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Predicting Fire Hazards to Building Occupants

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I'm going to show you some of the progress we've made in establishing an organized body of knowledge, which we call fire science, and how this technology benefits both American society and American industry.

As John Lyons mentioned in his opening remarks yesterday, the Bureau of Standards goes back to 1901. Our involvement in fire research goes back almost that far, to 1904, when a fire erupted on the west side of the City of Baltimore and spread steadily to the east, destroying some 25 percent of the city (fig. 1). It finally was stopped by the local fire department, while the fire departments from surrounding cities and counties stood by and watched. They had arrived at the scene with their equipment, but their hoses wouldn't connect to the Baltimore City water supply.

Shortly thereafter, the Bureau was asked to develop standard threads so that one could make adaptors for connecting foreign hoses to local water supplies. It turns out this played a significant role in eventually controlling the large Berkeley Hills fire just a few weeks ago.

Since then, there have been a number of pieces of legislation which installed at this location a variety of duties involving various aspects of fire, the latest of those being the Fire Safe Cigarette Act of 1990.

While the history of fire studies at NBS/NIST goes back to some fairly routine determinations some 87 years ago, the scientific quality of the work required to do the more recent legislative challenges has been

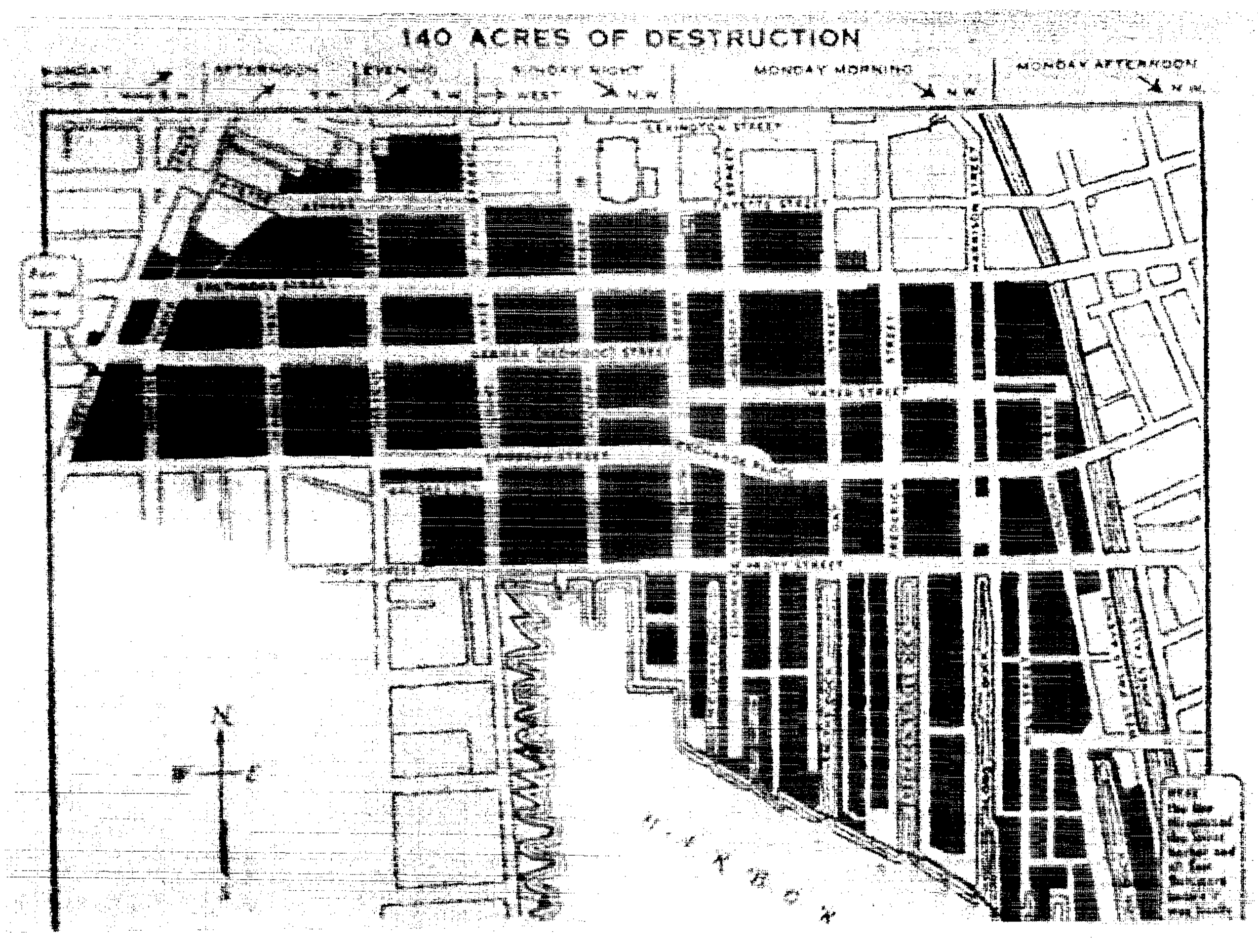

Figure 1. Fire in Baltimore, MD, in 1904. The fire spread from the west side of the city (left) to the east. Reprinted with permission from the National Fire Protection Association [1].

remarkably higher, and I'd like to give you a flavor of some of that today.

At this point the NIST organization is, in fact, the main source worldwide for new science and methods for understanding the phenomenology of fire.

The reason for the continued legislative activity is that the costs of fire in this country are extremely high. In 1990, over 4,000 people died and 125,000 were seriously injured [2]. To put this in perspective, during the course of the Vietnam War more people died and were injured in fires stateside than were killed or injured in combat.

The other component of the profile is even more startling. A recent survey of the totality of fire costs and losses showed that annually we ring up a burden on the economy of $128 billion or so (Table 1). In remarks at a meeting of the National Fire Protection Association, John Lyons pointed out that this is approximately 2.5 times the total world semiconductor market. One could also say that this amounts to a savings and loan bailout every year.

Table 1. Effects of fire on the U.S. population [3]

ANNUAL ECONOMIC COSTS OF FIRE ($ Billions)	
Losses	31
Insurance Premiums	6
Fire Service	43
Preventative Measures	48
	128

For industrial firms this takes a variety of different forms. Obviously there are direct losses—plants destroyed, stock damaged and so forth. Inevitably, when there is a fire of even modest size, immense amounts of litigation ensue and, in the course of that, enough mud gets slung back and forth so it's not uncommon for the firm involved to also suffer a loss of public image, which often has a negative impact on sales in the future. There is certainly a loss of competitive position while a firm gets back on its feet again, and there are documented cases where, as a result of single fire, even medium-sized companies have been forced into total bankruptcy [2].

Perhaps the best example of this kind of industrial deterioration comes from a fire about two years ago in Pasadena, Texas, in which a high-density polyethylene plant went up in flames—a plant that produced approximately one-fifth of the nation's output of that material. The direct fire losses for that were of the order of $750,000. The total cost, some of which includes the fact that the owner of the plant had to give away certain proprietary information to its competitors in order to meet their customers' needs, the total cost is estimated to run upwards to the order of $3 billion. That's a single incident.

There are multiple contributions to this kind of fire loss. The first is the design of the building. Figure 2 presents a dizzying view from the top of the Empire State Building looking down the side, and the crunched-up foreign object you see is a B-25 bomber that on a foggy day in 1945 parked itself in the 78th and 79th floors, dumping over a thousand gallons of aviation fuel. The fire that resulted was incredibly intense, but because the Empire State Building is built of what we refer to as fire-rated, or fire-resistive, construction, the fire was contained and there was limited loss of life. The rest of the building resumed business shortly thereafter.

By contrast, much more recently, there was a fire in the Dupont Plaza Hotel in San Juan, Puerto Rico. The fire resistance barriers were not present in all places. The fire spread quite rapidly and there were 96 fatalities (fig. 3).

Compliance with the general guidelines for fire-resistive construction, the basis for which was done here at NBS, at the old Van Ness Site, isn't enough.

In 1946, there was a classic example of a hotel fire, the LaSalle Hotel in Chicago, which met all the fire-resistive construction requirements. However, the fuel-loading of interior finish materials was sufficiently high that despite this kind of highly efficient evacuation, some 61 people didn't get to evacuate (fig. 4).

Figure 5 is a nighttime picture of the First Interstate Bank Building in Los Angeles in 1988. It provided a beacon that could be seen for long distances. This fire erupted on the 12th floor of the building. The main fuel for this was the furnishings and the building contents—the work stations, paper, et cetera. This fire was sufficiently intense that it blew out windows on the 12th floor and spread through the outside to the next, and the next, and the next floor, before it was finally controlled.

Add to these physical factors the human behavior aspects—that is, the actions that people take or are able to take—which often affect survivability, and one has an extremely complex process to be mitigated. And yet it makes good sense, in hindsight in 1991, that if we could predict the outcome of a fire, for instance in this room, and the changes in the outcome of that fire that might result if we made some changes in this room, we would, in fact, be in an ideal position to make intelligent decisions that would reduce the losses and reduce the burden, both on the occupants and on the commercial entities involved in the structure.

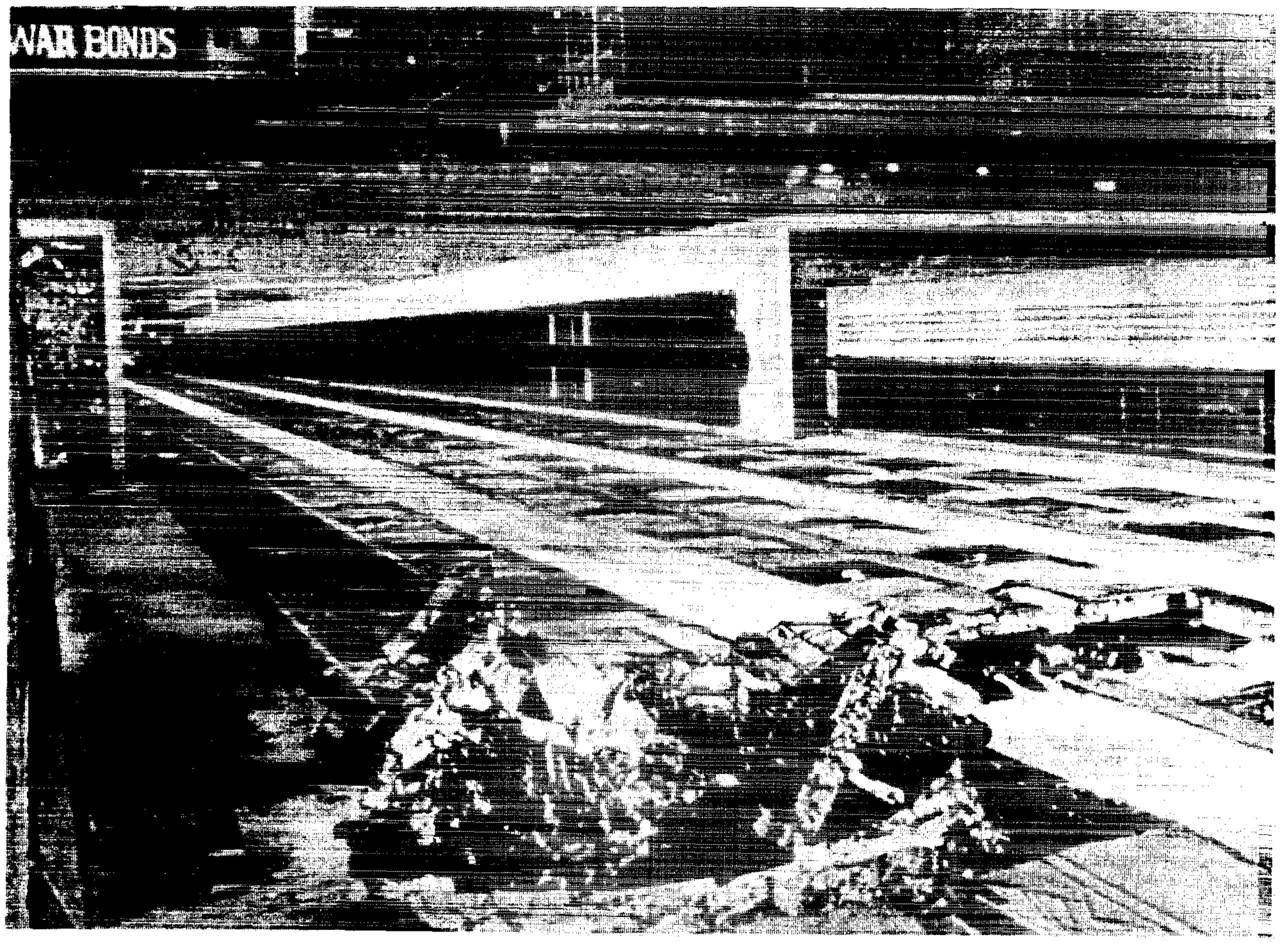

Figure 2. Crash of a B-25 bomber into the Empire State Building. Reprinted with permission from NFPA [1].

The technique for making these analyses we refer to as "fire hazard analysis," in which is included fire hazard modeling. As recently as 1988—that's 3 years ago—top-line professionals in the fire protection community were not making decisions to move ahead with this, because "it was a technology that would not be available until the next century." Approximately 1 year after those pronouncements were made, NIST released *Hazard I*, the first computer-based fire hazard assessment methodology [5]. It was developed by a team here within the Building and Fire Research Lab. It was recognized worldwide very rapidly. Over 400 copies are now in distribution around the world, and that work has been recognized by the award of a Department of Commerce Silver Medal for the team.

As complex as it is—and the complexity of the phenomena in this rivals the complexity of the analyses for the safety of nuclear power plants—this type of analysis is runable on a desktop computer.

The response to this has been remarkable. The EC-92 commission, putting together the unified fire criteria for the European Community, perhaps in 1992, perhaps at some later date, set an early goal that all fire tests selected should be consistent with fire hazard analysis and should provide the data needed for that kind of modeling.

The Japanese Building Research Institute of their Ministry of Construction has also established such a policy and even some procedures.

The Australians are moving in a similar direction, and other countries are also moving likewise. This is, in fact, the way of the future.

What we have, then, is a complex new technology that combines the elements of fundamental understanding of fire phenomena with some engineering-based estimation and the most modern of computerization techniques in modeling of those phenomena. It's going to allow us to move from a situation like the one shown in figure 6, where we have a sofa just barely ignited, developing to

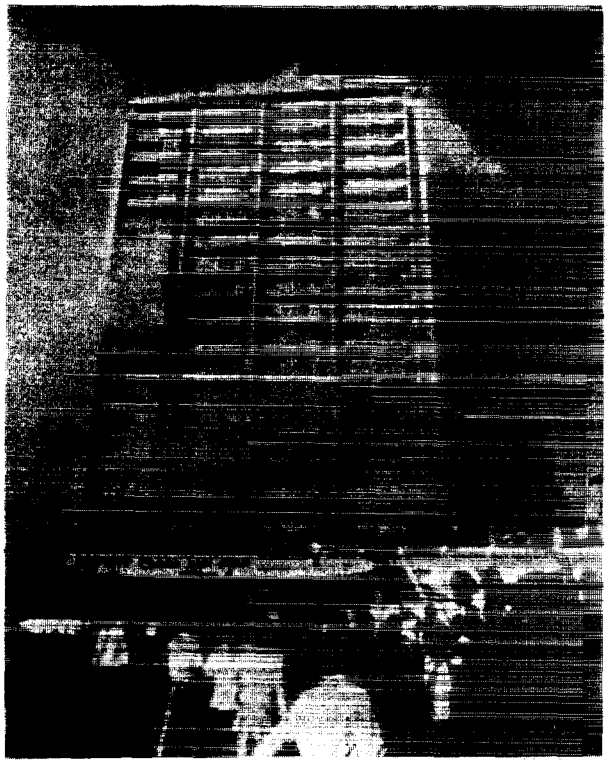

Figure 3. Dupont Plaza Hotel fire, San Juan, Puerto Rico. Reprinted with permission from NFPA [4].

Figure 4. LaSalle Hotel fire, 1946, Chicago, IL. Reprinted with permission from NFPA [1].

the condition shown in figure 7, and being able to predict the outcome and the impact of this degree of complex burning.

In laying out what a fire hazard model or fire hazard analysis entails, let's first take a quick look at the kinds of hazards that we're interested in.

The first and the most obvious is that which results from heat—burn injuries, buildings being burned to the ground, and so forth. In reality, however, some 70 percent of fire deaths result from the inhalation of smoke and toxic gases, a very interesting result that was established not that many years ago by a team from the Johns Hopkins University Applied Physics Lab based on an extensive study of State of Maryland fire fatalities. There have been other studies elsewhere in the world that have confirmed that general conclusion [6].

The smoke that's produced not only has this potential impact on people; it also has potential impact on things. Imagine a warehouse full of electronic equipment being blanketed with a very permeating smoke that has an acid character to it and a lot of warm moisture. It's not too hard to imagine that there could well be significant damage to electronic components, connectors and so forth.

In addition, the smoke, by dint of the very blackness that we saw in figure 7, provides a barrier to people getting out of buildings and also to the fire service coming in to do their job at locating the fire and quenching it.

The prediction of these kinds of hazards requires a systematic approach so that various people—corporate entities, regulators, scientists and building and product specifiers—all use the same approach towards reaching their decision as to what constitutes a worthwhile thing to do, a worthwhile product to buy, or a worthwhile product to sell.

And so, working with our colleagues, we have arrived at a four-step process.

The first step is to be very explicit about defining the problem that you're interested in. For the sake of discussion let's presume that I'm a manufacturer of upholstered furniture, and I'm interested in whether or not my new design is going to be sufficiently less fire-prone and contribute sufficiently less to a fire, should there be one, that in fact it's worth selling as such a product.

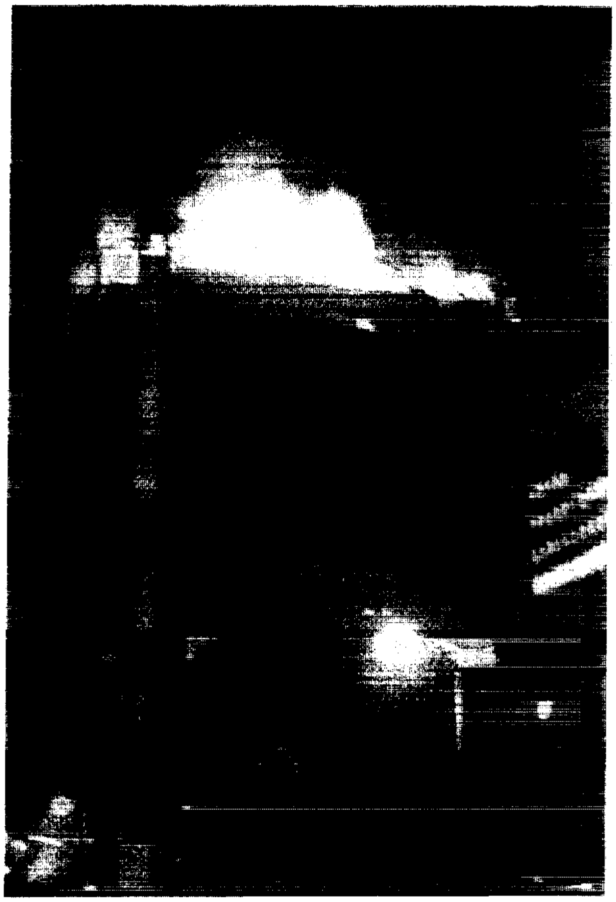

Figure 5. First Interstate Bank Building fire, Los Angeles, in 1988.

Figure 6. Sofa igniting (far right). NIST photo.

Figure 7. Same sofa with developed fire. NIST photo.

I've now defined the kind of problem that I'm interested in, in my terms. I now have to define it in terms that allow me to do this calculation. Where are my chairs going to be used? Auditoriums? Homes? Hotel rooms? Office buildings? Who are the people who are likely to be there? Are they likely to be awake, asleep, handicapped? At what time of day might I expect these fires to be present and to be of serious concern? (Obviously some office buildings, not like the laboratories at NIST, are unoccupied at night.)

Having now defined my problem and the situations that I'm interested in, I now proceed to the software, the equations, and I calculate the outcome of the fires for the products as they exist now and my comparative product that I'm either dreaming of or that maybe I've worked up in my pilot area.

Having done that, I now compare the results and I'm in a position to make a decision. The decision may be to go ahead, or it may be to drop this whole idea.

Now, it sounded very simple to just calculate the outcome of the fire. In fact, that is a massive undertaking if one tries to do this by hand. The software, which combines the best in fire phenomenology to date with some truly innovative computational techniques and some pretty nice graphics, requires that one do a certain amount of input to represent the fire phenomena.

Figure 8 is a pretty simple sketch. We've got, at the bottom right of this figure, some fairly benign flows coming in, but they still have to be treated quite accurately. The fluid mechanics change abruptly when one gets in the vicinity of the flames; and when one gets into the post-flame region, there is an immense amount of chemistry going on. The effect of the turbulence on that chemistry, at this point, is known to be important, but we don't know how to do it.

Down at the bottom of the figure we've got this fuel that's represented by a funny-looking arrow. There are real materials that are burning down there, and that has to be represented somehow in this computation.

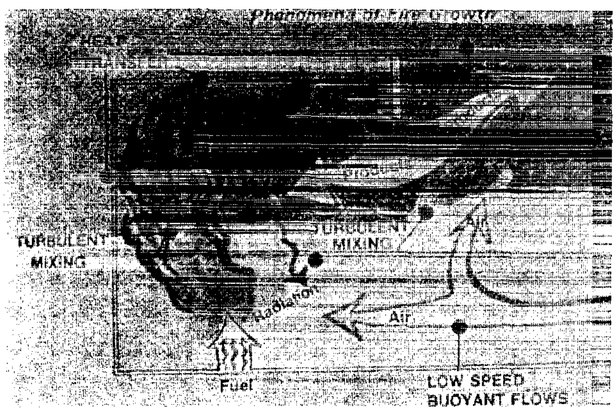

Figure 8. Preliminary sketch used for input to computerized fire analysis software.

While all this is going on, the temperature field under which the chemistry takes place and under which the fluid mechanics takes place is also changing. There are radiative losses, there are convective losses to the walls, and in some cases even conductive losses.

Therefore, to do this computation, one has to enter a description of the enclosure and, of course, the occupants who might be nearby. One has to describe at the beginning what the fuels are, where they are, and then compute as a function of time the fire growth, as the first item burns, perhaps spreads to the second, and so forth. One has to be able to compute the smoke and heat that are generated and how and where they move to, and then the impact on people.

Now, that list is overwhelming. That's a huge amount of both science and in some cases straight-out guesswork. But our capabilities over the last few years have grown remarkably. We're now in the position where we can predict a wide variety of aspects of smoke and heat movement throughout the building, and I'm going to show you some examples in a few moments. In those cases where the airflow into the fire room is insufficient for the combustion to go to completion, we have ways of approximating that vitiated burning. We can handle the rate of enthalpy transfer within the room. We can model what happens to the smoke particles after they leave the flame and as they change character when they move further and further away and cool off. And thanks to some excellent work done under grant by staff at the University of Washington, Seattle, we have a set of guidance rules for how families will behave when a fire hits their residence. And yet this still isn't enough to do the kinds of prediction that we want to be able to do. We want to be able not only to predict the course of the fire in its detail, but we also need to be able to predict what happens when you try to intervene. What happens when the sprinklers activate, and so on?

Let me give you an idea of some of the kinds of insights that are being worked on now to provide some of that future capability.

By far, the most important thing to a material or product manufacturer is to be able to predict how his product is, in fact, going to behave were it involved in a fire. Figure 9 is the output of some work by Takashi Kashawagi and his group in which they've determined what happens experimentally to the rate of flame spread as one starts to change the specific properties of the polymer, in this case the molecular weight [7].

Concurrent with that, Mark Nyden is doing some computational molecular dynamics on polymers [8]. Figure 10 shows seven ideally lined-up polyethylene molecules—red carbons, green hydrogens. He has instantaneously heated those, and he gets one of two different kinds of results depending on the chemistry and the specifics of the bonding that he's put into the model. In the upper case you can see fragments flying off into the gas phase very soon after the heat is applied. Those molecules flying off become legitimate fuel for the flames. By contrast, in the lower case, everything is still clustered together and, in fact, the white marked atoms have cross-linked, forming a char and greatly reducing the amount of fuel available for the fire.

We're also interested in and in need of a way of predicting the soot and the smoke. Kermit Smyth and his team have been looking at laminar diffusion flames, monitoring the detailed chemistry and chemical profiles enroute to a full chemical model of how soot is formed in those flames [9]. At some later date, the next move is to superimpose on that the turbulence that we saw in that earlier schematic and determine how that affects the chemistry, both the yields and the types of products coming out.

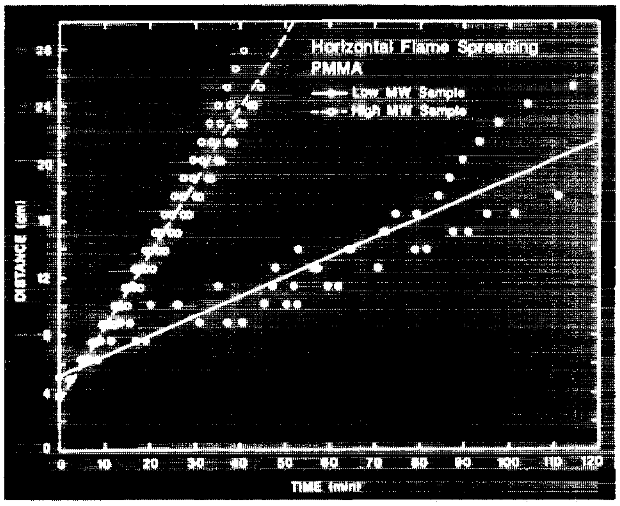

Figure 9. Effects of polymer properties on rate of flame spread.

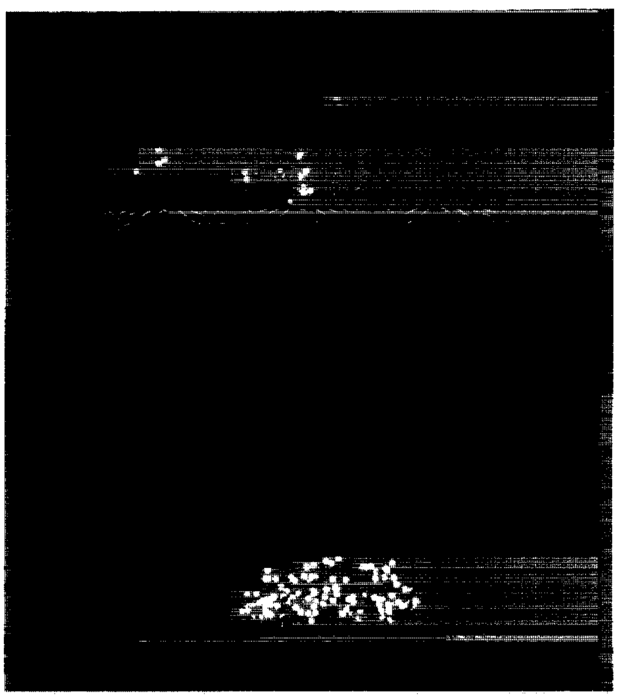

Figure 10. Effects of chemistry and bonding of polymer molecules on fire retardance.

In a particularly interesting paper, George Mulholland, Ray Mountain, and Howard Baum developed a model for the agglomeration of soot as the particles move away from the fire zone [10]. In figure 11 you can see on the right what their model predicts for arrays of small, spherical particles as they stick together. On the left are actual electronmicrographs of soot from an acetylene flame, and the similarity is remarkable.

The modeling that's been done to date generally applies to modestly sized rooms, generally the kind one finds in residences. As we go to larger structures, buildings with long corridors or large rooms, it's important to know how rapidly the smoke front, and therefore the heat and toxic gas front, moves down the corridor. What you see in figure 12 is the result of a collaboration by Howard Baum and Ron Rehm. It's a time sequence of the movement of a smoke plume down a long corridor. The colors represent different temperatures, the hot pink on the left being the warmest smoke and the light blue on the right being the coolest.

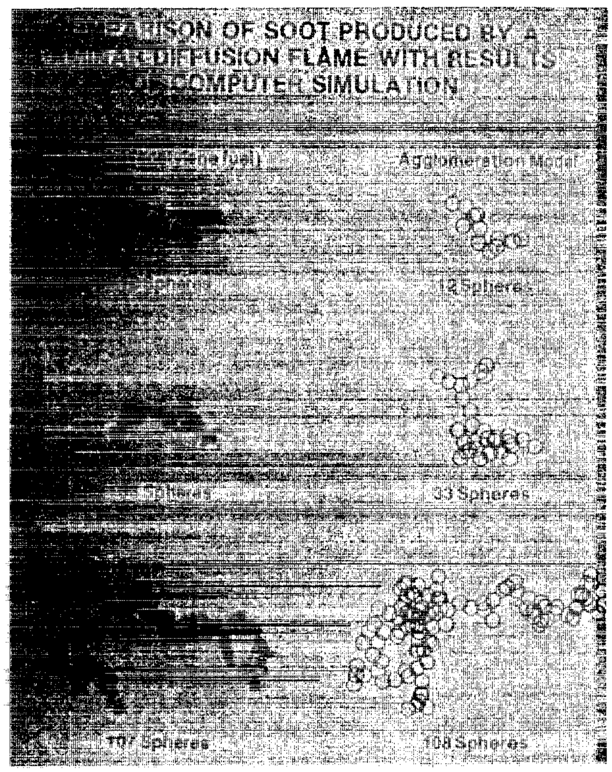

Figure 11. Predicted and actual soot agglomerates.

Experiments under grant from NIST at the California Institute of Technology have reproduced this phenomenon, and the agreement in the rate at which that smoke front moves between the model and the experiments is of the order of 2 percent.

Still on the horizon is a phenomenon that's absolutely essential, and that is, given the fact that we have a room burning like that and the sprinklers come on, how does the fire go out? We know that it doesn't go out

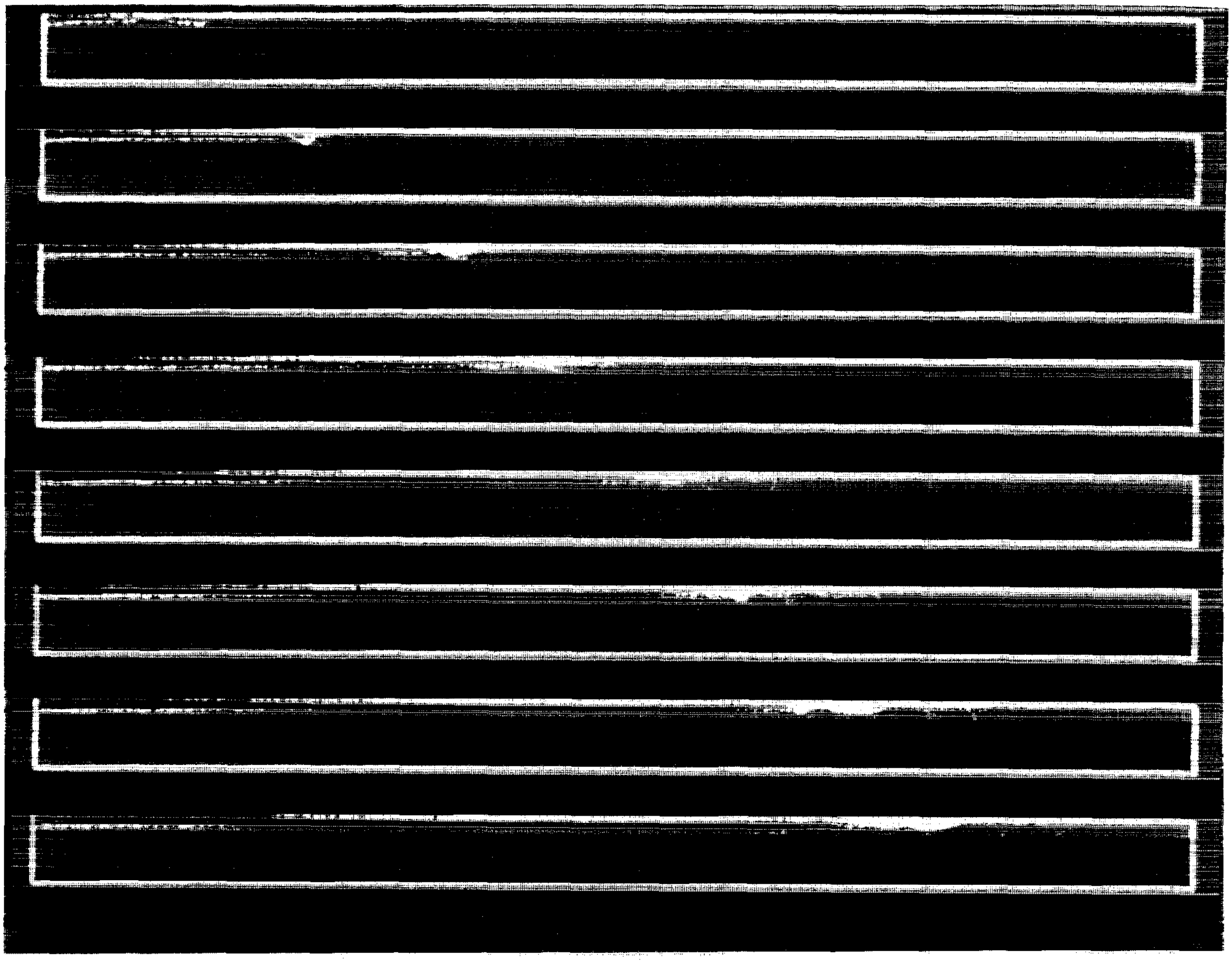

Figure 12. Time sequence showing movement of a smoke plume and temperature change.

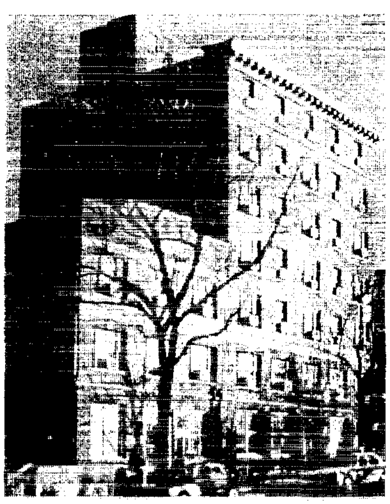

Figure 13. Plaza Hotel in Washington, DC, unoccupied at the time, in which fire experiments were conducted.

immediately. But how does it go out? And if we change the way we design the waterspray, or if we substitute some other suppressant for the waterspray, what's the interaction between the suppressant, the flames and the burning combustibles underneath, leading us to be able to predict accurately the efficiency of suppression?

Let's now talk about what we can do—I'll give you some concrete examples—of what the capability of the current hazard modeling is. Figure 13 is a picture of the Plaza Hotel, an unoccupied building at the time, in Washington, D.C., not too far from the Capitol. John Klote and a team ran a series of smoke movement tests in this hotel. They burned a large fuel supply on the second floor, and made measurements at various locations both on that floor and on other floors [11].

Figure 14 is a graphical representation of what the modeling shows, where the different colors indicate different levels of threat. That's just to show you that the modeling, in a time-dependent manner and a spatially variant manner, can be done.

This is the interesting stuff. In figure 16 we have plotted a comparison of the model results and the experiments at three different locations. We're now modeling the temperature. The upper pair of curves is in the room where the fire is. As we get down lower we move successively further away. The bottom curve, which barely departs from the abscissa, is the temperature profile on the seventh floor. Now, the curve shapes aren't perfect. After all, this is a prototype model and there are a number of phenomena yet to be added. But the magnitudes are very pleasantly in agreement.

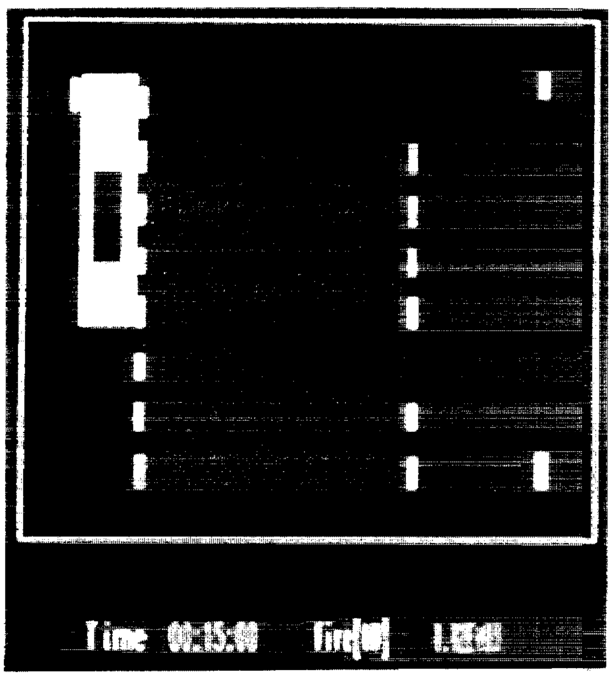

Figure 14. Conditions during the Plaza Hotel fire using a zone fire model. Colors indicate increasing levels of life hazard from blue (none), yellow, orange, and red (on the fire floor).

If we move to something that's even more sensitive, namely the prediction of carbon dioxide and carbon monoxide in those locations, it's once again gratifying that even though there are still some shape differences and some approximations that were made in the modeling, the magnitudes are, in fact, still coming out quite close.

The example I gave at the beginning of this talk on being able to compare a new product versus a currently available product is something that the modeling can also do. In this case we took a chair and burned it on the computer using experimental data representing the properties of that chair.

For the three-room "house," we modeled the carbon monoxide concentration in the room where the fire was, Room 1, and in a room two rooms away, Room 3. We then said, let's model a chair that looks the same but is constructed of materials that produce one-half the heat release and also is less prone to ignition, and one gets the second set of curves.

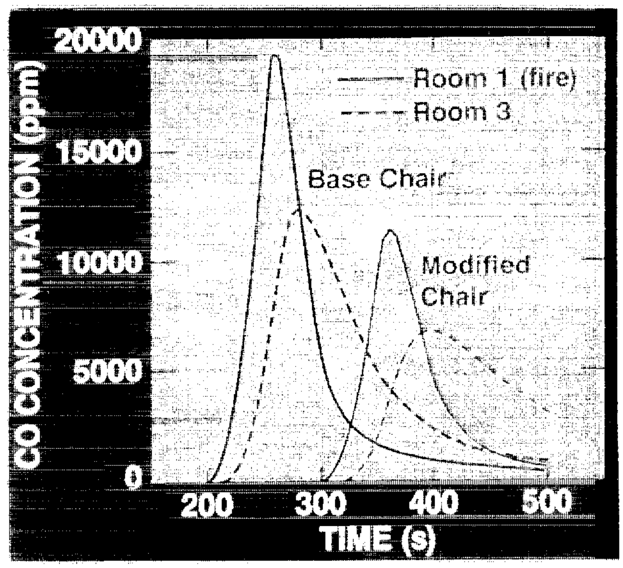

Figure 15. Comparison of modeling results from two locations.

Now, those differences are quite significant. The amount of time available to leave the room of fire origin, in the blue case, is extremely short. The time available in the orange case is quite significantly longer. That's a life-or-death difference.

We're also working with a prototype version of a model for the detailed burning of a piece of upholstered furniture, a chair. Figure 16 is a schematic of what that chair is represented to be. It consists of four panels, if you like, of fabric-covered padding, and the contours you see show the time-dependent evolution of the spread of flame across that chair. On the right-hand side, we've got the rate of heat release prediction that comes from that modeling calculation and some data from our own furniture calorimeter.

Now, I won't claim that all chairs are predicted this perfectly, but even for this chair that is remarkable agreement.

Last in my list of examples, we undertook to try to predict the national fire experience using this kind of fire hazard modeling [12]. I won't go into the details of this. But I think it's quite remarkable that for this

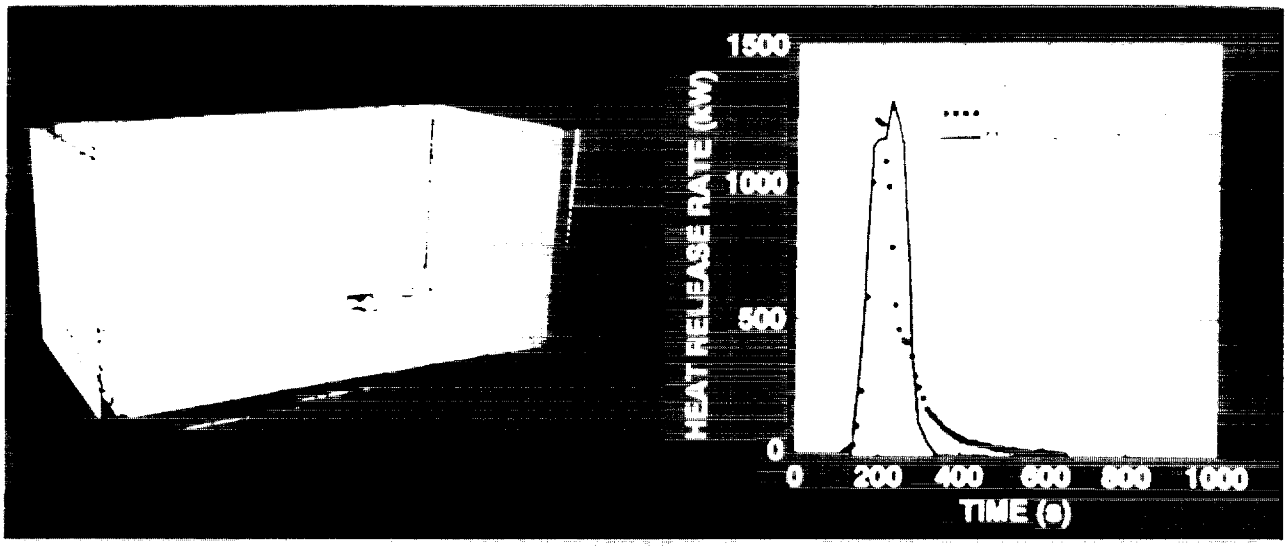

Figure 16. Representation of the time-dependent evolution of the spread of flame across that chair and the resulting rate of heat release.

particular scenario, which is upholstered furniture, in living rooms and bedrooms specifically, when that piece of furniture is the first item ignited the modeling produced an estimate that there should be in this country something on the order of 624 (a little over-precise) fire deaths per year. The actual experience is 643. That is, in my mind, a major accomplishment.

Table 2. National fire experience prediction for upholstered furniture fires: upholstered furniture in living rooms and bedrooms, first item ignited

	Statistics	Model
Total Deaths	643	624
Ignition Type		
Smoldering	498	460
Flaming	145	164
Time of Day		
Night	379	552
Evening	83	20
Day	180	52

The precision that may be implied from the totals is slightly fortuitous, as seen when one breaks down the data both in terms of type of ignition and time of day. But, nonetheless, this is the kind of thing that fire modeling is already capable doing to some degree of approximation, and soon we'll be able to do this to an even higher quality.

Fire science at NIST and in the U.S. has come a long way since the Baltimore fire of 1904. We have identified key components affecting fire initiation and growth; developed new ways of measuring those components; and established that fire models using such data can be valuable for product design, evaluation, and specification.

What lies ahead is even more exciting. Working with industrial partners, we have begun relating the chemical structure of a material to the outcome of a fire. We are probing the interaction between the time of sensing, the nature of suppression, and the level of hazard. We have begun developing techniques for evaluating the impact on a community of a large fire in its midst. As this new understanding emerges, we are using advanced electronic media to make it accessible to product designers and manufacturers, builders, engineers, and government officials, thus making true fire safety an achievable goal for the next century.

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