DETERMINISTIC COMPUTER FIRE MODELS

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Computer models are simply computer programs that model or simulate a process or phenomena. Computer models have been used for some time in the design and analysis of fire protection hardware. The use of computer models, commonly known as design programs, has become the industry's standard method for designing water supply and automatic sprinkler systems. These programs perform large numbers of tedious and lengthy calculations and provide the user with accurate, cost-optimized designs in a fraction of the time required for manual procedures.

In addition to the design of fire protection hardware, computer models may also be used to evaluate the effects of fire on people and property. These computer fire models can provide a faster and more accurate estimate of the impact of a fire and the measures used to prevent or control the fire than many of the methods previously used. While manual calculation methods provide good estimates of specific fire effects (e.g., prediction of time to flashover), they are not well suited for comprehensive analyses involving the time-dependent interactions of multiple physical and chemical processes present in developing fires.

In recent years, increasing attention has been given to the development and use of computer fire models. They have been used by engineers and architects for building design, building officials for plan review, the fire service for pre-fire planning, investigators for post-fire analysis, groups writing fire codes, materials manufacturers, fire researchers, and educators. While these models are not a replacement for building and fire codes, they still can be valuable tools for the fire professional.

The state of the art in computer fire modeling is changing rapidly. Understanding of the processes involved in fire growth is improving, and thus the technical basis for the models is improving. The capabilities, documentation, and support for a given model can change dramatically over a short period of time. In addition, computer technology itself (both software and hardware) is advancing rapidly. A few years ago, a large mainframe computer was required to use most of the computer fire models. Today, almost all of the models can be run on personal computers. Therefore, rather than provide an exhaustive discussion of rapidly changing state-of-the-art available computer models, the following discussion will focus on a representative selection. The reader should refer to the bibliography at the end of this chapter for in-depth reviews of particular models.

In general, computer models for fire hazard prediction can be grouped into two categories: (1) enclosure fire models and (2) special-purpose fire models.

ENCLOSURE FIRE MODELS

Major advancements have occurred in the development of computational models structured to predict the interaction of multiple fire processes involving heat transfer, fluid mechanics, and combustion chemistry occurring at the same time in an enclosure. These models provide estimates of particular elements of hazard development such as fire growth, temperature rise, and smoke generation and transport. Some models are able to address multiple rooms. Others are confined to the room of fire origin. Generally, the large number of mathematical expressions to be solved simultaneously in any of these models necessitates the use of a computer.

There are two general classes of computer models for analyzing enclosure fire development: (1) probabilistic and (2) deterministic.

Probabilistic Models

Probabilistic models treat fire growth as a series of sequential events or states. These models are sometimes referred to as state transition models. Mathematical rules are established to govern the transfer from one event to another (e.g., from ignition to established burning). Probabilities are assigned to each transfer point based on analysis of relevant experimental data and historical fire incident data. These models do not normally make direct use of the physical and chemical equations describing the fire processes.

Deterministic Models

In contrast, deterministic models represent the processes encountered in a compartment fire by interrelated mathematical expressions based on physics and chemistry. These models may also be referred to as room fire models, computer fire models, or mathematical fire models. Ideally, such models represent the ultimate capability, which means that discrete changes in any physical parameter

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could be evaluated in terms of the effect on fire hazard. While the state of the art in understanding fire processes will not yet support the ultimate model, a number of computer models are available that provide reasonable estimates of selected fire effects.[1,2]

Zone models: The most common type of physically based fire model in North America is the zone or control volume model, which solves the conservation equations for distinct regions (control volumes). A number of zone models exist, varying to some degree in the detailed treatment of fire phenomena. The dominant characteristic of this class of model is that it divides the room(s) into a hot upper layer and a lower cooler layer. The model calculations provide estimates of key conditions for each of the layers as a function of time.[3] Zone models have proved to be a practical method for providing first-order estimates of fire processes in enclosures.

Field models: The other general type of deterministic model is the field model or computational fluid dynamics (CFD) model. This type of model solves the fundamental equations of mass, momentum, and energy at each element in a compartment space that has been divided into a grid of small elements. Imagine an enclosure filled with a 3-D grid of tiny cubes; a field model will calculate the physical conditions in each cube as a function of time. The calculation will account for physical changes generated within the cube and changes in the cube originating from surrounding cubes. This model will permit the user to determine the conditions at any point in the compartment.

Figure 11-5A shows an example of a field model prediction for the gas velocity in a compartment fire. The figure shows the cross-section of a compartment with the door to the right of center and a fire near the floor to the left. The arrows represent the predicted gas velocity with the arrows pointing in the direction of gas flow, and the speed of the flow indicated by the length of the arrows. The prediction shows air entering the lower level of the compartment to the right, rising in the fire, and flowing under the door lintel as it leaves the compartment.

Generally, field models cannot be used with the current generation of personal computers. The computational demands and memory requirements necessitate the use of powerful desktop workstations, minicomputers, or mainframe/super computers to perform efficiently. (For example, an attempt to model an industrial rack storage fire with a field model on a current generation workstation using a computational domain of around 514,000 cells and a time step of 0.2 sec required 18 days of computer time.)[4] Minimum start-up costs associated with both the software programs and computer hardware to operate typical field models can conservatively range from $50,000 to $100,000.

In spite of the expense, field modeling is growing in popularity as the demand for more detailed fire hazard analyses has evolved. Field models have recently been successfully used to evaluate a wide range of fire problems including the well-known effort to simulate the King's Cross fire.[5] Several efforts to validate specific field models against limited experimental data have been performed.[6–8] An attempt to validate the accuracy of the commonly used "k-e" turbulence model to predict velocity and temperature fields in buoyant flows demonstrated the need to modify significantly the default values of physical constants, such as the turbulent viscosity constant of proportionality and the turbulent Prandtl number, in order to obtain reasonable agreement with experimental measurements.[9] Therefore, caution should be employed in adapting any of the currently available field models while the validation process continues.

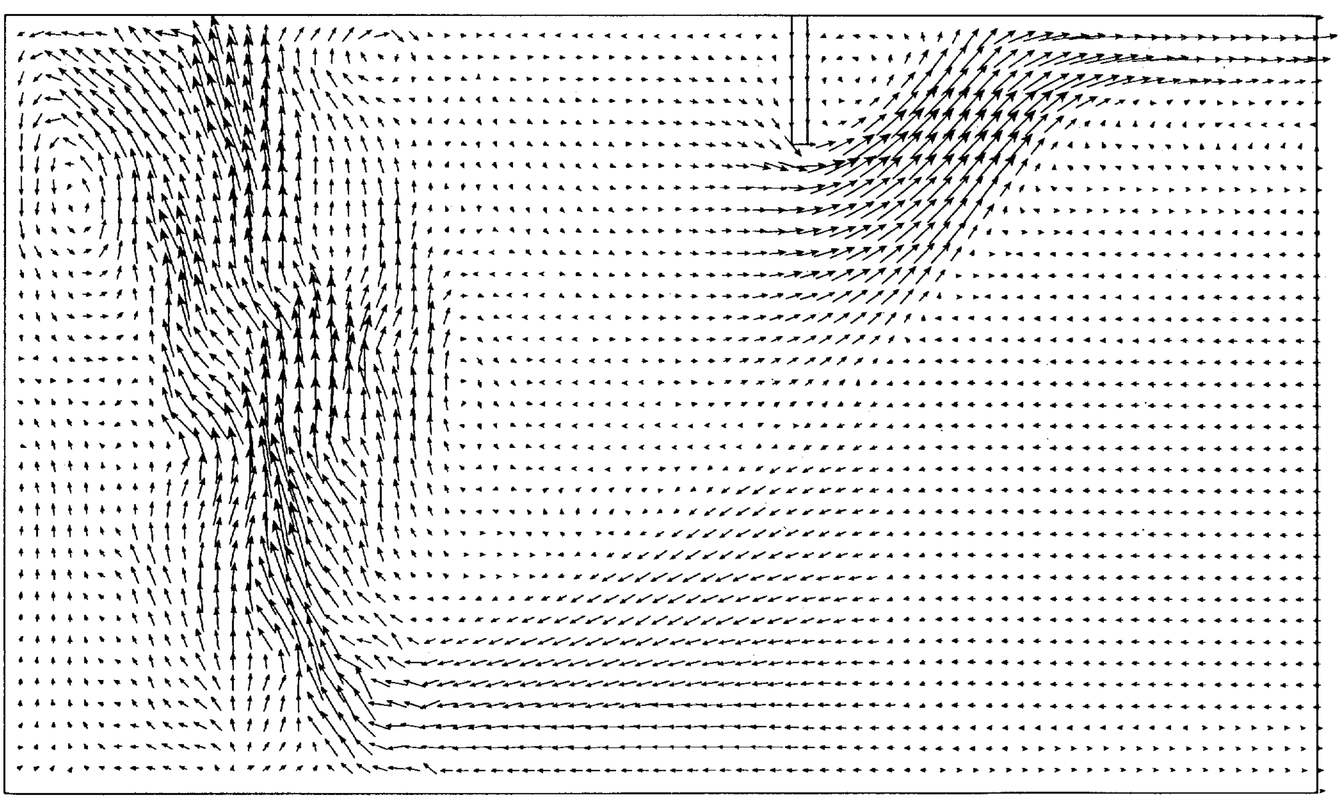

FIG. 11-5A. Field model prediction of gas velocity in a compartment fire.

OVERVIEW OF SELECTED ZONE MODELS

Table 11-5A lists a number of zone-type enclosure fire models that are widely used. A more detailed description of each model is also given.

ASET: ASET (Available Safe Egress Time) is a program for calculating the temperature and position of the hot smoke layer in a single room with closed doors and windows.[10] ASET can be used to determine the time to the onset of hazardous conditions for both people and property. The required program inputs are the heat loss fractions, the height of the fuel above the floor, criteria for hazard and detection, the room ceiling height, the room floor area, a heat release rate, and a species generation rate of the fire (optional). The program outputs are the temperature, thickness, and (optional) species concentration of the hot smoke layer as a function of time, and the time to hazard and detection. ASET can examine multiple cases in a single run.

ASET-B: ASET-B is a program for calculating the temperature and position of the hot smoke layer in a single room with closed doors and windows.[11] ASET-B is a compact version of ASET designed to run on personal computers. The required program inputs are a heat loss fraction, the height of the fire, the room ceiling height, the room floor area, the maximum time for the simulation, and the rate of heat release of the fire. The program outputs are the temperature and thickness of the hot smoke layer as a function of time. Species concentrations and time to hazard and detection calculated by ASET are not calculated in the compact ASET-B version.

CCFM (version VENTS): CCFM (Consolidated Compartment Fire Model) (version VENTS) is a two-layer zone-type compartment fire model computer code.[12–15] It simulates conditions caused by user-specified fires in a multiroom, multilevel facility. The required inputs are a description of room geometry and vent characteristics (up to nine rooms and twenty vents), initial state of the inside and outside environments, fire energy release rates as functions of time (up to twenty fires), and a user-specified heat loss fraction. If simulation of concentrations of products of combustion is desired, then product release rates must also be specified (up to three products). Vents can be simple openings between adjacent spaces (natural vents) or fan/duct-forced ventilation systems between arbitrary pairs of spaces (forced vents). For forced vents, flow rates and direction can be user-specified or included in the simulation by accounting for user-specified fan and duct characteristics. Wind and stack effects can be taken into account. The program outputs for each room are pressure at the floor, layer interface height, upper/lower layer temperature, and (optionally) product concentrations. CCFM (version VENTS) is supported by four-part documentation.

TABLE 11-5A. ***Enclosure Zone Fire Models***

Model Name	Author(s)	Maintaining Organization	Special Features
ASET	L. Y. Cooper D. W. Stroup	NIST	Single room
ASET-B	W. D. Walton	NIST	Single room
CCFM-VENTS	L. Y. Cooper G. P. Forney	NIST	Multiroom, multilevel
CFAST	W. W. Jones R. D. Peacock G. P. Forney P. Reneke R. Portier	NIST	Up to 15 compartments, 30 ducts, and 5 fans
COMPBRN III	N. Siu V. Ho	UCLA	Single room, developed for nuclear power facilities
COMPF2	V. Babrauskas	NIST	Single room, post-flashover
FIRST	H. W. Emmons H. E. Mitler	NIST	Single room, burning item
WPI/FIRE	D. B. Satterfield J. R. Barnett	WPI	Single room, ceiling vents

CFAST: The CFAST (Consolidated model of Fire growth And Smoke Transport) program is an upgrade of the FAST (Fire And Smoke Transport) program, and incorporates new and faster numerical solution techniques originally implemented in CCFM.[16,17] CFAST is a multiroom fire model that predicts the conditions within a structure resulting from a user-specified fire. CFAST version 2.0.1 can accommodate up to 15 compartments with multiple openings between the rooms and to the outside. The required program inputs are the geometrical data describing the rooms and connections; the thermophysical properties of the ceiling, walls, and floors; the fire as a rate of mass loss; and the generation rates of the products of combustion. The program outputs are the temperature and thickness of, and species concentrations in, the hot upper layer and the cooler lower layer in each compartment. Also given are surface temperatures and heat transfer and mass flow rates. CFAST also includes mechanical ventilation (up to 30 ducts and 5 fans), new heat transfer algorithms, a ceiling jet algorithm, capability of multiple fires (up to 16), and more accurate solutions due to new pressure equation formulations.

COMPBRN III: COMPBRN III has been generally used in conjunction with probabilistic analysis for the assessment of risk in the nuclear power industry.[18] The model is based on the assumption of a relatively small fire in a large space or fire involving large fuel loads early during the pre-flashover fire growth period. The model's emphasis is on the thermal response of elements within the enclosure to a fire within the enclosure and on modeling simplicity. The temperature profile within each element is computed and an element is considered ignited or damaged when its surface temperature exceeds the user-specified ignition or damage temperature. The model outputs include the total heat release rate of the fire, the temperature and depth of the hot gas layer, the mass burning rate for individual fuel elements, the surface temperatures, and the heat flux at user-specified locations.

COMPF2: COMPF2 is a computer program for calculating the characteristics of a post-flashover fire in a single building compartment, based on fire-induced ventilation through a single door or window.[19] It is intended both for performing design calculations and for the analysis of experimental burn data. Wood, thermoplastic, and liquid fuels can be treated. A comprehensive output format is provided that gives gas temperatures, heat flow terms, and flow variables. The documentation includes input instructions, sample problems, and a listing of the program.

FIRST: FIRST (FIRe Simulation Technique) is the direct descendant of the HARVARD V program developed by Howard Emmons and Henri Mitler.[20] The program predicts the development of a fire and the resulting conditions within a room, given a user-specified fire or user-specified ignition. It predicts the heating and possible ignition of up to three targets. The required program inputs are the geometrical data describing the room and openings, and the thermophysical properties of the ceiling, walls, burning fuel, and targets. The generation rate of soot must be specified, and the generation rates of other species may be specified. The fire may be entered either as a user-specified time-dependent mass loss rate or in terms of fundamental properties of the fuel. Among the program outputs are the temperature and thickness of, and species concentrations in, the hot upper layer and also in the cooler, lower layer in the compartment. Also given are surface temperatures, and heat transfer and mass flow rates.

WPI/FIRE: WPI/FIRE is a direct descendant of the HARVARD V and FIRST programs.[21] It includes all of the features of the HARVARD program version 5.3 and many of the features of the FIRST program. WPI/FIRE also includes the following features: improved input routine, momentum-driven flow through ceiling vents, two different ceiling jet models for use in detector activation, forced ventilation for ceiling and floor vents, and an interface to a finite difference computer model for the calculation of boundary surface isotherms and hot spots.

OVERVIEW OF SELECTED FIELD MODELS

Table 11-5B provides a list of available field models. Selected models from these lists are described below.

BF3D: BF3D is a computational model of three-dimensional buoyant flow in a single enclosure due to a fire source.[22] No turbulence model or other empirical parameters are introduced. The current algorithms have been verified by comparisons with exact solutions to the equations in simple cases, and predictions of the overall model have been compared with experimental results. The use of Lagrangian particle tracking allows visualization of the three-dimensional flow patterns. The model is used mainly for research and is generally not available in the public domain.

FISCO-3L: FISCO-3L is a three-dimensional single-room field model for unsteady and compressible buoyant heat flow.[23] Fire can be simulated under both natural and forced ventilation. An option is available for simulating fire suppression by water sprinklers. The program is menu-driven with a graphical user interface and a real-time system for graphical display of results. The algorithms used to calculate turbulence, flame region effects, and combustion processes are simplified in order to reduce computation demands. The model is copyright restricted.

FLOW-3D: FLOW-3D is a general-purpose computational fluid dynamics (CFD) code. The code includes a CFDS Environment for mesh generation and post-processing, and is capable of time-dependent or steady-state heat and mass transfer, and two- or three-dimensional coordinate systems. Model features include body-fitted coordinates, moving and adaptive grids, heat transfer in solid regions, porous media approximation, turbulence modeling, compressibility, scalar transport equations, and discrete particle transport. An optional feature is multifluid modeling. Additional information can be obtained from Harwell Laboratory (U.K.) or Computational Fluid Dynamics Services (U.S.).

JASMINE: JASMINE uses PHOENICS, a CFD code for computation of fluid motion, and provides full three-dimensional solutions for heat and mass transfer.[24] It solves the full partial differential equations describing the conservation of mass, momentum, energy, and species, using a two equation model for turbulence together with simple radiation models. Primary input requirements include a

TABLE 11-5B. ***Field Fire Models***

Model Name	Author(s)	Maintaining Organization	Applications and Special Features	Required Hardware
BF3D	H. R. Baum R. G. Rehm D. W. Lozier D. M. Corley	NIST (U.S.)	Single room treatment of buoyant heat-driven flows	Large memory needed for adequate resolution; mainframe, minisuper, or supercomputer
FISCO-3L	V. Scheider J. Hoffmann	INTELLEX, FR (Germany) SINTEF (Norway)	Single room treatment of fire development	80386 chip-based PC computer, MS-DOS operating system with math co-processor, EGA or VGA graphical display and 640 kB memory
FLOW-3D	Harwell Laboratory	Harwell Laboratory (U.K.)	General-purpose computational fluid dynamics (CFD) code	Supercomputer, mainframe, mini, or workstation
JASMINE	G. Cox S. Kumar	Fire Research Station (U.K.)	Analysis of smoke movement	Mini, super mini, VAX preferred
KAMELEON FIRE E-3D	B. F. Magnussen	NTH/SINTEF (Norway)	Single room fire growth model for pool fires	Post-processor needs MS-DOS and VGA or UNIX X-WINDOWS; 640 kB
KAMELEON II	B. F. Magnussen	NTH/SINTEF (Norway)	Multiroom fire and smoke spread	Post- and pre-processor are MS-DOS and VGA display or UNIX X-WINDOWS; 640 kB
KOBRA-3D	INTELLEX	INTELLEX (Germany)	3-D field model for determining hydrodynamical flow in a single fire compartment	IBM-compatible PC, MS-DOS 3.0, EGA graphics, co-processor recommended
PHOENICS	D. B. Spalding	CHAM, LTD. (U.K.)	A general-purpose 3-D transient fluid dynamics code	Supercomputer, mainframe, mini, or workstation
RMFIRE	G. Hadjisophocleous	National Research Council of Canada (Canada)	A 2-D field model for transient calculations of smoke movement in a room fire	Workstation
SPLASH	A. J. Gardiner	South Bank Polytechnic (U.K.)	A quasi-field model describing the interaction of sprinkler sprays with fire gases	VAX
STAR*CD	D. Gossman R. Issa	Computational Dynamics (U.K.)	General-purpose computational fluid dynamics (CFD) code	UNIX workstations and supercomputer

description of the fire source, the thermal properties of the structure, structure geometry, and ventilation conditions. Use of the code is through the Fire Research Station (U.K.).

KAMELEON FIRE E-3D: KAMELEON FIRE E-3D is a three-dimensional field model for transient calculation of pool fires in a single enclosure.[25] The model can be applied to problems involving multiple natural or forced vents. The fire source is characterized by either a predetermined leakage rate or a pool fire (liquid hydrocarbons only). Turbulence is modeled by k-e, and combustion and soot by eddy dissipation. Radiation is included. SINTEF (Norway) provides modeling services using this model, but the model is not directly available commercially.

KAMELEON II: KAMELEON II is an enhanced field model that is optimized for vector performance.[25] It has a graphical pre-processor that allows the user to generate input simply by making drawings. The post-processor provides color graphics of any cross-section and any variable in the calculation domain. The model predicts the spread of smoke and exhaust gases in complex multienclosure geometries and open configurations. Turbulence is modeled by k-e, and combustion and soot by eddy dissipation. Radiation is also modeled. A key input is the burning rate of the fire to be modeled. SINTEF (Norway) will perform customer calculations, but the code is not available commercially.

KOBRA-3D: KOBRA-3D is a three-dimensional field model for calculating the unsteady and compressible heat flow in a natural- or forced-ventilated compartment. The development of a fast converging iteration procedure for solving the hydrodynamic equations allows for effective use on a high-performance personal computer. The fire source can be defined by semi-empirical relations or by defining constant or time-dependent heat release rates. Turbulence modeling is not included. The model is embedded in a menu-driven user surface combined with data bases for fuel and room geometry input data. On-line graphic displays of temperature and velocity contours is possible. Additional information can be obtained from the developer, INTELLEX (Germany).

PHOENICS: PHOENICS is a computational fluid dynamics (CFD) code that includes calculation routines for turbulence effects, heat transfer, chemical reaction, multiphase behavior of fluids, and complex geometries.[26] Output displays include perspective views, contour mapping, vector diagrams, and gradients. Several field models developed for fire hazard applications rely on this code to perform the fluid dynamics processes. It is commercially available.

RMFIRE: RMFIRE is a two-dimensional field model developed for analysis of unsteady smoke movement and heat transfer in a fire compartment.[7] The governing equations are solved in boundary-fitted coordinate systems that allow compartments with complex geometries to be evaluated. Inputs include boundary conditions, initial conditions, and the fire heat release rate history. Output includes temperature contours, as well as velocity and pressure values within the compartment. This model will become available at a later date. Currently NRCC (Canada) will perform the calculations.

SPLASH: SPLASH is a quasi-field model describing the interaction of sprinkler sprays with fire gases in corridors. Inputs include detailed sprinkler parameters, corridor geometry, and smoke layer characteristics.[27] The model provides information on the effects of the spray on the smoke layer conditions, variation in heat transfer and drag to buoyancy ratio in the spray volume, the thermal and physical histories of individual droplets in the spray, and the water delivery pattern on the floor.

STAR*CD: STAR*CD is a general-purpose computational fluid dynamics (CFD) code.[28] STAR*CD is designed to solve a wide range of flow phenomena, including steady and transient, laminar and turbulent (from a choice of turbulence models), incompressible and compressible, heat transfer (convection, conduction, and radiation), mass transfer and chemical reaction (including combustion), porous media, and multiple fluid streams and multiphase flows.

SPECIAL-PURPOSE MODELS

Special-purpose deterministic computer models include computer models designed for special-purpose analyses such as: structural fire resistance, prediction of response time of heat detectors and automatic sprinklers, the design of sprinkler systems, and performance of smoke-control or ventilation systems. These models may require or permit coupling with other special-purpose models or with a more general enclosure fire development model.

Table 11-5C lists a number of special-purpose deterministic fire models that are widely used. A more detailed description of each model follows.

TABLE 11-5C. ***Special-Purpose Models***

Model Name	Author(s)	Maintaining Organization	Model Type	Special Features
ASCOS	J. H. Klote	NIST	Smoke control	Steady-state network flow model for smoke-control evaluation, no fire condition
BREAK1	A. A. Joshi P. J. Pagni	U. C. Berkeley	Glass breakage	Calculates glass breakage for window exposed to a compartment fire
DETACT-T2	D. W. Stroup	NIST	Thermal device activation	Calculates actuation time for heat detectors and sprinklers, time-squared fires
DETACT-QS	D. D. Evans	NIST	Thermal device activation	Calculates actuation time for heat detectors and sprinklers, user-defined fires
FIRES-T3	R. H. Idling B. Bresler Z. Nizamuddin	U. C. Berkeley	Structural heat transfer	Three-dimensional heat transfer through structural assemblies
LAVENT	W. D. Davis L. Y. Cooper	NIST	Thermal device activation	Calculates actuation time for sprinklers and link-actuated vents with draft curtains

ASCOS: ASCOS (Analysis of Smoke COntrol Systems) is a program for steady air-flow analysis of smoke-control systems.[29] This program can analyze any smoke-control system that produces pressure differences with the intent of limiting smoke movement in building fire situations. The input consists of the outside and building temperatures, a description of the building flow network, and the flows produced by the ventilation or smoke-control system. The output consists of the steady-state pressures and flows throughout the building.

BREAK1: BREAK1 (Berkeley algorithm for BREAKing window glass in a compartment fire) is a program that calculates the temperature history of a glass window exposed to user-described fire conditions.[30] The calculations are stopped when the glass breaks. The inputs required are the glass thermal conductivity, thermal diffusivity, absorption length, breaking stress, Young's modulus, thermal coefficient of linear expansion, thickness, emissivity, shading thickness, half-width of window, the ambient temperature, numerical parameters and the time histories of flame radiation from the fire, hot layer temperature and emissivity, and heat transfer coefficients. The outputs are temperature history of the glass normal to the glass surface, and the window breakage time.

DETACT-T2: DETACT-T2 (DETector ACTuation-Time squared) is a program for calculating the actuation time of thermal devices below unconfined ceilings.[31] It can be used to predict the actuation time of fixed-temperature and rate-of-rise heat detectors and of sprinkler heads subject to a user-specified fire that grows as the square of time. DETACT-T2 assumes that the thermal device is located in a relatively large area; that is, only the fire ceiling flow heats the device, and there is no heating from the accumulated hot gases in the room. The required program inputs are the ambient temperature, the response time index (RTI) for the device, the activation and rate-of-rise temperatures of the device, the height of the ceiling above the fuel, the device spacing, and the fire growth rate. The program outputs are the time to device activation and the heat release rate at activation.

DETACT-QS: DETACT-QS is a program for calculating the actuation time of thermal devices below unconfined ceilings.[32] It can be used to predict the actuation time of fixed-temperature heat detectors and sprinkler heads subject to a user-specified fire. DETACT-QS assumes that the thermal device is located in a relatively large area; that is, there is no accumulated hot gas layer in the room so only the fire ceiling flow heats the detection device. The required program inputs are the height of the ceiling above the fuel, the distance of the thermal device from the axis of the fire, the actuation temperature of the thermal device, the response time index (RTI) for the device, and the rate of heat release of the fire. The program outputs are the ceiling gas temperature at the device location and the device temperature both as a function of time and the time required for device actuation.

FIRES-T3: FIRES-T3 (FIre REsponse of Structures—Thermal 3-dimensional version) is a finite-element computer model designed to analyze heat transfer through structural assemblies.[33] A wide variety of structural assemblies can be examined with FIRES-T3, including columns, walls, beams, floor/ceiling assemblies, and roof/ceiling assemblies. The structural assembly may be solid or include air cavities. The input requirements include a description of the structural assembly and the fire exposure. The information necessary to describe the column assembly includes geometric factors (dimensions, shape of assembly) and material property values (thermal conductivity, specific heat, and density) as a function of temperature. The fire exposure is characterized in terms of the temperature of the surrounding media and appropriate heat-transfer coefficients. The output is a tabulation of the temperatures within the structural assembly as a function of time.

LAVENT: LAVENT (Link-Actuated VENT) is a program developed to simulate the environment and the response of sprinkler links in compartment fires with draft curtains and fusible-link-actuated ceiling vents.[34] The model used to calculate the heating of the fusible links includes the effects of the ceiling jet and the upper layer of hot gases beneath the ceiling. The required program inputs are the geometrical data describing the compartment, the thermophysical properties of the ceiling, the fire elevation, the time-dependent energy release rate of the fire, the fire diameter or energy release rate per area of the fire, the ceiling vent area, the fusible-link response time index (RTI) and fuse temperature, the fusible-link positions along the ceiling, the link assignment to each ceiling vent, and the ambient temperature. A maximum of five ceiling vents and ten fusible links are permitted in the compartment. The program outputs are the temperature, mass and height of the hot upper layer, the temperature of each link, the ceiling jet temperature and velocity at each link, the radial temperature distribution along the interior surface of the ceiling, the radial distribution of the heat flux to the interior and exterior surfaces of the ceiling, the fuse time of each link, and the vent area that has been opened.

COMBINED MODELS

A new category of deterministic fire models has emerged that can be called combined models or model suites. The first of these were FIREFORM[35] and HAZARD I.[36–38] The combined models contain several models under the control of a single program. The individual models may include zone fire models, egress models, and engineering calculations. The combined models may include fire models that are available in stand-alone form or fire models that are only available as part of the combined model. Table 11-5D lists a number of combined deterministic fire models that are widely used. A more detailed description of each model follows.

ASKFRS: ASKFRS is a collection of fire safety engineering routines.[39] The routines include fire heat release rate, flame height, fire plume calculations, plume rise, compartment hot gas layer temperature, flashover, smoke filling time, roof venting calculations, egress, and toxic threat.

ASMET: ASMET (Atria Smoke Management Engineering Tools) consists of a set of equations and a zone fire model for analysis of smoke management systems for large spaces, such as atria,

TABLE 11-5D. ***Combined Models***

Model Name	Author(s)	Maintaining Organization	Special Features
ASKFRS	R. Chitty G. Cox	FRS	Collection of fire safety engineering routines
ASMET	J. H. Klote	NIST	Collection of routines for smoke management in large spaces
FIRECALC	V. O. Shestopal S. J. Grubits	CSIRO	Collection of fire safety engineering routines
FPETOOL	H. E. Nelson S. Deal	NIST	Collection of fire safety engineering routines
HAZARD I	R. D. Peacock W. W. Jones R. W. Bukowski C. L. Forney	NIST	Predicts hazards to building occupants from fire (includes CFAST, EXITT, and DETACT-QS)

shopping malls, arcades, sports arenas, exhibition halls, and airplane hangars.[40] Routines calculate the height of the smoke layer during atrium filling from a steady or an unsteady fire, and the atrium filling time for a steady or an unsteady fire. Routines also calculate the plume mass flow rate, centerline temperature, and average temperature with or without a virtual origin correction. ASMET also contains a C language version of the ASET-B program.

FIRECALC: FIRECALC was developed from the original FPETOOL and is a collection of fire safety engineering routines.[41,42] About half of the routines in FIRECALC are the same as routines found in FPETOOL. FIRECALC also contains routines for steel beam load-bearing capacities, atrium smoke temperature, plume flow and temperatures, smoldering fires, smoke control with a common plenum, fire resistance time, and thermal radiation. FIRECALC has a one- and two-room hot layer model and a one-room natural ventilation model.

FPETOOL: FPETOOL is the descendant of the FIREFORM program.[43] It contains a computerized selection of relatively simple engineering equations and models useful in estimating the potential fire hazard in buildings. The calculations in FPETOOL are based on established engineering relationships. The FPETOOL package addresses problems related to fire development in buildings and the resulting conditions and response of fire protection systems. The subjects covered include smoke filling in a room, sprinkler/detector activation, smoke flow through (small) openings, temperatures and pressures developed by fires, flashover and fire severity predictions, fire propagation (in special cases), and simple egress estimation. The largest element in FPETOOL is a zone fire model called FIRE SIMULATOR. FIRE SIMULATOR is designed to estimate conditions in both pre- and post-flashover enclosure fires. The inputs include the geometry and material of the enclosure, a description of the initiating fire, and the parameters for sprinklers and detectors being tracked. The outputs include the temperature and volume of the hot smoke layer; the flow of smoke from openings; the response of heat-actuated detection devices, sprinklers and smoke detectors; oxygen, carbon monoxide, and carbon dioxide concentrations in the smoke; and the effects of available oxygen on combustion. FPETOOL also contains a routine to predict the characteristics of a moving smoke wave in a corridor, and a routine that predicts smoke conditions developing in a room and the subsequent reduction in human viability resulting from exposure to the conditions.

HAZARD I: HAZARD I is a method for predicting the hazards to the occupants of a building from a fire therein.[36–38] Within prescribed limits, HAZARD I allows one to predict the outcome of a fire in a building populated by a representative set of occupants in terms of which persons successfully escape and which are killed, including the time, location, and likely cause of death for each. HAZARD I is a set of procedures combining expert judgment and calculations to estimate the consequences of a specified fire. These procedures involve four steps: (1) defining the context, (2) defining the scenario, (3) calculating the hazard, and (4) evaluating the consequences. Steps 1, 2, and 4 are largely judgmental and depend on the expertise of the user. Step 3, which involves use of the extensive HAZARD I software, requires considerable expertise in fire safety practice. The heart of HAZARD I is a sequence of procedures implemented in computer software to calculate the development of hazardous conditions over time, calculate the time needed by building occupants to escape under those conditions, and estimate the resulting loss of life based on assumed occupant behavior and tenability criteria. These calculations are performed for a specified building and set of fire scenarios of concern. HAZARD I consists of a three-volume report and a set of computer disks containing the software necessary to conduct hazard analyses of products used in residential occupancies. The HAZARD I software is used to make detailed predictions of the fire-generated environment within a building; the evacuation process of occupants as they interact with the building, the fire, and each other; and the fate of the occupants as they either successfully escape or are killed. The underlying science—including a detailed presentation of the equations, constants, and assumptions contained in each of the programs—and a set of worked example cases are contained in the *Technical Reference Guide*. The *Software User's Guide* includes detailed instructions on use of the software and an extensively illustrated learning section that "walks" the user through a worked example. Specific applications depend on the user, but some include material/product performance evaluation, fire reconstruction and litigation, evaluation of code changes or variances, fire department pre-planning, and extrapolation of fire test data to additional physical configurations.

EGRESS MODELS

A growing number of deterministic fire-elated models deal with the topic of egress.[44] Although egress models are not fire models, they have been developed in response to the need to evaluate impact of fires on the occupants of a building. Egress models are often used with fire models in performing a hazard analysis. Most egress models describe the building as a network of paths along which the occupants travel. The occupant travel rates are usually derived from studies on people movement and vary with the age and ability of the occupant, crowding, and the type of travel path. Table 11-5E lists a number of prominent fire egress models. A more detailed description of each model is given below.

TABLE 11-5E. ***Egress Models***

Model Name	Author(s)	Maintaining Organization	Special Features
ELVAC	J. H. Klote	NIST	Evacuation using elevators
EVACNET+	T. M. Kisko R. L. Francis	U. of Florida	Optimum evacuation routes and times
EXITT	B. M. Levin	NIST	Occupant decisions and actions during fire
EXIT89	R. F. Fahy	NFPA	Large building evacuation

ELVAC: ELVAC (ELevator eVACuation) is an interactive computer program that estimates the time required to evacuate people from a building with the use of elevators and stairs.[45] It is cautioned that elevators are generally not intended as a means of fire evacuation, and they should not be used during fires. However, it is possible to design elevator systems for fire emergencies, and ELVAC can be used to evaluate the potential performance of such systems. ELVAC calculates the evacuation time for one group of elevators. If the building has more than one group of elevators, ELVAC can be run on each group separately. Input consists of floor-to-floor heights, number of people on floors, number of elevators in the group, elevator speed, elevator acceleration, elevator capacity, elevator door type and width, and various inefficiency factors. The output is a table of elevator travel time, round-trip time, people moved, number of round trips for each floor, and the total evacuation time.

EVACNET+: EVACNET+ (EVACuation NETwork computer model) is an interactive computer program that models emergency building evacuation.[46] It consists of a network of nodes and arcs to represent building locations and connecting paths. Input for this model includes a detailed geometry of the building and contents (multiple rooms and floors can be addressed), and information regarding the initial location of the occupants. Output can be selected from a menu and generally takes the form of optimum evacuation times and identification of impediments to smooth, orderly evacuation.

EXITT: EXITT is a discrete-event simulation of occupant decisions and actions in a simulated fire.[47] Before the simulation starts, the characteristics of a residence, a fire in that residence, and the occupants of the residence are entered into the computer. Based on a large set of decision rules, the occupants "make" decisions that are a function of the smoke conditions in the building, the characteristics and status of the occupants (including their capabilities), and the available travel routes. The occupants investigate the fire, alert and assist others, and evacuate the building. The simulation ends when all the occupants either are out of the building or are trapped by the smoke.

EXIT89: EXIT89 is an evacuation model for large buildings.[48] EXIT89 requires as input a network description of the building, geometrical data for each room and for openings between rooms, the number of occupants located at each node throughout the building, and smoke data if the effect of smoke blockage is to be considered. The user can select to have the occupants follow the shortest path out of the building or use familiar routes, whether smoke data is used and if it comes from a fire model or is input as blockages, whether there are delays within specified times, and if any occupants are disabled with a specified reduction in travel speed. The model either calculates the shortest route from each building location to a location of safety or follows user defined routes through the building. It moves people along routes until they are blocked by smoke, then recalculates the routes until everyone who can escape reaches a safe location that is usually outside the building. All occupants can begin evacuation at the same time or be assigned delays, and additional delays can be specified or randomly assigned to occupants. The program can output the location of each occupant with time, floor clearing times, stairwell clearing times, exit clearing times, and how many occupants used each exit.

WILDLAND FIRE MODELS

Wildland fire models used in the United States began as a series of charts, tables, and formulas that were computerized to speed their use.[49] Initially these were implemented as custom chips for programmable calculators and later as computer programs. These deterministic models are used for pre-fire planning like other fire models, but unlike other models they are also used real-time during the fire to aid in fire management. Table 11-5F lists two wildland fire models, the first of which is widely used, and the second of which represents the next generation of programs. A more detailed description of each model is also given.

TABLE 11-5F. ***Wildland Fire Models***

Model Name	Author(s)	Maintaining Organization	Special Features
BEHAVE	P. L. Andrews C. H. Chase	U.S. Forest Service	System of modules for a wide range of wildland fire predictions
FARSITE	M. A. Finney	U.S. Forest Service	GIS Interface

BEHAVE: BEHAVE is a collection of wildland fire behavior modules in an interactive program.[50,51] In some cases, output from one of the modules may be used as input to another module. Typical module inputs include fuel description parameters, moisture content, slope, wind speed, temperature, and mode of attack. The modules and their principal output features include CONTAIN—containment time and final fire size; DIRECT—rate of spread, flame height, fireline intensity, and direction of maximum spread; DISPATCH—automatic linking of DIRECT, SIZE, and CONTAIN for containment time and fire size; IGNITE—probability of ignition; MAP—map spread and spotting distance; MOISTURE—fuel level, temperature, wind speed, and relative humidity; MORTALITY—fuel mortality level and crown volume torch; RH—relative humidity; SCORCH—crown scorch height; SITE—rate of spread, flame height, fireline intensity, and direction of maximum spread; SIZE—area, perimeter, width, forward spread distance, and backing spread distance; SLOPE—slope and horizontal distance; and SPOT—maximum spot fire distance.

FARSITE: FARSITE (Fire Area Simulator) is a model for simulating the spread and behavior of wildland fires under conditions of heterogeneous terrain, fuels, and weather.[52] The model requires the support of a geographic information system (GIS) to generate, manage, and provide data for fuels, elevation, slope, topographic aspect, and canopy cover. Outputs include fire area, fire perimeter, fireline intensity, flame length, rate of spread, heat release per unit area, and time of arrival. FARSITE also includes spotting and crown fire routines. FARSITE simulates fire growth as a spreading elliptical wave. The fire is propagated over a finite time step using many small ellipses at points that define the flame front. The boundary formed by the small ellipses, calculated on the original flame front, becomes the new flame front. FARSITE supports graphical display of the input data and the model calculations.

RELATED ACTIVITIES

The development of deterministic fire models is a very active area. The above review is intended to offer the reader a perspective on what is currently available. One should also recognize that the information in this chapter is not exhaustive. Papers listed in the reference section provide additional information on the topic.

Before using any fire model, the user should be aware of the assumptions and limitations for that model. The brief descriptions provided in this chapter should not be used as the basis for the selection of a model for a particular application. Further, the range of validity for an individual computer fire model is difficult to determine and is the topic of a significant amount of continuing research. Before using any model, the user should study the comparisons of model predictions with experimental data to aid in determining if the use of the model is appropriate.

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