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AN INTERNATIONAL SURVEY OF COMPUTER MODELS FOR FIRE AND SMOKE

by

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SUMMARY

At the request of the Forum for International Cooperation on Fire Research, a worldwide survey was conducted of operational computer programs relevant to fire protection. A total of 62 programs, from 10 countries, were identified, and include compartment fire models, fire-sprinkler interaction models, and submodels for fire endurance, building evacuation, thermal detector actuation, fire spread on a wall, and smoke movement. These are listed, plus 12 additional models, including models from three additional countries. Then a general discussion is provided of the difficulties in achieving an accurate model of a growing fire in an enclosure, and of assessing the accuracy of a given model.

INTRODUCTION

A report was prepared for the Forum for International Cooperation on Fire Research in 1989, consisting of a survey of 36 fire computer models, and was distributed in 1990. A second edition of this report[1] was prepared in 1991, which updates and extends the previous report. It includes 62 models, each described in one or two pages, based on information mostly supplied by the modelers. These programs come from ten countries.

The intention has been to include computer programs relevant to fire protection *which are operational*, or soon to become operational. No attempt has been made to include programs currently under development, where there is uncertain as to when or if they will become operational. Some operational programs are listed in spite of their not being freely available. The survey indicates degree of availability in most cases.

Computer programs for calculating water flow through sprinkler piping systems have been deliberately excluded from the survey.

The purpose of this paper is to list the 62 models, divided into categories, and to provide a general discussion of models dealing with a growing, interacting fire in an enclosure. Details concerning the 62 models may be found in the survey report[1], available from Factory Mutual Research Corporation. Also, 12 additional models, more recently encountered, are added to the references in this paper (References 60-70).

The models are classified here as zone models for compartment fires, field models for compartment fires, submodels for fire endurance, submodels for evacuation of buildings, submodels for actuation of thermal detectors, fire-sprinkler interaction models, and miscellaneous models.

PRESENTATION OF MODELS

Table 1 lists 31 zone models relating to a fire in a compartment. (The distinction between zone models and field models is touched upon later.) These models come from 10 countries. Of the 31 models, 20 of them deal with only a single vented compartment, and the other 11 treat multiple interconnected compartments. Two models emphasize post-flashover; the others generally present the history of the fire both before and after flashover. In all cases, the user must be able to input a good deal of information about the heat release rate of the fire. All but six of these models are designed to run on a personal computer. The underlying physical assumptions of most of these models have a great deal of similarity. Some of the models, notably Hazard I, go further than others in predicting consequences of the fire, such as survival of building occupants.

Table 2 shows 10 field models for compartment fires. Two of these (FLOW3D and PHOENICS)

Table 1.

ZONE MODELS FOR COMPARTMENT FIRES

Model	Country of Origin	Reference	Runs on PC?	Comments
ARGOS	Denmark	67	Yes	Multi-compartment
ASET	U.S.	2	Yes	One room
ASET-B	U.S.	2	Yes	One room (BASIC source code)
BRI-2	Japan	3	Yes	Multi-compartment
CCFM.VENTS	U.S.	4	Yes	Multi-compartment
CFAST	U.S.	5	Yes	Multi-compartment
CFIRE-X	Ger./Nor.	6	Yes	One room
CiFi	France	7	No	Multi-compartment
COMPBRN-III	U.S.	8	Yes	One room
COMPF2	U.S.	9	Yes	Post-flashover
DACFIR-3	U.S.	69	No	Aircraft cabin
DSLAYV	Sweden	10	Yes	One room
FAST	U.S.	11	Yes	Multi-compartment
FIRAC	U.S.	66	No	Uses FIRIN, complex vent. systems
FIRIN	U.S.	65	No	Many rooms, ducts, fans, filters
FIRST	U.S.	12	Yes	One room
FISBA	France	13	No	One room
FPETOOL	U.S.	14	Yes	One room
HarvardMarkVI	U.S.	15	Yes	Multi-compartment
Hazard I	U.S.	16	Yes	Includes FAST and other models
HEMFAST	U.S.	62	Yes	Furniture fire in room
IMFE	Poland	63	Yes	One room; multiple vents
MAGIC	France	17	No	Multi-compartment
NRCC1	Canada	18	Yes	One room
NRCC2	Canada	19	Yes	For large office spaces
OSU	U.S.	68	Yes	One room
POGAR	Russia	64	Yes	One room
R-VENT	Norway	20	Yes	One room
SFIRE-4	Sweden	21	Yes	Post-flashover
WPI-2	U.S.	70	Yes	One room
ZMFE	Poland	63	Yes	One room

Table 2.

FIELD MODELS FOR COMPARTMENT FIRES

Model	Country of Origin	Reference	Comments
BF3D	U.S.	22	Treats buoyant heat-driven flow
FISCO-3L	Ger./Nor.	23	One room – runs on PC
FLOW3D	U.K.	24	General fluid-dynamics code
JASMINE	U.K.	25	Uses PHOENICS – treats radiation
KAMELEON E-3D	Norway	26	One room
KAMELEON II	Norway	26	Multi-compartment
KOBRA-3D	Germany	27	One room – no turbulence – runs on PC
PHOENICS	U.K.	28	General fluid-dynamics code
RMFIRE	Canada	29	One room – 2-D – B.F.C.
UNDSAFE	U.S./Japan	30	Treats buoyant, heat-driven flow

are general fluid dynamics codes which are usable as basic elements of models treating fire specifically. All these models except two rather limited ones (FISCO-3L and KOBRA-3D) require a much more powerful computer than a PC, and indeed could effectively use the most powerful computer available. The various field models originate in six countries.

Table 3.

SUBMODELS FOR FIRE ENDURANCE

Model	Country of Origin	Reference	Comments
CIRCON	Canada	31	Circular reinforced concrete columns
COFIL	Canada	32	Circular steel columns with concrete
COMPSL	Canada	33	Multilayer slabs
INSTAI	Canada	34	Insulated hollow steel columns
INSTCO	Canada	34	Insulated steel-concrete columns
NAT	France	35	–
RCCON	Canada	36	Rectangular reinforced concrete columns
RECTST	Canada	37	Insulated rectangular steel columns
SQCON	Canada	38	Square reinforced concrete columns
TASEF	Sweden	39	For 2-3 and axisymmetric shapes
TCSLBM	Canada	40	2-D concrete slab-beam assembly
WSHAPS	Canada	41	Protected W-shape steel columns

Table 4.

SUBMODELS FOR BUILDING EVACUATION

Model	Country of Origin	Reference	Comments
EESCAPE	Austria	42	
EVACNET+	U.S.	60	
EVACS	Japan	43	
EXITT	U.S.	61	
EXIT89	U.S.	44	
HAZARD I	U.S.	16	Includes an escape model

Table 5.

SUBMODELS FOR ACTUATION OF THERMAL DETECTORS

Model	Country of Origin	Reference	Comments
DETACT-QS	U.S.	45	Unconfined ceiling, arbitrary fire
DETACT-T2	U.S.	46	Unconfined ceiling, t^2 fire
LAVENT	U.S.	47	Includes ceiling vents, draft curtains
PALDET	Finland	48	Unconfined ceiling
TDISX	U.S.	49	Unconfined ceiling, treats flow transient

Table 3 shows 12 submodels for calculating the thermal response of various structural elements (circular, rectangular or W-shaped columns, or beams, or slabs) subjected to a known fire environment. Most come from Canada.

Table 4 lists six submodels for time to evacuate a burning building, based on assumed rates of movement of people through corridors, down stairways, etc. These come from three countries.

Table 5 presents five submodels for calculating the delay time for actuation of a ceiling-mounted thermal detector or sprinkler, for an assumed fire, mostly coming from the U.S.

Table 6 lists three models dealing with interaction of a sprinkler spray with a fire. These are all highly simplified, in that none of them adequately treat the interaction of the rising gases in a turbulent fire plume with the descending droplets and the accompanying entrained gases, so that the critical condition under which the droplets can just penetrate the fire plume and

Table 6.

FIRE-SPRINKLER INTERACTION MODELS

Model	Country of Origin	Reference	Comments
FISCO-3L	Norway	23	One-room field model including suppression
RADISM	U.K.	50	Zone model, includes venting
SPLASH	U.K.	51	Field model, no suppression

Table 7.

OTHER FIRE MODELS AND SUBMODELS

Model	Country of Origin	Reference	Comments
ASCOS	U.S.	52	Smoke control
FIREX-1.2	Ger./Nor.	27	Hydrocarbon fires: 8 scenarios
MFIRE	U.S.	53	Mine ventilation network
RISK-COST	Canada	54	Life and cost: multistory buildings
SMACS	U.S.	55	Smoke in HVAC system
SPREAD	U.S.	56	Spreading fire on wall
UFSG	U.S.	57	Upward wall fire spread
WALLEX	Canada	58	Window fire plume

reach the base of the fire can be predicted. (Models to treat this are under development at Factory Mutual Research and at the NIST Building and Fire Research Laboratory.)

Table 7 lists eight additional fire-related models, from four countries, which do not fit into any of the above categories. Three deal with smoke movement, two with flame spread on a wall, two with multi-story buildings, and one with hydrocarbon fires.

ZONE MODELS AND FIELD MODELS

A field model is two-dimensional or three-dimensional, divides the space of interest into thousands of cells, or elements, and generally requires a powerful computer.

A zone model is primarily one-dimensional, and divides the space of interest into a few zones. Often, a personal computer will suffice for the calculations.

The primary advantage of a field model over a zone model is that the former can provide detailed information on the fluid motions, while the latter cannot (except one-dimensionally). The primary advantage of a zone model is its relative simplicity, which permits the inclusion of more phenomena in a given zone model without becoming overwhelmed by complexity. Also, cases may be run far more rapidly and inexpensively.

At this time, zone fire models are more readily transferable from one organization to another than field models.

Neither field models nor zone models can currently make an accurate treatment of certain features of fires associated with the combustion process and with turbulence.

As one example of a zone model, consider a fire in a compartment with a vent. It is assumed that there is an upper zone containing hot fire products having uniform temperature and composition, and a lower zone containing air contaminated to some degree with fire products. The fire plume may be considered to be a third zone, the ceiling (and upper walls) a fourth zone, and the vent a fifth zone. Equations are written for transfer of mass and energy (and momentum, at the vent) between these various zones, and solved as a function of time. The ways in which the combustion rate may be introduced into the model are discussed later.

A second example of a zone model is a flame spreading up a wall. The wall is divided into three zones: a pyrolysis zone, a preheating zone above the pyrolysis zone, and ultimately a burned-out zone below the pyrolysis zone. The flame, which is taller than the pyrolysis zone, may be considered to be a fourth zone. As time continues, the zones move upward, heat flows into the interior of the wall, and the flame may change in size. Important features of the model are the rate of transfer of energy from the flame to the wall, the rate of re-radiation from the wall to the surroundings (a fifth zone?), and the rate of pyrolysis.

DISCUSSION OF A COMPUTER MODEL OF A FIRE IN A COMPARTMENT

The Inputs, Other Than the Fire Itself

The geometry of the fire compartment, as well as that of any connecting compartments of interest, must be specified. If a compartment of interest is not a simple box, but is irregular (e.g., a sloped or concave ceiling; a long corridor with or without bends; an open stairwell), a field model rather than a zone model may be required.

The thermal properties of the bounding surfaces (e.g., ceilings, walls) must be specified.

The location of the burning object or objects must be specified. If a burning object is elevated above the floor, this is relevant. A burning object next to a wall or in a corner will burn differently from one in the middle of the room. If the object is in the direct path of air flow (e.g., in front of an open door) this will make a difference.

The ventilation (natural, forced, or a combination) must be specified in detail.

The Fire

The fire may be specified in various ways.

A. In the simplest case, the fire is specified as starting at a certain time with a certain rate of heat release, and continuing at that rate for a specified interval, then stopping. The cross-sectional area of the base of the fire must be specified. It is also necessary to specify the rate of pyrolysis of the combustible and the stoichiometric fuel-air ratio. (The heat release rate, the pyrolysis rate, and the actual heat of combustion are interrelated, so knowledge of any two will define the third.)

B. The next level of complexity is to specify a fire with a heat release rate varying in a prescribed manner with time.

Certain fires may be accurately specified as constant or varying in a known manner. As one example, the fire may consist of the burning of a fluid leaking at a known rate. As a second example, the fire may be ventilation-controlled, and a knowledge of the rate of oxygen entry into the compartment will determine the rate of heat release. As a third example, the burning rate of the ignited object may be measured in the open, and it is assumed that it would burn at the same rate in the fire compartment. This may be somewhat valid for a burning object such as a "crib" of alternately stacked sticks, since the burning sticks in the interior of the crib cannot "see" the outside radiative environment.

Many burning objects *do* interact strongly with the surrounding radiative environment. Furthermore, the arrangement of combustibles is often such that the fire can spread. Some models assume a spread rate, as a function of radiative feedback. Finally, if the oxygen content of the air in the compartment is reduced by dilution with combustion products, or by descent of the smoke layer, the heat release rate will be reduced, and the fire may even self-extinguish. Thus, the type of model which requires the fire to be fully specified in advance is very limited in applicability. (Such a model could be used to make a *conservative* estimate of the fire consequence, by inputting the maximum conceivable heat release rate.)

C. More realism is added to the model if the input includes an instruction that the prescribed burning rate is reduced according to some formula as the percentage of oxygen decreases in the atmosphere surrounding the fire plume. This requires the computer program to keep track of the dilution of the incoming air by mixing with the fire products, and of the descent of the smoke layer.

In reality, for many solid combustibles, the burning mode will change from flaming to smoldering when the oxygen drops sufficiently. The rate of oxygen consumption in the smoldering mode will be much lower than in the former flaming mode, and as a result the oxygen level will then build up to a higher level. This may ultimately cause another transition, from smoldering back to flaming. The cycle may then repeat. The computer can accurately predict such behavior only if the input criteria for transition between flaming and smoldering, and vice versa, are correct.

Mixture of combustion products with the incoming air will not only reduce the oxygen percentage, but will also increase the temperature of the air. This would tend to modify the burning rate, and should be taken into account in a complete model.

D. The radiative feedback of energy from the compartment to the burning surface generally will have a major effect on the burning rate, and on the spread rate if spread is occurring. It is important in causing spontaneous ignition of noncontiguous combustibles.

The sources of this radiation are the hot smoke layer, the ceiling and upper walls, and the flame itself. The sensitivity of the burning of a sample to incident radiation is easily measured by a bench-scale experiment, for a simple combustible, and may be inputted into the model, but it is much more difficult for the model to calculate accurately the radiative flux impinging on the surface under radiative fire conditions.

The following difficulties exist.

a. The radiation intensity is proportional to T^4, so small errors in calculation of the temperature of the hot smoke or of the ceiling cause much larger errors in the radiant flux. (When re-radiation is taken into account, the *net* radiant flux may vary as about T^3.)

b. The temperature of the hot upper layer is sensitive to the amount of excess air entrained into the fire plume, and also to the rate of heat loss to the ceiling. Neither of these can be calculated with great accuracy, especially in a zone model.

c. The smoke not only emits radiation; it also absorbs and scatters radiation. In general, cooler smoke will be below the hot smoke, influencing radiation from above.

d. The "view factors" between the radiative sources and the targets require elaborate mathematical representation for accurate treatment.

e. The radiative properties of the smoke, the flame, the ceiling, and the targets must be accurately known.

f. Simple zone models do not take into account the fact that the region directly over the fire is much hotter than more remote upper regions, especially in large compartments. Field models can take this into account, but have to deal with the complexity that each of the thousands of elements in the field model can in principle exchange energy radiatively with all the other elements, instead of simply the immediate adjacent elements.

For these reasons, an accurate treatment of the radiative augmentation of burning rate or spread rate is hard to achieve.

E. The foregoing treatments of the burning rate usually assume that full-scale experimental results are available for burning rate of the combustible objects at least in the open. An alternative approach would be to use *bench-scale data* of relevant burning characteristics of the combustibles, using small samples.

One way of following this path is to measure properties such as time to ignition, rate of flame spread, and burning rate of small samples as functions of incident radiative flux and ambient oxygen percentage, and then to construct a semi-empirical model relating the full-scale burning to these data.

Another approach, which is generally preferred by fire scientists, is to do these same types of small-scale tests, and then analyze the results to obtain values for certain "basic" quantities. The next step is to develop a scientific (not empirical) theory of the full-scale burning in a compartment in terms of these "basic" quantities. When this is done, it is usually found that values for some additional "basic" quantities are needed. Delichatsios and Saito[57] have compiled a list of the quantities needed for a scientific model of upward flame spread over a charring surface:

a. the ignition (intensity, size, duration);
b. thermal conductivity, density and heat capacity of the virgin material and of the char;
c. surface temperature of the pyrolyzing surface;
d. surface reflectivity;
e. heat of gasification;
f. heat of combustion of pyrolysis gases;
g. combustion efficiency;
h. radiative fraction of flame heat output;
i. stoichiometric fuel-air ratio;
j. the fractions of toxic and corrosive gases in the combustion products.

This list is not definitive. It does not consider the heat of combustion of the char, which may be quite different from the heat of combustion of the pyrolysis gases. It may not be applicable to composite materials, e.g. laminates. It implicitly assumes that combustion efficiency and radiative fraction of flame heat output in a full-scale fire may be deduced from small-scale laboratory fires.

Many real-world combustibles are composite in nature. For example, a chair may consist of a wood frame, a polyurethane foam pad, and a vinyl outer covering, each of which burns at a different rate, has a different heat of combustion, requires a different stoichiometric amount of air, and produces different combustion products. As another example, the contents of a warehouse may consist of a plastic or flammable-liquid product in corrugated paper cartons supported on wood pallets. Accordingly, accurate modeling of composite combustibles may have to be based on realistic-scale tests more so than on small-scale data obtained from bench-scale tests, at least until further research progress occurs.

In summary, the input of the burning rate into any computer model of fire is often the most difficult and uncertain element of the model.

The Model Outputs

After the model has been provided with inputs as discussed above, a computation takes place, yielding various physical outputs versus time: temperatures and velocities at various locations; concentrations of smoke, oxygen, toxic species, corrosive species at various locations; and heat fluxes impinging on objects of interest. The model might then proceed to calculate *consequences* of these physical variables: for example, actuation times of detectors or sprinklers; feasibility of escape; feasibility of manual firefighting; thermal damage or corrosion or smoke damage to structural elements or critical equipment items; effectiveness of automatic suppression systems; etc. (Of course, in order to obtain outputs such as these, the locations and characteristics of the items of interest must be included in the inputs.)

Additional Uncertainties in Models

Uncertainties associated with burning rates (especially when the combustible is composite) and with radiative flux calculations have already been mentioned. Some other uncertain elements in fire models may be listed:

a. carbon monoxide by incomplete combustion;
b. entrainment rate into the plume;
c. mixing between hot and cold layers;
d. heat loss to the ceiling as a function of distance from the fire axis;
e. breakage of windows during fire;
f. smoke movement under conditions of other than box-like geometries;
g. flow through ceiling vents;
h. ignitability conditions of fuel-rich fire products encountering fresh air;
i. effects of fire products on humans.

Validation of Models

A model may not yield results in complete accord with actual fire behavior for any of five reasons: (1) idealizations and simplifications on which the model is based deviate significantly from reality; (2) input parameters supplied to the model are inaccurate; (3) "default" values of coefficients used internally in the model (because the user was unable to supply better values of these coefficients) are incorrect; (4) the computation process itself yields a wrong result, perhaps because the time steps or the mesh size used to approximate differential equations with finite-difference equations is not fine enough, or because of mathematical singularities or instabilities encountered; (5) the experimental measurements themselves are incorrect or non-repeatable.

Validation of a model involves comparison of model predictions with realistic fire tests. Very often, this involves "fine tuning" the model by adjusting uncertain values of input coefficients. Once the "tuned" model is brought into agreement with the measurements, the question remains as to the validity of the model when applied to a different set of conditions.

If the model can be shown to agree with a *series* of fire tests, with a wide range of conditions and with a minimum of "tuning", then one's confidence in the validity would be substantial. Even so, it would be risky to extrapolate to conditions drastically different from what has been tested.

Further Remarks on Assessing the Accuracy of a Model

If we look for a model to predict a certain quantified variable, such as temperature, velocity, CO concentration, or smoke density, at a specified location and time (or, the maximum value achieved by that variable), then, in principle, we may compare the prediction with a measured value of the variable in a full-scale test. Thus, we may express the accuracy of a model as a percentage deviation of prediction from measurement.

One problem with this is the cost of an adequate series of full-scale tests. A second problem is that the measurement itself may be in error, because of imperfect instruments. A third problem is that a given test may not be fully replicable. In spite of these problems, this is the usual method of assessing model accuracy.

There is another possible way to assess the accuracy of a model, other than looking at the percentage deviation between a measured and predicted variable. In many cases, what we want primarily from a model is a yes-no answer to a question such as the following: Will the radiation in the fire compartment be sufficiently intense to ignite a second object? Will the burning object cause the room to flash over? Will a relatively small fire be able to actuate a nearby sprinkler? Will an exposed beam fail, causing collapse? Will toxic conditions in a corridor near the fire compartment be such as to prevent escape through that corridor? What we really want to know is how often can the model give correct answers to such questions.

Let us assume for the moment that we have a model which is "perfect". That is, it precisely accounts for all the physical and chemical processes occurring, and treats these with perfect accuracy. Even so, it cannot always give reliable answers to yes-no questions such as listed above, because the model requires *inputs*, which will have uncertainties associated with them.

For example, we must tell the model the heat of combustion and the stoichiometric air requirements of the burning material. If the burning object is an upholstered chair consisting of wood, polyurethane foam, and vinyl exterior, each of these has different thermodynamic properties and all may be burning at once. There will be some uncertainty in the relative contributions of each material at each instant.

Again, we must input the "thermal inertia" of the ceiling. Assume it is gypsum board of known thickness. However, it will contain a certain percentage of absorbed moisture, depending on its previous history before the fire, which we do not know. Thus its thermal inertia is uncertain.

An even simpler example is the initial temperature of the fire compartment, which may not be known.

Recognizing this type of uncertainty, let us consider Figure 1.

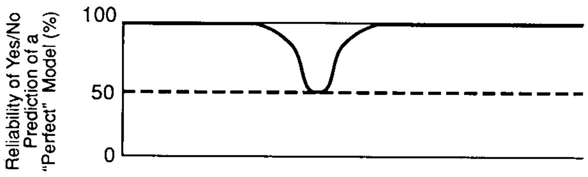

Figure 1. Value of an important input parameter. Reliability of the prediction of a "perfect" model.

Here we see that the yes/no prediction of our "perfect" model is only uncertain in a limited region of input parameter values. If we happen to be at the most sensitive point, the model's reliability is only 50% in regard to the yes/no question, which is, of course, no better than a random guess. However, if we are well away from this most sensitive value of the input parameter, we see that the model always gives 100% reliabe answers. If we had this perfect model, then the important questions would be, how wide is this zone of uncertainty of the important parameter and where is this zone located.

Answers could readily be found for both these questions, if there were only one important uncertain input parameter. However, in general, there will be a number of such input parameters. If there were N such parameters, Figure 1 would have to be plotted in N+1 dimensional space. But, the principles would be the same. For certain combinations of input parameters, the model would give unreliable predictions, while, outside this region, the model would be correct. (There are mathematical techniques for handling the multi-dimensionality.)

Let us turn now to consideration of a practical model rather than a perfect model. The practical model will still have the uncertainties of the input parameters, but will have additional uncertanties associated with its numerical techniques (e.g., approximating continuous time by finite steps, and finite mesh size in field models) and, more importantly, major uncertanties may be introduced because of simplified representations of the physics and chemistry. In field models, these simplifications might arise in the treatment of turbulence and the treatment of radiative transfer. In zone models, the simplifications are principally the assumption of uniformity within each zone and the assumption that entrainment, vent mixing, heat transfer, etc. can be represented by known formulas. In both types of models, simplified means of representing flame spread, burning rate, remote secondary ignition, etc. must be used.

Accordingly, the zone of uncertainty of an actual model concerning a yes/no question will be more like Figure 2 than Figure 1. A fairly broad, but finite, region will exist in which the yes/no answer is no better than 50% reliable. However, outside this region the model will be quite accurate.

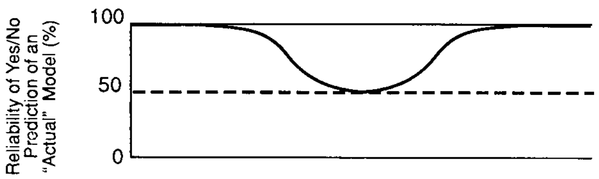

Figure 2. Value of an important input parameter. Reliability of the prediction of an actual model.

These considerations suggest the following methodology for assessing reliability of the model. Suppose we want to know if a 250 kW fire will cause flashover in a given room. We reformulate the question by asking the model to calculate the critical size of fire which will just cause flashover in the room.

Suppose the model gives us an answer of x kW. We now calculate the quantity 100 (x – 250)/250. This is the percentage by which the calculated critical size exceeds 250 kW. If this is a "large" percentage, compared with the estimated percentage variation caused by the uncertainties of the model, we conclude that the model can tell us reliably whether 250 kW will result in a flashover.

What remains is to estimate *how large* the percentage variation must be to permit us to trust the prediction. It is a major challenge for fire scientists to develop techniques for making such estimates.

REFERENCES

1. Friedman, R., *An International Survey of Computer Models for Fire and Smoke* (Second Edition, Dec. 1991). 89 pp. Available from Library, Factory Mutual Research

Corporation, 1151 Boston-Providence Turnpike, Norwood, MA 02062, USA.

2. Cooper, L.Y. and Stroup, D.W., "ASET-A Computer Program for Calculating Available Safe Egress Time," *Fire Safety Journal*, **9**, 1985, pp. 29-45.
3. Tanaka, T., *et. al.*, "Predicting Capability of a Multiroom Fire Model," *Proceedings of the Second International Symposium on Fire Safety Science*, 1988.
4. Cooper, L.Y. and Forney, G.P., *The Consolidated Compartment Fire Model (CCFM) Computer Code Application CCFM. VENTS*, Parts I, II, III, and IV, NISTIR, National Institute of Standards and Technology, Gaithersburg, MD, 1990.
5. Jones, W.W. and Forney, G.P., *A Programmer's Reference Manual for CFAST, the Unified Model of Fire Growth and Smoke Transport*, National Institute of Standards and Technology, Gaithersburg, MD, Tech. Note 1283, 1990.
6. Battelle Institute; Federal Republic of Germany; and SINTEF (Norway).
7. Bodart, X., and Curtat, M., CSTB-77420. Champs Sur Marne, France.
8. Apostolakis, G., Univ. of California at Los Angeles. 1985.
9. Babrauskas, V., and Williamson, R.B., "Post-Flashover Compartment Fires – Application of a Theoretical Model, *Fire and Materials*, **3**, 1-7, 1979.
10. Hägglund, B., and Karlsson, B., Dept. of Fire Safety Engineering, Lund Univ., Lund, Sweden, 1988.
11. Jones, W.W., and Peacock, R.D., "Refinement and Experimental Verification of a Model for Fire Growth and Smoke Transport," *Second International Symposium on Fire Safety Science*, 1988.
12. Mitler, H.E., and Rockett, J.A., *Users' Guide to FIRST, a Comprehensive Single-Room Fire Model,* NBSIR 87-3595, National Bureau of Standards, Gaithersburg, MD, 1987.
13. Curtat, M., Bodart, X., Fromy, P., and Beyhom, A., *Revue Generale de Thermique*, May 1988.
14. Nelson, H.E., *FPETOOL: Fire Protection Engineering Tools for Hazard Estimation*, NISTIR Report 4380, National Institute of Standards and Technology, Gaithersburg, MD.
15. Rockett, J.A., 4701 Alton Place, N.W., Washington, DC.
16. Peacock, R.D., Jones, W.W., Bukowski, R.W., and Forney, C.L., NIST Handbook 146, *HAZARD-I Fire Assessment Method*, 1991.
17. Ronger, F.X., *et. al.*, Electricite de France.
18. Takeda, H., and Yung, D., "Simplified Fire Growth Models for Risk-Cost Assessment in Apartment Buildings, *Journal of Fire Protection Engineering*, **4**, 2, 1992.
19. Takeda, H., National Fire Laboratory, National Research Council of Canada, Ottawa.
20. Meland, O., and Skaret, E., SINTEF, Trondheim, Norway, 1987.
21. Magnusson, S.E., and Thelandersson, S., Department of Fire Safety Engineering, Lund Univ., Sweden.
22. Baum, H.R., and Rehm, R.G., "Calculations of Three-Dimensional Buoyant Plumes in Enclosures," *Combustion Science and Technology*, **40**, 1984, pp. 55-77.
23. Scheider, V., and Hoffmann, J., "Modelluntersuchung von Offshore-Kohlenwasserstaff-Bränden Feldmodellierung von Löschversuchen," Intellex, Frankfort am Main, Germany.
24. Computational Fluid Dynamics Services, 1700 N. Highland Rd., Pittsburgh, PA 15241, USA.
25. Cox, G., and Kumar, S., *Combustion Science and Technology*, **52**, 1987, p. 7.
26. Magnussen, B.F., NTH/SINTEF, Trondheim, Norway, 1990.
27. INTELLEX, Bettinastrasse 14-16, W-6000 Frankfurt am Main 1, Germany.
28. Markatos, N.C., Malin, M.R., and Cox, G., *International Journal of Heat and Mass Transfer*, **25**, 1982, pp. 63-75.
29. Hadjisophocleous, G.V., Institute for Research in Construction, National Research Council of Canada, 1991.
30. Satoh, K., Fire Research Institute of Japan, Tokyo.
31. Lie, T.T., and Celikkol, B., "Method to Calculate the Fire Resistance of Circular Reinforced Concrete Columns," *ACI Materials Journal*, **88**, 1, 1991.
32. Lie, T.T., and Chabot, M., "A Method to Predict the Fire Resistance of Circular Concrete-Filled Hollow Steel Columns," *Journal of Fire Protection Engineering*, **2**, 4, 1990.
33. Lie, T.T., "Calculation of the Fire Resistance of Composite Concrete Floor and Roof Slabs," *Fire Technology*, **14**, 1, Feb. 1978.

34. Lie, T.T., "Model for the Calculation of the Fire Resistance of Insulated Circular Hollow Steel Columns," *Fire and Materials*, **8**, 1, 1984.
35. Curtat, M., CSTB-77420. Champs Sur Marne, France.
36. Lie, T.T., and Irwin, R.J., Institute for Research in Construction, National Research Council of Canada, 1990.
37. Lie, T.T., "Temperature Distribution in Fire-Exposed Building Columns, *Journal of Heat Transfer (ASME)*, **99**, 1, 1977.
38. Lie, T.T., Lin, T.D., Allen, D.E., and Abrams, S., *Fire Resistance of Reinforced Concrete Columns*, DBR Paper No. 1167, National Research Council of Canada, Ottawa, 1984.
39. Wickström, U., Swedish National Testing and Research Institute, Boras, Sweden, 1990.
40. Sultan, M.A., Lie, T.T., and Lin, J., *Heat Transfer Analysis for Fire-Exposed Concrete Slab-Beam Assemblies*, Int. Report No. 605, Institute for Research in Construction, National Research Council of Canada, 1991.
41. Lie, T.T., and Almand, K.H., "A Method to Predict the Fire Resistance of Steel Building Columns," *Engineering Journal*, **27**, 4, American Institute of Steel Construction , 1990.
42. Kendik, E., "Determination of the Evacuation Time Pertinent to the Protected Area Factor in the Event of Total Evacuation of High-Rise Office Buildings via Staircases," *Fire Safety Journal*, **5**, 1983, p. 223.
43. Tanaka, T., and Takahashi, K., "An Evacuation Model for Use in Fire Safety Design of Buildings," *Second International Symposium on Fire Safety Science*, 1991.
44. Fahy, R.F., "EXIT 89 – An Evacuation Model for High-Rise Buildings," *Third International Symposium on Fire Safety Science*, 1991.
45 Evans, D.D., and Stroup, D.W., "Methods to Calculate the Response Time of Heat and Smoke Detectors Installed Below Large Unobstructed Ceilings," *Fire Technology*, **22**, 1986, pp. 54-65.
46. Evans, D.D., Stroup, D.W., and Martin, P., *Evaluating Thermal Fire Detection Systems*, NBS SP 713, National Institute of Standards, Gaithersburg, MD, 1986.
47. Davis, W.D., and Cooper, L.Y., "A Computer Model for Estimating the Response of Sprinkler Links to Compartment Fires with Draft Curtains and Fusible Link-Actuated Ceiling Vents," *Fire Technology*, **27**, 1991, pp. 113-127.
48. Kokkala, M., and Björkman, J., VTT Technical Research Centre of Finland, Fire Technology Laboratory.
49. Yu, H-Z, Factory Mutual Research Corporation, Technical Report J.I. OR2E1.RA, Norwood, MA, 1991.
50. Hinckley, P.L., *Fire Safety Journal*, **14**, 1989, pp. 221-240.
51. Gardiner, A.J., *The Mathematical Modeling of the Interaction Between Sprinkler Sprays and the Thermally Buoyant Layers of Gases from Fires*, Ph.D. Thesis, South Bank Polytechnic, London, 1988.
52. Klote, J.H., "Computer Modeling for Smoke Control Design," *Fire Safety Journal*, **9**, 1985, pp. 181-188.
53. Chang, X., Laage, L.W., and Greuer, R.E., *User's Manual for MFIRE: A Computer Simulation Program for Mine Ventilation and Fire Modeling*, U.S. Bureau of Mines IC9254, 1990.
54. Yung, D., Hadjisophocleous, G., and Takeda, H., Institute for Research in Construction, National Research Council of Canada, Ottawa, 1989.
55. Klote, J.H., *Fire Technology*, **24**, 1988, pp. 299-311.
56. Mitler, H.E., "Predicting the Spread Rates of Fires on Vertical Surfaces," *23rd International Symposium on Combustion*, The Combustion Institute, Pittsburgh, PA, 1990, p. 1715.
57. Delichatsios, M.A., and Saito, K., "Upward Fire Spread: Key Flammability Properties, Similarity Solutions and Flammability Indices," *Fire Safety Science – Proceedings of the Third International Symposium*, 1991.
58. Oleszkiewicz, I., "Heat Transfer from a Window Fire Plume to a Building Facade," *ASME Collected Papers on Heat Transfer –* 1989, HTD, **123**, 163-170, New York.
59. Walton, W.D., "A Room Fire Program for Personal Computers," *Fire Technology*, **21**, 1985, pp. 293-309.
60. Kisko, T.M., "Network Models of Building Evacuation," NBS-GCR-85-489, Gaithersburg, MD, 1985.
61. Levin, B.M., "EXITT-A Simulation Model of Occupant Decisions and Actions in Residential Fires," *Intl. Assn. for Fire Safety Science, Second Intl. Symposium*, pp. 561-570.
62. Dietenberger, M.A., *Validated Furniture*

Fire Model with FAST (HEMFAST). NIST-GCR-89-564, 84 pp., 1989.

63. Wolanin, J., and Ciara, W., Science and Research Center for Fire Protection, 05-420 Jozefow, ul. Nadwislanska, 213, Poland, 1986.
64. Astapenko, V., Koshmarov, Y., Molchadski, I., and Shevlyakov, A., *Termogazodinamic of Fires in the Rooms*, Moscow, Stroiizdat, 1988, 448 pp. (from Higher Engineering Fire-Technical School, Moscow).
65. Chan, M.K., Ballinger, M.Y., Owczarski, P.C., and Sutter, S.L., *User's Manual for FIRIN 1: A Computer Code to Characterize Accidental Fire and Radioactive Source Terms in Nuclear Fuel Cycle Facilities*, Battelle Pacific Northwest Lab Report PNL-4532, NUREG/CR-3037 (Dec. 1982). Also Claybrook, S.W., *FIRIN Preprocessor User's Manual*, Numerical Applications, Inc., Richland, WA 99352, Nov. 1991.
66. Nicholas, B.D., and Gregory, W.S., *FIRAC User's Manual: A Computer Code to Simulate Fire Accidents in Nuclear Facilities*. NUREG/CR-4561, LA-10678-M. Los Alamos Natl. Lab, 1986.
67. Danish Institute of Fire Technology, *ARGOS User's Guide*, 1991, and *ARGOS Theory Manual*, 1992. Datovej 48, DK 3460 Birkeroed.
68. Sauer, J.M., and Smith, E.E., "Mathematical Model of a Ventilation-Controlled Compartment Fire," *Journal of Fire Sciences*, **1**, 1983, pp. 235-254.
69. MacArthur, C.D., *Dayton Aircraft Fire Cabin Model*, Version 3. U.S. Dept. of Transportation, Atlantic City, NJ, DOT/FAA.CT-81/69-I. June 1982, 52 pp.
70. Satterfield, D.B., and Barnett, J.R., *User's Guide to WPI-HARVARD Version 2 (WPI-2) – A Compartment Fire Model*. Worcester Polytechnic Institute, Center for Firesafety Studies, Worcester, MA, Aug. 1990.