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## Fire Hazards and the Compartment Fire Growth Process : Outline of a Swedish Joint Research Program

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LUND INSTITUTE OF TECHNOLOGY · LUND · SWEDEN  
DEPARTMENT OF STRUCTURAL MECHANICS  
REPORT NO. R80-5

OVE PETTERSSON

FIRE HAZARDS AND THE COMPARTMENT  
FIRE GROWTH PROCESS-OUTLINE OF A  
SWEDISH JOINT RESEARCH PROGRAM



LUND INSTITUTE OF TECHNOLOGY. LUND. SWEDEN

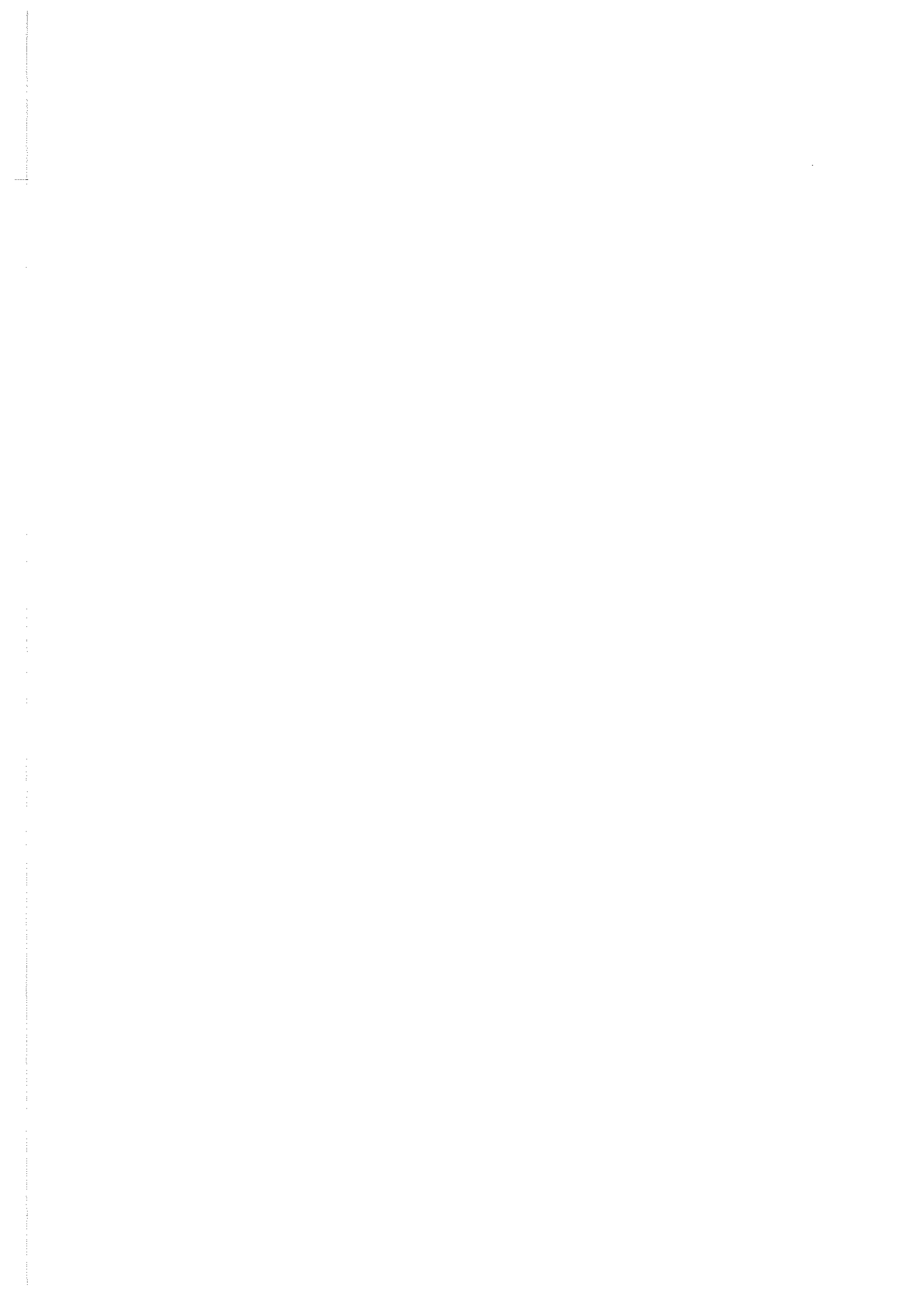
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## Fire hazards and the compartment fire growth process — outline of a Swedish joint research program



By Ove Pettersson<sup>1</sup>

### 1. NATIONAL SWEDISH FIRE RESEARCH PROGRAM

As has been reported in previous issues of this journal, an expanded fire research program has been initiated in Sweden [1] as a joint venture between government, insurance companies and private industry. Based on an extensive survey carried out within the National Defense Research Institute (FOA) [2], the present three year program (ending December 1981) is defined by 26 specified research projects. These are now in various stages of implementation under the supervision of the established board of directors and a program secretariat — the Swedish Fire Research Board. The overall program covers most of the major research areas: fire growth processes and spread of smoke and fires in buildings (sector B), their impact on human behaviour (sector H) and on materials and products (sector M), fire fighting and fire detection and extinction (sector K), systems and operational research (sector S), and general and overall functions and surveys (sector F).

Admittedly, there is a considerable variation in depth and scope. Natural limitations in resources and national competence necessarily led to project specifications in some cases merely asking for further survey and feasibility studies. One major sector where an

active and extensive contribution already has started concerns the area of building fire growth and spread in the pre-flashover stage. The aim of the presentation given here is to outline the scope, contents and organization of this particular effort and, in a few cases, indicate some of the experiences and results obtained so far.

### 2. SCOPE AND ORGANIZATION OF A JOINT PRE-FLASHOVER COMPARTMENT FIRE RESEARCH PROJECT

Among the 26 research projects, constituting the national program, the following four were thought to be interrelated to such a degree that great advantage could be gained by a combined study, made simultaneously and in parallel.

- The titles of these are
- project B2: generation of smoke and toxic gases,
  - project M3: surface lining materials — classification and fire hazards,
  - project M4: building materials — fire tests and fire growth,
  - project M6: upholstered furniture — fire safety requirements.

The combined project has the title "Fire Hazard — Fire Growth in Compartments in the Early Stage of Development (Pre-flashover)" and is carried out as a joint project by the Division of Fire Technology and the Labo-

ratory for Chemical Analysis at the Swedish National Testing Institute, Borås and the Division of Structural Mechanics at Lund Institute of Technology.

The ultimate goal of the project is to develop test methods in full or half-sized scale for surface lining materials as well as for furniture and other fittings, from which the real behaviour and contribution of the tested material or product in a natural fire can be predicted. To achieve this goal, it will be necessary to develop and exploit theoretical analyses, based on reliable mathematical models for all the fire processes, those making use of information obtained from the test methods and those processes describing the fire itself, e.g. the flows of gases and the energy transfers. Such analyses will also facilitate the formulation of functionally based requirements and performance criteria. An important, parallel task within the combined project is to evaluate those small scale "reaction to fire" tests, being developed within ISO/TC92/WG2 and 4, and to relate them to what

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## REDAKTÖREN

Under de senaste 20 åren har forskningen kring bränders förlopp och egenskaper i stort sett varit knutna till brandförloppet efter övertändning. Det är i det skedet som byggnadens bärande delar påverkas med risk för brott och sammanstörtning. Forskningsinsatserna har varit framgångsrika. Undan för undan har kunskapen ökat och burit frukt bl a i form av kvalificerade, ingenjörsmässiga beräkningsmetoder. Ett stort steg framåt var byggnadslagstiftningens godkännande av teoretisk beräkning som ett alternativ till provning.

Emellertid formas brandens verkningar i stor utsträckning av brandförloppets tidigare del. Det gäller särskilt verkan på människor och på ömtåligare delar av byggnadskonstruktioner och inredning. Den tidiga delen av brandförloppet är dock ur forskningssynpunkt mycket svår att hantera och förhållandevis få mera omfattande och djupgående projekt har kommit till stånd. Ett skäl härtill är att man måste räkna med en stor satsning på långsiktig kompetensutveckling innan man kan förvänta resultat för praktisk tillämpning. Med den finansiering som brandforskningen tidigare haft i vårt land, har det varit svårt att garantera så stora anslag under tillräckligt lång tid för att göra satsningen meningsfull.

Förhållandena har emellertid förändrats sedan BRANDFORSK tillkommit. En av dess första åtgärder blev därför att bevilja medel för ett stort projektblock av ny karaktär. Härigenom har Institutionen för byggnadsstatik vid Lunds tekniska högskola i samarbete med brandlaboratoriet vid statens provningsanstalt kunnat påbörja ett treårigt projekt — "det tidiga brandförloppet". De båda forskningsinstitutionerna har genom att skjuta till egna medel kunnat disponera ca 4 miljoner kronor t o m 1982. Projektet stöts ytterligare av formaliserat samarbete med Fire Research Station i Storbritannien och genom informellt samarbete med andra utländska institutioner och organ.

Professor Ove Pettersson redogör i artikeln för projektblockets syfte och innehåll. Artikeln publiceras på engelska som ett led i ansträngningarna att tidigt orientera omvärlden om vad som pågår inom den svenska brandforskningen. En vidare orientering för det svenska brandförsvarets personal förbereds i annan form.

happens at real fires. Undertaking such a project, will have a significant role in increasing the national fire research competence.

Tackling such an extensive and complex research area, an effective co-operation between research groups becomes a necessity. On the national level, an agreement to co-ordinate and co-operate in work within fire research was signed in 1978 between the Swedish National Testing Institute (SP) and the Fire Research Group at Lund Institute of Technology (LTH). As a consequence, the application for the research grant sent to the Swedish Fire Research Board was a joint one and directly based on a factual and continuous cooperation.

Internationally, documents outlining joint research interests between the Fire Research Station (FRS), UK and LTH has been agreed. This collaboration will be focused on problems in the growth of fire in compartments in the early stage of development (pre-flashover). Extensive discussions and consultations have taken place with FRS and form much of the background for the formulation of the research project, presented in this article. Chapter 3 is largely based on the original letter of intent for the FRS/LTH co-operation.

It should also be mentioned the role played for the project by the information disseminating from the National Bureau of Standards (NBS) in Washington. A number of people have willingly discussed projects in progress, given access to unpublished data, to computer programs and in other ways facilitated our work. Furthermore, the activities going on within the Ad Hoc Fire Mathematical Modeling Committee in USA and within CIB W14 — planning to organize a workshop on pre-flashover fire mathematical modelling during 1981 — will considerably support the research project.

### 3. GENERAL BACKGROUND OF THE RESEARCH PROJECT

Traditionally, efforts to increase the fire safety in buildings have been directed towards requirements on structural components and — to a lesser extent — also to building materials. Furnishings and other non-structural features of buildings have until recent time remained essentially non-regulated. It is now widely recognized that an increase in human firesafety levels requires an assessment of the role of furnishings and other building contents. Consumer demands in a number of countries have resulted in efforts to control the flammability of furnishing

by statutory or non-statutory requirements. The material or product selection is almost invariably related to performance in a specified small scale test method. As of now, the relationship between the behaviour of materials in a test and in a real fire, after the initial ignition, remains unknown in any general predictive sense. A wealth of data is gradually becoming available regarding ignition times, flame spread velocities, burning intensities, radiation output and so forth, but there is no satisfactory comprehensive theory of furnishing fire behaviour on which to base design or predict hazard. To a large degree, this also applies to the role of internal linings in the residential fire process. The problem is aggravated by the new materials and products being continually developed, expanding the range of fire responses and performance characteristics.

Fire science and technology are attacking the mountain fire problem by a number of avenues. In the area of internal linings, standard laboratory fire test methods are being designed which measure the quantitative response of a material to specified fire exposure situations. Examples are the "reaction to fire" tests being developed within ISO/TC92/WG2 and 4. By operating at a number of exposure levels, these tests will provide a comprehensive, quantitative description of basic fire performance characteristics (ignitability, surface flame spread, rate of heat release). Simultaneously, initial but nevertheless extensive efforts are being made to mathematically model fire process dynamics, in a number of areas, to determine the dominant controlling mechanisms. Examples of important submodels or aspects of the fire growth phenomena are

- field and zone models for part turbulent flows in enclosures,
- fire growth models (flame spread under arbitrary external radiation),
- characteristics of flame and hot gas radiation,
- convective heat transfer through ventilation openings,
- convective heat transfer within enclosure.

The modelling problems inherent in the list of transient, thermophysical processes enumerated above will not be solved in detail for many years to come. One of the major problems will be to strike a proper balance between the need for reasonably quick answers and the need for modelling accuracy. Tools to complement the analytical modelling comprise experiments in full or small scale, reliability studies and empirical data from standard tests. Attempts at interpreting standard tests by modelling them also helps to extract data from them in the most useful way for wider application.

## EDITORIAL

So far, most of the research on fires has been dealing with the fire situation after flashover. This is not surprising, as the fire effects on the loadbearing structural elements of the building, will be imposed during this stage of a fire. In later years, however, extensive research on postflashover problems has opened the way for an analytical structural fire engineering design, based upon well-defined functional performance criteria.

However, there are good reasons to pay more attention to the early stage of fire. A threat to humans will certainly become eminent already before flashover. Furthermore, in many cases, the early development of a fire will determine the fire loss regardless of later damage to the loadbearing structural elements. With this background, it is not difficult to see the reasons for the present worldwide trend in fire research to put more emphasis on the early stages.

The Swedish Fire Research Board is a new initiating and sponsoring body in the field of fire research. It is founded and funded by the Swedish Government and by private enterprises on a 50—50 basis. One of its first undertakings was to establish a block of projects aimed at studies of the early stage of fire.

In this article, professor Ove Pettersson of the Lund Institute of Technology tells about the intentions and scope of the work. The projects are conducted in co-operation between the Institute and the Fire Technology Laboratory of the National Testing Institute. By pooling financial resources, close to U.S. \$ one million has been set aside for a period of three years. The work includes considerable international collaboration.

A short term goal may be a predictive model of whether or not flashover will occur for a given set of initial conditions, and, if so, how long after ignition it will occur.

Our increasing capability in constructing physical or mathematical models for important fire scenarios implies that rational approaches to estimate life safety levels will gradually become available. The life safety problem must be approached by methodologies now being used within a number of other sectors for assessing efficiency, sensitivity to disturbance and reliability in complicated systems. Examples of analytical tools are probability theory, variance analysis,

mathematical programming (linear, dynamic), decision analysis, systems simulation. Most of these methods have been used previously in one form or another in the field of fire research. The choice of method has usually depended on the design level, i.e. on the size and complexity of the system involved.

## 4. DETAIL STRUCTURE OF THE RESEARCH PROJECT

For a more detailed planning of the total research project, it turned out to be useful to break down the project into eleven smaller research items. Table 1 enumerates these items and illustrates their relevance for and connection to the four original research projects B2, M3, M4 and M6 in the national Swedish fire research program. The different research items are not directly comparable in regard to extent and complexity. One research item — analysis of the Swedish box test — is rather limited. Some other items belong to very fundamental research areas with a high degree of complexity, for instance, items 6 and 7. For these items, the level of ambition for a joint Swedish contribution naturally must be limited to give only a few modest complements to the comprehensive international research development. Accordingly, Table 1 must be made concrete in order to give more detailed information on the scope and level of complexity of the different research items.

The remainder of the paper will be used to present the eleven research

items as well as the progress made up to now (August 1980). As will be noted, none of them is anywhere near completion, most are still in an initial planning stage.

### 4.1 Research Item 1. Analysis of SIS 02 4823 (the Swedish Box Test)

The standard instrument in Sweden for a fire classification of building lining materials is the so called box test. The test configuration has features similar to the British fire propagation test and the Dutch flashover test, the major difference being that the ventilation is controlled in the Swedish box test. The material to be tested is attached to the ceiling and three walls of a small enclosure and exposed to a rather strong gas flame without any additional impressed radiation. Materials are graded by the time curve of the flue gas temperature with three specified limit curves.

It is known that material fire properties, for instance, mass burning rate per unit surface area, varies widely, and in many cases non-linearly, with the level of thermal exposure. The value of the test as a measure of the contribution of lining materials to the fire growth and spread could thus be considerably enhanced, if the exposure levels during the testing process are measured and compared with those generated in common natural compartment fire scenarios. Useful information will also be gained by a more complete energy balance study of the test process, giving the rates of heat output and heat transfer within the enclosure. The practicality of using oxygen con-

**Table 1. Scheme of integration for the eleven research items of the total pre-flashover research project**

Research item	Project			
	B2	M3	M4	M6
1. Analysis of SIS 02 4823 (Swedish box test)	x	x	x	
2. Burn room sensitivity study		x	x	x
3. Fire behaviour of surface lining materials — full scale testing	x	x	x	
4. Fire behaviour of upholstered furniture — full scale testing	x			x
5. Interaction between burning items of furniture and combustible surface lining materials — full scale testing	x	x	x	x
6. Pilot studies of fire induced compartment flows	x	x	x	x
7. Mathematical fire modelling	x	x	x	x
8. Development of methods for analyzing combustion products of polymeric materials	x	x	x	x
9. ISO reaction to fire tests — correlation to real fire, classification	x	x	x	
10. Development of standardized full scale tests				
(a) Surface lining materials	x	x	x	
(b) Furniture	x			x
11. Testing of upholstered furniture using half-scale rigs	x			x



sumption calorimetry to measure the quantity of energy release by combustion will also be studied.

The investigation will be carried out at SP during autumn and winter 1980.

#### 4.2 Research Item 2. Burn Room Sensitivity Study

A full scale experimental burn room has been built and instrumented at SP. It will serve several functions during the project, viz.,

- to establish basic flame spread and combustion characteristics of lining materials as well as furnishings (upholstered furniture) under full scale conditions,
- to serve as basic configuration for a room corner test,
- to serve as a room size calorimeter.

The instrumentation basically follows the "Recommended Practice for Room Fire Test", issued by ASTM E-39.101, the main difference being the number of bi-directional probes found necessary to map door flow conditions.

An extensive energy and mass balance calibration with gas burner as fuel source has been carried out and summarily reported in [3]. Energy, released by combustion in the fire room, leaves the room by convection and radiation through the doorway and by conduction through the surrounding structures. The object of the calibration tests was to evaluate the various components at heat transfer and estimate the accuracy of the measurements by checking the heat balance.

In a first series of calibration experiments, gas velocity or rate of mass flow and temperatures were measured only along a vertical line in the center of the doorway. Considerable differences between calculated total rate of mass flows in and out of the fire room were, however, registered because the horizontal distributions of gas velocity are different in the flows in and out.

A second series of experiments was therefore made where the horizontal distribution was investigated. The mass flow and the temperature were thus measured in 66 points over the doorway.

Examples of the vertical mass flow profiles are shown in Fig. 1 — the mass flow is integrated horizontally over the doorway. Fig. 2 shows an example of the measured mass flow in and out, integrated over the doorway, and the difference between these two as a function of time. The total rate of energy flow  $\dot{Q}_a$  out of the compartment, integrated over the doorway, is given in Fig. 3. As shown by Fig. 2 and 3, the accuracy of the measurements is satisfactory.

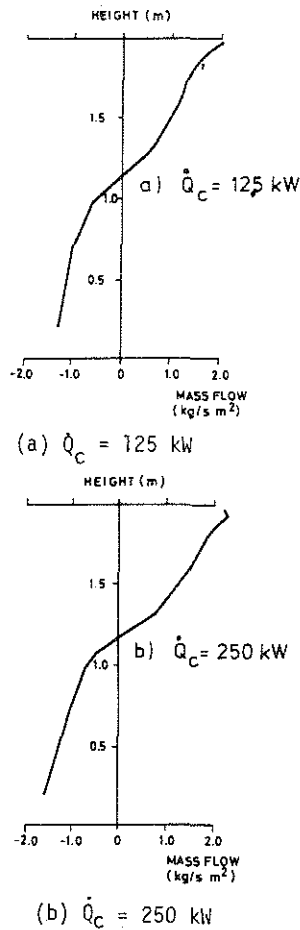


Figure 1. Mass flow profiles in the doorway at two rates of heat release levels [3]

#### 4.3 Research Item 3. Fire Behaviour of Surface Lining Materials — Full Scale Testing

Recently, the Swedish regulations regarding the use of surface finishing materials were substantially extended to cover new classes of buildings (essentially, one family homes) and interior surface areas, which previously had not been regulated. The minimum requirements for all surface finishing materials, sold to the consumer, are that their flammability characteristics must give at least equal safety as those of massive wood, when tested in the Swedish hot box.

The extension of governmental regulations brings a renewed urgency to some old and only partially solved problems regarding a functional classification of surface finishes. Among these are

- to what extent is the classification of a surface material dependent on the choice of base or backing material (degree of combustibility, value of thermal inertia)?
- what is the relation between the classification of a lining material in the box test and the contribution of the same material to room fire growth and spread? Or to be more

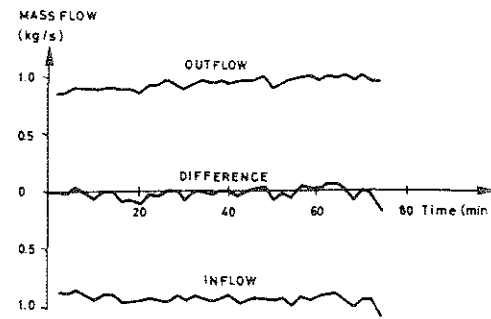


Figure 2. Measured mass flow in and out of fire compartment and the difference of these values versus time.  $\dot{Q}_c = 250 \text{ kW}$  [3]

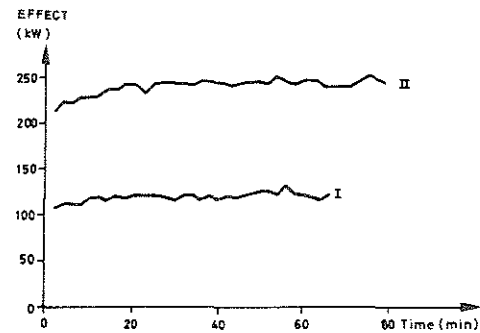


Figure 3. Measured rate of heat loss by convection  $\dot{Q}_a$  versus time. Stationary conditions. Test I:  $\dot{Q}_c = 125 \text{ kW}$ . Test II:  $\dot{Q}_c = 250 \text{ kW}$  [3]

precise: Given a fire source with known heat output near a wall, what will different classes of wall and ceiling surface materials mean in terms of time to untenable situations inside the room, time to flash-over, etc?

The Swedish full scale method for surface finishes now in use was initially modelled on the room-corridor fire spread situation. Being developed in the late 1950's, the test method inevitably has some inherent drawbacks when measured against modern standards and requirements. The test process may be sensitive to changes in weather conditions. Acceptance criteria are not firmly quantified but of a rather subjective nature. The test process has not been correlated to one-room fire growth scenarios.

As an alternative test procedure, the corner test was an obvious candidate, and the burn room at SP is being used for development work on a room corner test. To find suitable fire scenarios, a series of tests were run with various surface finishes. Heptane burners of various sizes were used and several sizes of the opening of the compartment were tried. The burners were open containers with water and heptane floating on top. Materials to be tested were mounted on walls and ceiling.

A square burner with a surface of 0.03 m<sup>2</sup> gives approximately a rate of heat release of 50 kW, thus simulating a burning waste paper basket. When the burner was placed in a corner, the following time intervals between ignition of the burner and flashover (defined here by flames coming out of the opening) were recorded

- untreated porous board 2 min,
- chip board 6 min,
- surface veneer, bonded to chipboard 20 min,
- polystyrene foam, flame retardant <2 min.

With the same test conditions, the following products did not cause flashover

- plaster board,
- PVC-wallcovering, on plaster board,
- traditional wall-paper, on non-combustible board.

The PVC wall paper was also tested with smaller openings and with a larger burner; on no occasion did flash-over occur.

To complement the full scale studies, a series of room corner tests in model scale has been planned. Some preliminary tests have been performed in a cubic room with dimensions 1 × 1 × 1 m<sup>3</sup> for a study of ignition, fire growth and flashover at different combinations of wall and ceiling linings, made of wood or wooden-based products. A gas burner, placed in a corner, was used for simulating a scaled-down, representative thermal exposure. Temperature, gas velocity, heat flow and heat radiation were measured. In the following tests, the measurement system will be expanded with an oxygen consumption calorimeter for a determination of the energy, released by combustion. An evaluation of the results of the preliminary tests is in progress.

#### 4.4 Research Item 4. Fire Behaviour of Upholstered Furniture — Full Scale Testing

The overall objective of project M6 is to study the fire behaviour of upholstered furniture to assess the hazards, associated with ignition, growth of fire and production of smoke and toxic gases. A major element is development and validation work to produce functionally based fire tests. Research item 4 in particular comprises a study of the full scale burning characteristics of upholstered furniture, as influenced by the choice of upholstery fabric, interlining and filling material. A first study, financed by the industry and the National Swedish Board for Technical

Development, has been carried out in the previously mentioned burn room at SP and been preliminary reported [4].

To get reproducible fire scenarios and clearly defined and measurable reactions to variations in the main parameter, i.e. material selection, the test furniture was a full scale mock up model of a three-seat sofa, designed with loose cushions on a steel frame. A liquid fuel burner with a heat output of 20–30 kW was used as ignition source.

The materials of the cushions was changed in a systematic way to represent the ranges available in the consumer market. In all, 11 sofas were tested. Extensive measurements were taken of mass burning rates, gas temperatures, gas flow velocities, heat fluxes to floor and ceiling, smoke concentration and gas species concentrations.

The experimental data have been processed and analyzed for a number of purposes, viz.

- to assess basic components of the risk profile of the product (rate of fire spread, maximum rate of heat release, concentration of produced smoke),

- to estimate the time available for escape or evacuation out of the room of fire origin, i.e. the minimum time for a hazard component (heat, smoke or toxic gas concentration, heat fluxes) to reach untenable conditions,
- to validate the results obtained by simulation computer programs. In our case the Harvard Computer Fire Code [5] and a time-dependent version of the Quintiere model, developed at FOA, Stockholm [6] were used,
- to find correlation with experiments carried out with a prototype scaled down test rig (see further research item 11).

As an example of the results derived in [4], Fig. 4 gives for five different material combinations the total, accumulated smoke production  $D_{acc}$  as a function of time.  $D_{acc}$  is expressed, in accordance with the terminology used in [7], as (dB/m) · m<sup>3</sup>, where the first factor expresses light attenuation as decibel per m of light path through the outflowing smoke, and the second one expresses the total flow of combustion products (smoke). Table 2 gives details of the material combinations used. Fig. 4 clearly illustrates the in-

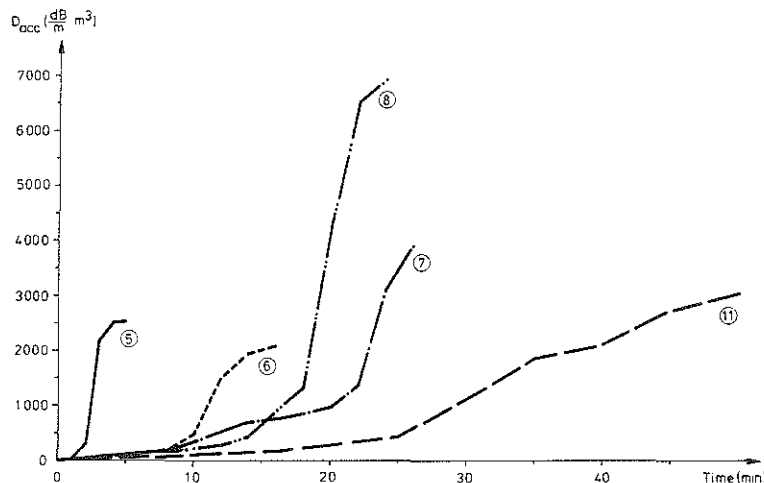


Figure 4. Total, accumulated smoke production  $D_{acc}$  as function of time for tests 5, 6, 7, 8 and 11 [4]

Table 2. Material combinations used in full scale tests of upholstered furniture

Test No.	Upholstery fabric	Interliner	Filling material
1	Acrylic 100%	—	Conventional polyurethane
2	Acrylic 100%	—	Conventional polyurethane
3	Acrylic 100%	—	Conventional polyurethane with FR additives
4	Wool 100%	—	Conventional polyurethane
5	Acrylic 100%	—	Conventional polyurethane
6	Wool 61%, viscose 39%	—	Conventional polyurethane
7	Wool 61%, viscose 39%	—	High-resilient polyurethane
8	Wool 61%, viscose 39%	—	Conventional polyurethane with FR-additives
9	Wool 61%, viscose 39%	Firend	Conventional polyurethane
10	Wool 61%, viscose 39%	Vonar	Conventional polyurethane
11	Wool 61%, viscose 39%	Kynol	Conventional polyurethane

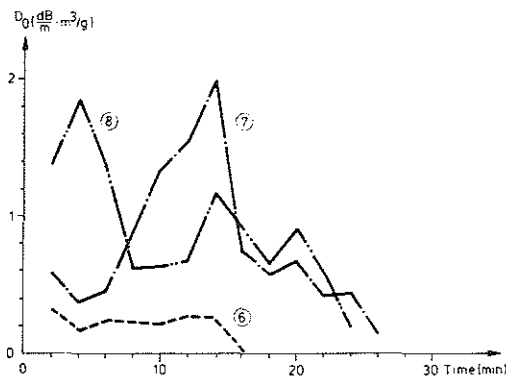


Figure 5. Smoke producing potential per unit weight of consumed fuel  $D_0$  as function of time for tests 6, 7 and 8 [4]

fluence of material selection on the rate of smoke production.

An effort was also made to examine how the quantity  $D_0$ ,  $(\text{dB}/\text{m}) \cdot (\text{m}^3/\text{g})$ , expressing the smoke producing potential per unit weight of consumed fuel, varied over the fire process. A constant value of  $D_0$  obviously would provide a convenient way of classifying materials. Unfortunately, as shown by Fig. 5,  $D_0$  varies strongly and shifts ranking order during the fire process.

#### 4.5 Research Item 5. Interaction between Burning Items of Furniture and Combustible Surface Lining Materials — Full Scale Testing

This item should be studied at the end of the three-year program, when results from items 3 and 4 are available and have been analyzed.

#### 4.6 Research Item 6. Pilot Studies of Fire Induced Compartment Flows

Throughout the series of full scale tests, which will be carried out for other, primary objectives, velocity measurements will be taken of the gas flow field inside the fire compartment (upper gas layer) as well as in the ventilation opening. The instrumentation will be based on the use of bi-directional probes, and one purpose will be to test the accuracy and speed, especially in highly transient compartment fires, of the measurement system. Other purposes include the need to check the limits and definition of the control volume concept now used in the zone

modelling approach. In particular two idealisations need further examination. The first is the concept that the fluid in the fire room is stratified into two horizontal layers of uniform temperatures with no mixing. The investigations in [8] imply that secondary and recirculatory flows near the enclosure opening may be an important cause of reducing the oxygen concentration of the combustion air and hence the mass burning rate. The second concept is the one of a ventilation outflow, driven by a hydrostatic pressure distribution and without influence from the kinetic energy of the rising fire plume gas flow. These two approximations concern the basic problem of predicting the temperature rise in the upper part of the enclosure and the concentrations of combustion products and unburnt fuel, and the way the fire interacts with the enclosure. In addition, measurements taken under research item 2 are being used to compute an effective flow coefficient. It is important to investigate how the flow coefficients vary with the range of size of ventilation openings and fire source strengths, encountered under practical conditions.

#### 4.7 Research Item 7. Mathematical Fire Modelling

The developments, taking place in the last five years within the area of computerbased simulation of the enclosure fire process, has led to a number of models for common fire scenarios. The range of practical application as well as the predictive capability of these models is steadily increasing. The more recent developments were sketchily summarized in a review report to the 1980 CIB W14-meeting in Athens [9].

In [9], available models were, somewhat arbitrarily, divided into general purpose enclosure fire models (the Quintiere model and its successor [6]), models of growth of compartment fires involving combustible lining materials, models for a specified application — such as early growth of the closed room fire or the ventilation required to permit sustained burning or growth of compartment fire — and, finally, models for a simplified prediction of room flashover. Other important modelling areas include probabilistic models for fire spread, modelling of laboratory scale tests, modelling of essentially micro-scale fire physics (ignition, flame spread, extinction), see e.g. the very recent survey in [17].

The research group expects to participate actively in the efforts taking place within the CIB framework to vitalize and co-operate with the European work on fire modelling.

The specifications for project M4 emphasizes the need for establishing a national competence in this sector of fire research. Within the project, the efforts will be concentrated on two tasks.

With the kind assistance of NBS and the Harvard Fire Research Group, version four of the Harvard computer fire code [5] has been transferred to LTH, and is now being used to simulate the full scale tests, mentioned under item 4. Simultaneously, the predictive capacity of the FOA simulation program FLASHOVER [6] for this kind of compartment fires is being looked into.

The second task concerns a model for the prediction of wall fire spread. Very recently, important elements of an analytical model describing the flame spread process across a combustible wall were for the first time outlined by Quintiere [10]. An effort will be made to couple the experimental data produced in the model and full scale tests under research item 3 with the ongoing efforts to put the mathematical model on a firmer base.

#### 4.8 Research Item 8. Characterization of Combustion Products from Small and Full Scale Laboratory Fires

The overall responsibility for this part of the total project will be with the Laboratory for Chemical Analysis at SP. The primary aim of the research task is the development and calibration of a measurement system, based on gas chromatography and mass spectrometry, to analyze the combustion products from laboratory fires. These can be generated in small scale standard tests such as the Swedish box test or the Smith RHR apparatus as well as by full scale experiments using the burn room. In the first year, the system will be assembled and calibrated, while the second and third year, will be used to qualitatively and quantitatively identify possible toxic species from a number of natural and synthetic polymeric materials, with and without fire retardant additives.

#### 4.9 Research Item 9. ISO Reaction to Fire Tests — Correlation to Real Fires, Classification

The procedures available for predicting fire hazard from small scale tests are outlined in the ISO Technical Re-

port TR 6585 "Fire Hazard and Design and Use of Fire Tests", October 1979 and in [16]. In the absence of analytical models for a standard test and/or the full scale experiment, multi-dimensional regression analysis can be used to correlate test results with values of specified full scale experiment variables (maximum room temperature, time of flashover, etc). On the other hand, an analytical model of the small scale test dynamics can provide information on a number of important aspects. Identification of the test sample characteristics (area, orientation, exposure conditions), which control the test outcome, forms the basis for numerical simulations and a sensitivity analysis of the test method itself. With a mathematical model of the test dynamics to hand, important material characteristics controlling fire growth can be given quantitative values, which then can be used as input for full scale. This procedure would be of value, especially for non-homogeneous materials, where relevant material properties, like thermal inertia, otherwise might not be obtainable.

The research group participates actively in ongoing development and validation work on the ISO reaction to fire tests. The apparatus for ignitability, surface spread of flame and smoke generation is being evaluated at SP. At LTH, calibration work is now being done on the rate of heat release (RHR) apparatus, designed by Prof. Smith at Ohio State University. The apparatus is instrumented to measure the rate of heat release by convective heat flow as well as by oxygen consumption. Among the problems likely to be encountered, if basic data are to be obtained for wide use, is the fact that the apparatus, designed to work during tests at constant levels of impressed radiation, progressively heats up and increases the thermal exposure [11].

Other RHR standard tests under development include an unconfined design configuration. To this group of test methods belongs the NBS rate of heat release test, based on measurement of the oxygen depletion. A grant for a further study of this test has been given to the Swedish Forest Products Research Laboratory.

Also the Swedish box test, cf. item 1, may be considered as a crude prototype to a RHR test method.

If a given material is being tested with the three methods mentioned, the test results will certainly differ. An understanding of the differences in the test processes will help to provide a rational explanation of the divergences as well as of the relation between the test methods and the natural fire process.

A key element in the Quintiere conceptual quasi-steady model for wall fire spread is a simplified theoretical model of surface spread of flame under supporting radiation, such as can be studied on the equipment being developed by ISO [12]. A simple expression for the horizontal flame spread  $V_f$  as may occur in a corner test fire can be theoretically derived if the material is preheated so that its rear surface is still cold when the front face has reached thermal equilibrium, viz.

$$V_f^{-1/2} = C(\dot{q}_{0,ig}'' - \dot{q}_e'')$$

where

- C is a material parameter, including radiation from flame, effective width of this radiation, thermo-physical properties,
- $\dot{q}_{0,ig}''$  is minimum radiation flux for piloted ignition, and
- $\dot{q}_e''$  is the imposed radiation flux.

Quintiere also shows how values of C and  $\dot{q}_{0,ig}''$  may be determined for a specific material from a single test run with the surface spread of flame apparatus. Values of  $\dot{q}_{0,ig}''$  can also be obtained by imposing a uniform flux over a smaller sample.

For a thermally thick material, there is a unique relation between  $\dot{q}_e''$  and the corresponding equilibrium temperature. This implies that an alternative expression for  $V_f$  is

$$V_f^{-1/2} = C^1 (T_{ig} - T_s)$$

with

- $T_{ig}$  = effective ignition temperature, and
- $T_s$  = surface equilibrium temperature.

#### 4.10 Research Item 10. Standardized Full Scale Tests

This research item is considered one of the more important part objectives of the total project. Experience has clearly demonstrated that small scale laboratory tests may give misleading and even erroneous information regarding material or product performance in a natural fire. The need for further full scale studies, using internationally standardized procedures, where possible, is thus direct and urgent. This applies to surface lining materials as well as furnishings.

For *surface lining materials*, initial development work has been described under research item 3. The work being carried out in the USA to produce an ASTM room corner test is being closely monitored [13].

The development of standardized full scale tests for *furnishings*, e.g. upholstered furnitures and beds, for the post-ignition phase, is in a still more tentative stage of development.

A number of factors determine the hazard profile of a specified product, involved in the post-ignition stages of a room fire: flame spread and fire growth properties in general, maximum rate of combustion heat release, generation of smoke and toxic gases. The components in the first and third category determine the time available for safe escape, while the maximum rate of heat release indicates the risk of room flashover and spread to other rooms. The flashover phenomena have been the subject of a number of recent papers and certain quantified limit criteria have been proposed. The other hazard components, acceptance criteria cannot yet be determined objectively.

The most extensive work has probably been carried out in the UK and, by way of an example, resulted in a series of "fire retardant specifications", issued by DOE/PSA [14]. One of these, DOE/PSA FR 6, tests the burning characteristics of upholstered chairs by a burn-out test in an instrumented room. Data collected during the test include smoke temperature, optical density and volume, heat fluxes to the environment and CO-concentration.

To test, for instance a full scale piece of an upholstered furniture in a fully instrumented burn room, using calorimetric measurements and energy balance equations, involves a considerable amount of time and cost. Also, as long as effective ventilation flow coefficients are not available as a function of opening geometry and heat source strength, the number of velocity probes necessary for accurately mapping highly transient gas flow velocity fields makes for a rather unwieldy test procedure. An attractive alternative in this situation is to use oxygen consumption techniques [13]. Still another approach is the room size dynamic room calorimeter, developed at Monsanto [15], working under forced air flow conditions. The impact on burning characteristics of the artificial flow system may not be negligible, however. As a further alternative and if the influence of the enclosure on the fire growth process is of minor importance, pieces of furniture could be tested by free burning under an exhaust hood and with rate of heat release measured by oxygen consumption.

The problem of enhancement of burning rate by thermal feed back, from enclosing structures and upper gas layer, was investigated by Thomas [16], who found that the ratio of rate of burning at the flashover point for a

fire in an enclosure to the rate of burning when the same product is allowed to burn freely in the open, is nearly a constant  $\approx 1.7$ . The implications are that results from a free burning test, indeed can be used to indicate the risk for the same product causing room flashover.

Finally, as our own and others experiments have demonstrated, a test to assess the horizontal flame spread properties of furniture with extended surfaces remains essential both to provide basic input data in computer-based mathematical models of enclosure fire growth and as a more direct risk classification tool. As pointed out in [16], fire spread may be more susceptible to radiative enhancement than pure rate of burning.

#### 4.11 Research Item 11. Testing of Upholstered Furniture Using Half-Scale Rigs

It follows from the discussions under research item 10 that obvious advantages would be gained, if testing of pieces of furniture could be made on specimens of a reduced size.

As a part of the project, briefly described under research item 4, a number of burning tests (52) were performed with a testing rig designed according to DD 58:1978, the original proposal for a British ignitability standard. The test configuration is described by Fig. 6.

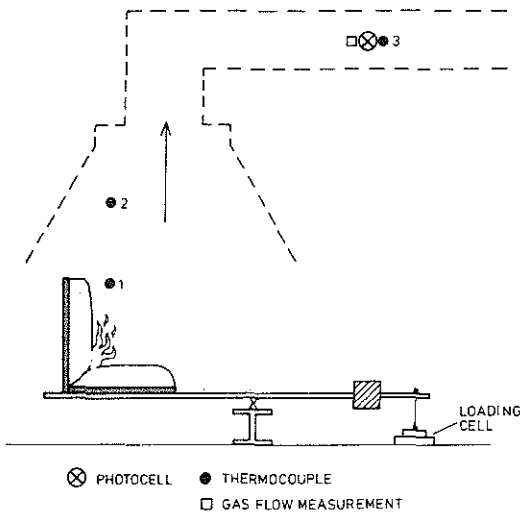


Figure 6. Arrangements for testing upholstered furniture, using a half-scale rig.

To illustrate the results obtained, Fig. 7 outlines the range in total accumulated smoke production  $D_{acc}$ , obtained by material changes and modifications. Finally, Table 3 gives the correlation between full scale and model scale testing for those few cases where results are obtainable.

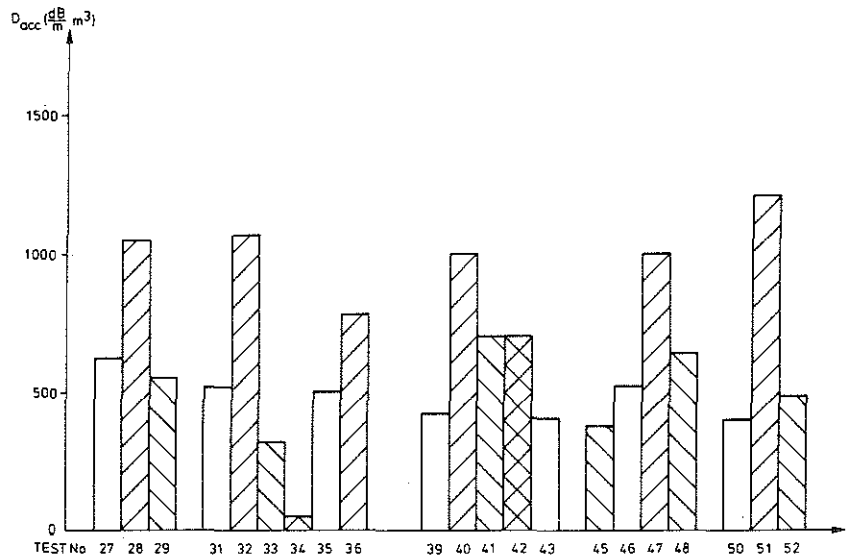
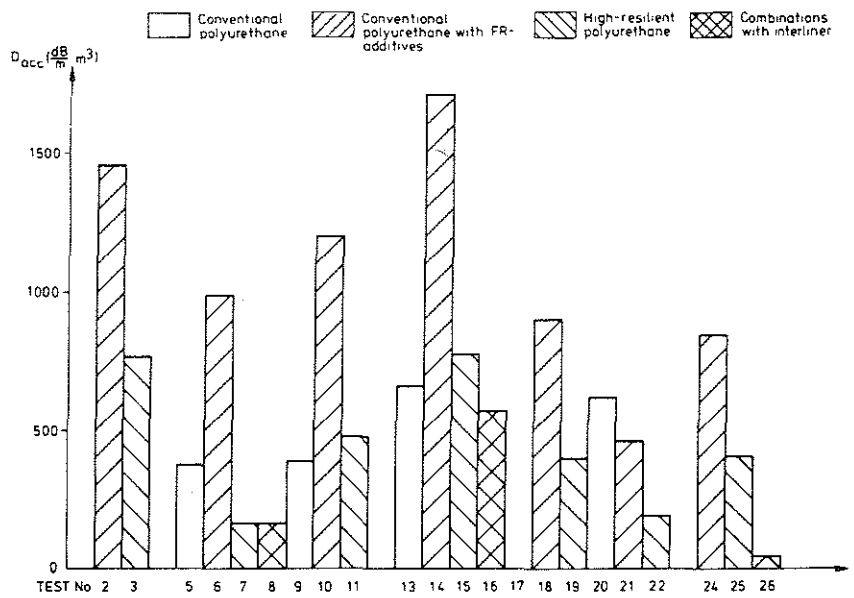


Figure 7. Total, accumulated smoke production  $D_{acc}$  for pieces of upholstered furniture, determined in half-scale tests. In the tests, not reported in the figure, the smoke production was too small to enable any evaluation [4]

Table 3. Total accumulated smoke production  $D_{acc}$  for upholstered furniture, obtained in half-scale and full scale tests [4]

Test No.		Smoke production $D_{acc}$ ( $\frac{dB}{m} \cdot m^3$ )	
Half-scale	Full scale	Half-scale	Full scale
1	5	465	2530
46	6	603	2080
48	7	639	3905
47	8	1296	6910

The table indicates a positive correlation but shows simultaneously that the relative ranking order is not unambiguous. Before more definite conclusions can be drawn, further tests must be carried out.

#### 5. SUMMARY

The following four projects from the present National Swedish fire research program

- generation of smoke and toxic gases (B2),
- surface lining materials — classification and fire hazards (M3),
- building materials — fire tests and fire growth (M4),
- upholstered furniture — fire safety requirements (M6)

have been brought out and integrated to a research project with the title "Fire Hazards — Fire Growth in Com-

partments in the Early Stage of Development (Pre-flashover)". The integrated project is carried out as a joint project by the Division of Fire Technology and the Laboratory for Chemical Analysis at the Swedish National Testing Institute (SP), Borås and the Division of Structural Mechanics at Lund Institute of Technology (LTH). Within the framework of a collaboration agreed between the Fire Research Station, UK and LTH, extensive discussions and consultations have taken place and are forming much of the background for the formulation of the research project. The project is financed by the Swedish Fire Research Board.

The paper presents the general background, scope, organization and detailed structure of the integrated research project. In order to facilitate the detailed planning, it turned out to be useful to break down the project into eleven smaller research items. Table 1 enumerates these and illustrates their relevance for and connection to the four original research projects B2, M3, M4 and M6 in the national Swedish fire research program.

The main part of the paper is devoted to a presentation of the eleven research items as well as the progress made up to now (August 1980). As it appears, none of them is anywhere near completion, most are still in an initial planning stage.

The final goal of the project is defined as the development and validation of test methods, for surface lining materials as well as furniture and other fittings, having the capability of predicting the behaviour and contribution of the tested material or product to natural fire growth and spread in a compartment. In order to achieve this goal, analytical modelling of the compartment fire process becomes a necessity, e.g. as a tool to perform sensitivity studies. In this sense, the use of mathematical models also facilitates the formulation of performance-based classification requirements. Specifically, evaluation and verification of the ISO reaction to fire tests represents an important task.

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