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Fire and Explosion Investigations – A Historical and Hysterical Perspective

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Abstract

This is the first of a series of Fire/Explosion Safety Briefs introducing engineering and science into fire/explosion investigations. Just as the "magic" of alchemy preceded the science of chemistry, so has a large body of cause-and-effect mythology developed in fire investigation. These myths, which have been given the name "Old Fire Investigators' Tales" or OFITs, are described and the lack of validity of common OFITs is discussed.

With the use of engineering analysis supplemented by experimental data, we can replace those OFITs and provide the forensic engineer with new tools for identifying the origin and cause of fires and, often even more important, the cause of the resultant fire loss. Computer-aided fire models, heat transfer calculations and other engineering analyses can often be used to establish or validate possible causes, failure of protective devices and adequacy of fire protection features. Data to support these analyses should be obtained from government agencies and from private organizations experienced in fire research and experimentation. Data from demonstration fires or inexperienced "testers" should be avoided.

INTRODUCTION

The introduction of modern technology into fire and explosion investigations is the subject of this first of the Fire/Explosion Series Safety Briefs. Part 1, "Science, Art or Sorcery," concerns fire investigation mythology and unacceptable methods. Part 2, "Engineering and Scientific Tools," describes the application of analytical and experimental tools to fire and explosion investigation. Future Safety Briefs will include: Electrical Fire Causes (How electricity can and cannot cause a fire); Floor Surface Burning, Its Real Significance; Real Ignition and Fire Temperatures; and a Glossary of Forensic Fire Terminology.

Correct and reliable determination of the cause of fire and explosions is very important for fire/explosion prevention and when there is litigation after a loss. In addition to determining the cause of the fire or explosion, it is often equally important to determine the cause of the loss, which can be quite distinct from the cause of the fire or explosion.

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PART 1: SCIENCE, ART OR SORCERY?

Fire and explosion investigations have developed from a flawed art into a science as a result of new analytical techniques supported by extensive scientific data. Until recent years, almost all fire and explosion investigations were performed as an art. Many conclusions were based on a mythology developed over years of after-the-fact observations and assumptions as to the cause of what was observed. Cause and origin were commonly determined using methodologies which a 1977 Law Enforcement Assistance Administration (LEAA) report (10) characterized as having "little or no scientific testing" and "no published material in the scientific literature to substantiate their validity."

The 1977 LEAA study identified the fact that there was no scientific basis for techniques commonly used to determine cause and origin of fires. What was not explicitly stated was that even then there was engineering and scientific data that proved many of these techniques erroneous. Some of the investigative methods described depended on violations of the laws of chemistry, physics, and heat transfer. Many fire investigators still persist in using and teaching methods and myths which have been proven invalid.

In the past, the qualifications of investigators have been judged on the basis of how many fires they had investigated, regardless of whether they understood the chemistry, physics and heat transfer of fire phenomena. This is like saying that eating a lot of cakes and pies makes one a good cook. Seeing and participating in after-the-fact results do not teach the process needed to achieve the observed results. The eating experience makes you fat, not a good cook. After-the-fact fire investigations alone do not make experts in origin and cause.

A qualified investigator should understand fire phenomena and the chemistry and physics of fire, have experimental fire knowledge, and have observed fires and post-fire scenes. Many fire-cause determination courses are taught at the technician level and directed toward fire and police personnel, some of whom have not even had high school physics or chemistry courses. At times, the course instructor may not have the scientific knowledge needed to understand how fires start and spread. Both instructor and student may be completely unfamiliar with the basic principles of ignition such as: critical surface temperatures for piloted and auto-ignition; the scenario, time and configuration specificity of ignition temperatures; critical radiant flux; and other basic parameters.

Double, double, toil and trouble; Liquid burn and concrete bubble.
Dark black smoke with red orange flame; Softened glass will fix the blame.
Round about the cauldron go; In this fire, myths will grow.

The start and behavior of fires is an interdisciplinary topic which requires knowledge often not even taught in engineering schools. The typical college engineering curriculum contains nothing related to the cause of fires. Those engineering curricula which lack both organic chemistry and heat transfer courses can leave an engineer poorly equipped even to learn fire cause determination. Information on course programs that are available at both the technician and engineering levels can be obtained from the Fire Science and Technology Educators Section of the National Fire Protection Association and from the Society of Fire Protection Engineers.

Fire investigation myths have developed in a manner analogous to the development of other myths. A cause-and-effect relationship was assigned to post-fire observations and to fire behavior. Persons developing and accepting the cause-effect correlation often had little understanding of the chemistry, physics and heat transfer of fire. In addition, prior to the late 1950's, little engineering and scientific work had been performed on structural fire phenomena. Many of these myths appear rational under narrow scrutiny, but resemble the flat-earth concept. That concept seems valid as long as you do not look too far nor expect the myth to conform to basic physical laws. Fire investigation myths die hard. Many investigators do not read the engineering and scientific fire literature. In addition, there are many who do not want to admit that their mythological-based testimony has caused serious injustices when insurance companies have denied legitimate claims or when innocent people have been sent to prison.

Old Fire Investigators' Tales, OFITs, is the term we have assigned to elements of this mythology. Many investigators still depend on OFITs even though they violate basic laws of chemistry, physics and heat transfer. OFITs retain common credibility because of the number of persons still depending on them. For example, a conviction in a recent capital arson case was obtained with OFIT evidence that violated the laws of physics and heat transfer. In addition, some OFITs have a semblance of credibility because they appear correct under specific fire scenarios.

Certain fire investigator training has been based on OFITs and other unscientific principles. For example, many investigators have been taught that there are four modes of heat transfer – convection conduction, radiation and "direct flame contact." The world's engineering and scientific community recognizes only convection, conduction and radiation. Direct flame contact is a form of convective heat transfer. Those who believe direct flame contact is another form of heat transfer do not understand what flame is. From a heat transfer standpoint, flames are hot gases in motion; their luminescence is the result of incandescent particles, principally carbon.

COMMON OFITs

Some of the more common Old Fire Investigators' Tales are described below, followed by referenced discussions of their flaws. Additional OFITs will be discussed in future Safety Briefs.

OFIT:
"V burn patterns show the point of origin."

A "V" pattern is a signature of a fire plume on a vertical surface and indicates that there was burning at the base of the plume (17, 48). Such a pattern reveals nothing about whether this was the origin or whether it occurred later in the fire. When a fire starts near a vertical surface, such as a wall, it often produces a "V" pattern signature. This residual pattern may be the result of one or a combination of things such as paint damage, corrosion, char, deposits of carbon (soot), calcination of gypsum, surface burning, etc. If the fire were extinguished before room flashover, the "V" pattern likely will be still distinguishable. The presence, however, of the "V" pattern alone will not indicate whether that is the point of origin or whether the fire spread from another point, e.g. from an item in the center of the room to the item by the wall that produced the "V" pattern. If a fire has developed to flashover or substantial room involvement, however, post-fire observations can reveal multiple, single or no "V" patterns and give no indication of their significance.

OFIT:
"The low burn point is the fire's origin."

This is another OFIT which requires suspension of the laws of gravity, physics, and heat transfer. Scientific methods show that fires spread downward in several ways through falldown of burning debris, melt drip properties of polymers, and radiant heat. If this OFIT were valid, a fire starting in an attic or an upper floor would never damage lower floors. Anyone who still believes that is ignoring the fact that burning debris will drop down and ignite combustibles. They should read of the vast destruction in World War II caused by fires burning down after being started on upper floors by incendiary bombs. (4)

OFIT:
"Char depth of wood indicates time of burning."

The char depth of wood depends on many parameters in addition to burning time. One of the important parameters is fire environment. Burning rate of wood can vary by a factor of ten, depending on whether it is burning freely or burning in a fully developed room fire. Burning rate also depends on the moisture content, type of wood and dimensions of the burning wood (4, 17).

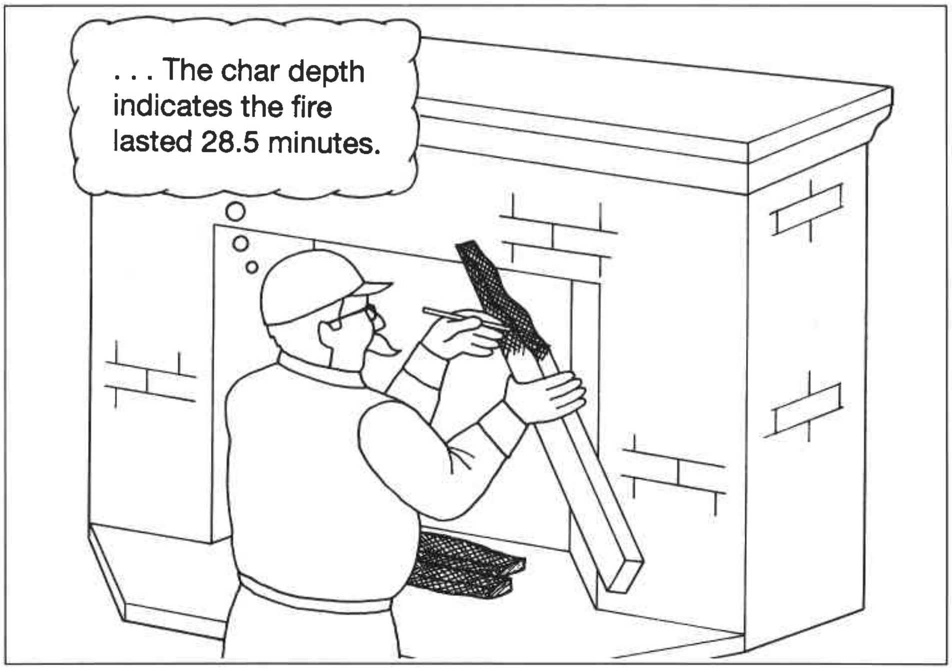
OFIT:
"The area of greatest fire damage is the point of origin."

The logic behind this OFIT is that the fire burns longest at the point of origin and therefore that is where the most damage occurs. This OFIT has an initial appearance of respectability because it is correct in very simplistic fire scenarios; however, the more combustibles available to burn and the larger the fire, the more irrational this OFIT becomes. Factors that determine the local fire damage include: the amount of material available to burn at that point; the heat release rate of that material; the size, construction, loading, and interior finish of the space in which the material is burning; the ventilation history and what fire suppression activities have been performed and when. The above factors establish the duration and temperature of the fire and the susceptibility of that location to fire damage. It is purely coincidental when the area of greatest damage also corresponds to the point of origin.

OFIT:
"Floor surface burn pattern indicates the use of an accelerant."

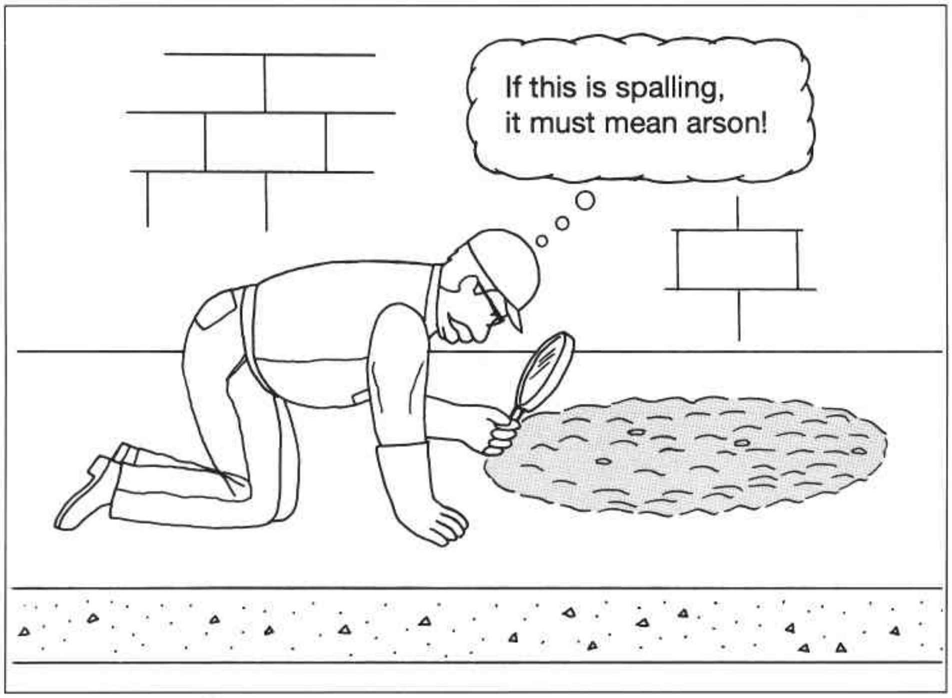
This is another OFIT which ignores the laws of physics and heat transfer; however, it has an appearance of credibility because some accelerants ignite some flooring. Of course, there are many other causes of floor burning. This myth is covered in detail in Campbell's 1982 NFPA paper (13). As a general rule, gasoline and other flammable liquids are the least likely to ignite floor surfaces and generally burn off too quickly to ignite such non-porous floor surfaces as tile, linoleum and finished wood. Floor surface burning is commonly caused by radiant heat or by burning of ordinary combustibles such as wood, paper and plastic on the surface.

Accelerants are effective in igniting contents, not floor surfaces. The one excep-



tion is stairways which have both horizontal and vertical surfaces. These can be ignited by accelerants and may cause a "trench effect" fire spread in which the flame plume tends to follow the slope of the stairs instead of rising vertically. This fire movement phenomenon was first identified after the London King's Cross subway station fire (20). Additional investigation is still needed to establish the application of the trench effect phenomena to multiple flights of combustible stairs.

OFIT:
"Spalling of a concrete floor indicates the use of an accelerant".



This OFIT is so strongly espoused by some that an investigators' association newsletter even repudiated a paper by a professor who had conducted tests showing this OFIT was not true.

Spalling of concrete can be caused by vaporization of water in the concrete which "blows" out solid pieces and can be caused by heat from any fire. It requires that the concrete below the surface be heated above the boiling point of water. When a liquid is burning on any surface, the temperature of the surface cannot exceed the boiling point of the liquid. Since water boils above the boiling point of flammable liquid compounds, the temperature of the concrete under the liquid cannot be hot enough to cause spalling. Burning of a high-boiling-point combustible liquid on concrete might cause spalling, but combustible liquids spilled on concrete are difficult to ignite (33, 45).

Spalling can also be used to describe the breaking off of pieces of concrete, stone or masonry as a result of differential thermal expansion. When one part of a construction element is significantly hotter than another part, the resultant differences in thermally expanded dimensions produce stresses sometimes sufficient to break off pieces. This differential thermal expansion can occur as a result of rapid heating during a fire or cooling by water during fire extinguishment. Differential thermal expansion stresses are also developed in composite structures when one material has a different coefficient of expansion than another.

OFIT:
"Electric arcs and sparks produced at normal household voltage will ignite paper, wood, wire insulation, plastic and other ordinary combustibles."

These arcs and sparks can ignite gasoline vapors but typically do not ignite ordinary combustibles. Beaded wires and other wire damage are commonly caused by the fire rather than a cause of the fire. (7, 8. 18. 19). A complete and documented discussion of electrical fire causes will be the subject of a future Fire Safety Brief.

OFIT:
"The condition of the springs in furniture after a fire indicates whether it was a smoldering-cigarette ignition or a fast developing (accelerated) fire."

This OFIT has numerous flaws. Anyone with rudimentary knowledge of metallurgy knows the basic premise is false; anyone knowledgeable in fire phenomena knows the interpretation is false. Recent tests conducted by the Federal Bureau of Investigation should completely bury this tale (49).

OFIT: "Fires seek oxygen"

This OFIT is based upon a faulty interpretation of how fire sometimes spreads. Fire gases are governed by the same laws of physics as any other fluid. Fire plume dynamics are well described in the scientific literature (17, 48). Combustion produces heated fire gases which are lighter than the surrounding air. Their normal movement is upward until they are deflected by a barrier such as a ceiling. Moving fire gases entrain air causing the plume to expand in an inverted cone configuration. Oxygen in air entrained near the base of the plume mixes with pyrolysates and participates in combustion. When the fire plume is deflected by a ceiling or other barrier, it moves outward and entrains additional air from below.

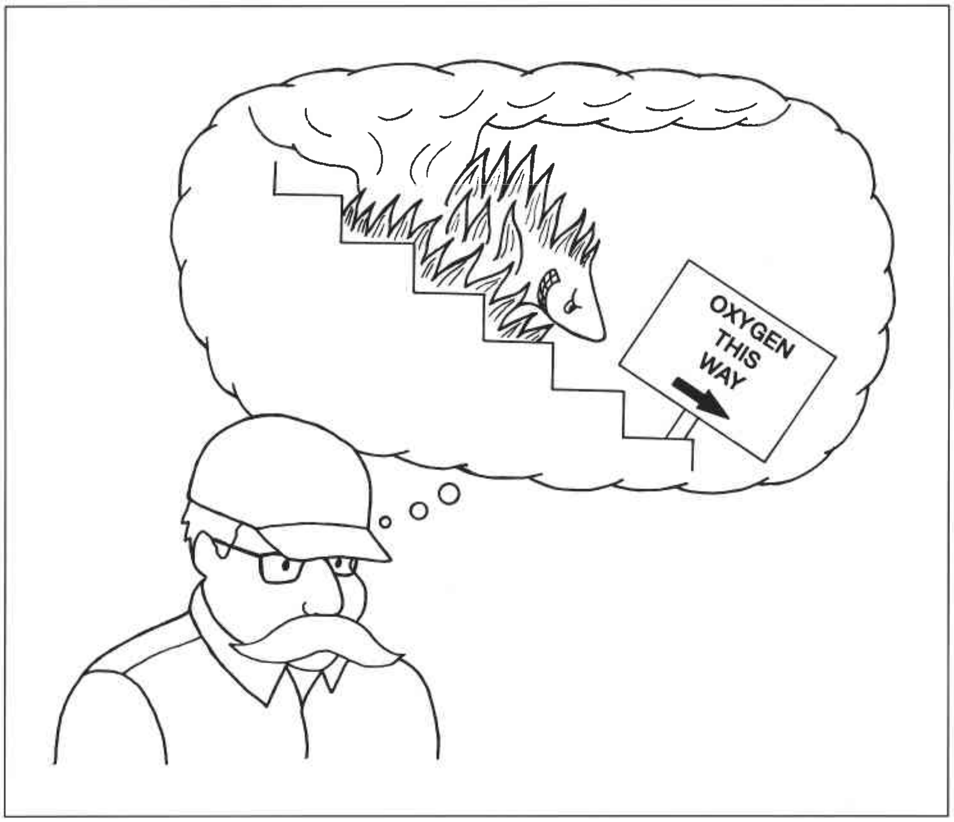
When a fire room is ventilated through a single door or window, pressure differences which are the result of the buoyancy of hot gases result in cool air going through the bottom of the door (or window) and part of it participating in combustion. Hot fire gases are discharged out the top of the opening. When these hot fire gases are not completely burned, they may mix with air outside the fire space and continue flaming combustion.

Observations of the results of these plume dynamics could lead one to believe the fire sought oxygen when it was actually moving according to basic physical laws. When there are multiple openings or ventilation in a fire area, fire gas movement is more complex and it may or may not appear to be seeking oxygen. A fire may also appear to be seeking oxygen when it does not spread into an oxygen deficient space. Hot fire gases will still flow as determined by plume dynamics, but if a space is deficient in oxygen, fire will not propagate into that space.

A fire may or may not move in the direction of a supply of oxygen. When it coincidentally moves that way it is following basic physical laws, it is not seeking oxygen.

OFIT:
"Window glass condition is indicative of fire development"

The condition and appearance of window glass after a fire is a common clue. Clean glass versus heavily sooted glass or glass which has broken into small pieces or into large shards have been used as *de facto* evidence of particular fire phenomena. Little consideration is given to the age, type or condition of the glass, type and geometry of the frame, fire growth rate, temperature differential or convection currents (26, 29). Used carefully and with support by other fire scene patterns, the condition of the glass may provide data and support a cause-and-origin hypothesis, but it is not conclusive evidence.



PART 2:
ENGINEERING & SCIENTIFIC TOOLS

Mathematical modeling supplemented by experimental data provides the forensic engineer with new tools for identifying or verifying the cause and origin of a fire and, often even more important, the cause of a resultant fire loss. Even when the cause and origin of a fire is not at issue, it is often possible and important to establish the cause of loss.

The 1983 edition of the National Fire Protection Association's *Manual on Investigation of Fires of Electrical Origin (NFPA 907M) (37)* stated that, "A clue by itself is not sufficient to classify a fire as electrical. A clue must be validated by proving the necessary physical cause and conditions were present. If clues cannot be validated, the fire cause should not be listed as electrical. The physical clues in a fire scene may be created by a hostile fire of other than electrical origin."

The validation of clues is a prudent practice that should be applied before identifying the cause of any fire or fire loss. If clues cannot be validated by proving the necessary physical cause and conditions were present, then those clues should not be used as the basis for determining the cause. The tools and databases available to assist in determining the cause of a fire or fire loss have greatly expanded in recent years. Engineering analysis in fire and explosion investigations has become very practical with the use of personal computers. There is a vast amount of experimental information available to the investigator which can be used to support or provide input for analyses. Computer-aided fire models, heat transfer calculations and other engineering analyses can often be used to establish or validate:

- Whether a particular cause, origin and ignited fuel coincides with the known fire development history and conditions existing before the fire;
- Whether a suspected ignition source could have generated and maintained sufficient energy or temperature to start this fire;
- Whether protective devices such as sprinklers or smoke detectors did operate or should have operated;
- Whether a protective device would have prevented the injuries or reduced the property damage; and
- Whether a suspected or alleged gas leak or chemical reaction could have caused the fire/explosion that occurred.

The scope of this discussion emphasizes models and analyses that can be exercised using state-of-the-art microcomputers. Both public domain and custom analyses are described together with source references. The type of models and analytical tools to be discussed include:

1. Systems Safety Analysis;
2. Heat Transfer Modeling;
3. Gas Concentration Modeling;
4. Thermodynamic Chemical Equilibrium Analysis;
5. Hydraulic Modeling of Sprinklers & Water Supply; and
6. Fire Modeling.

These analytical and experimental tools are currently available; however, whether an investigator uses such tools depends on the particular incident and the practical purpose of the investigation. The effort that can be justified in the investigation depends on the scope of the investigtor's assignment and generally on the magnitude of the loss. If the total loss is relatively small, a comprehensive analysis of the cause of either the fire or the loss is rarely justified. Unsupported conclusions as to cause, however, are never justified. On fires with large property loss and/or serious injuries, a comprehensive analysis is not only justified but is usually essential.

The scope of an investigator's effort may also be limited if his assignment is limited (e.g., refuting a product liability claim). Often the analysis needed to prove a product could not have started a fire is straight forward and does not require determination of the real cause. Even in such cases it is still desirable to identify a reasonable alternative ignition source. People (i.e., juries) are conditioned to expect that a cause can always be determined. Consequently, they may prefer to accept a physically impossible opinion rather than an opinion that the cause is undetermined.

SYSTEMS SAFETY ANALYSIS

Systems Safety Analysis techniques are important tools in identifying when and how engineering analysis and modeling may be useful. These techniques include: Failure Modes and Effects Analysis, Fault Tree Analysis, Sneak Circuit Analysis, etc. In general, these tools provide a systematic method for analyzing large complicated systems, to determine hazards or faults. The tools can utilize either qualitative or quantitative formats. Hazard probabilities or failure rates can be factored in when using quantitative formats.

Failure Modes and Effects Analysis (FMEA) has been particularly useful for work in fire investigation. It can help identify potential causes of a fire/explosion or a loss, and indicate where further analysis should be directed. A Failure Modes & Effects Analysis only formalizes the type of systematic approach an investigator should be using implicitly. A formalized FMEA is generally justified on large losses or more complex investigations. It can be very effective in identifying all factors, both physical and human, which did or could have contributed to the cause of the fire/explosion or loss.

A FMEA is a relatively simple and straightforward technique to identify basic sources of failure and the consequences of these failures. In loss investigations, the purpose of the FMEA is systematic evaluation of all equipment and/or actions that could have contributed to the cause of the incident or loss.

A FMEA is prepared by filling in a table with column headings. Table 1 is a sample FMEA for a lunchroom fire. In this case, two room items, a coffee maker and an electrical branch circuit box with wire nut connections, are suspected of being related to the possible cause of the fire. Columns are provided to list the failure modes, cause of failure, the immediate effect of failure, the hazard created, necessary conditions, and a physical indication of the failure. This FMEA was constructed to demonstrate all possibilities and their associated indications of failure. The column headings and format of the table are flexible, but at least three items are common: (1) the item or action being analyzed, (2) the basic fault or error that creates the hazard, and (3) the consequences of the hazard.

Additional columns are added by the analyst according to his needs and the nature of the problem. An assessment of the likelihood of an individual occurrence can also be included. In addition, FMEA tables can be cataloged by item and serve as reference material for future investigations. When filling out the form, the analyst should consider for each item/action the ranges of environmental conditions and the process status (i.e., normal operation, shutdown, startup, etc.). Qualitative or quantitative values can be assigned as probabilities of occurrence and levels of criticality.

A spread-sheet computer program and some word processing programs are excellent tools for handling, organizing, and processing FMEA tabulations. A data-base or file code may be particularly attractive for cataloging failure reference material.

Fault Tree Analysis is a very useful and comprehensive method of system safety analysis and can be applied at all levels of complexity. It is used to determine how a given accident or any other specified undesired event can be brought about. The causes of the undesired event can be traced to any required level of detail to identify the individual basic failures or the interplay of combinations of basic failures that could cause the undesired event. The basic failures are not limited to hardware components, but can also be human actions, environmental factors or combinations of these. An example of a fault tree analysis of an attic fan as the cause of fire is given in Figure 1.

HEAT TRANSFER MODELING AND CAUSE-OF-FIRE DETERMINATIONS

Heat transfer models and analysis are particularly useful in fire cause evaluation for determining if:

a. A specific combustible did or could have reached the temperature necessary for ignition as a result of an electrical overheating fault in the circuit and/or of a product; and

b. Necessary and/or sufficient conditions existed for ignition by an overheated or improperly installed "appliance" or by such appurtenances as heaters, furnaces, fireplaces, chimneys, etc.

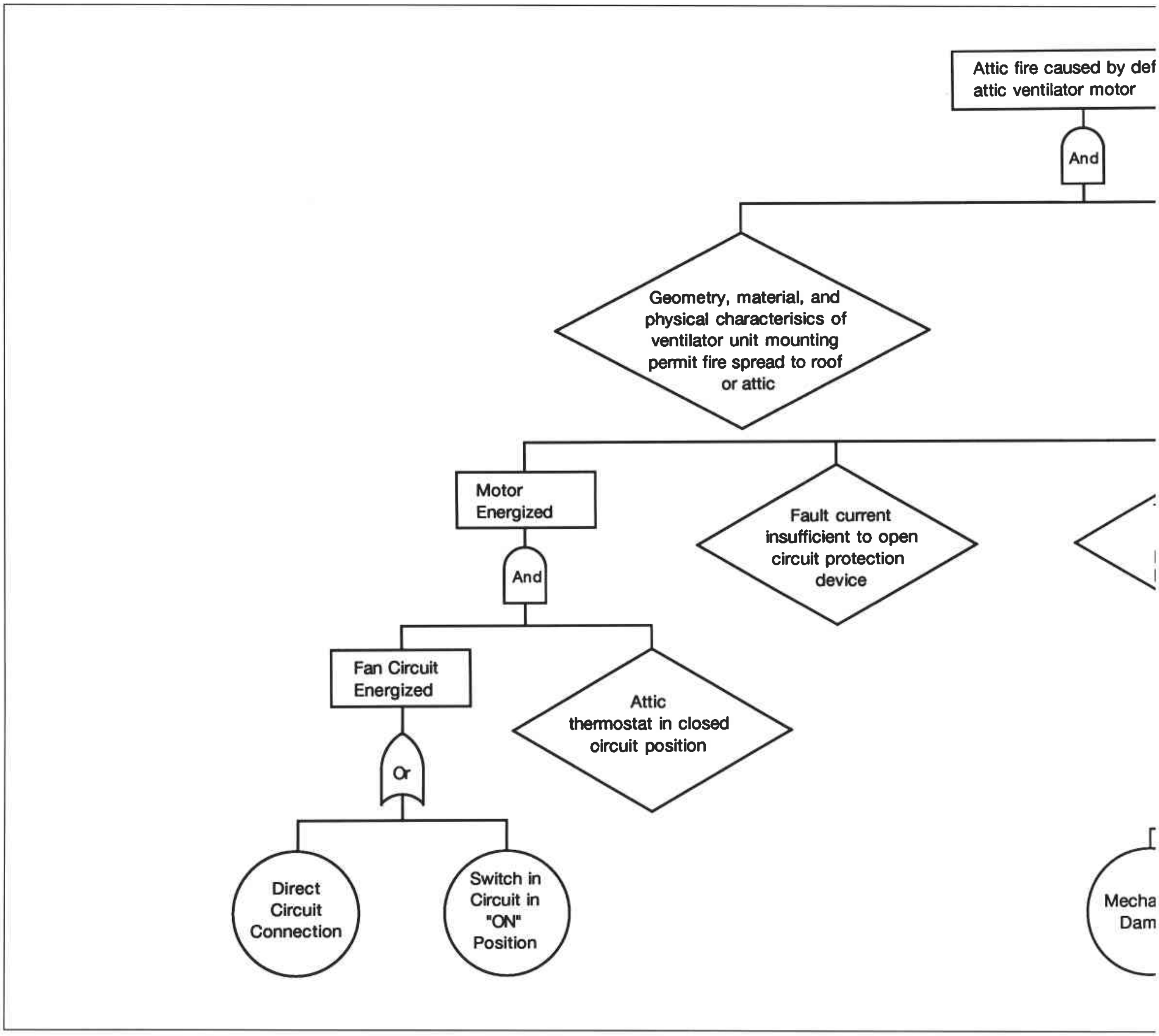
To evaluate, verify or eliminate a suspected or alleged electrical-overheat fire cause, the heat generation and dissipation at the point of the suspect device must be modeled. The electric power consumed at the possible heating point defines the heat generation in the majority of cases; it may be a constant or a function of other parameters.

Often, only an upper limit of the power generation can be established. The upper limit is established by the inherent circuit current limits or maximum addition of impedance/ resistance that can be tolerated without altering some observable function, such as operation of a fluorescent light or electric motor. Circuit currents are limited by over-current protection, wire capacity before fusing open, and impedance/resistance within the circuit. Many devices such as small fractional horsepower motors, some heating devices, electronic equipment, etc., can "fuse" open at relatively low current. This limiting current is used to establish the maximum power that can be generated in that part of the circuit. In most cases the value of the limiting current is determined experimentally.

Once the power generation limit has been identified, the heat dissipation and temperatures are calculated as a function

Table 1 Sample Failure Mode and Effects Tabulation For Lunchroom Fire

Component Item	Failure Mode	Cause of Failure	Effect of Failure	Hazard Created	Necessary Conditions	Indication of Failure
Coffee Maker	Heater current flows without shut off	Switch left on or/and Controls failure	"Boils" out any water in reservoir Thermal runaway of heating element Local temperature increases above 600°C	Ignition of plastic housing	Power on Switch on or fails closed Thermostat fails in "on" position Both thermal fuses fail to open	Melting of aluminum housing around heating element Condensed aluminum at base of maker Thermostat closed circuit Both fuses closed circuit
Electrical Branch Circuit box (Wire nut connects branch circuit wires to light fixture wires inside metal octagon box)	Excessive resistance	Wrong size nut used or Improper installation or Defective product	Localized heating to about 125-220°C	Long-term heating to ignition if attached to wood	Box in contact or closely connected to wood material Current draw of light sufficient to cause heating at connection Light will operate with the amount of resistance in series needed for heating Fixture on for extended cummulative period of weeks to year, temperature dependent Insulation around box sufficient to minimize heat dissipation	Very deep local char on exposed wood High circuit resistance at nut connection Previous experience light dimming or flickering Heat balance calculations indicate equilibrium temperature 125-220°C



of time and location. This can be a straightforward finite difference solution of the differential equations of unsteady state heat transfer or, if the power dissipation is continuous, a steady state solution is possible.

The same modeling techniques can be used to determine if necessary and/or sufficient conditions existed for ignition by an overheated or improperly installed "appliance" or appurtenances. The input data needed includes the operating temperature of the suspect appliance or appurtenance. Usually temperature data must be obtained experimentally using similar equipment. Occasionally eye-witness observations, such as a statement that the item was "red-hot" may suffice within limitations. Physical evidence, such as paint or coating damage, softening or fusing of material, and pyrolysis must be evaluated cautiously since it may have been caused by either the fire or overheat condition.

For a combustible to be ignited by exposure to heat alone, i.e., without flame contact, a sufficient quantity of it has to be heated to its autoignition temperature. In addition to temperature, the source must have a sufficient quantity of energy; temperature alone is not enough. For example, although a 400°C hot plate would ignite solid wood; a small 1000°C metal globule would not. Friction sparks are an excellent example of a high-temperature ignition source which usually do not have sufficient energy to ignite flammable dusts and vapors (19, 42). Scenario-specific autoignition temperature data must be used; autoignition temperatures published in handbooks are rarely applicable. The autoignition temperature of both solids and fluids is highly dependent on the ignition scenario, particularly on the manner and the duration of heating. Data published in handbooks comes from results of specific tests which rarely are related to the

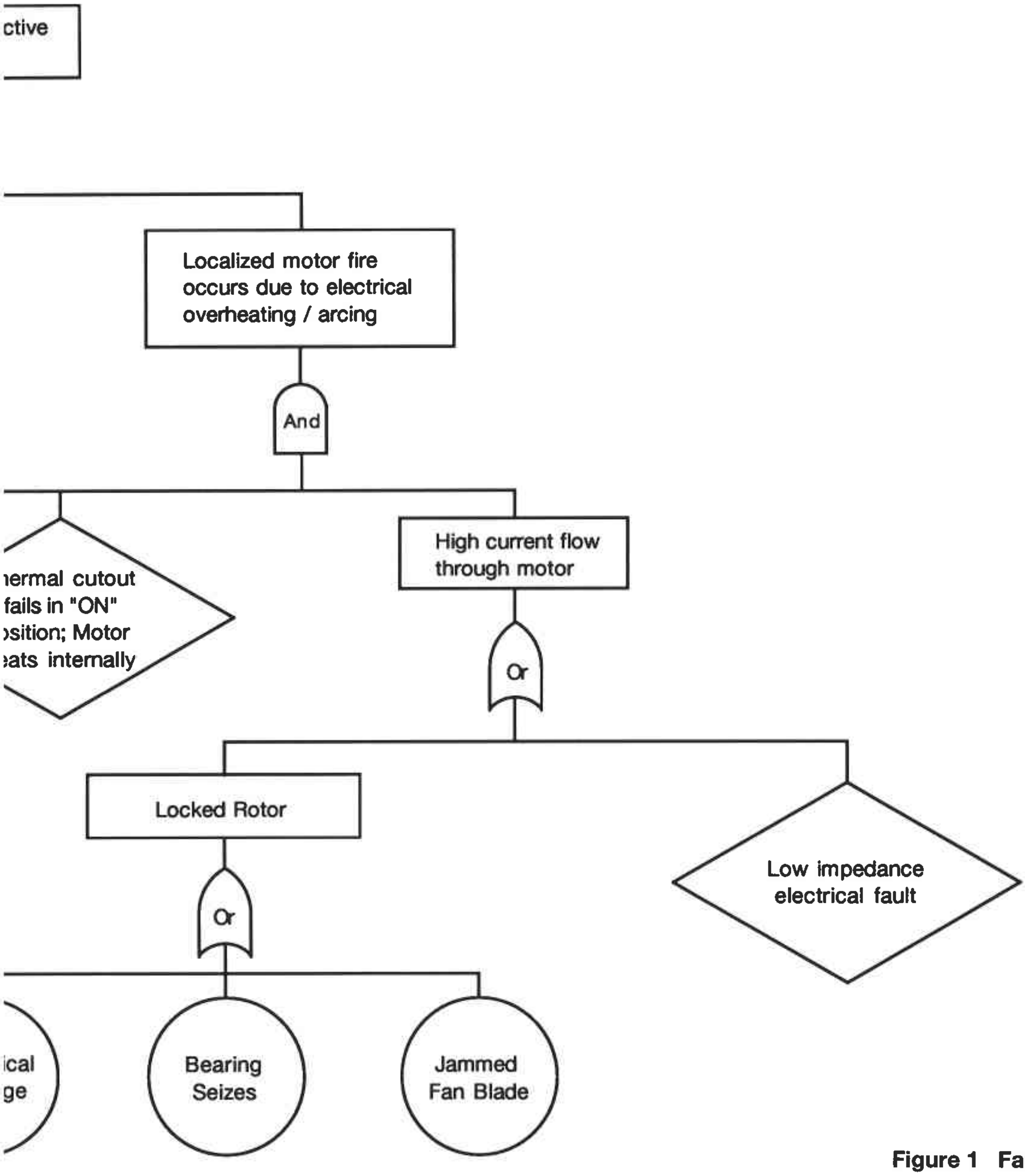


Figure 1 Fault Tree Example for Attic Fan

ignition scenario being investigated. Materials with handbook autoignition temperatures of 300°C can have a scenario-specific autoignition temperature of 500°C (2). TFEE tested a hydraulic fluid with a published autoignition temperature of 240°C and found a scenario-specific autoignition temperature of 510°C. Unless very scenario-specific experimental data is published, experiments to determine the autoignition temperature are necessary. Experience indicates similar behavior for pilot ignition temperatures of solids and liquids.

Published data (2) and tests conducted by TFEE show that short-term exposures of about 315°C are necessary to produce glowing combustion in most cellulosics under simulated realistic ignition scenarios. Ignition temperatures of polymers are even higher. TFEE has also conducted scenario-specific tests in which polymers and rubber shrank and moved away from the heat source as the temperature rose. Ignition never occurred.

If the fire scenario indicates the possibility of long-term heating of wood at temperatures below about 220°C, data from the U.S. Forest Product Laboratories (44) can be used to determine if the temperature-duration of exposure was sufficient for ignition. Evidence of long-term prolysis will be localized, with deeply charred wood at the point of origin. This evidence can be destroyed if the fire burns long enough.

Considerable useful flammable liquid autoignition data applicable to common scenarios is available in publications of fire research experiments by (or for) the National Aeronautics and Space Administration, the Bureau of Mines and the Federal Aviation Administration. Minimum ignition energies are defined for gases, vapors and dusts in the literature (32). Data for solids has to come from general experience or experimentation. For example, die casting foundry experience shows that small molten aluminum globules may char, but do not ignite wood, cardboard and normal fabrics. Although above the autoignition temperature of wood, these globules do not have sufficient energy to ignite solid wood.

Cause-Of-Loss Determinations

Heat transfer models and analysis of the burning fire itself can frequently answer such questions related to the cause of loss as:

- Would certain protective features, (e.g., wired glass windows, automatic sprinklers, etc.) have prevented fire spread?
- Would certain protective features have prevented an injury?
- Was the direct cause of injury burns from the fire or burns from clothing ignited by the fire?
- Does fire spread indicate a failure of a protective feature?
- Why did the fire or fire environment spread the way it did?

Cause-of-loss analysis typically requires modeling an exposing fire/flame plume and computing either heat transfer to or the incident radiant flux on the target of interest. The target of interest can include an item to which fire may spread, damage from radiant heat or a person injured by exposure to heat.

Experimental data needed in this evaluation includes: (a) autoignition temperatures which were discussed above; (b) piloted ignition temperatures in which the exposed object may also be contacted by a small flame; (c) levels of critical incident radiant flux for both auto and piloted ignition; and (d) personal injury thresholds due both to hot gas inhalation and to radiant heat.

FLAMMABLE GAS CONCENTRATION MODELING

Analysis of gas concentrations has been used to evaluate whether a gas leak could have been responsible for a fire or explosion incident and to assist in determining the source of gas. These models can (a) calculate the gas concentration as related to time and elevation in the space; (b) assist in identifying ignition sources; and (c) be correlated with explosion damage.

Flammable gas concentration modeling, combined with an evaluation of explosion/fire damage and the location of possible ignition sources, has been used to:

- Establish whether or not a suspected or alleged leak could have been the cause of an explosion/fire; and
- Determine what source(s) of gas or fuel vapor were consistent with the explosion/fire scenario, damage, and possible ignition sources.

Analytical models and experimental investigations have shown that a leak of a heavier-than-air gas (e.g., liquefied petroleum gas), near floor level, produces a flammable gas concentration that increases in height with time. The concentration exhibits a sharp gradient between the flammable layer and a relatively nonflammable layer (43, 50). The exact inverse occurs with the leak of a lighter-than-air gas (e.g., natural gas) near a ceiling. These models only apply to stable atmospheres in a room which would have to be without significant mechanical mixing or convective motion, as would be expected with an HVAC system, open window or a stack effect.

One model (43) describes a mixing phenomena of flammable gas introduced at a constant flow rate into the top or bottom of a stable column of air. One-dimensional molecular diffusion and bulk flow move the flammable gas in the column and create a steep concentration gradient. A second-order partial differential equation was utilized to describe the concentration space-time history with a finite difference approximation.

A closed-form analysis (50) presents an exact solution for gas concentration, which involves infinite series summations. Another analysis in this same reference computes the average flammable gas concentration within a volume. This can be used to estimate concentrations of natural gas in stratified volumes above the leak and of LP gas in stratified volumes below the leak.

Buoyant gas movement must be considered for leaks of natural gas significantly below the ceiling and leaks of LP gas significantly above the floor; no exact solutions have been presented. Experiments have shown, however, that for the LP gas leak there is an approximately uniform accumulation of gas below the leak and very little above the leak. The inverse occurs with natural gas; therefore, the above analysis from Malhotra's report (33) is a reasonable solution using the room volume above or below the leak as the stratified volume of interest providing the time period is not too long.

The modeled-gas concentration profiles and stratified-volume size/arrangement can be correlated with explosion damage and ignition source(s) to determine if the leak source analyzed was consistent with the history and damage. The results of gas explosion experiments, such as those at British Gas's Midland Research Station, can be used as a basis for relating observed damage to calculated forces (26, 27).

THERMODYNAMIC CHEMICAL EQUILIBRIUM ANALYSIS

Fires and explosions suspected of being caused by reactions of known or suspected chemical mixtures can be investigated by a thermodynamic analysis of the probable chemical mixtures and potential contaminants. The equilibrium reaction products and state of these products are calculated. No kinetics describing the rate of reaction are predicted with thermodynamics. An estimate of the material's potential to explode or to burn violently can be made, however, by the use of correlations which involve the reaction's adiabatic temperature, heat of reaction, heat of combustion and oxygen balance. If spontaneous reaction is unlikely, component vaporization or reaction products might be considered as a potential source of flammable vapors that could be ignited by a source of energy. If a mixture is likely to explode, the severity of the explosion can be estimated from the heat of reaction and the amount of gas formed in the instantaneous reaction.

This type of analysis can be used to answer causal investigative questions such as:

- What reaction(s) could have caused the fire/explosion?

- Was the reaction spontaneous or did it require an outside source of energy?
- Was there an improper mixture of chemicals or a contamination?
- Did a chemical or chemical mixture overheat?
- Was there a human procedural error or an equipment/system failure and, if so, what was it?
- Was there a vapor release followed by an outside ignition?

Thermodynamic reaction equilibrium analysis requires tedious hand calculations or the use of a complex computer code. Several of these thermodynamic codes are available. Necessary material properties input includes chemical formula, density, mass, entropy and heat of formation. Sources of needed information include chemical and chemical engineering handbooks, published papers and material safety data sheets.

One code that is available for running on personal computers is a version of TIGER (12) which was originally written for Department of Defense agencies to predict performance of explosive materials. The TFEE staff has used it successfully for solid and liquid mixtures. It utilizes BKW-R and JCZ equations of state to handle the enormous pressures possible from condensed explosives. Another code which recently became available for use on a personal computer is CHETAH (Chemical Thermodynamic and Energy Release Evaluation) (22). CHETAH was prepared for screening possible hazardous materials by the ASTM E-27 Committee on Hazard Potential for Chemicals. The program provides predictions of the potential maximum reaction energy, a measure of the relative sensitivity of chemical compounds, as well as estimates of enthalpy, entropy and heat capacities from 300° to 1500° K for an unlimited number of organic and organometallic compounds.

Mini or mainframe computers are required to run other codes, mainly because the codes have not been converted to run on small computers. Some mainframe codes found to be useful include CECTRP and BLAKE. CECTRP (Chemical Equilibrium Compositions and Transport Properties) (23) was developed at NASA-Lewis to calculate rocket performance. The ideal gas equation of state is utilized for reaction products. Thermodynamic data for over 400 species (including gases, solids and ions) are available over a range of 300-5000° K.

BLAKE was derived from the TIGER code at the U.S. Army Ballistic Research Laboratory (21), primarily for gun propellant applications. A truncated viral equation of state is utilized as optimum for such applications. A library of input data for ingredients in gun propellants is available.

In conjunction with equilibrium analysis, other functions of these thermodynamic codes found to be useful include: estimation of flame temperatures, heats of reaction/combustion, Chapman-Jouguet detonation parameters and thermodynamic material properties. Further details on these codes can be found in Freedman's ASTM User's Guide (22).

Once a suspect combination of chemicals is identified, experimental verification can be made using standard small-scale tests. In one such test (3) test-tube-size sample mixtures are heated in an isothermal block. The temperature of the mixture is monitored as the block is heated; an incipient reaction is indicated when the mixture temperature begins to increase above the block temperature. This test method requires the least equipment investment, but is labor intensive when a number of mixtures and temperatures must be evaluated. It can be continued, however, until a visible reaction occurs that can be photographed. Other standard tests (e.g. Thermogravimetric Analysis, Accelerated Rate Calorimetry, etc.) take less time and labor, but require a much larger investment in equipment.

HYDRAULIC MODELING OF SPRINKLER AND WATER SUPPLY SYSTEMS

Analyses of automatic sprinkler and water supply systems are often required in the evaluation of the cause of loss. The same mathematical models and computer codes used to design these systems are used in the loss analysis. The designer needs only to consider a single sprinkler system operating at a given time while the forensic engineer may have to analyze simultaneous operation of two or three automatic sprinkler systems. Such an analysis may represent a number of realistic fire

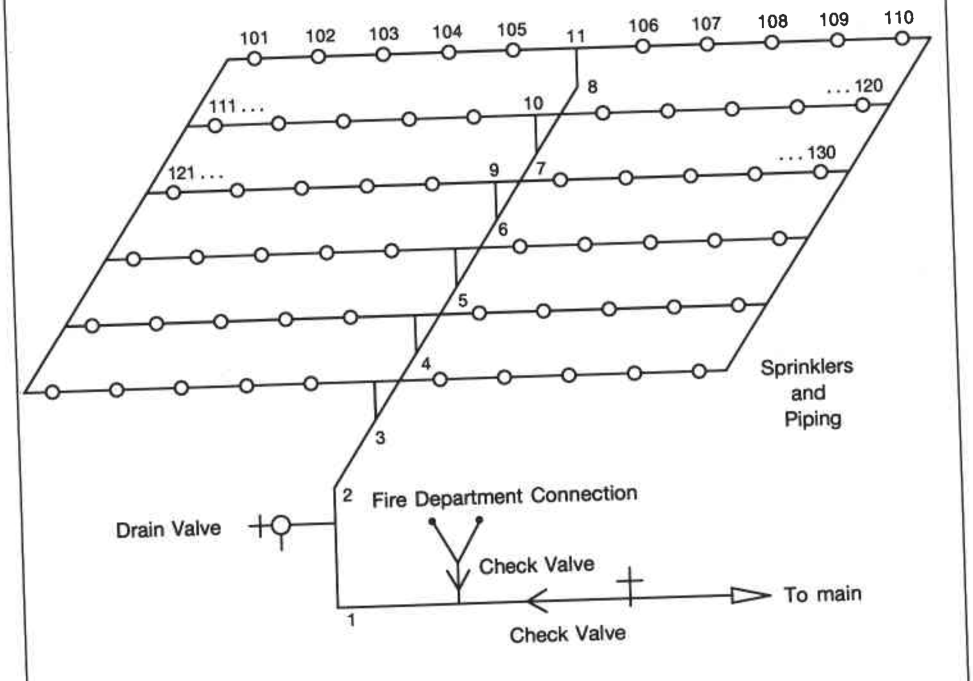


Figure 2 Typical Hydraulic Schematic For Modeling Automatic Sprinkler System

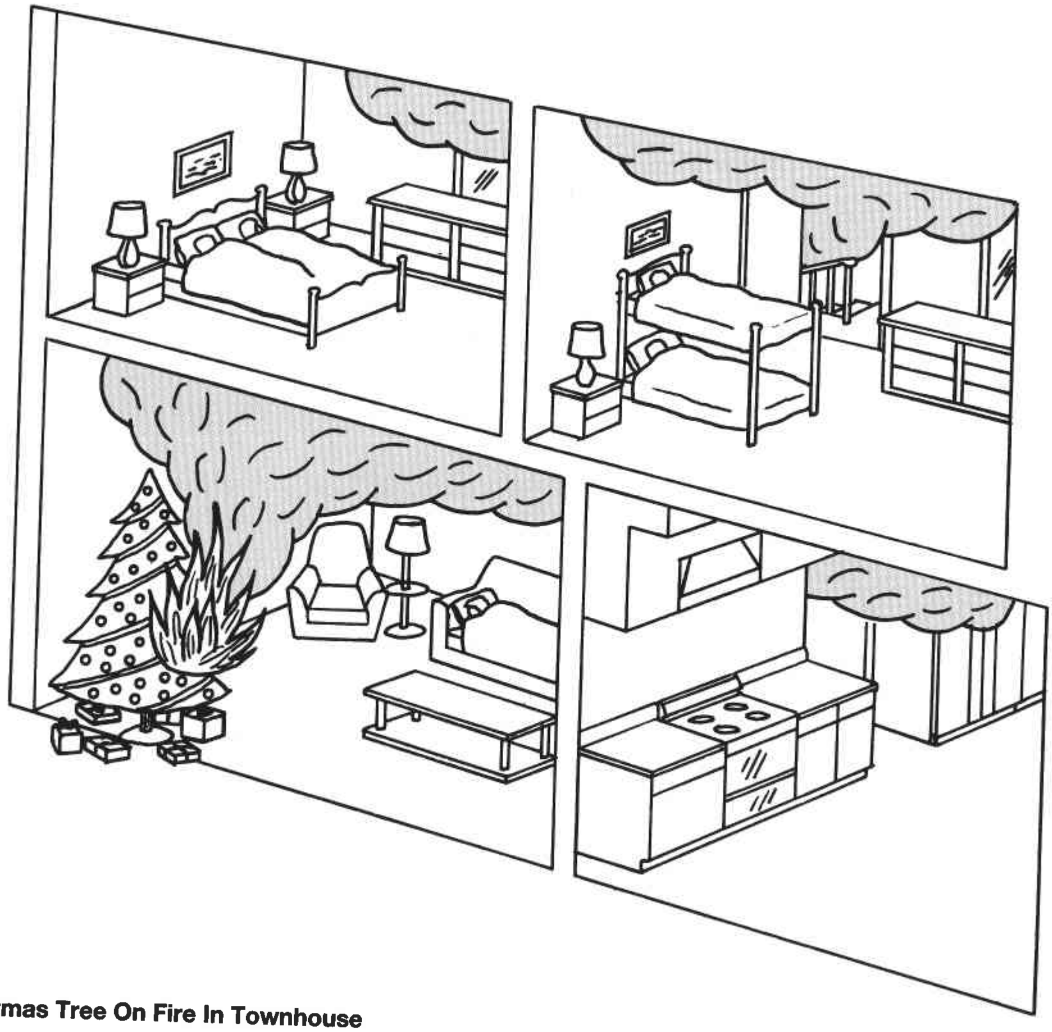


Figure 3 Christmas Tree On Fire In Townhouse

scenarios, including an incendiary fire with an accelerant and/or multiple points of origin and also an exposure fire that is entering a building at several points.

An example of hydraulic modeling is provided in Figure 2, which shows how a sprinkler system may be represented in schematic form for use in modeling exercises. A skeleton of piping is shown with all nodes (transition points, inflow points, outflow points) identified. Pipe sizes, elevations and lengths are usually identified as well. This information then allows the engineer to transfer the piping information to the computer for analysis.

The most common application of hydraulic modeling is in determining why an automatic sprinkler system did not control a fire. Modeling can also be used to investigate the loss associated with a single sprinkler head opening, the effect of fouling in the piping and to determine the position of valves at the time of loss. The objective of a typical investigation is to determine:

1. Whether or not the sprinkler system was designed and installed to meet nationally recognized standards and applicable codes;
2. Whether any deviation from these codes and standards affected the loss;
3. Whether the occupant of the protected premises increased the fire hazard above that for which the sprinkler system was designed.

Aside from hydraulic and code considerations, an investigator must consider physical and human failures such as: electrical pump power problems, incendiary fires with possible multiple points of origin, water utility deficiencies, poor fire fighting tactics, and explosion or mechanical damage to piping/controls.

To evaluate the adequacy of the sprinklers requires knowledge of sprinkler and water-supply arrangement and of the "fuel" arrangement the sprinklers were protecting. The greatest uncertainty in almost all analyses is in assessing the classification of this fuel arrangement. Codes and standards require that a fire protection sprinkler system design be based on specific parameters, including the classification of the hazard being protected and/or of the commodity being stored. Determination of these classifications frequently requires application of engineering judgment, particularly in classifying stored commodities, since products and packaging often do not conform to any exact definition. Experienced persons can each arrive at a different conclusion when they all have had the opportunity to examine the products on site. An exact conclusion may be close to impossible when the products are in ashes.

Water supply systems can change due to increased demand, system improvements, and uncorrected deficiencies. Whenever possible, an experimental evaluation of the water source, such as a municipal water supply, should be performed as soon as possible after the loss. This will determine if the supply is approximately the same as when the system was designed or last tested. Such a test could indicate changes in the supply or deficiencies such as a closed valve. It may not disclose, however, a deficiency such as automatic control of a water utility's pumps being shut off. The analysis of the water supply must also include consideration of fire control tactics, particularly use of fire and yard hydrants with and without sprinkler support.

A sprinkler system in full compliance with current codes and standards may not always successfully control a fire. This is particularly true in those high-piled and rack-storage occupancies which can generate a high-challenge fire. Sprinkler protection standards for those occupancies have been based on a large number of full-scale fire tests. In developing standards, however, there was a practical limit on the number of tests that could be conducted. It was not possible to simulate all possible storage arrangements and stored material combinations. The persons developing these standards had to apply technical judgment in preparing criteria based on the limited data available. Recent fire protection research and development investigations have resulted in changes in test procedures and water application methods, which may be an improvement over previous work. Fire tests and modeling to determine the effectiveness of automatic sprinkler protection is still a continual learning process.

FIRE MODELING

One of the possibilities of fire modeling is illustrated in Figure 3, a drawing depicting a Christmas tree fire in a townhouse living room. Family members are asleep throughout the house. Fire modeling enables the prediction of various life-threatening/property-threatening parameters such as heat release of the fire, as well as temperatures, smoke concentrations, and toxic gas concentrations throughout the rooms. Figure 4 shows some of the parameters calculated by the use of a fire model.

A number of simple and complex fire analysis methods or models are available to assist the forensic engineer in fire cause and loss investigations. Application of these analytical tools to a fire scenario frequently can:

1. Identify the relative contribution of specific contents, construction features and building/contents arrangements to the fire loss. This would include demonstrating that a particular material, item or feature did or did not contribute to causing the loss;
2. Identify what protective features, changes in combustible properties of contents or construction materials or other features could have minimized or reduced the loss;
3. Establish whether a particular fire protection feature would have prevented the loss; the loss being considered could include either property damage and/or injury. Similarly, establish whether the failure of a fire protection system to operate contributed to the severity of loss. Analysis often may be performed in response to a specific allegation.

   Examples include:

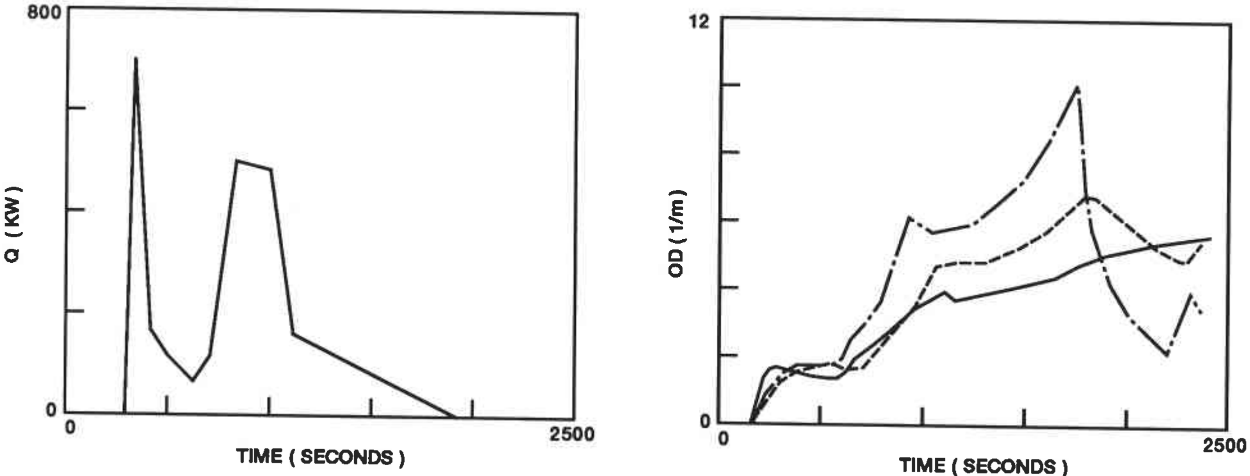
   a. Would a heat or smoke detection system have prevented or reduced the loss in a specific fire?
   b. Did the location of a smoke or heat detector contribute to the cause of loss?
   c. Would sprinklers in the room of fire origin have prevented or reduced the loss in a specific fire?
   d. Could a properly installed in-duct smoke detector have reduced the loss in a specific fire?
4. Determine whether the fire development history was or was not consistent with pre-fire conditions. This could be used to support or more typically refute a claim that added fuel, such as a gas leak or an accelerant, would have been necessary for the known fire development;
5. Calculate if the fuel load in the building presents a greater or lesser fire hazard than the fuel load for which the buildings sprinklers were designed. This would be determined in conjunction with analysis of failure of automatic sprinklers to control a fire; and
6. Establish, confirm or refute a possible point of origin of a specific fire.

Available analytical tools have generally been developed for research and development or fire protection design, not for forensic engineering purposes. These analytical methods must be adapted to the specific problem and may require merely a proper statement of the problem to be solved and/or the combining of two or more models and/or modifying the formula or computer code.

These tools can be used to perform a number of specific calculations including:

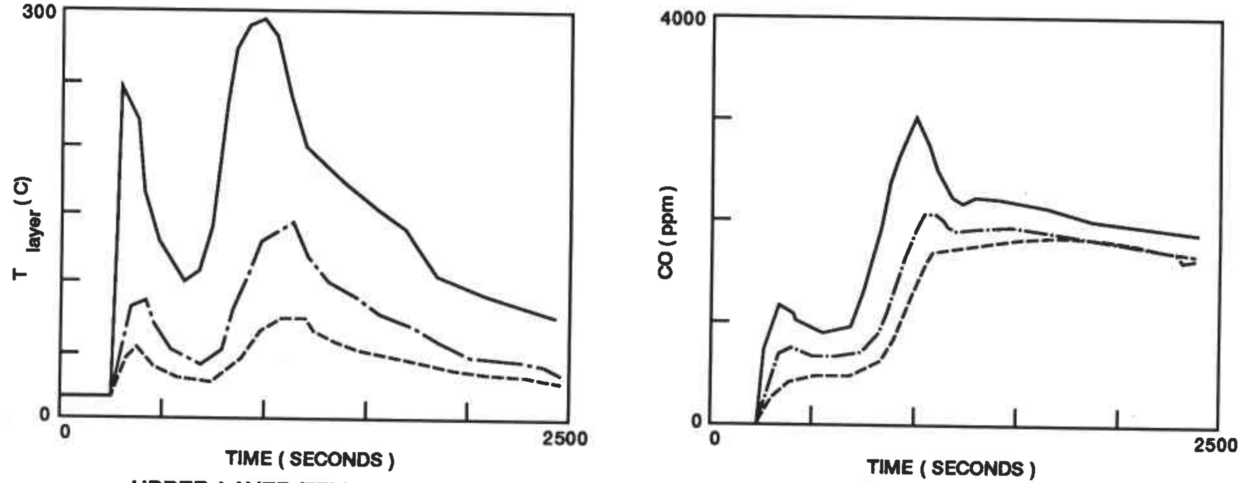
- Estimating the time when sprinklers or detectors would or should have operated in the fire;
- Estimating the time that smoke or hot gases would have accumulated to a certain level in a fire room or adjacent corridor, as well as what would be the average hot gas layer temperature in the corridor at the ceiling level at that time;
- Estimating history of the development of a fire up to room flashover (if it occurs) with the known contents, interior finish, construction and ventilation; and
- Estimating the airflows and pressures in a multi-story building with an operating HVAC system.

These analytical tools range from algebraic equations to computer-aided solutions of ordinary and partial differential equations. Some are empirical or semi-empirical. Many algebraic solutions are compiled in "Slide-Rule Estimates of Fire Growth" (31). Solutions of some of these algebraic equations and numerical solutions of some differential equation models are found in the computer code FIREFORM (40). Other applicable codes include: DETACT-QS, for estimation of heat detector/sprinkler response time; ASCOS, for evaluation of smoke control in buildings (30); and ASET/ASETB, for calculation of available safe egress time from a room fire (51). These latter three codes are available from the Society of Fire Protection Engineers. Variations of DETACT-QS and ASETB are also included in FIREFORM.



HEAT RELEASE RATE OF FIRE

SMOKE OPTICAL DENSITY



UPPER LAYER TEMPERATURE

CARBON MONOXIDE CONCENTRATION

Key:

——— Room of Origin

-·-·-·- Top of Stairs

------ Bedroom

Figure 4 Townhouse Fire Parameters Calculated By Use of Fire Model

Sophisticated room fire models that can run on personal computers include FIRST, HAZARD I and LAVENT. FIRST (35) is a direct descendant of the Harvard Computer Fire Code (34). It is a single-room, two-zone fire model which includes a detailed radiation exchange between items and the walls of the room.

HAZARD I (11) which incorporates the FAST (28) room fire model, is the first comprehensive hazard analysis model suitable for personal computers. It is a multiroom,two-zone fire model. HAZARD1 is supported by NIST (National Institute for Standards and Technology, formerly National Bureau of Standards) staff members and is regularly updated. Improvements and new features are present in each updated version.

LAVENT (16) is a two-zone fire model which predicts the fire environment and the response of sprinkler links in compartment fires with draft curtains and fusible-link-actuated ceiling vents. One unique feature of the code is that it includes two-dimensional temperature profiles at the ceiling and ceiling jets.

Room fire models generally fall into two categories: zone models and closed form approximations. Typical zone models divide the fire room into homogeneous and isothermal upper and lower zones, and a fire plume. The upper zone consists of a stratified hot gas/smoke layer and the lower zone ambient air. There is a sharp discontinuous interface between the two layers. The fire plume entrains air and rises to the ceiling and then spreads out uniformly under the ceiling. The hot layer then begins to descend to fill the room.

Simplifying assumptions are necessary in order to develop analytical solutions; this is true in every physical science. These assumptions are a simplified representation of the real world; users of the models must recognize the significance of their limitations and how results are affected. Field experience and experimental data identify valid applications and limitations of the assumptions, as well as what modifications may be appropriate in the analysis.

For example, the simplest zone models use equations which assume there are no vents in the room except some venting near the floor level to prevent excess pressure buildup. The fire is modeled as a predefined heat release rate history, which generates a hot gas plume. The user selects the fire heat release rate history as an input to these models. Simple models (e.g. ASET) do not check to see if there is enough air available to supply the oxygen needed to achieve the specified burning rate. In addition, many two-layer models use fire plume equations developed for the case in which the fuel source is located well below the ceiling. If flames impinge on and burn along the ceiling, it becomes a near-field phenomenon and corrections may be necessary (6).

The user of any analytical technique must be familiar with experimental work and the limitations of the equations used. Because of approximations and lack of validation, unrealistic answers may be computed. For example, analyses may indicate very high room fire temperatures, 1,500-2,000°C; these are obviously inaccurate and well above flashover temperatures. Such temperatures are unrealistic even for the post-flashover fire. Experiments and analysis indicate an upper realistic temperature limit in a post-flashover room fire of about 1,200°C, with wood as the fuel. Pool fires of liquids or melted plastics in a room generally produce a lower post-flashover temperature (5, 25).

The foregoing models can often be used with reasonable accuracy for only particular portions of the fire development period. In some scenarios being investigated, this will be sufficient. Many two-zone models are reasonable for the period of fire development from the start of flaming until transition to room flashover approaches. As the upper hot gas layer increases in temperature above about 350 to 450°C, the accuracy begins to degrade.

Reasonable answers to fire questions can frequently be obtained with simple equations and/or by modifying the model with an understanding of what is being calculated. For example, the availability of oxygen to support the postulated fire might be checked in advance or with a simple subroutine added into the code. As a rule of thumb, combustion of most fuels with the oxygen in one cubic meter of air can release about 3,700 joules of energy. This rule of thumb can be used to determine when, in a postulated fire scenario, the oxygen concentration in the air would drop below that needed to maintain flaming combustion. FAST and FIRST have this feature incorporated in the code.

The major uncertainty in most fire analyses is the heat release rate history. Sources of this data and a tabulation of considerable data has been compiled by Gross (24). We rarely know enough about conditions before the fire, however, to define accurately the type and arrangement of combustibles. Even if we know the general type of combustibles, we can usually only estimate their heat release rate based on limited published free burning data. For example, a fire may have started in a sofa and there may be published heat release rate data on a few sofas out of hundreds of models available. Also, care must be taken to adjust any data from calorimeter experiments so that it is more representative of room fire data. An exact and reliable heat release rate history can be determined only for some very definitive fires. We can and should, however, judiciously bracket the fire development history within a reasonable range of upper and lower limits.

Generic heat release rates are often used when it is not possible to define the fire history more accurately. The common generic heat release rate is identified as a "t^2" (time squared) fire growth (38), where the fire growth is proportional to the square of the time after ignition. Upper and lower generic heat release rate curves can reasonably define many potential heat release rate histories.

A comprehensive example of the application of these analytical tools to a determination of the cause of loss is the fire which occurred in the DuPont Plaza Hotel Fire in San Juan, Puerto Rico, described by Nelson (41). This report shows how a combination of available tools with some additional analytical features, was used to analyze the initial phase of fire development and identify contents and construction features responsible for most of the losses. The early stage of this fire development was responsible for almost all the loss of life. The analysis also confirmed the validity of the point-of-origin determination and that no accelerants were necessary to produce this rapidly developing fire. The potential impact on this loss if smoke detectors or sprinklers had been installed was also considered. Nelson's report is recommended as a tutorial for anyone interested in expanding their knowledge in the application of fire modeling to loss investigation.

CAUTIONS

Experimental data used in forensic analysis should be selected from organizations familiar with and experienced in fire and explosion experimentation. Inexperienced experimentalists may not properly instrument nor document the experiments. Organizations in the U.S. currently active and familiar with large scale experimental fires include the National Institute of Standards and Technology and the Factory Mutual Research Corporation. A substantial database is also available from experimental work performed by: the National Advisory Committee for Aeronautics (now NASA), the Bureau of Mines, the Federal Aviation Administration, IIT Research Institute, and other government and private research organizations. Experimental results are also available from work in a number of other countries including: Canada, Great Britain, Japan, Sweden, Germany and Russia.

The forensic engineer should use great caution in interpreting the results of demonstration fires and experiments conducted or instrumented by inexperienced personnel. In addition, sometimes what is designated as an experiment is really a fire set up to sell a particular product. Such experiments may or may not represent a realistic fire scenario.

Some of the experiments needed to support fire/explosion forensics can be very dangerous. The qualified forensic engineer would necessarily be aware of the dangers and know what precautions to observe on all experiments being performed.

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What is a Defect?

The definition of a defective product in a state may be found in the case law of that state. In each issue we explore leading product liability case law for one or more states. Triodyne Inc. relies on the trial bar for selection of the cases cited.

MISSOURI

In 1969 Missouri recognized a rule of strict liability in tort for claims involving defective products, *Keener v. Dayton Electric Manufacturing Company*, 445 S.W.2d 362 (Mo. en banc. 1969). *Keener* specifically adopted the rule stated in Section 402A of the *Restatement of Torts, Second.* Among other things that rule permits the user of a product "in a defective condition unreasonably dangerous" to recover if he sustains damage from its use. This rule is applicable whether the product is defective because of a defect in manufacturing, design, *Blevins v. Cushman Motors*, 551 S.W.2d 602 (Mo. en banc. 1977), or an inadequate warning, *Racer v. Utterman*, 629 S.W.2d 382 (Mo. App. 1981).

Unfortunately, the meaning of product defect has never been well articulated in Missouri law. Missouri's pattern jury instruction on strict products liability does not define what is meant by the term "defective", M.A.I. 25.04. In *Nesselrode v. Executive Beechcraft, Inc.*, 707 S.W.2d 371 (Mo. en banc. 1986), the Missouri Supreme Court reviewed various tests for determining when a product design is defective. The Court specifically declined to incorporate the *Restatement's* "consumer expectation" test or the risk-utility test for product defect into Missouri law, 707 S.W.2d, at 377. The closest the Court came to giving a definition of design defect was that a product's design is defective if "the design renders the product unreasonably dangerous." *Ibid.* The Court went on to hold, in turn, that the question of what constitutes an "unreasonably dangerous" design is a jury question not requiring further definition.

In 1991 the question of whether the phrase "unreasonably dangerous" requires further definition was revised by the Supreme Court in *Hagen v. Celotex Corp.*, — S.W.2d —, No. 73520 (Mo., en banc. September 10, 1991). In that case the plaintiffs' decedent died as a result of exposure to asbestos. The defendants sought a definitional instruction at trial which defined the phrase "unreasonably dangerous" as meaning "the utility or usefulness of the product was outweighed by its risks." Slip Opinion at 13. The Supreme Court declined to depart from its holding in *Nesselrode*, supra. It did note, however:

> We cannot say the existing case law and present MAI instructions answer all possible legal questions which may arise in products liability cases. A party who believes that additional instructions are legally appropriate must request a correct instruction and must develop an evidentiary record in support.

Because defendants did not offer any proof that the utility of asbestos outweighed its risks, the Court held that the definitional instruction offered by defendants lacked an evidentiary basis. *Ibid.* The opinion leaves the door open, however, for parties who do offer proof on the risk-utility issue.

One other case on the meaning of "unreasonably dangerous" should be noted. In *Higgins v. Paul Hardeman, Inc.*, 457 S.W.2d 943 (Mo. App. 1970), the decedent was killed while working on a dump truck when he accidentally hit a control rod of the truck's hydraulic lift system, causing the bed of the truck to crush him. Plaintiff's theory was that the design of the truck was unsafe due to the lack of any kind of safeguard to prevent inadvertent activation of the control rod. In discussing whether this rendered the design unreasonably dangerous (and thereby defective), the Court of Appeals noted that a dangerous condition which would permit imposition of liability included "the failure of the design to include a safety factor." 457 S.W.2d, at 947. Another case by the Court of Appeals held that the term "defective" includes the notion of "excessive preventable danger." *Crysts v. Ford Motor Co.*, 571 S.W.2d 683, 690 (Mo. App. 1978).

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Montana

In *McJunkin v. Kaufman and Broad Home Systems* 748 P.2d 910 (Mont. 1987), the buyers of a mobile home brought suit against the manufacturer and seller alleging misrepresentation, negligent breach of warranty and strict products liability. Upon delivery of the home, the buyers identified the following problems: Misaligned frame, poorly fitting doors, missing shutters, defective ceiling fan, noisy furnace, loose carpeting, loose paneling, improper installation of door trim, loose shingles, minor electrical problems and other problems. The court examined the buyer's claim for strict liability based upon their contention that the mobile home was in a defective condition unreasonably dangerous. First, the court noted that Section 401A of the Restatement (Second) of Torts has been adopted in Montana. However, Montana will not blindly follow the dictates of the Restatement Commentaries.

The court provided the following discussion of design defects and manufacturing defects:

> In *Rix v. General Motors Corp.* (Mont. 1986), 723 P.2d 195, 43 St.Rep. 1296, we distinguished a design defect from a manufacturing defect. Under a manufacturing defect theory, the central question is whether the product is flawed due to improper construction.

[M]anufacturing defects, by definition, are "imperfections that inevitably occur in a typically small percentage of products of a given design as a result of the fallibility of the manufacturing process. A [defectively manufactured] product does not conform in some *significant* aspect to the intended design, nor does it conform to the great majority of products manufactured in accordance with that design."...Stated differently, a defectively manufactured product is flawed because it is misconstructed without regard to whether the intended design of the manufacturer was safe or not. Such defects result from some mishap in the manufacturing process itself, improper workmanship, or because defective materials were used in construction...(Emphasis added.) In contract, a design defect is one which "presents an unreasonable risk of harm, notwithstanding that it was meticulously made according to [the] detailed plans and specifications" of the manufacturer. Thus, unlike manufacturing defects, design defects involve products which are made in precise conformity with the manufacturer's design but nevertheless result in injury to the user because the design itself was improper.
723 P.2d at 200, 43 St. Rep. at 1302-02.

Naturally, a product is defective if it is unreasonably dangerous. *Rost v. C.F. & I. Steel Corp.* (1980), 189 Mont. 485, 488, 616 P.2d 383, 385. The lack of a dangerous aspect does not automatically preclude a finding that the product is defective, however. As *Thompson* demonstrates, the Brandenburger rationale is equally appropriate in situations of purely economic loss without a finding of unreasonable danger.

We do not adopt a theory of absolute liability for all defects. As *Rix* indicates, in order for a product to be "defective" within the meaning of a manufacturing defect theory, the defect must be significant. Strict liability is not intended to replace a breach of contract action for minor defects. However, defining strict liability solely in terms of unreasonably dangerous does not adequately set forth the concept enunciated in *Brandenburger*. The proper test of a defective product is whether the product was unreasonably unsuitable for its intended or foreseeable purpose. If a product fails this test, it will be deemed defective. *(Emphasis added)*
748 P.2d 917 and 918.

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