results yielded by Projects B and C constitute
the initial information for the above project which
is principally theoretical in nature. However, in-
tegration of a simplified model for moisture trans-
fer requires experimental determination of a number
of material constants. In addition, some verifica-
tion tests are required for the overall model.

The staff requirement for Project E - exclusive of
the extraction of the necessary information from
Projects B and C - is 1 theoretician and 1 experi-
mentalist, and assistants, for about 1 year. Finan-
cial commitment: SEK. 500,000.

F   Development of an analytical material model for the
      stress-strain behaviour of wood in conjunction with
      transient stress, temperature and moisture states
      (Section 5.3).

      For practical calculation in timber structures ex-
      posed to fire of the deformations, instability loads
      and induced forces and moments due to restraint on
      deformations, it is necessary to have access to an
      experimentally verified material model of the mecha-
      nical behaviour of wood in conjunction with simul-
      taneous transient stress, temperature and moisture
      states. Development of such a model is therefore an
      urgent necessity.

      Experimentally, such a project comprises both inves-
      tigations on small specimens and supplementary tests
      on structural elements of ordinary dimensions. A
      natural arrangement of a small scale investigation
      would be:

      (a) Rapid loading tests at stable temperatures and
      variable initial moisture ratios for determination
      of the complete stress-strain curve.

(c) heating tests to failure at stable load and
variable initial moisture ratio,

(d) measurement of the moisture ratio for the same
types of specimen as in (a) - (c) for unloaded spe-
cimens under variable heating.

Parallel tests on sealed specimens may have to be
included.

Staff requirement for the project is 1 researcher
and assistants for about 2 years. Financial commit-
ment:SEK. 500,000.

For a project of the above type, the Swedish Board
for Technical Development STU has allocated SEK.
413,000 to the Division of Building Fire Safety and
Technology, Lund Institute of Technology. Work on the
project is in progress. Further, the Swedish Forest
Products Research Laboratory has previously been
granted SEK. 118,000 by STU for experimental produc-
tion, by means of small specimens of 5-10 mm^2 cross
section, of data concerning the mechanical proper-
ties of wood at high temperatures and variable moi-
ture ratios. A report on this investigation is under
preparation.

G   Experimental and theoretical study of the effect of
    biological and chemical structure on the mechanical
    properties of wood under different temperature and
    moisture conditions (Section 5.3).

    No investigations have been published as to why tem-
    perature and moisture affect the mechanical proper-
    ties of wood, only the way in which these are changed
    A project which elucidates whether the biological
    differences between different species of timber or
    within the same species can explain phenomenologic-
    ally some of the large scatter in test results rela-
    ting to the mechanical properties of wood for differ-
    ent combinations of temperature and moisture condi-
    tions is therefore of urgent necessity /5.1/. Such
    a project should also comprise a simplified analy-
    tical model which takes into consideration the
    growth ring structure of wood and the relationship
    between cellulose and lignin.

    The staff requirement for this project is 1 wood
    chemist and 1 materials engineer, and assistants,
    for about 1 year. Financial commitment: SEK. 500,000.

H   Further development of analytical methods and com-
    puter programs for calculation of the behaviour and
    limit states of timber structures of solid section
    in the event of fire (Subsection 6.1.5).

on simplified assumptions regarding all the compo-
nents of the method. Applicability of these methods
is thereby confined to approximate calculations of
ultimate limit states and critical loads for certain
types of instability phenomena. The methods do not
permit calculation of the deformations of the fire-
exposed timber structures, nor calculation of the
induced forces and moments due to restraint on de-
formation.

Access to a more advanced model for calculation of
the rate of charring, temperature gradient and mois-
ture distribution according to Project E, and an
analytical material model for the mechanical beha-
viour of wood in conjunction with transient stress,
temperature and moisture states according to Project
F, is essential in order that existing design methods
for fire-exposed timber structures of solid section
may be brought into an advanced state of improvement
and expanded as regards fields of application.

Such work incorporates development of numerical meth-
ods based on finite elements or finite differences,
and associated computer programs, for the fire beha-
viour and limit states of different types of struc-
ture. The failure modes of interest are bending,
shearing, torsion, buckling and lateral torsional
buckling.

A project of this content is predominantly theore-
tical in nature. Verification tests at full or re-
duced scale must be added. Staff requirement is 1
researcher and assistants for about 2 years. Finan-
cial commitment: SEK. 600,000.

I   Development of analytical and numerical methods and
     computer programs for calculation of the behaviour
     and limit states of lightweight and composite tim-
     ber structures under fire exposure conditions (Sec-
     tion 6.2).

     All the information concerning the behaviour and
     limit states of lightweight and composite structures
     under fire exposure conditions, with regard to their
     loadbearing and/or separating function, has been
     obtained from standard fire tests under thermal ex-
     posure according to ISO 834. No analytical methods
     have been published as yet regarding the design of
     these types of timber structure.

     Research work which may result in the development
     of such analytical methods is therefore of great
     urgency. This applies both for thermal exposure
     according to ISO 834 and for real fire exposure. A
     simplified model for calculation of the depth of
     combustion for thin panels of wood and wood based

methods. The analytical methods must be verified
by experimental investigations at full or reduced
scale.

A project which has the object outlined above can
be tackled on the basis of two alternative aspira-
tion levels:

(a) Design is confined to limit states for certain
simple types of structure,

(b) design is extended so as to comprise deformations
and forces and moments induced due to restraint on
deformation, application being of a more general
character with respect to the type of structure.

A project based on the higher aspiration level in-
cludes development of numerical methods on the basis
of finite elements or finite differences, and asso-
ciated computer programs, for the fire behaviour of
different types of structure. Access to a material
model for the mechanical behaviour of wood at tran-
sient stress, temperature and moisture states accord-
ing to Project F is therefore essential.

For aspiration level (a) the staff requirement – ex-
clusive of Project D – is 1 researcher and assist-
ants for about 1 year. Financial commitment: SEK
350,000.

For aspiration level (b) the requirement – exclusive
of Projects D and F – is 1 researcher and assist-
ants for about 2 years. Financial commitment: SEK.
600,000.

J   Development of analytical models for calculation of
     the behaviour of splices, attachments and connec-
     tions, and their loadbearing capacity, under fire
     exposure conditions (Section 6.3).

     A research project made up of two parts appears to
     be of urgent necessity in this respect.

     The first part comprises production of design data
     for determination of the required thickness of cover
     sheets and other types of insulation for bolted and
     nailed connections under real fire exposure condit-
     ions. In conjunction with cover sheets of wood or
     wood-based materials, the results provided by Pro-
     ject D constitute essential input information.

     The second part comprises development of an analyti-
     cal model for calculation of the behaviour and load-
     bearing capacity under fire exposure conditions of
     e.g. a bolted or nailed connection, and experimen-
     tal verification of this at full or reduced scale.

Staff requirement for the project is 1 researcher
and assistants for about 18 months. Financial comm-
itment: SEK. 600,000.

Funds amounting to SEK. 155,000 have been allocated
to the Technical Department of the Swedish Fire Pro-
tection Association by BRANDFORSK and the firm of
Svenskt Limträ AB for an investigation relating to
the second part of this project.

K   A review of the existing state of knowledge and
preparation of a detailed research programme concern-
ing the effect of fire retardants on phenomena and
properties which are critical with regard to fire
design of loadbearing and separating timber con-
structions (Section 7.6).

Examples of such critical phenomena and properties
are ignition, rate of charring, thermal properties,
mechanical properties and the mode of action of
splices and connections.

Staff requirement is 1 researcher for about six
months. Financial commitment: SEK. 100,000.

L   A review of the existing state of knowledge and fur-
ther analysis of the physical and chemical mecha-
nisms involved in the action of flame retardants,
and a study of the possibilities of achieving opti-
mum interaction between different mechanisms at the
different stages of a fire (Section 7.6).

The project is a combination of experimental and
theoretical work. Description of the background to
the project is given in Sections 7.1 - 7.5.

Staff requirement is 1 theoretician and 1 experimen-
talist and assistants for about 18 months. Finan-
cial commitment: SEK. 800,000.

8.2   Overriding projects which have a bearing
         on the entire research process

A   Development of a method for analytical determination
of the fire resistance of elements of construction
of timber (Sections 1.2 and 1.6).

Determination of the fire resistance of elements of
construction is at present entirely dominated inter-
nationally by standard fire tests according to ISO
834. As an alternative, an increasing number of

With regard to timber structures, the present state
of knowledge permits such analytical determination
of fire resistance with acceptable accuracy for
solid timber structures such as beams and columns.
On the other hand, analytical determination of fire
resistance is not possible at present for light-
weight and composite structures of loadbearing and/or
separating function. The same also applies for all
types of structure which contain splices, attach-
ments and connections.

An overriding research project which has the object
of providing data for more general utilisation of
the possibility of analytically determining the fire
resistance of elements of construction of timber
comprises the component projects D, I and J described
in Section 8.1. Apart from these projects, the over-
riding project also contains systematised calculation
of design data and a special study of consistency
problems in view of the differences in conditions
which may occur when fire resistance is determined
analytically and when it is obtained by standard
tests.

One of the reasons why this project is of great im-
portance is that it may provide greater opportunities
for analytical fire classification in the place of
classification based on the results of standard fire
tests, which may in future produce appreciable sav-
ings in cost in conjunction with the development and
marketing of new products and design solutions. In
conjunction with increased international acceptance
of analytical fire classification, this project may
also be instrumental in facilitating the type app-
roval procedure for Swedish timber products for ex-
port.

Staff requirement for the overriding project – apart
from the requirement for the component projects D,
I and J – is 1 researcher and assistants for about
1 year. Financial commitment: SEK. 300,000.

B   Development of a method for fire design of loadbear-
ing and separating elements of construction on the
basis of real fire exposure (Sections 1.3 and 1.6).

Analytical design of loadbearing and separating ele-
ments of construction on the basis of real fire ex-
posure is feasible at present for most types of steel
structure and for certain types of concrete struc-
ture. In the course of 1983, a manual which will
appreciably improve the practical design situation
will probably be published for analytical design
of concrete structures.

It is essential that knowledge of the behaviour and
design of fire-exposed timber structures should be
developed to a level equivalent to that for steel

An overriding research project for such a development comprises the component projects B, C, D, E, F, I and J described in Section 8.1 if practical application is to be universal. In addition to these component projects, the overriding project therefore includes as a primary task the production of a design manual. The staff requirement for this - exclusive of the staff required for the component projects - is 2 researchers and assistants for about 2 years. Financial commitment: SEK. 600,000.

C   Production of data for determination of the equivalent fire duration for elements of construction of timber (Sections 1.4 and 1.6).

The concept of equivalent fire duration has been introduced to enable real fire exposure and thermal exposure according to standard fire tests (ISO 834) to be interrelated. Equivalence is defined with reference to the criterion that both types of exposure should, for the structure concerned, produce the same critical effect with respect to the relevant limit state.

Data are available at present for calculation of the equivalent fire duration for steel structures and reinforced concrete structures subject to certain types of failure. For other types of structure, including timber structures, the concept of equivalent fire duration is incomplete or has not been studied at all.

A project which has the object of producing data for determination of the equivalent fire duration for elements of construction of timber must be based on the results of the overriding projects A and B. On the basis of an international perspective, this project is of great urgency. Nationally, in view of the fire design philosophy adopted by Swedish Building Code, this project is of lower priority than the other overriding projects.

With the results of the overriding projects A and B as the points of departure, the staff requirement for the project concerning equivalent fire duration is 1 researcher and assistants for about 9 months. Financial commitment: SEK. 200,000.

D   Further development of the design method according to the overriding project B so as to adapt this to modern loading and safety regulations (Sections 1.5 and 1.6).

Safety theory methods are being applied to an increasing extent internationally for the design of

In order that such development may be meaningful,
the design method must be made up of functionally
well defined and verified analytical models, the
uncertainties and reliability levels of which can
be defined. The design method described by means
of the overriding project B meets this requirement.

A design method for structures exposed to fire,
which is based on safety theory and in which the
statistical influences are taken into consideration
by means of characteristic values and partial safety
factors for the quantities involved, would make
possible a greater degree of economic optimisation.
In principle, such a method would also eliminate
the present differences in fire requirements and
application limitations between structures of com-
bustible and non-combustible materials.

Further development of the overriding project B as
described above, so as to adapt this to modern load-
ing and safety regulations, requires 1 researcher
and assistants for about 2 years. Financial commit-
ment: SEK. 600,000.

8.3   Interrelationship   between the projects.
           Priorities.

The interrelationship between the projects described
in Sections 8.1 and 8.2 is illustrated by the flow chart
in FIG. 8.1. Projects associated with the different
stages of the design process have been designated 8.1A,
8.1B, 8.1C etc, where A, B and C directly refer to the
project designations in Section 8.1. Similarly, over-
riding projects which concern the entire design process
have been designated 8.2A, 8.2B, 8.2C etc, where A, B
and C directly refer to the project designations in
Section 8.2.

Arrows drawn with full lines between projects denote a
strong relationship, and arrows drawn with dashed lines
a weaker relationship. Projects inside double frames
have been assigned the highest priority, and projects
inside single frames a lower priority - but without
being of low priority. Projects 8.1K and 8.1L which
deal with the effects of fire retardants, and their
relationship with other projects, have been placed as a
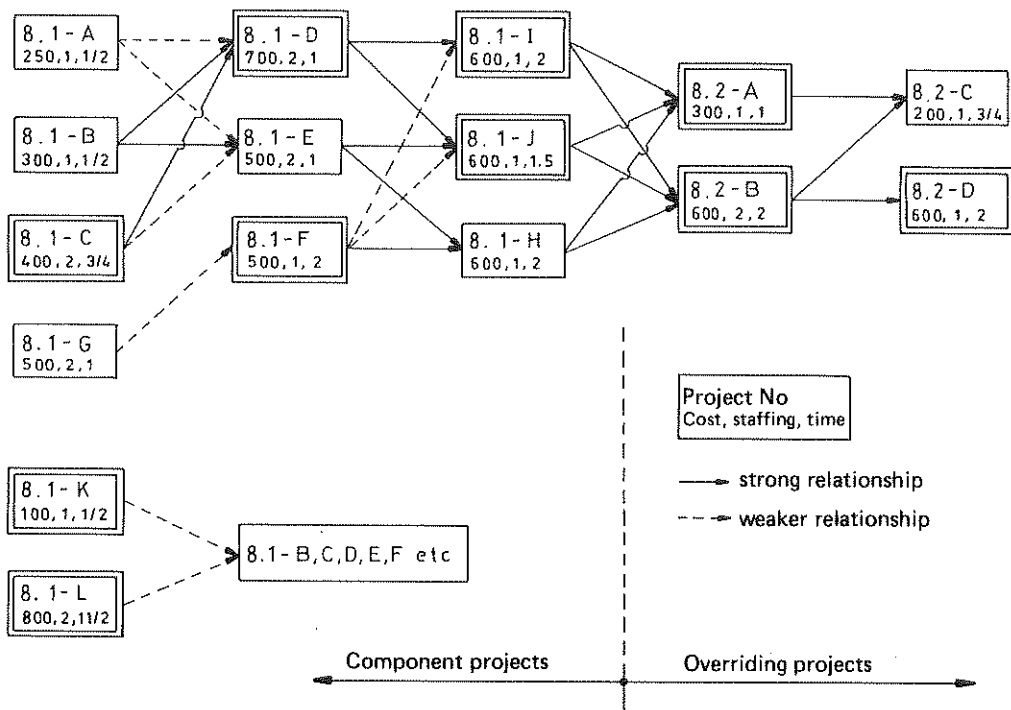separate group in order to emphasise that, from the

FIG. 8.1. Interrelationship of the research projects.
Double frames denote projects of the highest
priority, and single frames projects of lower
priority.

Each frame specifies the project number, financial comm-
itment in 1000 SEK, staff requirement and required pro-
ject duration. The estimated overall cost of the whole
package of projects is SEK. 7.55m, of which SEK. 5.85m
is needed for the projects associated with the stages
of the design process, and SEK. 1.7m for additional
expenditure in respect of the overriding projects. The
total cost of the projects of the highest priority
which have been placed in double frames is SEK. 5.2m.
To an absolutely dominant extent, all projects are of
an applied character. Some projects (8.1C, D, E, F and
G) contain elements of fundamental research character
amounting, roughly, to about SEK. 500,000 in all.

The interrelationship between the different projects in
the overall research programme, which is illustrated in
the flow chart in FIG. 8.1, emphasises the urgent need
for a national coordination of current and future re-
search within this programme. Planning for such coordi-
nation comprises a review and assessment of the staff
and equipment requirements for integrated overall comm-
itment, including calculations of resources and time

development and production of practical design data com-
prised in the overriding projects. This is exemplified
in FIG. 8.2 with regard to the final goal 8.2-A in
relation to lightweight and composite structures, and
in FIG. 8.3 with regard to the final goal 8.2-D in re-
lation to solid timber structures. The coordinated plan
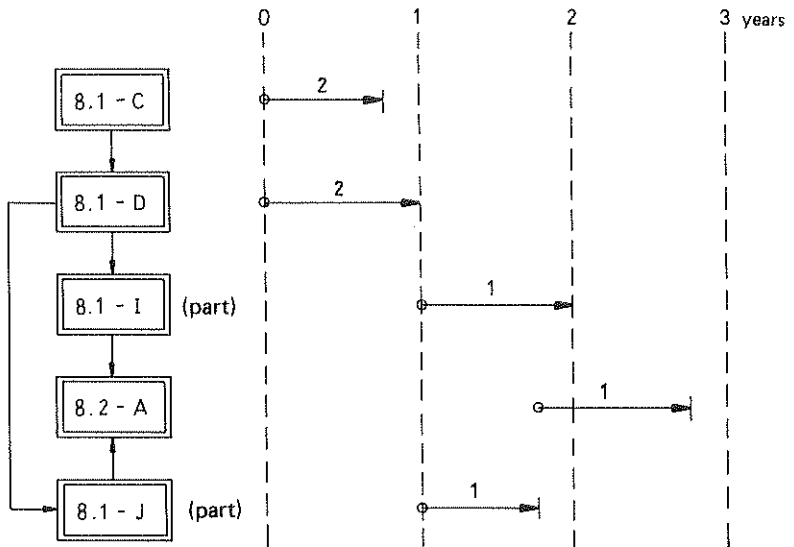

FIG. 8.2. Time and resource scheme for a nationally
           coordinated research effort for development of
           a method for analytical fire classification
           of lightweight and composite timber structures,
           adapted for practical application. The numbers
           above the arrows indicate the estimated number
           of researchers needed for each project.

for research should also include an investigation of
the way in which other activity, primarily current and
planned international research and development work,
may provide support for the research programme. It is
probable that a number of standard fire tests on newly
developed elements of construction of timber will be
carried out during the programme period. It is essential
that these should be made use of for the information
they may give to the research programme. An analysis
of the supplementary measurements which are required
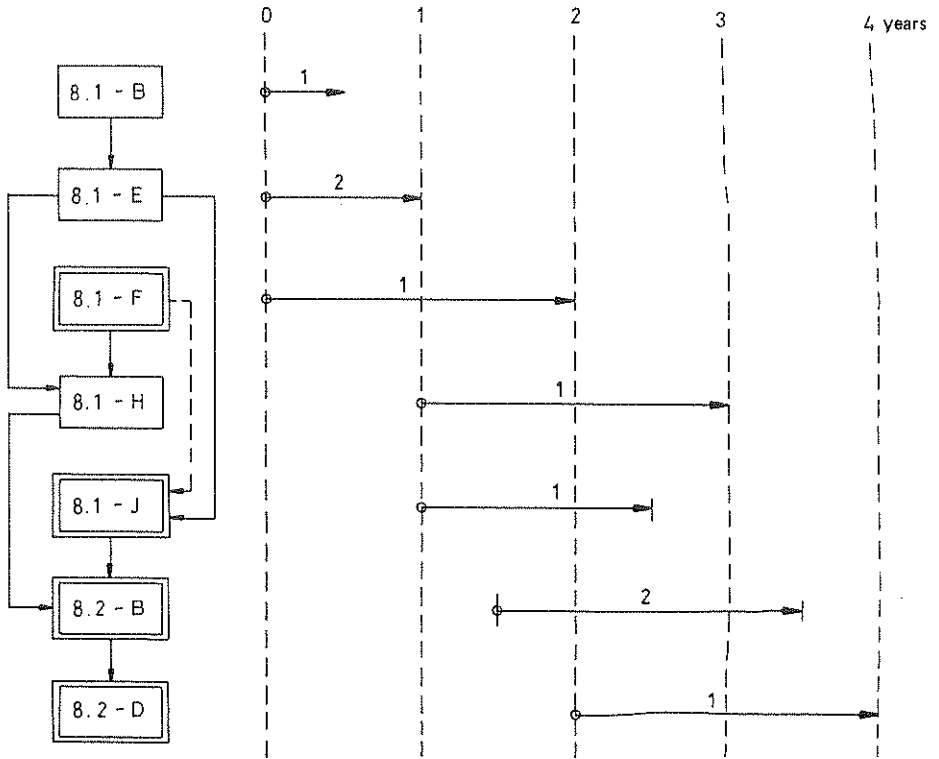for such information is therefore an urgent initial

FIG. 8.3. Time and resource scheme for a nationally
coordinated research effort for development
of an analytical fire design method for solid
timber structures, based on the characteris-
tics of real fires and adapted to modern load-
ing and safety regulations. The numbers above
the arrows indicate the estimated number of
researchers needed for each project.