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FIRE PREVENTION TECHNOLOGY FOR HIGH-RISE BUILDINGS

DP/CPR/88/009/11-51/J13428

CHINA

Technical report: Fire prevention concepts in the design of high-rise buildings

Prepared for the Government of the People's Republic of China
by the United Nations Industrial Development Organization,
acting as executing agency for the United Nations Development Programme

Based on the work of Ezel Kendik, consultant

Backstopping officer: H. S. Yalçindag, Chemical Industries Branch

United Nations Industrial Development Organization
Vienna

Explanatory notes

The monetary unit in China is the yuan renminbi (¥RMB)

Besides the common abbreviations, symbols and terms, the following have been used in this report:

BFRD	Building Fire Research Department
BS	British Standard
CABR	China Academy of Building Research
CICETE	China International Centre for Economic and Technical Exchanges
DIN	Deutsche Industrie Norm

The annexes have not been formally edited.

ABSTRACT

Within the context of the project "Fire prevention technology for high-rise buildings" (DP/CPR/88/009), a consultant was fielded to Beijing on 17 October 1990. During her one-month assignment, the consultant has given several lectures at the Building and Fire Research Department (BFRD) of the China Academy of Building Research (CABR), at the Shanghai Research Institute of Building Sciences and the Northwest Institute of Architectural Engineering at Xian, introducing regulations and standards for fire prevention and smoke control in high-rise building construction.

Participants of these lectures were given documentation on designing escape routes in buildings, design methods for means of egress, various national codes and regulations for high-rise buildings as well as on smoke-control systems. Discussions with concerned groups in China focused on:

(a) Fire-prevention concepts which should ensure integration of building design with aspects such as size; number and type of occupancy; and quantity, distribution and arrangement of combustible contents;

(b) Relationship between fire and fire tests to assess the burning behaviour of a material or structure under standardized and reproductive test conditions as well as fire safety as a guidance for the classification of materials and structures;

(c) Documentation on standards, regulations and codes of practice;

(d) Training of architects, officers in charge of the control of codes' applications and users of buildings.

The consultant found that the main problem of BFRD related to the service and maintenance of existing equipment. Recommendations are made concerning the training of certain staff and relevant information for future linkages and contacts is provided.

CONTENTS

INTRODUCTION

Within the context of the project "Fire prevention technology for high-rise buildings" (DP/CPR/88/009), a consultant was fielded to Beijing on 17 October 1990 for the period of one month. According to the job description, the consultant was expected to:

(a) Present lectures on design codes and standards applied in high-rise buildings for fire prevention to Chinese technicians/scientists;

(b) Introduce test standards on fire prevention of building elements and equipment;

(c) Outline programmes for the appropriate training of national experts abroad.

During initial discussions with the Director of the Building Fire Research Department (BFRD), as well as at a meeting with the Vice-President of the China Academy of Building Research (CABR) and the National Project Director, strong emphasis was placed on the presentation of lectures about different aspects of fire prevention.

According to the needs expressed, the consultant gave four lectures at BFRD, an outline of which is presented in chapter I. During several formal and informal meetings, the following topics were also discussed:

(a) Fire prevention concepts;

(b) Fire prevention systems as a feature of a broader life safety concept;

(c) Research activities in different countries;

(d) Training possibilities abroad;

(e) Further needs of BFRD for its testing laboratories.

Furthermore, the consultant was requested to lecture at the Shanghai Research Institute of Building Sciences and at the Northwest Institute of Architectural Engineering at Xian.

The National Project Director also stated that CABR would appreciate to initiate and maintain, through the consultant, contacts to Austrian institutions in the field of fire prevention as well as in other areas of building research.

I. LECTURES AT THE BUILDING FIRE RESEARCH DEPARTMENT

The consultant gave four lectures at BFRD, based on material reproduced in annexes I and II.

A. Introductory lecture

In his introduction to the lecture, the Director of BFRD, Mr. Li Guiwen, explained the work carried out in the Divisions of the Department related to:

(a) Fire resistance of structural elements;

(b) Smoke control;

(c) Burning behaviour of building materials;

(d) Alarm and sprinkler systems.

The consultant's lecture of 2 1/2 hours included the following aspects:

Fire-prevention concepts

Fire-prevention systems play a major part in the context of life safety in high-rise buildings and should be designed as an integral part of a system including such other components as: size of the building; number and type of occupancy; quantity, distribution and arrangement of combustible contents of the building; shape and size of rooms; openings in a room; vertical and horizontal paths for fire spread in the building and their appropriate sealing; electrical installations; non-combustible piping etc. Other aspects to be considered are the design of escape routes, i.e. the provision of protected means of egress of adequate size, and the emergency escape planning, which is no doubt an essential component of life safety, especially in high-rise buildings, and hence a major concern of building regulations throughout the world.

The relationship between fire and fire tests

It was pointed out that, essentially, fire tests are attempts to assess the burning behaviour or performance of a material, product, structure or system under standardized and reproductive test conditions which approximate to one or more stages of a real fire. Thus, no fire test or combination of tests can guarantee safety in a particular situation. They constitute only one of many factors which need to be taken into account in assessing fire safety and should be understood as a guidance for the classification of materials and structures.

Documentation

A comprehensive set of documents was handed out to officials of BFRD, consisting of: standard fire tests of ISO, of the National Fire Protection Association (NFPA), United States, and of the British Standards Institute (United Kingdom); the Austrian testing regulations and the classification of structures and materials, ONORM 3800; technical guidelines for the assessment of fire prevention systems in Austria (TRVB 100); Austrian regulations for high-rise buildings; handbooks on fire-alarm systems and smoke control in fire safety design; the British Standards Institute Code of Practice: fire precautions in the design of buildings (BS 5588, part 4, 1978: smoke control in protected escape routes using pressurization); the British Standards Institute Code of Practice: fire precautions in the design of buildings (BS 5588, part 3: office buidings); British Building Regulations B2, 3 and 4, the German standard DIN 18232 for smoke venting as well as three papers, prepared by the consultant, on the design of means of escape summarizing research work and methods of calculating pedestrian movement.

Training

The necessity of training of architects, as well as of officers who are in charge of controlling the codes' application, and, last but not least, the education of the buildings' users as a major aspect of fire prevention were addressed. An educational programme starting at primary schools (as children's playing with fire is a major cause of fires) as well as drawing the attention of the population at large to ways and means of fire prevention (e.g. through television spots) was highly recommended.

B. Regulations pertaining to high-rise buildings

In this 3-hour lecture the German Model Code on High-rise Buildings (see summary in annex III) has been discussed in detail. Some aspects of the German Code such as the fire resistance requirements according to the structural elements were compared with existing Austrian and British building regulations.

Furthermore, fire-fighting lifts and staircases required in the British Standard BS 5588: part 3: office buildings, for buildings higher than 18 m were discussed. Apparently the concept of fire-fighting staircases has not yet been addressed in the Chinese regulations for high-rise buildings.

C. The design of means of escape in high-rise buildings

After a brief discussion of the previous lecture, the means of egress requirements in the revised British building regulations were introduced in a lecture of 2 hours.

The consultant emphasized the necessity of fire modelling for the safe and economic design of buildings, and presented a design method for the assessment for pedestrian movement during evacuations in high-rise buildings developed by her. A numeric data application where the design calculations were compared with real evacuation tests in high-rise buildings was also provided. A summary of the above-mentioned design method is given in annex I.

D. Smoke control

In the first part of this 3-hour lecture the major driving forces causing smoke movement, i.e. stack effect, buoyancy, expansion due to the fire heat, wind, and the heating, ventilating and air conditioning system were discussed and the corresponding mathematical formulae for their calculation provided. Furthermore, the principles of traditional methods of smoke management such as the use of barriers, smoke vents and smoke shafts as well as modern principles of smoke control like airflows, purging and pressurization were addressed and their advantages in comparison with the traditional systems outlined. The consultant also presented the German standard DIN 18232, part 2, on the sizing of smoke vents.

After discussing the components of a pressurization system, BS 5588, part 4: smoke control in protected escape routes using pressurization was introduced and an example of a pressurization scheme designed according to that code presented.

II. OTHER TOPICS DISCUSSED IN MEETINGS AT THE BUILDING FIRE RESEARCH DEPARTMENT

In addition to discussions of technical matters relating to high-rise building codes, means of escape and smoke-control systems, there have been meetings during which the funds provided by the Chinese Government in support of the project, the items successfully carried out by BFRD as well as further needs and anticipated problems of the Department were discussed.

A. Funds provided by the Ministry of Construction of China

The Ministry of Construction provided approximately ¥RMB 1,000,000 for the erection of a new laboratory building which has been finished and is ready for the installation of the expected test equipment.

An old building, near the new laboratory building, was made available to BFRD by the Ministry of Construction for the erection of the test furnace. This building will be renovated and extended with an additional fund of ¥RMB 150,000 from the Government.

The Ministry of Construction also provided ¥RMB 370,000 for research into testing techniques for pressurization systems in high-rise buildings. BFRD will carry out experiments in the two-storey staircase shaft erected within the new laboratory for the analysis of pressurization systems and their components (such as air leakage through windows) as well as full-scale experiments in cooperation with the Building Research Institute at Shanghai and the Tienjin Design Institute. An experiment will be carried out in the Hua Ting Sheraton Hotel at Shanghai and further experiments are planned for 1991 at Beijing, Tienjin and Shanghai.

In addition, the Government is providing funds for the following research work:

(a) ¥RMB 600,000 for testing the fire resistance of structural elements in high-rise buildings;

(b) ¥RMB 100,000 for research on fire alarm systems;

(c) ¥RMB 200,000 for research on the burning behaviour of materials.

Another existing building of about 300 m^2 and 6 m height, originally built for the heating unit of the Academy, will also be used by BFRD in the future.

The salaries of the employees for the period of the project will amount to approximately ¥RMB 200,000-300,000.

B. Funds provided by the National Science Foundation

The National Science Foundation will support research into leakage areas of stairwells through stairwell walls and via other paths by providing an amount of ¥RMB 80,000.

C. Additional funds required

For the above-mentioned tasks BFRD signed a three-years' contract with the Ministry of Construction.

All above-mentioned funds will be used exclusively for research-related work, including travel costs and the purchase of material and equipment for the experiments. BFRD suggests that in view of the comprehensive tasks ahead, the provided funds are still insufficient. Experience during the purchase of the furnace showed that UNDP funds had to be supplemented by the Government in order to be able to erect the furnace for a total cost of ¥RMB 600,000.

Sixty per cent of the UNDP funds, which are more or less evenly distributed between the four research sections of the Department, will be used for the purchase of the testing equipment such as calorimeter, computers which cannot be obtained in China, data acquisition system etc., and the remaining 40 per cent for study tours of Chinese directors and training of researchers abroad, as well as for experts coming to China.

D. Additional equipment required

BFRD would need the following equipment, the purchase of which is not foreseen in the original project document:

(a) For a separate project office, the establishment of which has already been approved by CICETE and the UNDP office:

(i) A telefax machine;

(ii) An air conditioner;

(iii) A photocopying machine;

(b) A car for site investigations in case of fire, which would certainly help to improve the experience of BFRD members in real fires. Since car rental is very expensive, and travelling in Beijing by public transportation appears to be very restricted to almost impossible, and considering the immense distances within the city, the purchase of a car would be quite important for both, BFRD staff and experts;

(c) A portable video recorder and one record unit to be used in the laboratory.

It was also pointed out that the above-mentioned items are government-controlled goods which cannot be obtained without government permission. This procedure may take up to two years. On the other hand, the import of any goods supported by UNIDO is tax-free (e.g. the customs rate for cars is up to 200 per cent).

E. Project tasks completed

BFRD has completed the following research work:

(a) A new kind of sprinkler has been introduced and will be released soon for production;

(b) An automatically activated fire door closer has been developed;

(c) Fire-resistant conduit for wires has been developed;

(d) The load-bearing capacity of structures in two buildings damaged by fire was assessed and assistance was given in their reconstruction.

F. Additional activities carried out by BFRD

During the past two years four courses had been arranged for architects and engineers focusing on fire safety considerations in the design of high-rise buildings.

The Institute of Building Fire Protection has been established. The President of the China Academy of Building Research (CABR) is the Chairman of the Institute. The Standing Chairman is the Chief Engineer of CABR. The Director of BFRD is the Vice-Chairman of the Institute. The aims of the Institute are:

(a) Exchange of research experience between fire institutes within China;

(b) Dissemination of research findings to industry;

(c) Holding of national and international symposia in China.

The Institute's office is located in BFRD.

G. Training abroad

In September 1990, two research engineers started a training programme of six months at Warrington Testing Centre, United Kingdom, and another two engineers went to Edinburough University in November 1990. Two engineers are scheduled to undergo training at the Building Research Institute at Helsinki, Finland.

H. Difficulties encountered

BFRD pointed out that difficulties have been encountered concerning the acceptance of Chinese researchers for training in foreign countries.

Another difficulty concerned the service and maintenance of testing equipment and computers bought outside China, since BFRD cannot expect any assistance in their potential repair and maintenance from local agencies. For that reason, BFRD suggested that, to the extent possible, equipment should be ordered in China through local agents who would then be obliged to carry out related maintenance work.

I. Recommendations for future training

BFRD seeks to train a group of staff attached to the fire-alarm and sprinkler-systems laboratory in repair and maintenance, the main objectives being for BFRD to become a recognized repair and maintenance laboratory and to train Chinese scientists and technicians on a regular basis.

The consultant recommended to apply for the training of the engineers to the following research institutes in Europe:

(a) Forschungsstelle für Brandschutztechnik an der Universität Karlsruhe (TH), Hertzstrasse 16, 1071 Karlsruhe, Germany (Paul Gerhard Seeger, Director of the Research Institute for Fire Technology);

(b) Department of Fire Safety Engineering, Institute of Science and Technology, Lund University, P.O. Box 118, 22100 Lund, Sweden (Eric Magnuson, Professor);

(c) Institute für Baustoffe, Massivbau und Brandschutz der Technischen Universität Braunschweig, Germany (Dietmar Hosser, Professor);

(d) Swedish National Fire Testing Institute, Department of Fire Technology, P.O. Box 857, 50115 Boras, Sweden (Ulf Wickström);

(e) Brandverhütungsstelle für O.Ö. Reg.Ges.m.b.H. Staatlich Autorisierte Prüfanstalt für Materialprüfung, Petzoldstr. 45, 4020 Linz, Austria (Klaus Moser, Director).

III. MEETINGS AND LECTURES AT THE SHANGHAI RESEARCH INSTITUTE OF BUILDING SCIENCES AND THE NORTHWEST INSTITUTE OF ARCHITECTURAL ENGINEERING AT XIAN

BFRD arranged for two seminars to be held in the above-mentioned Institutes at Shanghai and Xian.

At the Shanghai Research Institute of Building Sciences a meeting was held with the Deputy-Director Mr. Wang Fu-yuan and the chiefs of two different research divisions which are involved in the fire research of building materials and structure. After an introduction of their activities, the consultant gave a lecture of three hours on building regulations for high-rise buildings and on the design of means of escape. Discrepancies and affinities of high-rise building codes in different countries were pointed out and the design method for the assessment of pedestrian movement during evacuations in high-rise buildings developed by the consultant was presented. A numeric data application where the design calculations were compared with real evacuation tests in high-rise buildings was provided and the requirements concerning means of egress contained in the British Standard 5588, part 3, Office buildings, were evaluated by way of this method.

Apart from the members of the Institute, the seminar was attended by engineers from the Public Security Unit and the Far East Fire Testing Centre.

At the Northwest Institute of Architectural Engineering at Xian the consultant presented a lecture covering the same areas as at Shanghai, including smoke control, to professors and students from the departments of architecture, structural engineering, environmental engineering and electrical engineering.

Annex I

METHODS OF DESIGN FOR MEANS OF EGRESS: TOWARDS QUANTITATIVE COMPARISON OF NATIONAL CODE REQUIREMENTS

Ezel Kendik

Special lecture held at the First International Symposium on Fire Safety Science in National Bureau of Standards, Gaithersburg, MD, USA, October 8, 1985

ABSTRACT

This paper provides a brief review of the modelling of people movement during the egress from buildings and discusses some of the questions raised by each type of modelling. Furthermore, it compares the predictions of a selected calculation method with regulatory requirements on means of escape in various countries.

INTRODUCTION

The increasing complexity of buildings concerning functions, size and configurations require a broader attention to the problems related to egress. Over the last two decades there has been considerable activity in modelling egress from buildings. According to the overall tendency in the technical literature the available models can be divided into two categories, viz. movement models and behaviour models. Although the former studies are generally concerned with the exiting flow of a buildings' occupants the design concepts show a somewhat dispersed variation.

The behavioural models as they have been developed, are essentially of two types, conceptual models which have attempted to include the observed, empirical and reported actions from collective interview or questionnaire studies, by Canter (1) and by Wood (2), and computer models for the simulation of the behaviour of the human individual in the fire incident. The conceptual models have attempted to include a theoretical design in the model which attempts to provide some understanding of decision making, and alternative choice processes of the individual involved with a fire incident situation. Most of the current models that have been developed of this type would probably be identified as describing the process of the participant in the fire incident as an information seeking and processing model. (after J. Bryan, ref.3)

The current models evolving from people movement may be classified as follows:

1. Flow models based on the carrying capacity of independent egress wav components;
2. Flow models based on empirical studies of crowd movement;

3. Computer simulation models; and
4. Network optimization models.

This presentation will primarily be concerned with the first and second items, since the former is still world-wide governing the regulatory approaches covering the exit geometry whilst the latter studies are supported by extensive research work conducted in real-world settings. But, before we turn to our primary concern two other models supported by U.S. National Bureau of Standards should be acknowledged.

BFIRES II: A BEHAVIOUR BASED SIMULATION OF EMERGENCY EGRESS DURING FIRES

This model by F.Stahl (4),(5) is a dynamic stochastic computer simulation of emergency egress behaviour of building occupants during fires. It is a modified and expanded version of BFIRES I (6), which was originally developed for the application to the health care occupancy. The model is not calibrated against real-world events, but a sensitivity analysis of the model proved that BFIRES outcomes are sensitive to (a) floor plan confuguration, (b) occupants' spatial locations at the onset of the emergency event, (c) the existence of any impairments to occupants' mobility, (d) occupants' familiarity with the building layout, and (e) permissible levels of occupant density.

The most interesting finding of this sensitivity analysis is that, when the individuals vary on the basis of occupant parameters (mobility impairment and and knowledge of safe exit location) the effects of variation in enviromental parameters (occupant density and spatial subdivision) disappear. As a result of this Stahl suggests that occupants unfamiliar with the building's physical layout will not be helped by designs providing shorter and more direct egress routes. This challenges the traditional design conventions.

The concept and structure of the model is described by Stahl as follows:

BFIRES conceptualizes a building fire event as a chain of discrete "time frames" and for each such frame , it generates a behavioural response for every occupant in accordance with their perceptions of a constantly changing environment. When preparing a behavioural response at Ti, a simulated occupant gathers information-which describes the state of the environment at this point in time. Next, the occupant interprets this information by comparing current with previous distances between the occupant, the fire threat, and the exit goal and by comparing "knowledge" about threat and goal locations possessed by the occupant, with amounts possessed by other nearby simulated persons. Current locations of physical barriers and of other occupants are also taken into account...The selection of a behavioural response (i.e. the decision to move in a particular direction) results from the comparison of available move alternatives with the occupant's current move criteria.

Here, the choise of exits and the selection of alternative moves appear to be critical . In the first report of BFIRES (6) it is suggested that, as the literature in human behaviour in fires (or fire drills) provide no guidance, that , if 60% (or more) of the occupants inhabiting a space favor a particular exit from the space, they will "convince" the remaining occupants of the quality of their opinion, and all the occupants will seek the exit. This option is not necessarily consistent with the human nature. The opposite choice might be that the majority follows one person.

About the criteria of selecting alternative moves, Stahl writes as follows:

To date, it has not been possible to calibrate computed values of the probability that an occupant will, during a given time frame select some move alternative, against data from actual fire situations. This is because no data on human behaviour during fires exist to describe emergency decision making processes at so fine a level of detail. Considerable research will be necessary to understand the mechanism by which people under emergency conditions perceive alternative courses of action, relate such alternatives to broader egress strategies and then select appropriate actions.

In spite of the limitation, that the model deals with maximum 20 persons in a simulation, it appears to be the only computer program attempting to simulate the individuals' information processing, decision making and responses to a migrating fire threat, like smoke and toxic agents.

EVACNET: A COMPUTERIZED NETWORK FLOW OPTIMIZATION MODEL (8),(9)

This model, developed by R.L.Francis et al. determines an evacuation routing of the people so as to minimize the time to evacuate the building. Network models are not behavioural in nature. Rather they demonstrate a course of action which, if taken could lead to an evacuation of a building in an "appropriate" manner. The model represents the building's evacuation pattern as it changes over time, in discrete time periods. The model is able to answer several "what if" questions like "how should the building be evacuated if the fire breaks out on the tenth floor or what if more stairwells are added. (9)

The static network model is basically a transshipment model, where origins represent work centers, transshipment nodes represent portions of the building and destinations represent the building exits. The static capacity of the node gives the maximum number of persons simultaneously allowed to stay in this space. The nodes are connected by arcs, of which the dynamic capacities are upper bounds on flow rates. Based on J. Pauls'"effective width" model, the model assumes constant flow rates in stairwells for a given number of occupants in the building. This assumption that the stairwell flow rates are independent of stairwell usage, appears to be a limitation of the network flow model, since its approach is somewhat contradictory to the effective width model. Pauls' equation predicts the mean flow rate for the assessment of the overall evacuation performance, while the network model looks at the evacuation pattern every ten seconds.

The network flow optimization model is able to deal with large number of people as well as with complex buildings.

FLOW MODELS BASED ON THE CARRYING CAPACITY OF INDEPENDENT EGRESS WAY COMPONENTS

The historical development of carrying capacity investigations has been already broadly reviewed by F.Stahl and J.Archea (10), (11) and J.Pauls (12),(13), in several publications. Hence, this presentation will be confined to the discussion of the calculation methods based on these investigations.

An early NFPA document recommended as a guideline for stair design an average flow rate of 45 persons/minute/22" width unit. (after ref.10) In 1935, in a publication of the U.S. National Bureau of Standards, test results about measurements of flow rates through doors corridors and on stairs under non-emergency conditions were presented. There,for different types of occupancy the measured maximum flow rates varied between 23 and 60 persons/min/ unit stair width, and 21 and 58 persons/min/unit door or ramp width. (14) Up to date, the NFPA Life Safety Code 101 (15) maintained the unit exit width concept together with the travel distances and the occupant load criteria. But, for some reason the time component is left out in the present code.

In the U.K. the first national guidance for places of public entertainment was produced in 1934 (16) ; the recommendations in which had been "based not only on experience gained in the U.K., but on a study of disasters which have happened abroad and of the steps taken by the authorities of forein countries". (17) In this document the following formulae for the determination of total width of exits required from each portion of a building were provided reflecting the concept of the unit exit width:

$$A = Z\ (\text{Floor area in sq f}) / E\ \ B\ \ C\ \ D \qquad (1)$$

A is the number of the units of exit width required,
B is a constant as to the construction type of building,
C is a constant for the arrangement and protection of the stairs,
D is a constant for the exposure hazard,
E is a factor dependent apon height of floor above or below ground level,
Z is the class of user of the building (closely seated audience etc.).

$$N = A/4 + 1 \qquad (2)$$

N is the number of exits required. In this document it was also stated, that about 40 persons per minute per unit exit width downstairs or through exits is an appropriate figure in connection with these formulae.

In fact the width of exits had been discussed ten years previously in a document for the fire protection in factories, (7), where it was reported that tests in the U.K. and in America had found that on average 40 persons per foot of width per minute was possible for "young and active lads" moving "through door-ways with which they were aquainted", but that figure would have to be reduced very conciderably for theatre audiences, it was considered that in factories a figure of 20 persons per foot of width per minute was quite safe under conditions ruling in a factory.(after ref.17)

40 persons/min/unit of exit width is also recommended in the Post-War Building Studies No.29. (18). In this report another calculation method is suggested. (Appendix II) The width of staircases in the current GLC Code of Practice (19), as well as in the BS 5588 Part 3 (20) are computed by this method (21), which calculates the total population a staircase can accomodate based on the following assumptions:

1. Rate of flow through an exit is 40 persons per unit width per minute;
2. Each storey of the building is evacuated on to the stairs in not more than 2.5 min. (This average clearance time was proposed after an evacuation experience during a fire in the Empire Palace Theatre in Edinburgh in 1911; (18)
3. There is the same number of people on each storey;
4. Evacuation occurs simultaneously and uniformly from each floor;
5. In moving at a rate of 40 persons/unit width/min, a staircase can accomodate one person per unit width on alternate stair treads and 1 person per each 3 sq. ft. of landing space;
6. The storey height is 10 ft;
7. The exits from the floors on the stairs are the same width as the stairs; and
8. People leaving the upper floors are not obstructed at the ground floor exit by persons leaving the ground floor.

$$P = (\text{staircase capacity})(\text{nu.of upper storeys}) + (t_e - t_s)\, r\, w \qquad (3)$$

t_e is the maximum permissible exit time from any one floor onto the staircase (taken as 2.5 min.);
t_s is the time taken for a person to traverse a storey height of stairs at the standard rate of flow (predicted as 0.4 min);
r is the standard rate of flow (taken as 40 persons/unit/min); and
w is the width of staircase in units.

The staircase capacity is predicted after point 5 of the above assumptions.

This method of calculation predicts with increasing number of storeys fewer persons per floor.

K.Togawa in Japan (1955), whose studies are hardly accessible, was apparently the first researcher who attempted to model mathematically the people movement through doorways, on passageways, ramps and stairs. (after Pauls,(13), Stahl and Archea,(10), and Kobayashi,(22)) He provided the following equation:

$$v = V_o D^{-0.8} \qquad (4)$$

v is the flow velocity;
V_o is a constant velocity (1.3 m/sec, which is apparently the velocity under free flow conditions); and
D is the density in persons per sq m.

Hence, the flow rate N is given by

$$N = V_o D^{0.2} \qquad (5)$$

This N is the same as the specific flow "q" referred to later.

Based on the data from the investigations by Togawa and the London Transport Board (23) S.J. Melinek and S.Booth (24) analysed the flow movement in buildings and provided the following formulae:

1. The maximum population M which can be evacuated to a staircase, assuming a permitted evacuation time of 2.5 min, is given by

$$M = 200\ b + (18\ b + 14\ b^2)\ (n-1) \tag{6}$$

b is the staircase width in m; and
n is the number of storeys served by the staircase.

This equation predicts higher number of persons than the method presented in the Post-War Building Studies No.29.

. If the population Q and the staircase width b are the same for each floor then the minimum evacuation time is the larger of T_1 and T_n where

$$T_1 = n\ Q/(N'\ b) + t_s \tag{7}$$

$$T_n = Q/(N'\ b) + n\ t_s \tag{8}$$

T_1 corresponds to congestion on all floors and T_n to no congestion. Melinek and Booth suggested as typical values of N' and t_s 1.1 persons/sec/min and 16 sec. Compared with evacuation tests in multi-storey buildings the method predicted in most cases evacuation times which are too low.

A further application of the unit width concept has been the mathematical model of W.Müller in East Germany. (25),(26), (27). Assuming a flow rate of 30 persons/min/0.6 m stair width Müller provided the following equation for the assessment of the total evacuation time in multi-storey buildings:

$$t = (3\ h_G\ /\ v) + (P\ /\ (b\ f_o\ /\ 0.6)) \tag{9}$$

h_G is the floor height;
P is the number of persons in the building;
b is the stair width in m;
v is the flow velocity down stairs of 0.3 m/sec; and
f_o is the flow rate/unit stair width of 0.6 m.

The minimum evacuation time via the staircase is

$$t = 10\ h_G + 15\ h_G\ n \tag{10}$$

Müller suggested the limitation of building height rather than to widen the staircases.

FLOW MODELS BASED ON EMPIRICAL STUDIES OF CROWD MOVEMENT

During the last decade Jake Pauls (Canada) developed the "effective width" model. This model is based upon his extensive empirical studies of crowd movement on stairs as well as the data about the mean egress flow as a function of stair width. In this context he conducted several evacuation drills in high-rise office buildings and observed normal crowd movement in large public-assembly buildings. The model describes the following phenomena (13), (29), (30):

1. The usable portion of a stair width , i.e. the effective width of a stair begins approximately 150 mm distance from a boundary wall or 88 mm distance from the centerline of a graspable handrail. (edge effect)
2. The relation between mean evacuation flow and stair width is a linear function and not a step function as assumed in traditional models based on lanes of movement and units of exit width. The evacuation flow is directly proportional to the effective width of a stair.
3. Mean evacuation flow is influenced in a nonlinear fashion by the total population per effective width of a stair.

Pauls provides the following equation for the evacuation flow in persons per metre of effective stair width:

$$f = 0.206\ p^{0.27} \qquad (11)$$

p is the evacuation population per metre of effective stair width. The total evacuation time is given by

$$t = 0.68 + 0.081\ p^{0.73} \qquad (12)$$

This calculation method has been recently accepted for an appendix to the NFPA Life Safety Code, 1985 edition.

Now, we turn to another flow model developed by Predtechenskii and Milinski in the Soviet Union. (31) This method is a deterministic flow model, which predicts the movement of an egressing population on a horizontal or a sloping escape route instantaneously in terms of its density and velocity.

Predtechenskii and Milinski measured the flow density and velocity in different types of buildings nearly 3600 times under normal environmental conditions. Their observations indicated, that the flow velocity shows a wide variation, especially in the range of lower densities. The following equation relating the ratio between the sum of the persons' perpendicular projected areas (P f) and the available floor area for the flow, estimates the flow density homogeneously over the area of an escape route:

$$D = P\ f\ /\ b\ l \qquad (13)$$

P is the number of persons in the flow;
f is the perpendicular projected area of a person;
b is the flow width, which is identical with the width of the escape route; and
l is the flow length.

Note D has no dimensions.

The egress populatian passing a definite cross section on an escape route of the width of b, is referred to as flow capacity.

$$Q = D\ v\ b \qquad \mathrm{m}^2\ \mathrm{min}^{-1} \qquad (14)$$

Here, v is the flow velocity. Another flow parameter is the flow capacity per metre of the escape route width, which is defined as the specific flow:

$$q = D\,v \qquad \mathrm{m\ min^{-1}} \tag{15}$$

The efficiency of an evacuation depends on the continuity of the flow between three restrictions, viz. the horizontal passages, doors and stairs. Hence, the main condition for the free flow is the equivalence of flow capacities on the successive parts of the escape route:

$$Q_i = Q_{i+1} \tag{16}$$

If the value of the specific flow q exceeds the maximum, the flow density increases according Predtechenskii and Milinski to a maximum value, which in effect leads to queuing at the boundary to the route i+1. At this stage, the flow consists of two parts, viz. of a group of persons with the maximum flow concentration who has already arrived at the critical section of the escape route, and the rest of the evacuees approaching by a higher velocity and a density less than D_{max}. In this case the rate of congestion is given by the following equation:

$$v''_{STAU} = (q_{Dmax}\ b_{i+1} / b_i - q_i)/(D_{max} - D_i) \tag{17}$$

q_{Dmax} is the specific flow at the maximum density;
b_{i+1} is the width of the congested flow;
b_i is the initial width of the flow;
q_i is the initial value of the specific flow; and
D_i is the initial flow density.

After the last person moving at the higher velocity reaches the end of the queue, the congestion diminishes at

$$v_{STAU} = v_{Dmax}\ b_{i+1} / b_i \tag{18}$$

where v_{Dmax} is the flow velocity at the maximum density.

This calculation method has been mainly applied by Predtechenskii and Milinski to the evacuation of auditoriums and halls.

A MODEL FOR THE EVACUATION OF MULTI-STOREY BUILDINGS VIA STAIRCASES

Kendik (32)-(35) developed an egress model based on the above work. This has been calibrated against the data from the evacuation tests carried out by the Forschungsstelle für Brandschutztechnik at the University of Karlsruhe. (36) If the following simplifications

1. The length l of the partial flow built up by the occupants of each floor (defined between the first and the last persons of the flow) is assumed to be equivalent to the greatest travel distance along the corridor;
2. The number of persons as well as the escape route configurations are identical on each storey; and
3. Each partial flow attempts to evacuate simultaneously, and enters the staircase at the same instant.

are introduced into the general mode the flow movement via staircases shows some regularities:

1. If the evacuation time on the corridor of each floor, t_F, is less than the evacuation time on the stairs per floor, t_{TR}, then the partial flows from each floor can leave the building without interaction. In this case, the total evacuation time is given by the following equation:

$$t_{Ges} = t_F + n\ t_{TR} \qquad (19)$$

t_F is the evacuation time on the corridor of each floor;
n is the number of the upper floors; and
t_{TR} is the evacuation time on the stairs per floor.

2. If the evacuation time on the corridor of each floor, t_F exceeds the evacuation time on the stairs per floor, t_{TR}, then the partial flows from each floor encounter the rest of the evacuees entering the staircase on the landing of the storey below. Even though this event causes the increase of density on the stairs, the capacity of the main flow remains under the maximum value, Q_{max}, which indicates, that the stair width is still appropriate to take up the merged flow, i.e. if

$t_F > t_{TR}$, and

$$q_{TR;n-1} = (Q_{T;n-1} + Q_{TR}) / b_{TR} < q_{TR;max} \qquad (20)$$

where

$q_{TR;n-1}$ is the value of the specific flow on the stairs after the merging process,
$Q_{T;n-1}$ is the flow capacity through the door to the staircase on each floor,
Q_{TR} is the initial flow capacity on the stairs, and
$q_{TR;max}$ is the maximum flow capacity on the stairs,

then the total evacuation time is given by

$$t_{Ges} = t_F + n\ t_{TR} + m\ dt \qquad (21)$$

where the last term of the equation relates the delay time of the last person from the top floor. The factor m is the number of patterns of higher density, which reduces during the course of the evacuation process. m can be assessed by an iteration.

3. If the value of the specific flow on the stairs exceeds the maximum during the merging of the partial flows at the storey (n-1) congestion occurs on stairs as well as at the entry to the staircase. In this case, the total evacuation time of a multi-storey building is determined by the following equation:

$$t_{Ges} = t_{TR;STAU} + (n-1)(l_{TR}/v_{TR;n-1}) + (n-2)\ dt \qquad (22)$$

$t_{TR;STAU}$ is the length of time required for the flow to leave the floor level (n-1);
l_{TR} is the travel distance on the stairs between adjoining storeys;
$v_{TR;n-1}$ is the velocity of the flow emanating from the con-

gested area at the floor level (n-1);
dt is the delay time due to congestion; and
n is the number of the upper floors in the building.

The total evacuation time t_{Ges} is influenced in a non-linear fashion by the projected area factor (or the density increase).

The above results follow from the three simple situations described earlier. Recently, Kendik prepared a computer program in Basic language for a HP 150 personel computer based on the described egress model. The program enables the user to change the dimensions of the building's means of egress and the occupant load easily and work out the influence of the variation on the complete circulation system.

Kendik's egress model addresses the time sequence from when people start to evacuate the floors until they finally reach the outside or an approved refuge area in the building within the available safe egress time. Hence, it doesn't consider the time prior to their becoming aware of the fire nor their decision-making processes. But, it can cope with the problem of the potential congestion on stairs and through exits including the interdependencies between adjacent egress way elements, which appear to be a major problem, especially in case of high population densities.

The method differs from other egress models mainly in its flexibility in predicting the variation of the physical flow parameters during the course of the movement. In this it does not assign fixed values to the flow density or velocity for each individual or seperate groups but considers them to be a single group of a certain mean density on each section of the escape route.

A QUANTITATIVE COMPARISON OF NATIONAL CODE REQUIREMENTS ON MEANS OF EGRESS

As already mentioned elsewhere in this paper the regulatory requirements covering the exit geometry in several countries involve explicitly or implicitly the unit exit width concept accompanied by other criteria such as travel distances, occupant load, total number of occupancy, dead ends or maximum floor area. At the present moment only the building codes in Soviet Union (37) require a mathematical proof for the width of escape routes in buildings where the travel distance to one exit is more than 25 metres and the occupancy per floor using an exit exceeds 50 persons. The building codes in the Soviet Union as well as the new building codes in East Germany (38) use the flow model of Predtechenskii and Milinski under free flow conditions.

The building codes selected for inclusion in this study have been the Greater London Council Code of Practice (19), NFPA 101 New Business Occupancies (15), the German Building Codes for High-rise Buildings and Assembly Occupancies, the Japanese Design Guideline for Building Fire Safety (from ref.22), the Russian Building Codes (37) and the Building Codes for Vienna (41). The requirements in these codes have been compered with the predictions of the egress model developed by Kendik based on the data after Predtechenskii.

An example from an earlier paper (42) illustrates how the calculation method have been employed for this purpose:

According to the National Fire Codes (101-316, Chapter 26) the capacity of stairs, outside stairs and smokeproof towers for new business occupancies has to be one unit for 60 persons. (120 persons per 1.12 m). Furthermore, it is written that "for purposes of determining required exits, the occupant load of business buildings or parts of buildings used for business purposes shall be no less than one person per 100 sq ft (9.29 sqm (sic)) of gross floor area and the travel distance to exits, measured in accordance with Section 5-6, shall be no more than 200 ft (60.96 m (sic)). Not less than two exits shall be accessible from every part of every floor". After Section 5-6.1 the maximum travel distance in any occupied space to at least one exit, shall not exceed the limits specified for individual occupancies, in this case 200 ft.

These provisions might permit one to design a multi-storey office building of roughly 2400 sq m per floor with two remote exits each with a width of two units and circa 240 occupants per floor.

Assuming the stairs to be used at capacity levels and the widths of all exits (doors and stairs) as well as the escape routes leading to the staircases to be identical, the described flow model predicts for new business occupancies, that the last person from a floor enters the staircase after 2.15 min under congested flow conditions. The number of persons moving in the overcrowded flow would be 37. This means that a protected lobby of at least 10.5 m2 (37 x 0.28 m2) or two staircases with a width of 1.20 m were necessary to accomodate 120 persons per floor. In the latter case the exiting time of the last person from a storey would be 1 min. Without interaction of flows a staircase with a width of 1.12 m (2 units) would be able to accomodate 35 persons per floor. In this case the egress time from a floor would be about 0.4 min.

Time is an important criterion for the flexible and cost effective design of escape routes. Figure 1 illustrates the comparison of the calculated stair capacities with the requirements of various building codes on means of escape. Here, the calculated number of persons per floor are predicted under the assumption that the egress time from a floor will be 1 min. The horizontal axis gives the number of persons a staircase with a certain width would accommodate required in various codes, while the vertical axis are the predicted figures. It is interesting to notice, that most of the investigated code provisions relating stair capacity lie under the reference line. This might indicate, that the requirements of the existing codes imply floor evacuation times greater than 1 min. (In one case up to 5 min, ref.19).

The correlation between the reference line and required number of persons in regulations would change in accordance with the egress time from a floor. Namely, if the available time for all occupants to evacuate one floor is expected to be about 2 min for the above example the required stair capacity would suffice to accomodate the given occupancy. If the available evacuation time is expected to be 3 min the required stairs widths are likely overestimated for the given occupancy.

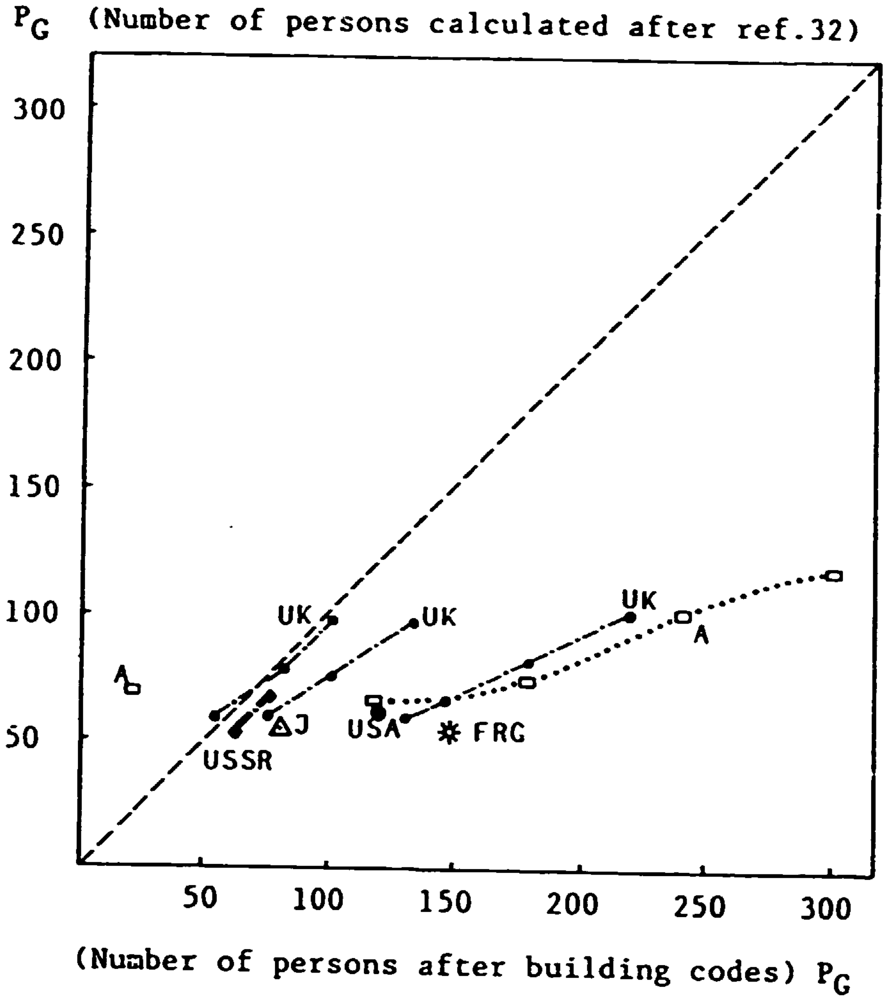

FIGURE 1. Graphical representation of the calculated stair capacity against requirements of building codes on means of escape.

CONCLUSIONS

Recently, there has been considerable activity in modelling egress from buildings. The numerous methods available are basicly either behaviour or movement models. All of them appear to make several assumptions, partly to overcome the gaps in the technical literature, which makes their validation against real-world events or fire drills necessary. In fact, only a few of these models are calibrated in this manner and able to provide quantitative results.

The physical structure of a building is apparently an elementary determinant of its occupants' behavioural responses and actions to the changing environmental conditions in terms of time. The time needed to reach a place of safety inside or outside the building might strech from the time people need to escape by their own unaided efforts, as very often stated or implied in most of the national fire codes, until the time handicapped as well as non-handicapped persons need to be rescued. Hence, the critical nature of time requires an analysis that enables the designers to select an appropriate egress system and to estimate the escape facilities by exploiting performance-oriented calculation methods.

This paper also provided a quantitative comparison of the predictions of a selected flow model with the requirements of various codes that do not employ such methods but appear to be based on experience and judgment. In this way time should be regarded as a design component for means of escape in order to improve cost effectiveness and design flexibility.

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Annex II

DESIGNING ESCAPE ROUTES IN BUILDINGS

EZEL KENDIK

ABSTRACT

This paper discusses a design method for calculating pedestrian movement developed by Predtechenskii and Milinski and provides an egress model based upon this work for the evacuation of multistorey buildings via staircases with regard to real evacuation tests in high-rise office buildings. Furthermore, it briefly compares its predictions with regulatory requirements on means of escape.

INTRODUCTION

During the last twenty years a number of experimentally based design methods for calculating the movement of people in buildings have been developed. (1), (2), (3), (4), (5), (6), (7), (8) Among these, extensive research work relevant to the egress from buildings has been made by Predtechenskii and Milinski, whose eloborate mathematical model developed from this data has been applied to buildings and building codes in several eastern european countries and in USSR. (9)

DESCRIPTION OF THE METHOD OF PREDTECHENSKII AND MILINSKI

The calculation method of Predtechenskii and Milinski is a deterministic flow model, which predicts the movement of an egressing population on a horizontal or a sloping escape route instantaneously in terms of its density and velocity.

The following equation relating the ratio between the sum of the persons' perpendicular projected areas and the available floor area for the flow, estimates the flow density homogeneously over the area of an escape route:

$$D = P \; f \,/\, b \; l \qquad (1)$$

where
P is the number of persons in the flow,
f is the perpendicular projected area of a person,
b is the flow width, which is identical with the width of the escape route, and
l is the flow length.
Note D has no dimensions.

In the literature, the mean concentration or the density of flow is very often defined as the number of persons per unit area and sometimes the reciprocal has been used. (10) These definitions are based on the implicit assumption, that the physical dimensions of the human frame are identical for all people or the differences might be negligable.

The values for the perpendicular projected areas of persons of different age groups are given in Table 1 and Table 2.

In Table 2 the mean values for the perpendicular projected areas of persons by means of anthropometric measurements of a randomly selected austrian group of people of different ages are represented. (11)

There, by using an artificial sun, which provided parallel rays of light, and a mirror arrangement set up with an angle of 45° the body frames of the test persons have been projected to the floor, drawn and planimetred. Thus in all, approximately 600 drawings of different test persons in standing position with and without wearing coats and by making a step have been evaluated.

The results from the statistical analysis of the Austrian measurements do not comply with the Russian data, given in Table 1. This might indicate, that the projected area per person (projected area factor), f, also varies in terms of population.

The egress populatian passing a definite cross section on an escape route of the width of b, is referred to as flow capacity.

$$Q = D \quad v \quad b \qquad m^2 \, min^{-1} \qquad (2)$$

Here, v is the flow velocity.

Predtechenskii and Milinski define the flow velocity on horizontal escape routes, through doors and on the stairs in terms of the flow density, given in the eqn.1.

$$v = f(D) \qquad (3)$$

Being a steady state expression, eqn.1 implies that the flow density remains constant provided neither the escape route configurations nor the flow outlines change. Theoretically, the density distribution of an infinite flow may change during the lateral displacement of the crowd. Namely, the density increase escalates in the direction of the flow, as the persons running into the part of the flow with increased density are moving faster. Inversely, the density diminution in the course of flow leads to decomposition of the flow into seperate parts of distinct densities. Hence, a correction term, which is proportional to the density increase, should be added to the eqn.3:

$$v = f(D) - c(dD/dx) \qquad c>0 \qquad (4)$$

This approach has been applied to a computer simulation model for the emergency evacuation of buildings on the data basis of Predtechenskii and Milinski. (12) A sensitivity analysis of this model by changing the projected area factor did not produce the expected variation in the evacuation time. (11) The model predicted higher evacuation times for the tested building, as the value of the projected area factor (inherently, the flow density) was decreased.

On the other hand, observations of crowd movement with limited flow lengths as in the case of egress from buildings do not corroborate the above mentioned considerations, which might indicate that the eqn.1 provides sufficient proximity for the determination of flow density on escape routes in buildings, but obviously, further research is needed on this subject.

Predtechenskii and Milinski measured the flow density and velocity in different types of buildings under normal environmental conditions. Their observations indicated, that the flow velocity shows a wide variation, especially in the range of lower densities. Hence, they assumed the values of the flow velocity and capacity above the mean walking speeds and capacities under normal environmental conditions to be analogous to the pedestrian parameters in emergency. Therefore, three movement levels have been defined:

1. Normal flow conditions,
2. Comfortable flow conditions, and
3. Emergency flow conditions.

The mean values of velocity under comfortable flow conditions have been estimated from the lower range of the measured walking speeds and for emergency flow conditions from the upper range of the measured values. Fig.1 shows the comparison of the evacuees' speed down stairs in terms of the density, given by J.Fruin (10), J.Pauls (6) and Predtechenskii and Milinski (5).

Another important flow parameter is the flow capacity per metre of escape route width, which is defined as the specific flow:

$$q = D \; v \qquad \text{m min}^{-1} \qquad (5)$$

The specific flow is a function of density. It increases over an interval and after passing an absolute maximum (q_{max}), it decreases again. The value of q_{max} is different for distinct kinds of escape routes. Fig.2 illustrates the variation of the specific flow in terms of the density.

The efficiency of an evacuation depends on the continuity of the flow between three restrictions, viz. the horizontal passages, doors and stairs. Hence, the main condition for the free flow is the equivalence of flow capacities on the successive parts of the escape route:

$$Q_i = Q_{i+1}$$

or from the equations (2) and (5) (6)

$$q_i \; b_i = q_{i+1} \; b_{i+1} \qquad (7)$$

Fig.3 illustrates a scheme for the merging of three partial flows coming from different directions.(from ref.5) In this case, the condition of the free flow can be described as follows:

$$Q_{i;1} + Q_{i;2} + Q_{i;3} = Q_{i+1}$$

or

$$q_{i+1} = Q(I) \, / \, b_{i+1} \qquad (8)$$

where
Q(I) is the sum of the capacities of all partial flows.

If the value of the specific flow q_{i+1} exceeds the maximum, i.e.

$$q_{i+1} > q_{max}$$

the flow density increases spontaneously to its maximum value, (D_{max} = 0.92) , which leads to queuing at the boundary to the main route i+1.

Due to this congestion, not all persons may attempt to participate in the merging process simultaneously. It is presumed, that the contribution of the partial flows to the main flow is proportional to their capacity Q. The percentage of the contribution of each flow to the main flow can be obtained from the ratio between the width of each partial flow and the sum of the widths of all partial flows:

$$p_1 = b_{1;i} / B_i$$
$$p_2 = b_{2;i} / B_i$$
$$p_n = b_{n;i} / B_i \qquad (9)$$

where
B_i is the sum of the widths of all partial flows.

If during the merging process of the partial flows the specific flow q_{i+1} do not exceed the maximum value, i.e.

$$q_{i+1} < q_{max}$$

no congestion occurs on escape routes.

Observations of crowd movement under normal environmental conditions show that during the merging of two flows with distinct density and velocity, the movement parameters of the incoming flow will be changed by adjusting its density and speed to the parameters of the uptaking flow. According to the context a boundary will be formed between the flows with the parameters D_i ; q_i and D_{i+1} ; q_{i+1} and its location changes at the following speed:

If $v_i < v_{i+1}$, then

$$v'' = q_i - q_{i+1} / D_i - D_{i+1} \qquad (10)$$

If $v_i > v_{i+1}$, then

$$v'' = q_{i+1} - q_i / D_{i+1} - D_i \qquad (11)$$

A graphical representation of this process is shown in Fig.4. The merging of flows terminates at point (C) on the graph.

One may consider this phenomenon to be appropriate also for emergency evacuations,where groups of persons having initially different flow densities and velocities, but a common purpose, viz. leaving the building, try to reach people moving ahead, seeking for contact, information, etc.

The formation of a congested flow (queuing) is an analogous process. If

$$Q_i > Q_{i+1}$$

queuing begins at the boundary between the passages of distinct flow capacities. At the beginning of congestion the flow consists of two parts, viz. of a group of persons with the maximum flow concentration ($D_{max} = 0.92$), who have already arrived at the critical section of the escape route, and the rest of the evacuees approaching by a higher velocity and a density less than Dmax. In this case the rate of congestion is given by the following equation:

$$v''_{STAU} = (q_{Dmax} \; b_{i+1} / b_i - q_i) / (D_{max} - D_i) \qquad (12)$$

where

q_{Dmax} is the specific flow at the maximum density,
b_{i+1} is the width of the congested flow,
b_i is the initial width of the flow,
q_i is the initial value of the specific flow, and
D_i is the initial flow density.

After the last person moving at the higher velocity reaches the end of the queue, the congestion diminishes at the following rate:

$$v_{STAU} = v_{Dmax} \; b_{i+1} / b_i \qquad (13)$$

v_{Dmax} is the flow velocity at the maximum density.

This calculation method, of which the basic considerations have been summarized above, has been mainly applied by Predtechenskii and Milinski to the evacuation of auditoriums and halls. The next section deals with the calibration of the method and its application to multi-storey buildings and provides an illustrative example.

AN EGRESS MODEL FOR THE EVACUATION OF MULTI-STOREY BUILDINGS VIA STAIRCASES

This section is partly taken from an earlier paper, viz. "Determination of the Evacuation Time Pertinent to the Projected Area Factor in the Event of Total Evacuation of High-Rise Office Buildings via Staircases". (13) The aim of this work was the calibration of the russian method with regard to real evacuation tests, (19), carried out by the Forschungsstelle für Brandschutztechnik at the University of Karlsruhe in Germany, while setting up an egress model for the prediction of flow movement in multi-storey buildings. For this purpose, the total evacuation times in three high-rise office buildings have been estimated in terms of the projected area factor and compared with the measured evacuation times during the above mentioned tests.

	t_{Ges}	n	P_{TR}	P_G	b_{TR}
Building A	8.78 min	23	427	19	1.20 m
Building B	10.48 min	22	567	26	1.25 m
Building C	10.47 min	32	502	16	1.25 m

where

t_{Ges} is the measured evacuation time after ref. (19),
n is the number of upper floors,
P_{TR} is the number of the evacuees via the observed staircase,
P_G is the number of persons per floor, and
b_{TR} is the stair width.

If the following simplifications

1. The length of the partial flow built up by the occupants of each floor (defined between the first and the last persons of the flow) is assumed to be equivalent to the greatest travel distance along the corridor;
2. The number of persons as well as the escape route configurations are identical on each storey; and
3. Each partial flow attempts to evacuate simultaneously, and enters the staircase at the same instant.

are introduced into the general mode the flow movement via staircases shows some regularities:

1. If the evacuation time on the corridor of each floor, t_F, is less than the evacuation time on the stairs per floor, t_{TR}, then the partial flows from each floor can leave the building without interaction. (Fig .5) In this case, the total evacuation time is given by the following equation:

$$t_{Ges} = t_F + n \; t_{TR} \tag{14}$$

where
t_F is the evacuation time on the corridor of each floor,
n is the number of the upper floors, and
t_{TR} is the evacuation time on the stairs per floor.

2. If the evacuation time on the corridor of each floor, t_F exceeds the evacuation time on the stairs per floor, t_{TR}, then the partial flows from each floor encounter the rest of the evacuees entering the staircase on the landing of the storey below. Even though this event causes the increase of density on the stairs, the capacity of the main flow remains under the maximum value, Q_{max}, which indicates, that the stair width is still appropriate to take up the merged flow, i.e. if

$t_F > t_{TR}$, and

$$q_{TR;n-1} = (Q_{T;n-1} + Q_{TR}) / b_{TR} < q_{TR;max} \tag{15}$$

where
$q_{TR;n-1}$ is the value of the specific flow on the stairs after the merging process,
$Q_{T;n-1}$ is the flow capacity through the door to the staircase on each floor,
Q_{TR} is the initial flow capacity on the stairs, and
$q_{TR;max}$ is the maximum flow capacity on the stairs,

then the total evacuation time is given by

$$t_{Ges} = t_F + r. \; t_{TR} + m \; dt \tag{16}$$

where the last term of the equation relates the delay time of the last person from the top floor. The factor m is the number of patterns of higher density, which reduces during the course of the evacuation process. (These are the areas between the dashed lines on the Fig.6. The dashed lines are representing the boundaries between the population of distinct flow parameters.) m can be assessed by an iteration.

dt (delay time) is given by the following equation:

$$dt = v'' (t_F - t_{TR}) (v_{TR;n} - v_{TR;n-1}) / (v_{TR;n-1} - v'') v_{TR;n} \qquad (17)$$

where

t_F is the travel time of the last evacuee along the corridor,

t_{TR} is the travel time of a person from the top floor on the stairs, in order to arrive at the adjoining storey,

v'' is the velocity, by which the boundary between the initial flow on the stairs with the parameters $D_{TR;n}$ and $q_{TR;n}$ and the merged flow with the parameters $D_{TR;n-1}$ and $q_{TR;n-1}$ changes its location,

$v_{TR;n}$ is the velocity of the flow at the density $D_{TR;n}$, and

$v_{TR;n-1}$ is the velocity of the flow on the stairs at the density $D_{TR;n-1}$.

3. If the value of the specific flow on the stairs exceeds the maximum during the merging of the partial flows at the storey n-1 congestion occurs on the stairs as well as at the entry to the staircase. In this case

$$q_{TR;n-1} = (Q_{T;n-1} + Q_{TR}) / b_{TR} \quad > q_{max} \qquad (18)$$

where

$q_{TR;n-1}$ is the value of the specific flow on the stairs after the merging process,

$Q_{T;n-1}$ is the flow capacity through the door to the staircase on each floor,

$Q_{TR;n}$ is the initial flow capacity on the stairs,

b_{TR} is the stair width, and

$q_{TR;max}$ is the maximum flow capacity on the stairs.

From the eqn.7 the percentage of the contribution of each partial flow to the main flow can be obtained as follows:

$$p_T = b_T / b_T + b_{TR} \qquad (19)$$

$$p_{TR} = b_{TR} / b_T + b_{TR} \qquad (20)$$

where

b_T is the width of the door to the staircase, and

b_{TR} is the stair width.

In order to determine the new widths of the partial flows on the stairs the main width of the flow, b_{TR}, is multiplied by the above fractions.

$$b_{T1} = p_T \; b_{TR} \qquad (21)$$

$$b_{TR1} = p_{TR} \; b_{TR} \qquad (22)$$

Due to the congestion on the stairs, the evacuees from the floors cannot enter the staircase immediately. Queuing occurs at the floor exit and the partial flow on the corridor extends backwards at a speed of

$$v''_{T;STAU} = (q_{T;Dmax}\, b_{T1}/b_T) - q_T \Big/ D_{max} - D_T \tag{23}$$

where

$v''_{T;STAU}$	is the speed of congestion on the corridor,
$q_{T;Dmax}$	is the specific flow at the maximum density through doorways
b_{T1}	is the width of the partial flow from each floor in the main flow on the stairs,
b_T	is the door width to the staircase (or the width of flow from each floor under free flow conditions),
q_T	is the specific flow through the door to the staircase under free flow conditions on the stairs,
D_{max}	is the maximum flow density, and
D_T	is the density through the door to the staircase without congestion on the stairs.

After the last person of the flow on the corridor reaches the queue at the entry to the staircase, the congestion diminishes at the following speed:

$$v_{T;STAU} = v_{T;Dmax}\ b_{T1} / b_{TR} \tag{24}$$

where

$v_{T;Dmax}$ is the velocity of a flow through a doorway at the maximum density.

The flow movement on the corridor ends at the instant $t_{F;STAU}$ indicated as F;STAU on the Fig.7. $t_{F;STAU}$ is the egress time from a storey.

From the beginning of the merging process of the partial flows until the end of queuing at the exit door to the stairway, congestion also occurs on the stairs. Due to this, the flow on the stairs extends backwards at a rate of

$$v''_{TR;STAU} = (q_{TR;Dmax}\, b_{TR1} / b_{TR} - q_{TR;n}) \Big/ D_{max} - D_{TR;n-1} \tag{25}$$

where

$v''_{TR;STAU}$	is the speed of congestion on the stairs,
$q_{TR;Dmax}$	is the specific flow on the stairs at the maximum density,
b_{TR1}	is the width of the partial flow from the top floor n in the main flow on the stairs,
b_{TR}	is the stair width or the width of flow on the stairs under free flow conditions,
$q_{TR;n}$	is the specific flow on the stairs without congestion
D_{max}	is the maximum density, and
$D_{TR;n}$	is the flow density on the stairs without congestion, (or the density of the partial flow from the top floor.)

Here, two different situations may arise:

1. If $\quad t_F + t_{TR} > t_{F;STAU}$

viz. if the last person from the floor under the top most storey enters the staircase, before the last person from the top floor reaches the queue on the stairs, then the partial flow

from the top floor can use the total stair width after $t_{F;STAU}$ again. (Fig.7) In this case, the speed of congestion on the stairs changes as follows:

$$v''_{TR;STAU} = (q_{TR;Dmax} - q_{TR;n}) / (D_{max} - D_{TR;n}) \qquad (26)$$

After the last person from the top floor reaches the queue on the stairs, the congestion diminishes at the speed $v_{TR;Dmax}$, which corresponds to the flow velocity on the stairs at the maximum density.

2. If $t_F + t_{TR} < t_{F;STAU}$,

then the last person from the top floor reaches the queue on the stairs, before the last person from the storey below enters the staircase. In this case, the congestion on the stairs diminishes until $t_{F;STAU}$ at the following speed:

$$v_{TR;STAU} = v_{TR;Dmax}\, b_{TR1} / b_{TR} \qquad (27)$$

where

$v_{TR;STAU}$ is the flow velocity on the stairs at the maximum density,

b_{TR1} is the width of the partial flow from the top floor in the main flow,

b_{TR} is the stair width or the width of the flow from the top floor under uncongested flow conditions.

After the end of congestion at the entry to the staircase, the partial flow from the top floor can use the total width of the stair again. The movement process at the storey (n-1) is complete at the point indicated as TR;STAU on the graph.

The flow moving downstairs from the floor (n-1) consists of two different groups of people. The movement parameters of the part ahead are $q_{TR;n}$ and $v_{TR;n}$, which are the initial flow parameters. This group is followed by the evacuees emanating from the overcrowded area at the level (n-1) and moving by the specific flow $q_{TR;Dmax}$ but at a lower density than the maximum. (After Fig.1 there are two different density values corresponding to the specific flow at the maximum density, $q_{TR;Dmax}$.)

During the merging process of the people of both groups, the boundary between them changes its location at a speed of v", which can be determined by the following equation:

$$v'' = (q_{TR;Dmax} - q_{TR;n}) / (D_{TR;n-1} - D_{TR;n}) \qquad (28)$$

where

$q_{TR;Dmax}$ is the specific flow on the stairs at the maximum density,

$q_{TR;n}$ is the specific flow on the stairs at the beginning of the flow movement,

$D_{TR;n-1}$ is the density of the group of people emanating from the overcrowded area at the level (n-1), and

$D_{TR;n}$ is the initial flow density on the stairs.

Simultaneously, on the corridor of the storey (n-2) and on the stairs between the floors (n-1) and (n-2) the flow motion forms in a similar manner to the flow movement on the upper flows. There, the velocity of the flow queuing backwards on the stairs will be different, according to whether it reaches the above mentioned boundary before or after $t_{F;STAU}$. ($t_{F;STAU}$ is the egress time from a floor.)

If the end of the queue arrives at the boundary before $t_{F;STAU}$, then the rate of congestion is determined by eqn.(21).

Otherwise, the rate of congestion is predicted by the following equation:

$$v''_{TR;STAU} = (q_{TR,Dmax}\ b_{TR1}/b_{TR} - q_{TR;Dmax}$$

$$/\ D_{max} - D_{TR;n-1} \qquad (29)$$

It should be noted, that in this case, the value of the specific flow for both groups, i.e. for the incoming flow as well as for the uptaking flow, is the same.

After the last evacuee from the floor (n-2) enters the staircase, the length of the congested flow on the stairs remains constant, until the last person from the storey (n-1) reaches the queuing population on the stairs. Then the congestion diminishes at the rate $v_{TR;Dmax}$, which is the flow velocity at the maximum density. The flow movement at the storey (n-2) ends at the point $t_{TR;STAU}$ indicated as B on the graph.

If the last person from the floor (n-1) had reached the adjoining storey without any delay due to congestion, he/she would arrive there after the time t_1. The delay time due to congestion on escape routes (dt) , repeated at each floor level, is predicted by

$$dt = t''_{TR;STAU} - t_1 \qquad (30)$$

$t''_{TR;STAU}$ is the length of time required for the flow to leave the floor level (n-2).

In case of congestion on escape routes, the total evacuation time of a multi-storey building is determined by the following equation:

$$t_{Ges} = t_{TR;STAU} + (n-1)\ l_{TR}/v_{TR;n-1} + (n-2)\ dt \qquad (31)$$

where

$t_{TR;STAU}$	is the length of time required for the flow to leave the floor level (n-1),
l_{TR}	is the travel distance on the stairs between adjoining storeys,
$v_{TR;n-1}$	is the velocity of the flow emanating from the congested area at the floor level (n-1)
dt	is the delay time due to congestion, and
n	is the number of the upper floors in the building.

The total evacuation time t_{Ges} is influenced in a non-linear fashion by the projected area factor (or the density increase). Figure 8 illustrates the change in evacuation time in three high-rise administration buildings, plotted against the projected area factor, f and the number of persons per floor, P_G.

On the Figure 8, the curves (1), (2) and (3) have the following equations:

Building A (1) $t_{Ges} = 4.6334 \times 208.6954^{f}$ (32)

$r^2 = 0.99$

Building B (2) $t_{Ges} = 4.1981 \times 1441.4973^{f}$ (33)

$r^2=0.87$

Building C (3) $t_{Ges} = 6.3630 \times 74.1593^{f}$ (34)

$r^2=0.84$

By an average value of f=0.12 m2 per person, the equations (32), (33) and (34) predict the measured evacuation times, obtained from the real evacuation tests. In the Table 1, f=0.12 m2 corresponds to the value of the projected area of an adult wearing coats.

Within the range of experimental data underlying real evacuation tests and by using the average value of f=0.12-0.14 m2 per person, the predictions of the presented egress model are likely to provide an adequate basis for the assessment of flow movement on escape routes. The improvement of the model is certainly possible, but this would require additional specific data in terms of flow density.

OPTIMIZATION OF ESCAPE ROUTE DIMENSIONS

Fig. 9 shows the diagram of an office occupancy floor of one of the high-rise administration buildings where a real evacuation test was conducted.

This building consists of a ground floor, one mezzanine, twenty-one upper floors and two tower storeys. The height between two floors was measured as 3.60 m. The building is arranged around a triangular core with a staircase sited at each corner of the core layout. Each staircase is approached by a protected lobby with a length of 0.90 m. The continuous corridor leading to a staircase has a width of b_F= 1.87 m. The greatest travel distance along the corridor measured l_F= 29.40 m. The doorway opening between the corridor and the protected lobby, as well as the exit door to the staircase measures b_T= 0.82 m. Due to the triangular form of the ground plan the staircases are also arranged around a triangular pillar, with three flights between two floors. The width of the stairs is b_{TR}= 1.25 m. During the evacuation test 567 persons were evaucuated via the observed staircase. The average number of persons per floor was P_G= 26. (approximately 20 sqm / person) Although the building was apparently underoccupied the flow downstairs has been delayed for the first 3-4 min since the floor exit door was swinging into a protected lobby which had fairly inappropriate dimensions.

In this case, the model predicts the flow from the floors,through the protected lobby into a staircase and downstairs to the final access. Furthermore, it presumes that the evacuation have been already initiated and at the time 0 the first person of the partial flow on each floor passes through the doorway into the protected lobby.

By changing the number of persons per floor per staircase,the corridor width leading to the staircase or the width of the floor exits the described egress model predicts the following:

Table 1 An illustrative comparison for the optimization of flow for the assessment of optimum escape route dimensions

	I	II	III	IV
NUMBER OF PERSONS	26	40	40	40
CORRIDOR LENGTH m	29.4	29.4	29.4	29.4
CORRIDOR WIDTH m	1.87	1.87	1.25	1.25
DOOR WIDTH m	0.82	0.82	0.82	1.25
FLOW DENSITY ON THE CORRIDOR	0.07	0.10	0.15	0.15
FLOW VELOCITY ON THE CORRIDOR m/min	44.43	39.00	32.73	32.73
SPECIFIC FLOW ON THE CORRIDOR m/min	2.94	3.97	4.99	4.99
EGRESS TIME FROM THE TOP FLOOR min	0.69	0.80	0.93	0.93
INITIAL FLOW DENSITY STAIRS	0.10	0.16	0.12	0.12
SPEED OF CONGESTION AT THE FLOOR EXIT OF ANY UPPER FLOOR	-1.75	-6.76	-3.17	-0.63
MAX.LENGTH OF CONGESTION AT THE FLOOR EXIT m	0.71	2.48	1.87	0.41
EGRESS TIME FROM ANY UPPER FLOOR m/min	0.79	1.10	1.18	1.00
SPEED OF CONGESTION ON STAIRS m/min	-2.11	-4.31	-2.90	-3.48
MAX.LENGTH OF CONGESTION ON STAIRS m	1.11	2.57	2.23	2.59
TOTAL EVACUATION TIME VIA THIS STAIRCASE min	10.29	15.34	14.50	14.55
REAL EVACUATION TIME AFTER REF.8	10.47			

Given the data corresponding to the real evacuation test (column

I) the model predicts the total evacuation time to be 10.29 min which is fairly close to the measured time of 10.47 min. The floor egress time from an upper floor (except the top most and the ground floors) is estimated to be 0.79 min under congested flow conditions. The length of the congestion would be 0.71 m at the floor exit and 1.11 m on stairs.

By increasing the number of persons per floor per staircase from 26 to 40 the total evacuation time increases significantly.(15.34 min from column II)

By decreasing the corridor width from 1.87 m to 1.25 m the total evacuation time by 40 persons per floor per staircase is predicted to be 14.50 min which is less than the time estimated in the previous example, since due to higher density in the corridor less persons can enter the staircase in the same time period. Hence, the initial stair density on stairs and the speed of congestion decreases. (column III)

Widening the floor exit from 0.82 m to 1.25 m which corresponds to the stair width does not change the evacuation pattern significantly. In this case, the floor egress time decreases and leads to a greater congestion on stairs.(column IV)

For the predicted building the total length of the gangway on each floor is approximately 110 m. Decreasing the corridor width about 0.60 m would not threaten the flow movement. (The predictions show that the total evacuation time even slightly decreases. But, less corridor width would mean ca. 70 m2 additional space on each storey and ca.1540 m2 more rental area for the whole building corresponding to the area of one floor.

A COMPUTER PROGRAM FOR THE DESIGN AND EVALUATION OF ESCAPE ROUTES

Recently, the author wrote a computer program in Basic language for a Hewlett Packard 150 personal computer based on the described egress model. It is written as a dialogue between the user and the computer, where the escape route configurations (the width and the length of each section) as well as the number of occupants are put in gradually during the course of the computation. The program enables the user to change the dimensions of the building's means of escape and the occupant load easily and work out the influence of the variation on the complete circulation system.

COMPARISON WITH UNITED STATES REQUIREMENTS

It is interesting to compare the requirements of the National Fire Codes (14) with the predictions of the described egress model.

If fire occurs in a building, from the point of view of people movement the egress time from a storey, $t_{F,STAU}$, into a protected staircase or any other refuge area needs primarily to be considered.

According to the National Fire Codes (101-316, Chapter 26) the capacity of stairs, outside stairs and smokeproof towers for new business occupancies has to be one unit for 75 persons. (150 persons per 1.12 m). Furthermore, it is written that "for purposes of determining required exits, the occupant load of business buildings or parts of buildings used for business purposes shall be no less than one person per 100 sq feet (9.29 sqm) of gross floor area and the travel distance to exits, measured in accordance with section 5-6, shall be no more than 200 ft (60.96 sqm). Not less than two exits shall be accessible from every part of every floor". After section 5-6.1 the maximum travel distance in any occupied space to at least one exit, shall not exceed the limits specified for individual occupancies, in this case 200 ft.

These provisions might permit one to design a multi-storey office building of roughly 2800 sq m per floor with two remote exits each with a width of two units and circa 300 occupants per floor.

Assuming the stairs to be used at capacity levels and the widths of all exits (doors and stairs) as well as the escape routes leading to the staircases to be identical, the described flow model predicts for new business occupancies, that the last person from a floor enters the staircase after 2.73 min under congested flow conditions. The number of persons moving in the overcrowded flow would be 51. This means that a protected lobby of at least 14.28 m2 (51 x 0.28 m2) or two staircases with a width of 1.40 m were necessary to accomodate 150 persons per floor. In the latter case the exiting time of the last person from a storey would be 1 min. Without interaction of flows a staircase with a width of 1.12 m (2 units) would be able to accomodate 35 persons per floor. In this case the egress time from a floor would be about 0.4 min.

Time is an important criterion for the flexible and cost effective design of escape routes. Figure 10 illustrates the comparison of the calculated stair capacities with the requirements of various building codes on means of escape. Here, the calculated number of persons per floor are predicted under the assumption that the egress time from a floor will be 1 min. The horizontal axis gives the number of persons a staircase with a certain width would accommodate required in various codes, while the vertical axis are the predicted figures. It is interesting to notice, that most of the investigated code provisions relating stair capacity lie under the reference line. This might indicate, that the requirements of the existing codes imply floor evacuation times greater than 1 min. (In one case up to 5 min, ref.15).

The correlation between the reference line and required number of persons in regulations would change in accordance with the egress time from a floor. Namely, if the available time for all occupants to evacuate one floor is expected to be about 3 min for the above example the required stair capacity would suffice to accomodate the given occupancy. If the available evacuation time is expected to be 4 min the required stairs widths are likely overestimated for the given occupancy.

CONCLUDING REMARKS

The increasing complexity of buildings concerning functions, size and configurations require a broader attention to the planning of means of escape to ensure the evacuation of buildings in an emergency. In this way, the presented egress model provides a flexible predictive tool for the designers. The model estimates the movement of the building's occupants in terms of time and can cope with the problem of potential congestion on stairs and through exits with regard to the complete circulation system.

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APPENDIX

Table 1: Values for the projected area per person, f, after ref.(5)

	f in sq m
Children	0.04....0.06
Teen-agers	0.06....0.09
Adults in	
summer clothes	0.10
spring clothes	0.113
winter clothes	0.125
Adults in spring clothes and carrying	
a briefcase	0.18
a suitcase	0.24
two suitcases	0.39

Table 2 ANTHROPOMETRIC MEASUREMENTS OF AN AUSTRIAN GROUP OF PEOPLE (AFTER REF.11)

Age group	5 years	10-15 years			15-30 years			>30 years
Sex		w	m	all	w	m	all	all
A(Du);x	0.705	1.300	1.290	1.291	1.683	1.894	1.825	1.872
Standard deviation	0.171	0.175	0.203	0.208	0.115	0.379	0.334	0.252
f(N);x	0.0696	0.1092	0.1126	0.1113	0.1383	0.1484	0.1458	0.1740
Standard deviation	0.0078	0.0202	0.0174	0.0187	0.0172	0.0171	0.0172	0.0315
f(M);x	-	0.1453	0.1326	0.1386	0.1809	0.1892	0.1862	-
Standard deviation	-	0.0178	0.0191	0.0186	0.0213	0.0296	0.0272	-
f(S);x	-	0.1262	0.1221	0.1238	0.1508	0.1645	0.1600	0.1918
Standard deviation	-	0.0198	0.0170	0.0180	0.0163	0.0191	0.0193	0.0358

w	women
m	men
f(S);x	mean projected area per person by walking in m2
A(Du);x	DuBois-Area (mean value)
f(N);x	mean projected area per person in m2 standing and without coats
f(M);x	mean projected area per person in m2 standing and wearing coats

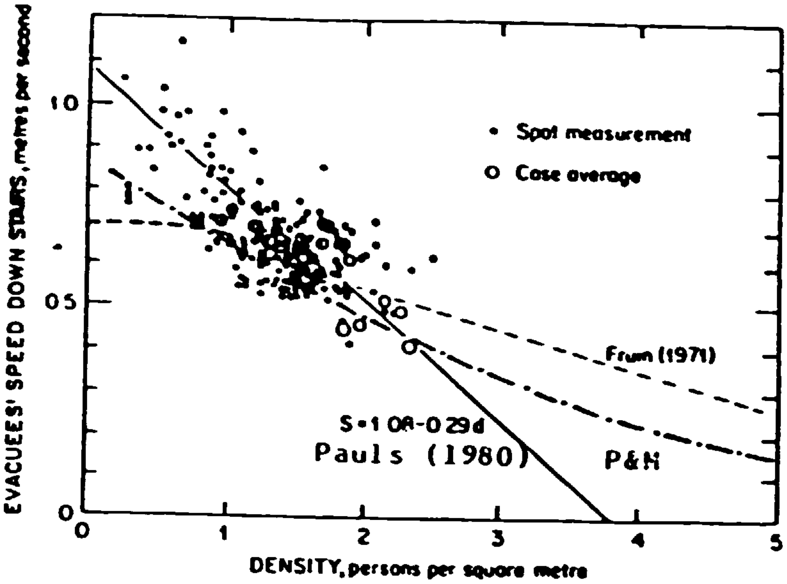


Fig. 1 Relation between speed and density on stairs

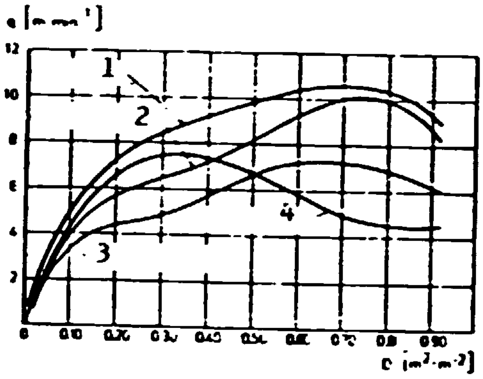
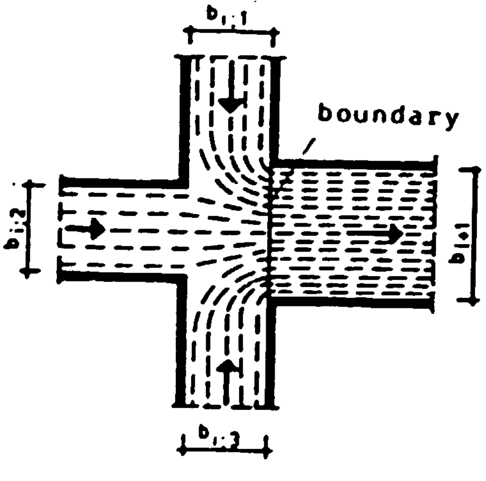


Fig. 2 Illustration of the specific flow pertinent to the flow density for different kinds of escape routes under normal environmental conditions (after ref. 5)
1 doorways
2 horizontal routes
3 stairs (upwards)
4 stairs (downwards)



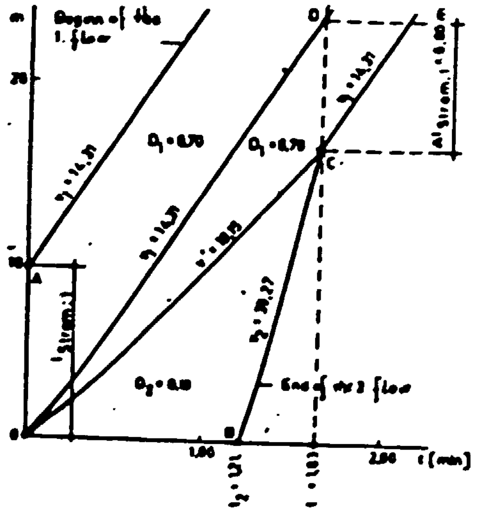


Fig. 3 Merging of flows

Fig. 4 Illustration of the merging process of flows

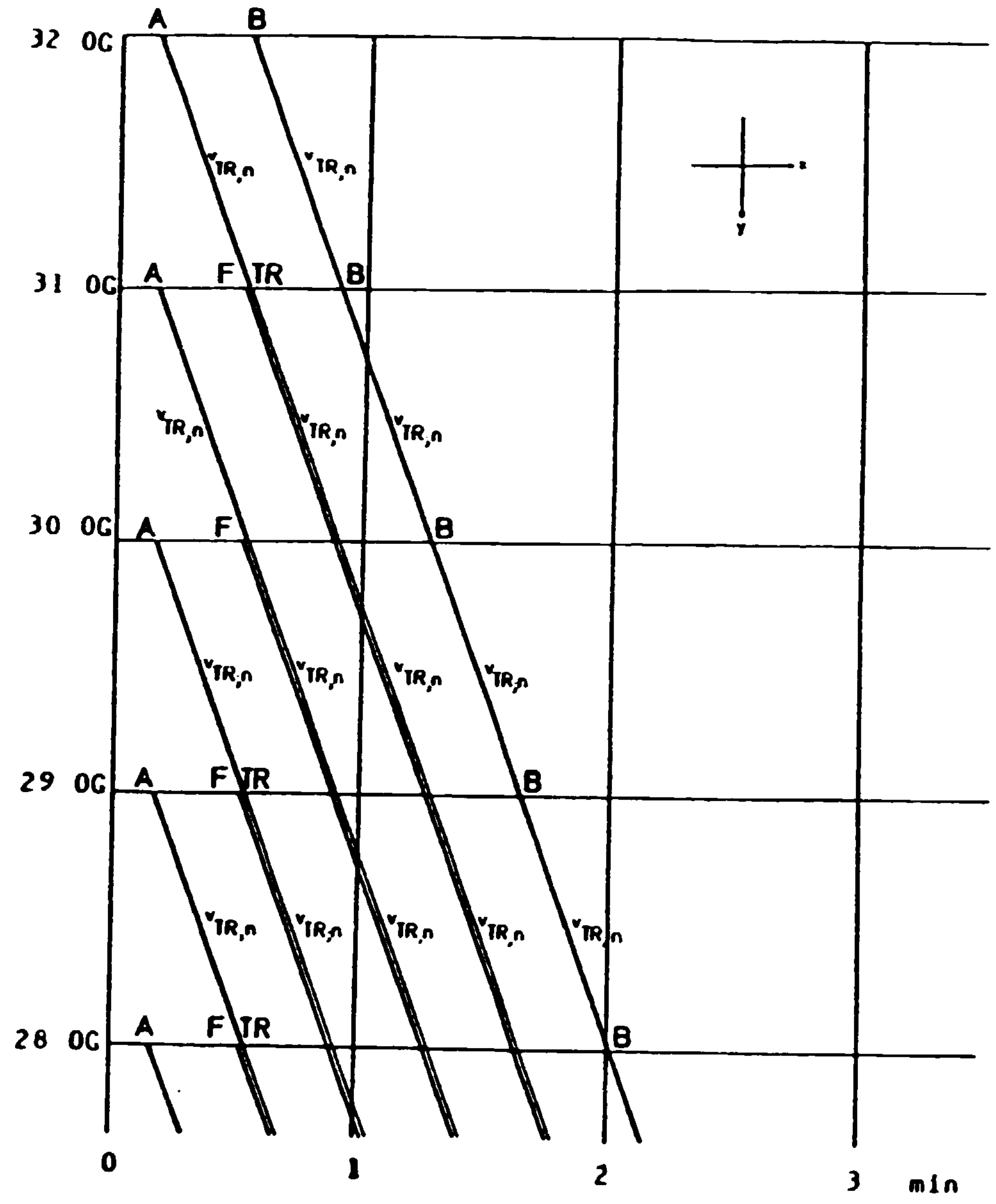


Figure 5 : Building C

Flow motion process calculated by f=0,18 m²/person. The partial flows move downstairs without interaction. Due to the brief delay in the protected lobby on each floor level a merger of the partial flows does not occur.

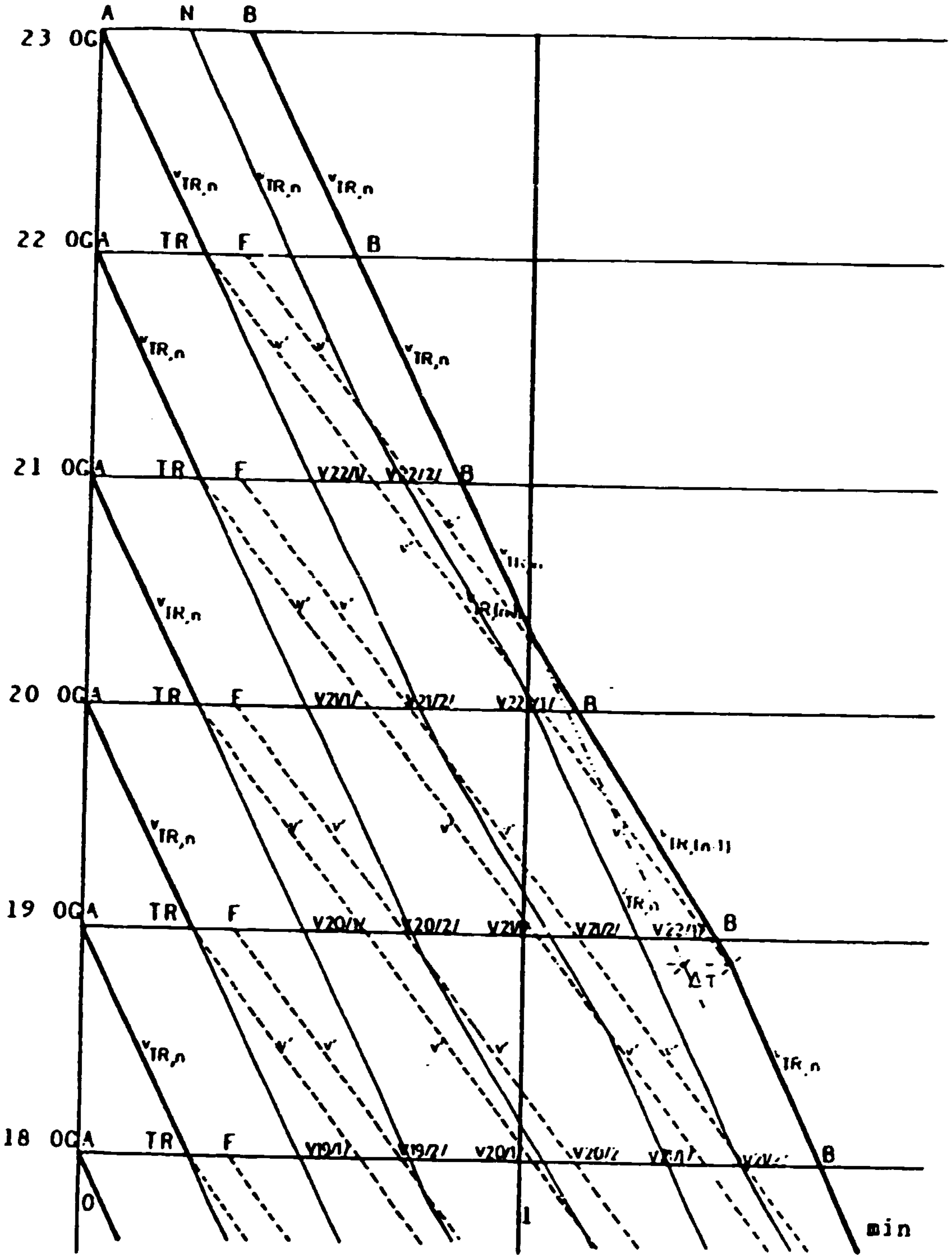


Figure 6 : Building A
Flow motion process calculated by $f = 0,07\ m^2$
The flow movement is delayed due to periodical increase of density on each floor level.

T_{Ges} = 6,67 min.

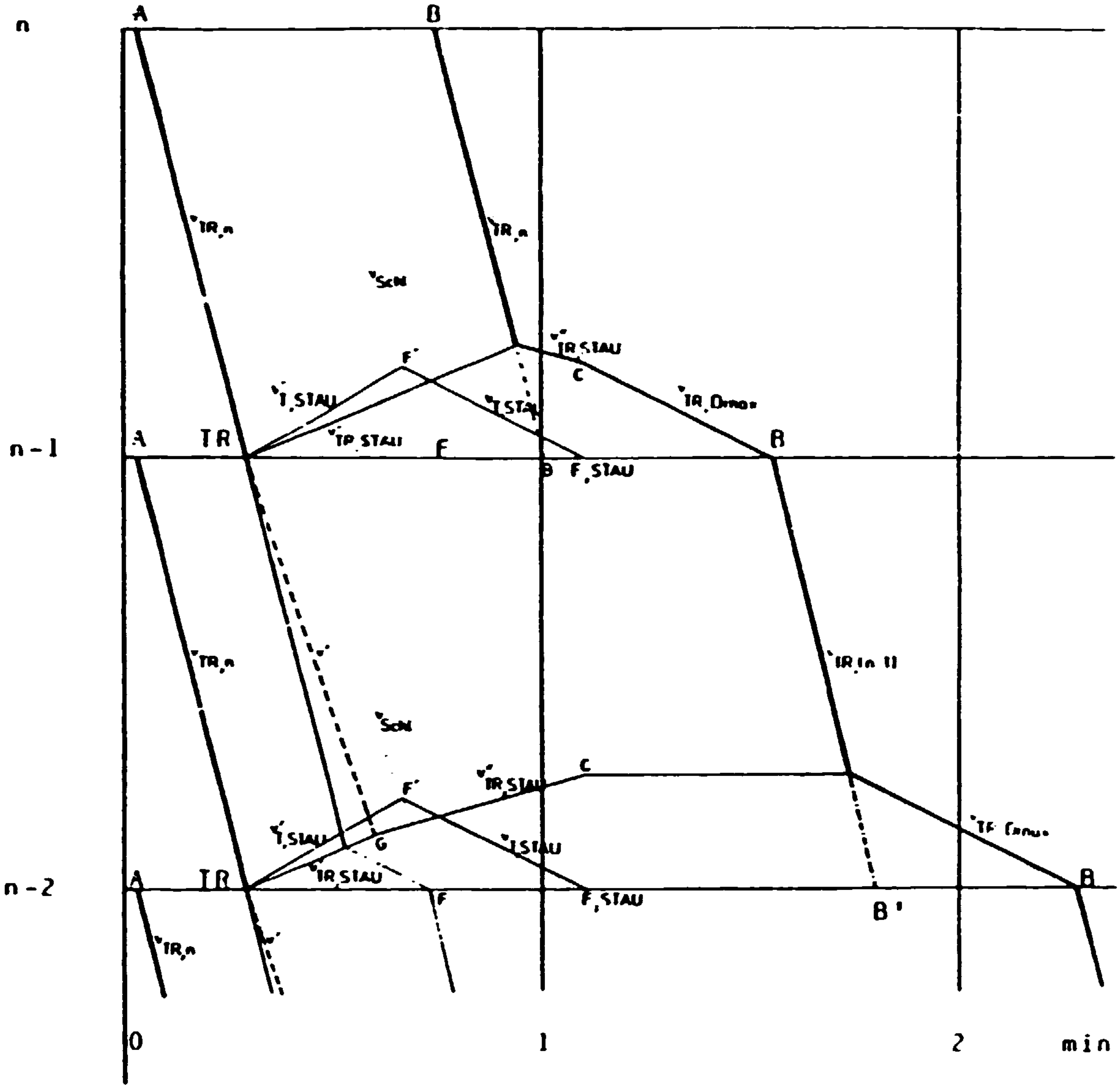


Figure 7 : Building B

Flow motion process calculated by $f = 0,18\ m^2$
The delay time due to congestion is $\Delta\tau = 0,49$ min repeating on each floor level. The protected lobby with a length less than 1 m does not influence the total evacuation time.

$\tau_{Ges} = 16,39$ min .

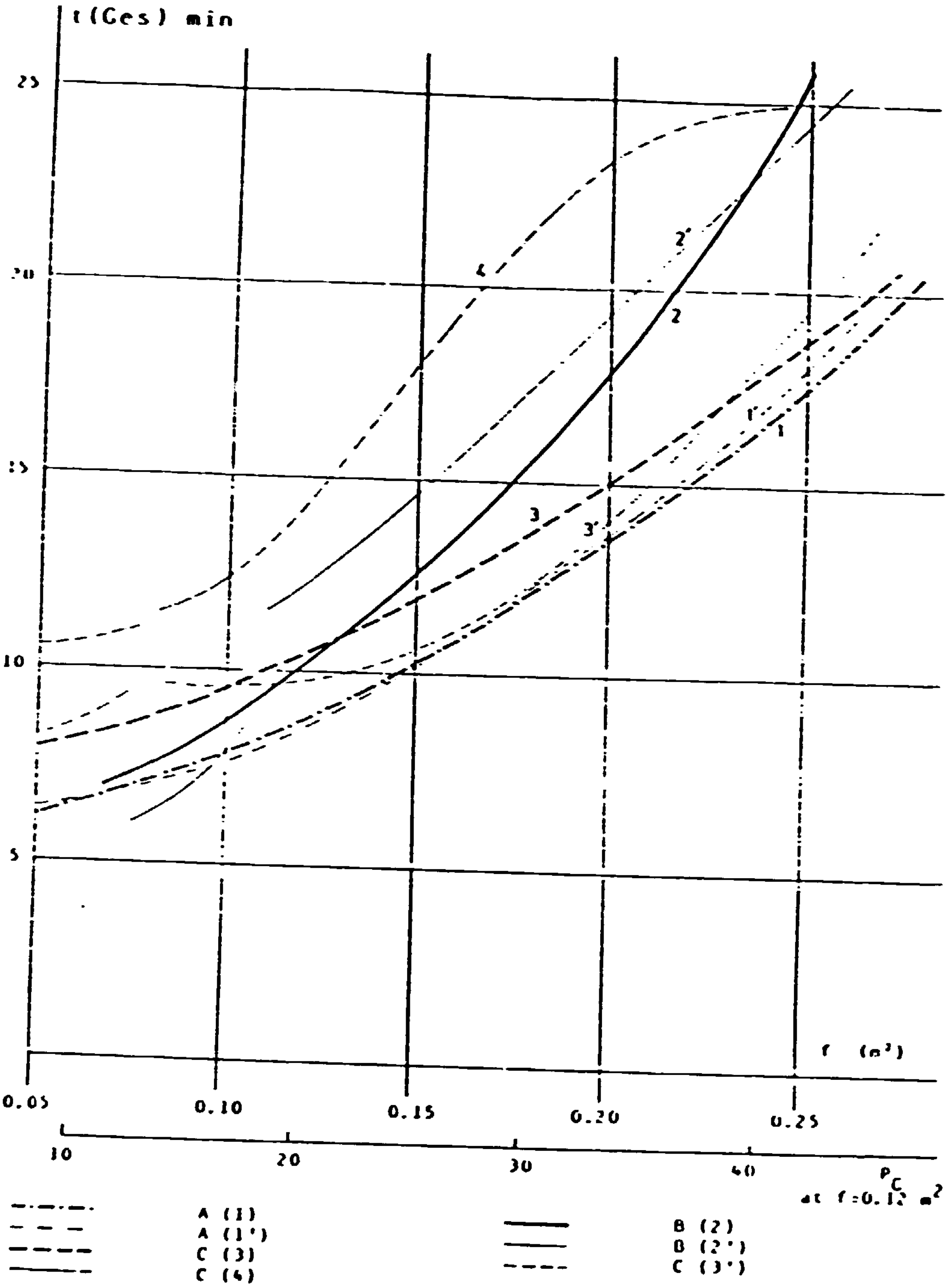


Fig.6 Graphical representation of the total evacuation time, t(Ges), in three high-rise office buildings in terms of the projected area factor f and the number of persons per floor P(C).

In case of the determination of the total evacuation time in terms of the number of persons per floor P(C) the projected area factor is assumed to stay constant at f=0.12 m².

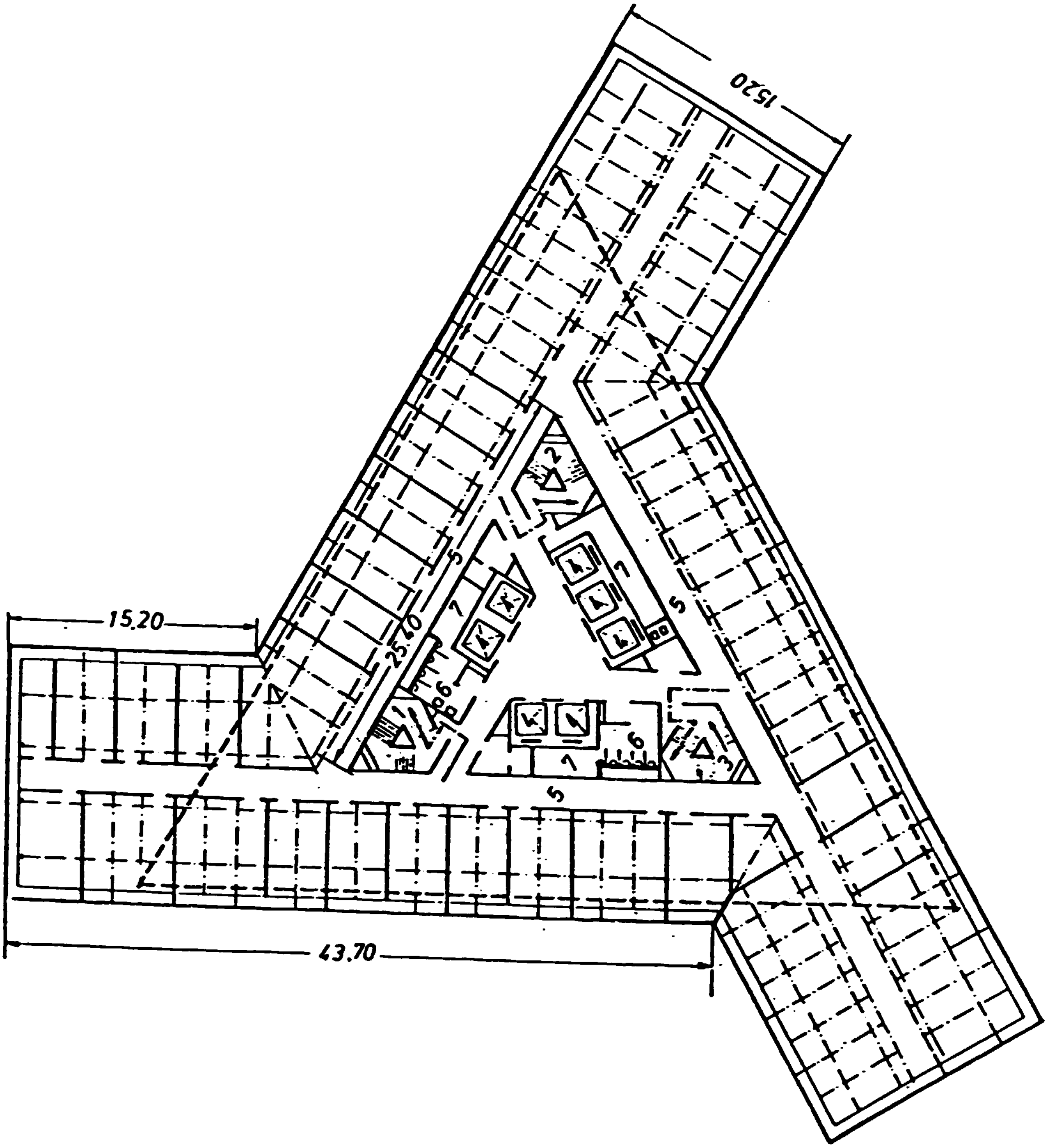


Fig. 9 Diagram of an office floor of the high-rise administration building B

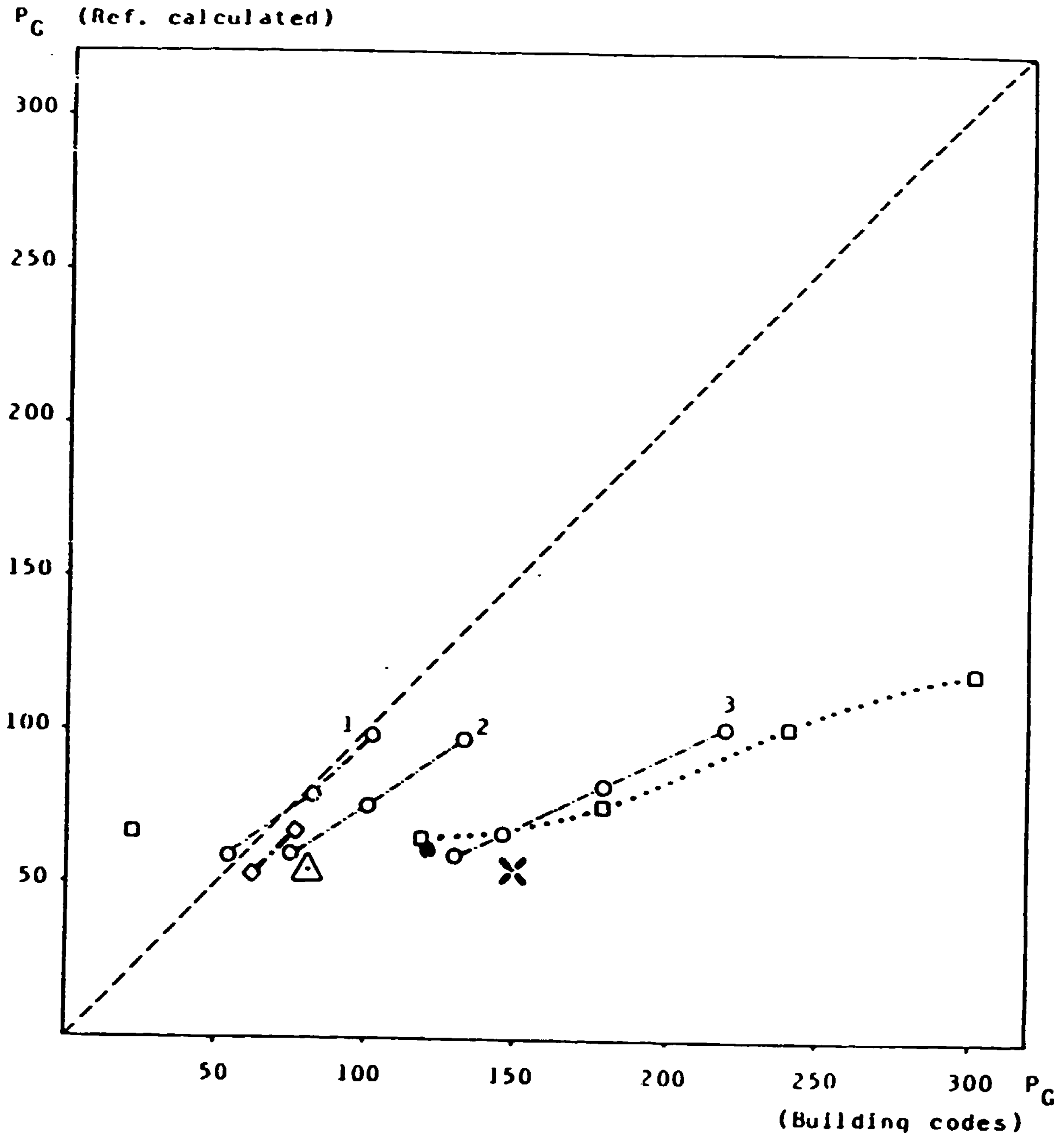


Fig. 10 Graphical representation of the calculated stair capacity against requirements of building codes on means of escape

P_G (Ref. calculated)	number of persons per floor under the assumption of an exiting time from a storey of 1 min
○—○ 1, 2, 3	British Standard BS 5588 (1983)[15] 1 10-storey buildings 2 5-storey buildings 3 2-storey buildings
□····□	Building Codes for Vienna (1976)[16]
✕	German Building Codes (1974)[17]
△	Japanenese Building Codes (1976)[18]
●	National Fire Codes, NFPA 101 - 316 (1981)[14]
◇—◇	Russian Building Codes (1950)[9]

Annex III

REGULATIONS FOR HIGH-RISE BUILDINGS (GERMANY)

These regulations apply to buildings greater than 22 m.

Fire brigade access not further than 15 m to appropriate entries of staircases, vertical hoses and water supply points shall be provided.

Loadbearing walls shall be constructed of non-combustible materials and have at least 90 min fire resistance. In buildings >60 m a min f.r. of 120 is required. These requirements also apply to other structural elements, like columns and beams.

Non-loadbearing walls shall be constructed of non-combustible materials. The glazing, frames, sun protection devices shall also be non-combustible.

The vertical spread of fire shall be prevented by structural elements of at least 90 min fire resistance with a min height of 1 m between the lintel of the lower window and the sill of the one above. A horizontal projection of 1.5 m height may also be provided.

A greater distance between the vertical openings as well as fire resistant glazing may be required in case of a higher fire load greater than in a residential building.

All external claddings and their substrates (the construction underneath), frames, supports and other fixing materials, as well as insulations shall be non-combustible.

B1 materials (like wood wool panels - combustible but near the limit of non-combustibility) can be applied to external walls without openings in case it is not a wall of a protected escape staircase.

If the buildings heigt >30m the external claddings shall be throughout non-combustible.

Any wall and partition inside the building shall be constructed of non-combustible materials. Walls seperating corridors forming a part of an escape route from other spaces will have at least 90 min fire resistance and be of non-combustible materials. Doors in such walls will prevent the penetration of smoke, be at least of 30 min fire resistance and without glazing in flats and hotel rooms.

High hazard areas and storages will be seperated by walls constructed of non-combustible materials and have at least 90 min fire resistance, with 30 min fire resistant, self-closing doors. The maximum floor area is 150 m2 for these type of spaces. Smoke vents will be provided in these areas.

Floors (without floor coverings) will be constructed of non-combustible materials and have at least 90 min fire resistance. In buildings over 60 m height they will be of non-combustible materials and have at least 120 min fire resistance.

Are there any electrical conduits and wires installed under the floor slab over an escape route, the seperating internal walls will form a barrier in full height from one floor to another. The electrical conduits and wires will be plastered over and a non-combustible suspended ceiling shall be provided.

Is the fire load from electrical conduits and wires > 7 kWh/m2 the suspended ceiling shall be of non-combustible materials and have at least 30 min fire resistance.

If there are no cavity barriers in the concealed space the suspended ceiling shall be of non-combustible materials and have at least 30 min fire resistance. Ceiling shall be jointless (ie not contain access panels).

Roofs:

The roof construction, as well as the roof coverings and any construction on the roof including their claddings have to be of non-combustible materials .

Flat roofs will be of non-combustible materials and have at least 90 min fire resistance. The roof shall be covered with mineral based materials with a min thickness of 5 cm. The bounding walls of the roof area shall be at least 90 cm taken up above the roof, be of non-combustible materials and have at least 90 min fire resistance.

The roof of any lower part of a building or the roof of any lower adjacent building shall have a distance of min 5 m from the external walls of higher building parts or buildings.

The internal surfaces of any wall and ceiling in escape routes including their supports and fixings will be of non-combustible materials. In other rooms B1 type materials are required. Any surface material of any walls may be combustible when the adjacent surface of ceiling exposed to room is non-combistible. In escape routes any paints, wallpapers and other wall linings not exceeding 0.5 mm thickness are acceptable when they have the B1 classification, do not promote the smoke developnent and are not toxic.

If the building's height is >30 m all internal surfaces of any wall and ceiling including their supports and fixings will be of non-combustible materials. In spaces like meeting rooms the use of combustible finishes would be acceptable.

Insulation linings, seal sheatings, dilation openings in and on walls, ceilings and roofs, as well as insulations of pipes, conduits, shafts and ducts including their supports and fixings will be of non-combustible materials. This does not apply to combustible sheatings which have been threated with flame retardant coatings. B1 class insulation linings can be used in perefabricated structural elements, when they are covered with mineral based panels not less than 6 cm in thickness on both sides and 2 cm fillets at the edges.

Means of escape:

Escape routes (corridors, lobbies, protected lobbies, stairs and exits will have a min width of 1.25 m. This can be decreased in doorways, but connot be less than 1.10 m. Winders are allowed. The slope of the ramps shall be less than 6%.

Illumination of means of egress shall be provided. In case of failure of the public utility or any other outside electrical power supply an emergency lighting system will maintain an illumination level of at least 1 lx throughout the escape routes.

Means of egress shall be marked according to DIN 4844 Part 3 such as staircases and exits are easily recognized by the people.

Every sign shall be illuminated by a reliable light source. Externally and internally illuminated signs will placed on doors and doors into the staircases such as they will be visible from any direction of exit access in both the normal and emergency lightning mode.

Exit signs shall be provided to show the way to the exit at intersections and be placed at least every 15 m in long corridors. The bottom of the exit sign shall be approximately 2 m above the floor.

In emergency balkonies the way to other escape routes shall be marked. In staircases each level shall be clearly marked. In case the final exit is in an upper storey the upwards travel direction shall be indicated by arrows at each level.

The final exit (exit discharge) leading to a public way shall be clearly indicated.

In high-rise buildings there will be at least 2 seperate staircases or one protected staircase placed at an external wall. If there are more than 2 staircases they shall be located in different smoke compartments and be remote from each other. If the building's height exceeds 60 m all staircases which are a component in the means of escape will be placed in protected shafts. At least 2 protected staircases shall be provided.

The travel distance to a staircase shall not exceed 25 m. Staircases shall have openings only to corridors, lobbies and to public ways.

Stairs and landings shall be of permanent fixed construction and have a fire resistance of 90 min. Guards and handrails shall be non-combustible.

Doors opening to common passages and lobbies shall have at least 30 min fire resistance, be self-closing and of non-combustible materials. Smokeproof, self-closing doors are allowed if they are located in doorways outside the radiation area of fire.This applies when the distance to the adjacent door is no [illegible] than 5 m.

A staircase shall have a ventilation opening of at least 1 m2 claer area. If the opening is placed in a wall the clear area will be at least 1.5 m2.

Staircases located on an external wall shall have windows of sufficient area to the outside which can be opened. The opening area shall be at least 0.9m x 1.2 m. The distance to other openings in the same wall will be at least 1.5 m. If the external wall coincides with another external wall at an angle of less than 120 degrees, this distance shall be at least 3 m.

Interior staircases shall be approached only by means of a lobby (vestibule) which has openings to a corridor, a lift and/or sanitary accomodation and washrooms. The doorsways shall be protected with fire door assemblies of at least 30 min fire resistance, will be self-closing and of noncombustible materials.

A ventilation system will be provided in interior staircases which maintaines at least one air change per hour in normal service. In case of fire this or another ventilation system shall supply fresh air of at least 10 000 m3 per hour from the buttom towards the top of the shaft. Maximum over pressure due to the air supply shall not exceed 50 Pa. This can be achieved by way of sufficient large openings in the upper part of the staircase. The ventilation system shall be activated by automatic smoke detectors at every level. The staircases shall not be seperated by walls nor be divided into smoke compartments.

Basement storeys shall have at least 2 seperate exits in every compartment. One of these exits will provide direct access to an exit discharge by means of a staircase located at an external wall which does not continue in upper storey unless there is a smokeproof lobby between it and the upper stairway.

A protected stairway shall only be approached by way of an open bridge or balcony. The open passage shall have the same width as the protected stairway, but at least 1.25 m. Its length will be at least twice of its width. The bounding walls and floors of the open passage shall be 90 min fire resistant and of noncombustible materials. The openings therein shall be protected with 90 min fire resistant doors. The distance between openings along the open passage shall measure at least 3 m.

If an interior protected stairway is laid out as a firetower, access will be provided only by way of the naturally ventilated shaft of a min area of 5m x 5m. The ventilated shaft shall be constructed of noncombustible materials and the fire resistance is required to be 90 min and more. At the buttom of the shaft an opening for air supply shall be provided. The area of the shaft shall not be decreased more than 10 m2 by the open passage.

An interior protected staircase shall be approached by way of a protected lobby of min 1.5 m width and 3 m length. The exit doors shall be at least 30 min fire resistant.

A ventilation system will be provided in interior protected staircases and their protected lobbies to prevent the penetration of fire and smoke into the staircase. In case of fire this or another ventilation system shall provide fro the staircase into the fire room air current of at least

$V= k \times b \times h^{1.5}$ cu m /s

There b is the door width im and h is the door height in m. k is a factor which depends on the temperature in the adjacent room in case of fire. Is the adjacent floor space a corridor k shall be 1.5 and in all other cases 1.8.

The degree of the necessary pressure difference for this air current depends on how smoke gases will be exhausted from the fire room into outside. In case that the smoke gases are exhausted throught a horizontal duct the pressure in the lobby has to be increased according to the current resistance in the duct. If there are shafts or exhaust ventilators which cause a negative pressure in the fire room, by enclosures without any openings the pressure in the protected lobby can be decreased as much as the negative pressure in the fire room. In enclosures with openings the ventilation system shall provide a pressure of min 10 Pa.

The travel distance on corridors between two staircases shall not be greater than 40 m. Horizontal passages shall be divided into smoke compartments every 20 m by self-closing and at least smokeproof doors. Glazings therein shall be constructed of 7 mm wired glass in steel frames only. From each smoke compartment there will be a direct access to a staircase.

If escape is possible in one direction only the travel distance to an open passage, to a staircase or lobby shall not be greater than 10 m. This may be encreased to 20 m if there is another escape route like a balcony providing escape in two direction to a second staircase or to a protected staircase.

If the a horizontal escape route cannot be ventilated by opening the windows, there shall be a mechanical ventilation facility permitting one air change per hour through equally dimensioned air supply and exhaust ducts.

Buiding services:

High-rise buildings shall have at least 2 two lifts serving every storey which can be approached from any point of the floor. In windowless enclosures or underground structures access to lifts shall be provided only by way of lobbies.

At least one fire- fighting lift shall be provided in buildings of more than 30 m height. The distance travelled from any part of the floor area of that storey to the fire-fighting lift will not exceed 50 m.

A fire- fighting lift shall be placed in a seperate shaft with at least 90 min fire resistance and constructed of noncombustible materials. At each level the fire- fighting lift shall be entered by means of a lobby enclosed with walls of at least 90 min fire resistance. The lobby shall be sufficiently measured to allow a stretcher (0.6 x 2.26 m) easily be carried into the lift.

The lobby in front of the fire-fighting lift shall only have openings to protected lobies, to a corridor, a lift and/or sanitary accommodation and washrooms. The doorways shall be protected with fire door assemblies of at least 30 min fire resistance, will be self-closing and of noncombustible materials. One hose reel will be provided in the lobby. The lobby can be omitted if the fire-fighting lift is approached by means of an open passage.

An additional electric generator shall be provided for the fire-fighting lift which shall be in operation within 15 sec.

Any system of mechanical ventilation should be designed to ensure that the normal airflow pattern is away from protected escape routes. Ventilation ducts shall have at least 90 min fire resistance. Ventilation systems for staircases shall be seperated from other ventilation systems serving the remainder of the building. Central heating by way of water, steam or air shall be acceptable. The storage of solid , fluid or gaseous fuel is not allowed above the ground floor.

Each rubbish chute shall be seperately enclosed by 90 min fire resisting walls or partitions. Doors for such chutes being self-closing and at least of 30 min fire resistance shall open only to seperate room exclusively designed for that purpose. An automatic suppression system may be required in the chutes.

In high-rise buildings with an higher fire risk fire alarm systems may be required. In high-rise buildings with a height > 60 m shall be installed according DIN 14 675 and VDE 0833/DIN 57833 entsprechen. In room with a greater risk, both fire and explosion, automatic dedectors may be required.

An alarm control center will be provided in high-rise buildings>120 m.

A wet standpipe shall be provided close by every protected staircase together with a hose system at each level.

An automatic sprinkler system shall be provided in buildings with a height >60 m.