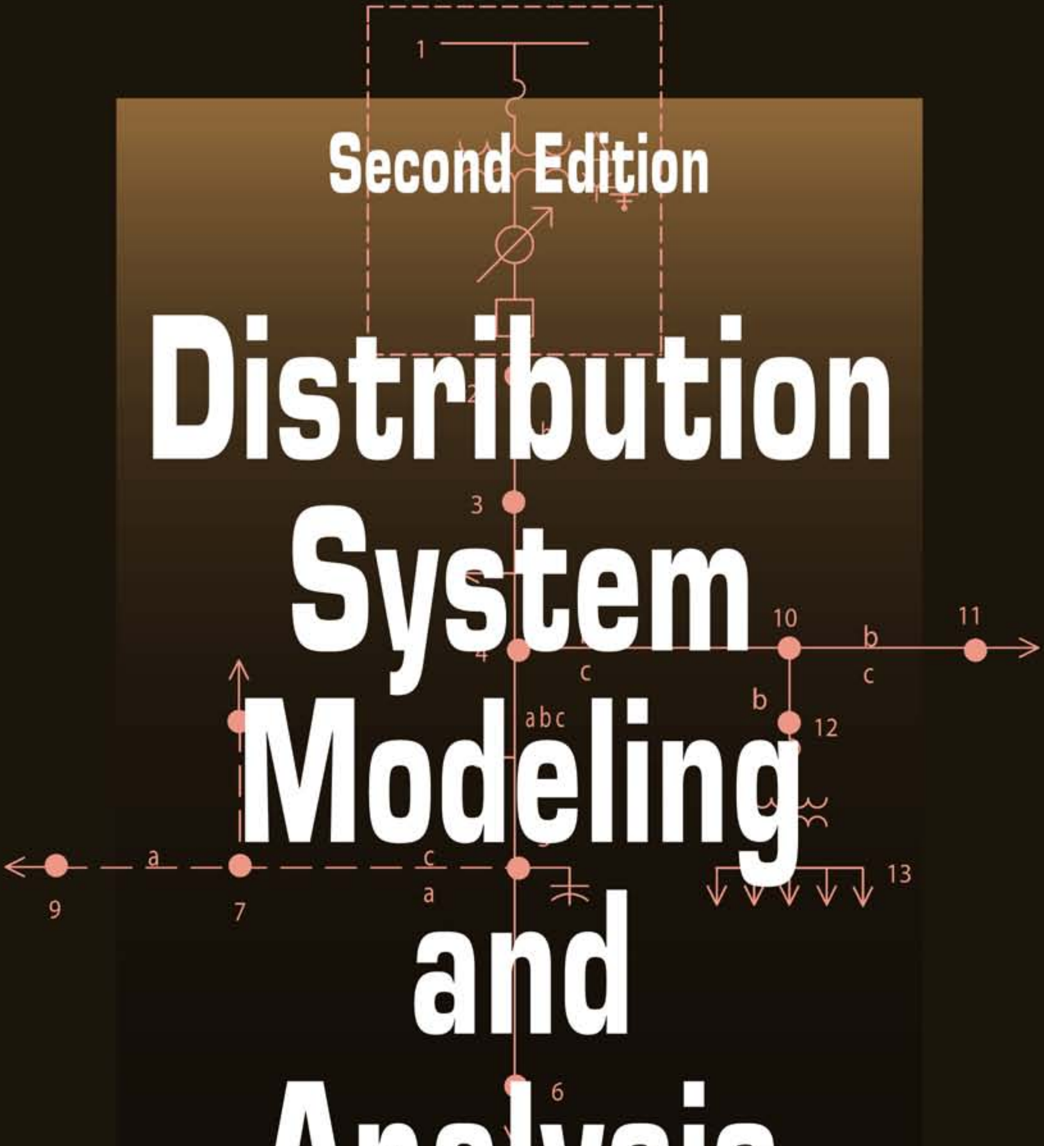

Second Edition

Distribution System Modeling and Analysis

William H. Kersting

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FORENSIC ENGINEERING INVESTIGATION

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Randall K. Noon

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Preface

Forensic engineering is the application of engineering principles, knowledge, skills, and methodologies to answer questions of fact that may have legal ramifications. Forensic engineers typically are called upon to analyze car accidents, building collapses, fires, explosions, industrial accidents, and various calamities involving injuries or significant property losses. Fundamentally, the job of a forensic engineer is to answer the question, what caused this to happen?

A forensic engineer is not a specialist in any one science or engineering discipline. The solution of "real-world" forensic engineering problems often requires the simultaneous or sequential application of several scientific disciplines. Information gleaned from the application of one discipline may provide the basis for another to be applied, which in turn may provide the basis for still another to be applied. The logical relationships developed among these various lines of investigation usually form the basis for the solution of what caused the event to occur. Because of this, skilled forensic engineers are usually excellent engineering generalists.

A forensic engineering assignment is perhaps akin to solving a picture puzzle. Initially, there are dozens, or perhaps even hundreds, of seemingly disjointed pieces piled in a heap. When examined individually, each piece may not provide much information. Methodically, the various pieces are sorted and patiently fitted together in a logical context. Slowly, an overall picture emerges. When a significant portion of the puzzle has been solved, it then becomes easier to see where the remaining pieces fit.

As the title indicates, the following text is about the analyses and methods used in the practice of forensic engineering. It is intended for practicing forensic engineers, loss prevention professionals, and interested students who are familiar with basic undergraduate science, mathematics, and engineering. The emphasis is how to apply subject matter with which the reader already has some familiarity. As noted by Samuel Johnson, "We need more to be reminded than instructed!"

As would be expected in a compendium, the intention is to provide a succinct, instructional text rather than a strictly academic one. For this reason, there are only a handful of footnotes. While a number of useful references are provided at the end of each chapter, they are not intended to represent an exhaustive, scholarly bibliography. They are, however, a good starting point for the interested reader. Usually, I have listed references commonly used in “the business” that are available in most libraries or through interlibrary loans. In a few cases I have listed some hard-to-get items that are noteworthy because they contain some informational gems relevant to the business or represent fundamental references for the subject.

The subjects selected for inclusion in this text were chosen on the basis of frequency. They are some of the more common types of failures, catastrophic events, and losses a general practicing forensic engineer may be called upon to assess. However, they are not necessarily, the most common types of failures or property losses that occur. Forensic engineers are not usually called upon to figure out the “easy ones.” If it was an easy problem to figure out, the services of a forensic engineer would not be needed.

In general, the topics include fires, explosions, vehicular accidents, industrial accidents, wind and hail damage to structures, lightning damage, and construction blasting effects on structures. While the analysis in each chapter is directed toward the usual questions posed in such cases, the principles and methodologies employed usually have broader applications than the topic at hand.

It is the intention that each chapter can be read individually as the need for that type of information arises. Because of that, some topics or principles may be repeated in slightly different versions here and there in the text, and the same references are sometimes repeated in several chapters. Of course, some of the subjects in the various chapters naturally go together or lead into one another. In that regard, I have tried to arrange related chapters so that they may be read as a group, if so desired.

I have many people to thank for directly or indirectly helping me with this project. I am in debted to my wife Leslie, who encouraged me to undertake the writing of this book despite my initial reluctance. I also thank the people at CRC Press, both present and past, who have been especially supportive in developing the professional literature associated with forensic science and engineering. And of course, here’s to the engineers, techs, investigators, and support staff who have worked with me over the years and have been so helpful. I’ll see you all on St. Paddy’s at the usual place.

R. N.

About the Author

Mr. Noon has written three previous texts in the area of forensic engineering: *Introduction to Forensic Engineering*, *Engineering Analysis of Fires and Explosions*, and *Engineering Analysis of Vehicular Accidents*. All three are available through CRC Press, Boca Raton, FL.

For
Nub and Donna,
Pete and Dickie,
Fanny, Ethel, Althea, and Marcus,
Jeanette, Leo Audel, Emery, and Paul,
Bob and Ruby,
Violet, Sheila, and Vera Mae,
Helen, Ernest, Darwin, Billy, and Thomas E.,
Leo, Leroy, Everet, and Gerald Marcus,
and
Tommy Ray.

Remember me when I am gone away,
Gone far away into the silent land;
When you can no more hold me by the hand,
Nor I half turn to go, yet turning stay.
Remember me when no more, day by day,
You tell me of our future that you planned;
Only remember me; you understand
It will be late to counsel then or pray.

Yet, if you should forget me for a while
And afterwards remember, do not grieve;
For if the darkness and corruption leave
A vestige of the thought that once I had,
Better by far that you should forget and smile
Than that you should remember and be sad.

—Christina Rossetti 1830–1894

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Introduction

1

Every man has a right to his opinion, but no man has a right to be wrong in his facts.

— **Bernard Baruch,** *1870–1965*

A great many people think they are thinking when they are merely rearranging their prejudices.

— **William James,** *1842–1910*

1.1 Definition of Forensic Engineering

Forensic engineering is the application of engineering principles and methodologies to answer questions of fact. These questions of fact are usually associated with accidents, crimes, catastrophic events, degradation of property, and various types of failures.

Initially, only the end result is known. This might be a burned-out house, damaged machinery, collapsed structure, or wrecked vehicle. From this starting point, the forensic engineer gathers evidence to “reverse engineer” how the failure occurred. Like a good journalist, a forensic engineer endeavors to determine who, what, where, when, why, and how. When a particular failure has been explained, it is said that the failure has been “reconstructed.” Because of this, forensic engineers are also sometimes called reconstruction experts.

Forensic engineering is similar to failure analysis and root cause analysis with respect to the science and engineering methodologies employed. Often the terms are used interchangeably. However, there are sometimes implied differences in emphasis among the three descriptors.

“Failure analysis” usually connotes the determination of how a specific part or component has failed. It is usually concerned with material selection, design, product usage, methods of production, and the mechanics of the failure within the part itself.

“Root cause analysis” on the other hand, places more emphasis on the managerial aspects of failures. The term is often associated with the analysis of system failures rather than the failure of a specific part, and how procedures and managerial techniques can be improved to prevent the problem from reoccurring. Root cause analysis is often used in association with large systems, like power plants, construction projects, and manufacturing facilities, where there is a heavy emphasis on safety and quality assurance through formalized procedures.

The modifier "forensic" in forensic engineering typically connotes that something about the investigation of how the event came about will relate to the law, courts, adversarial debate or public debate, and disclosure. Forensic engineering can be either specific in scope, like failure analysis, or general in scope, like root cause analysis. It all depends upon the nature of the dispute.

To establish a sound basis for analysis, a forensic engineer relies mostly upon the actual physical evidence found at the scene, verifiable facts related to the matter, and well-proven scientific principles. The forensic engineer then applies accepted scientific methodologies and principles to interpret the physical evidence and facts. Often, the analysis requires the simultaneous application of several scientific disciplines. In this respect, the practice of forensic engineering is highly interdisciplinary.

A familiarity with codes, standards, and usual work practices is also required. This includes building codes, mechanical equipment codes, fire safety codes, electrical codes, material storage specifications, product codes and specifications, installation methodologies, and various safety rules, work rules, laws, regulations, and company policies. There are even guidelines promulgated by various organizations that recommend how some types of forensic investigations are to be conducted. Sometimes the various codes have conflicting requirements.

In essence, a forensic engineer:

- assesses what was there before the event, and the condition it was in prior to the event.
- assesses what is present after the event, and in what condition it is in.
- hypothesizes plausible ways in which the pre-event conditions can become the post-event conditions.
- searches for evidence that either denies or supports the various hypotheses.
- applies engineering knowledge and skill to relate the various facts and evidence into a cohesive scenario of how the event may have occurred.

Implicit in the above list of what a forensic engineer does is the application of logic. Logic provides order and coherence to all the facts, principles, and methodologies affecting a particular case.

In the beginning of a case, the available facts and information are like pieces of a puzzle found scattered about the floor: a piece here, a piece there, and perhaps one that has mysteriously slid under the refrigerator. At first, the pieces are simply collected, gathered up, and placed in a heap on the table. Then, each piece is fitted to all the other pieces until a few pieces match up with one another. When several pieces match up, a part of the picture begins to emerge. Eventually, when all the pieces are fitted together, the puzzle is solved and the picture is plain to see.

1.2 Investigation Pyramid

It is for this reason that the scientific investigation and analysis of an accident, crime, catastrophic event, or failure is structured like a pyramid (Figure 1.1). There should be a large foundation of verifiable facts and evidence at the bottom. These facts then form the basis for analysis according to proven scientific principles. The facts and analysis, taken together, support a small number of conclusions that form the apex of the pyramid.

Conclusions should be directly based on the facts and analysis, and not on other conclusions or hypotheses. If the facts are arranged logically and systematically, the conclusions should be almost self-evident. Conclusions based on other conclusions or hypotheses, that in turn are only based upon a few selected facts and very generalized principles, are a house of cards. When one point is proven wrong, the logical construct collapses.

Consider the following example. It is true that propane gas systems are involved in some explosions and fires. A particular house that was equipped with a propane system sustained an explosion and subsequent fire. The focus of the explosion, the point of greatest explosive pressure, was located in a basement room that contained a propane furnace. From this information, the investigator concludes that the explosion and fire were caused by the propane system, and in particular, the furnace.

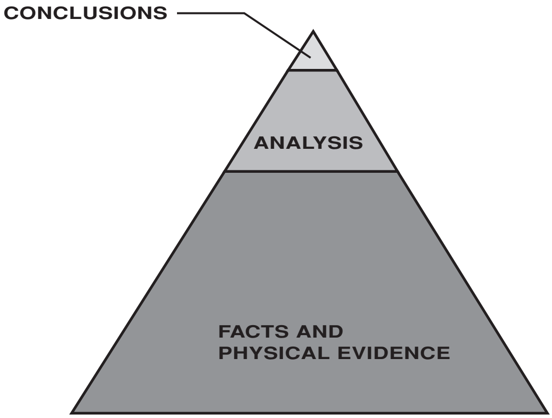

Figure 1.1 Investigation pyramid.

The investigator's conclusion, however, is based upon faulty logic. There is not sufficient information to firmly conclude that the propane system was the cause of the explosion, despite the fact that the basic facts and the generalized principle upon which the conclusion is based are all true.

Consider again the given facts and principles in the example, rearranged in the following way.

Principle:	Some propane systems cause explosions and fires.
Fact:	This house had a propane system.
Fact:	This house sustained a fire and explosion.
Fact:	The explosion originated in the same room as a piece of equipment that used propane, the furnace.
Conclusion:	The explosion and fire were caused by the propane system.

The principle upon which the whole conclusion depends asserts only that *some* propane systems cause explosions, *not all* of them. In point of fact, the majority of propane systems are reliable and work fine without causing an explosion or fire for the lifetime of the house. Arguing from a statistical standpoint, it is more likely that a given propane system will *not* cause an explosion and fire.

In our example, the investigator has not yet actually checked to see if this propane system was one of the "some" that work fine or one of the "some" that cause explosions and fires. Thus, a direct connection between the general premise and the specific case at hand has not been made. It has only been assumed. A verification step in the logic has been deleted.

Of course, not all explosions and fires are caused by propane systems. Propane systems have not cornered the market in this category. There is a distinct possibility that the explosion may have been caused by some factor not related to the propane system, which is unknown to the investigator at this point. The fact that the explosion originated in the same room as the furnace may simply be a coincidence.

Using the same generalized principle and available facts, it can equally be concluded by the investigator (albeit also incorrectly) that the propane system did not cause the explosion. Why? Because, it is equally true that some propane systems never cause explosions and fires. Since this house has a propane system, it could be concluded in the same manner that this propane system could not have been the cause of the explosion and fire.

As is plain, our impasse in the example is due to the application of a generalized principle for which there is insufficient information to properly deduce a unique, logical conclusion. The conclusion that the propane system caused the explosion and fire is based implicitly on the conclusion that the location of the explosion focus and propane furnace is no coincidence. It is further based upon another conclusion, that the propane system is one of the "some" that cause explosions and fires, and not one of the "some" that never cause explosions and fires. In short, in our example we have a conclusion, based on a conclusion, based on another conclusion.

The remedy for this dilemma is simple: get more facts. Additional information must be gathered to either uniquely confirm that it *was* the propane system, or uniquely *eliminate* it as the cause of the explosion and fire.

Returning to the example, compressed air tests at the scene find that the propane piping found after the fire and explosion does not leak despite all it has been through. Since propane piping that leaks before an explosion will not heal itself so that it does not leak after the explosion, this test eliminates the piping as a potential cause.

Testing of the furnace and other applicances find that they all work in good order also. This now puts the propane equipment in the category of the "some" that do not cause explosions and fires. We have now confirmed that the conclusion that assumed a cause-and-effect relationship between the location of the epicenter and the location of the propane furnace was wrong. It was simply a coincidence that the explosion occurred in the same room as the furnace.

Further checks by the investigator even show that there was no propane missing from the tank, which one would expect to occur had the propane been leaking for some time. Thus, now there is an accumulation of facts developing that show the propane system was not involved in the explosion and fire.

Finally, a thorough check of the debris in the focus area finds that within the furnace room there were several open, five-gallon containers of paint thinner, which the owner had presumed to be empty when he finished doing some painting work. Closer inspection of one of the containers finds that it is distended as if it had experienced a rapid expansion of vapors within its enclosed volume.

During follow-up questioning, the owner recalls that the various containers were placed only a few feet from a high wattage light bulb, which was turned on just prior to the time of the explosion. A review of the safety labels finds that the containers held solvents that would form dangerous, explosive vapors at room temperature, even when the container appeared empty. The vapors evolve from a residual coating on the interior walls of the container.

A "back of the envelope" calculation finds that the amount of residual solvent in just one container would be more than enough to provide a cloud of vapor exceeding the lower threshold of the solvent's explosion limits. A check of the surface temperature of the light bulb finds that when turned on, it quickly rises to the temperature needed to ignite such fumes. A subsequent laboratory test confirms that fumes from an erstwhile empty container set the same distance away can be ignited by the same type of light bulb and cause a flash fire.

The above example demonstrates the value of the "pyramid" method of investigation. When a large base of facts and information is gathered, the conclusion almost suggests itself. When only a few facts are gathered to back up a very generalized premise, the investigator can steer the conclusion to nearly anything he wants. Unfortunately, there are some forensic engineers who do the latter very adroitly.

As a general rule, an accident or failure is not the result of a single cause or event. It is usually the combination of several causes or events acting in concert, that is, at the same time or in sequence, one after another in a chain. An example of causes acting in sequence might be a gas explosion.

- Accumulated gas is ignited by a spark from a pilot light.
- The gas originated from a leak in a corroded pipe.
- The pipe corroded because it was poorly maintained.
- The poor maintenance resulted from an inadequate maintenance budget that gave other items a higher priority.

An example of causes acting in concert might be an automobile accident.

- Both drivers simultaneously take dangerous actions. Driver A has to yield to approaching traffic making a left turn and has waited for the light to turn yellow to do so. He also doesn't signal his turn. At the end of the green light, he suddenly turns left assuming there will be a gap during the light change. Coming from the opposite direction, driver B enters the intersection at the tail end of the yellow light. They collide in the middle of the intersection.
- Driver A is drunk.
- Driver B's car has bad brakes, which do not operate well during hard braking. Driver B is also driving without his glasses, which he needs to see objects well at a distance.

Often, failures and accidents involve both sequential events and events acting in concert in various combinations.

1.3 Eyewitness Information

Eyewitness accounts are important sources of information, but they must be carefully scrutinized and evaluated. Sometimes eyewitnesses form their own opinions and conclusions about what occurred. They may then intertwine these conclusions and opinions into their account of what they say they observed. Skillful questioning of the eyewitness can sometimes separate the factual observations from the personal asumptions.

Consider the following example. An eyewitness initially reports seeing Bill leave the building just before the fire broke out. However, careful questioning reveals that the eyewitness did not actually see Bill leave the building at all. The witness simply saw someone drive away from the building in a car similar to Bill's. The witness presumed it must have been Bill. Of course, the person driving the car could have been Bill, but it also could have been someone with a car like Bill's, or someone who had borrowed Bill's car.

Of course, some eyewitnesses are not impartial. They may be relatives, friends, or even enemies of persons involved in the event. They may have a personal stake in the outcome of the investigation. For example, it is not unusual for the arsonist who set the fire to be interviewed as an eyewitness to the fire. Let us also not forget the eyewitnesses who may swear to anything to pursue their own agendas or get attention.

What an honest and otherwise impartial eyewitness reports observing may also be a function of his location with respect to the event. His perceptions of the event may also be colored by his education and training, his life experiences, his physical condition with respect to eyesight or hearing, and any social or cultural biases. For example, the sound of a gas explosion might variously be reported as a sonic boom, cannon fire, blasting work, or an exploding sky rocket. Because of this, eyewitnesses to the same event may sometimes disagree on the most fundamental facts.

Further, the suggestibility of the eyewitness in response to questions is also an important factor. Consider the following two exchanges during statementizing. "Statementizing" is a term that refers to interviewing a witness to find out what the witness knows about the incident. The interview is often recorded on tape, which is later transcribed to a written statement. Usually, it is not done under oath, but it is often done in the presence of witnesses. It is important to "freeze" a witness's account of the incident as soon as possible after the event. Time and subsequent conversations with others will often cause the witness's account of the incident to change.

Exchange I

Interviewer: Did you hear a gas explosion last night at about 3:00 A.M.?

Witness: Yeah, that's what I heard. I heard a gas explosion. It did occur at 3:00 A.M.

Exchange II

Interviewer: What happened last night?
Witness: Something loud woke me up.
Interviewer: What was it?
Witness: I don't know. I was asleep at the time.
Interviewer: What time did you hear it?
Witness: I don't know exactly. It was sometime in the middle of the night. I went right back to sleep afterwards.

In the first exchange, the interviewer suggested the answers to his question. Since the implied answers seem logical, and since the witness may presume that the interviewer knows more about the event than himself, the witness agrees to the suggested answers. In the second exchange, the interviewer did not provide any clues to what he was looking for. He allowed the witness to draw upon his own memories and did not suggest any.

1.4 Role in the Legal System

From time to time, a person who does this type of engineering analysis is called upon to testify in deposition or court about the specifics of his or her findings. Normally the testimony consists of answers to questions posed by an attorney for an involved party. The attorney will often be interested in the following:

- the engineer's qualifications to do this type of analysis.
- the basic facts and assumptions relied upon by the engineer.
- the reasonableness of the engineer's conclusions.
- plausible alternative explanations for the accident or failure not considered by the engineer, which often will be his client's version of the event.

By virtue of the appropriate education and experience, a person may be qualified as an "expert witness" by the court. In some states, such an expert witness is the only person allowed to render an opinion to the court during proceedings. Because the U.S. legal system is adversarial, each attorney will attempt to elicit from the expert witness testimony to either benefit his client or disparage his adversary's client.

In such a role, despite the fact that one of the attorneys may be paying the expert's fee, the expert witness has an obligation to the court to be as objective as possible, and to refrain from being an advocate. The best rule to follow is to be honest and professional both in preparing the original analysis and in testifying. Prior to giving testimony, however, the expert witness has an obligation to fully discuss with his or her client both the favorable and the unfavorable aspects of the analysis.

Sometimes the forensic engineer involved in preparing an accident or failure analysis is requested to review the report of analysis of the same event by the expert witness for the other side. This should also be done honestly and professionally. Petty one-upmanship concerning academic qualifications, personal attacks, and unfounded criticisms are unproductive and can be embarrassing to the person who engages in them. When preparing a criticism of someone else's work, consider what it would sound like when read to a jury in open court.

Honest disagreements between two qualified experts can and do occur. When such disagreements occur, the focus of the criticism should be the theoretical or factual basis for the differences.

1.5 The Scientific Method

The roots of the scientific method go back to ancient Greece, in Aristotle's elucidation of the inductive method. In this method, a general rule or conclusion is established based on an accumulation of evidence obtained by making many observations and gathering many corroborative facts. In assessing all these observations and facts, an underlying commonality is shown to exist that demonstrates a principle or proposition.

However, a possible pitfall of the inductive method is that the number of observations may be too small or too selective for a true generalization or conclusion to be made. A false conclusion may be reached if the observations or facts are representative of a special subset rather than the general set.

Roger Bacon, a 13th century English Franciscan monk, is often credited with defining the modern scientific method. He believed that scientific knowledge should be obtained by close observation and experimentation. He experimented with gunpowder, lodestones, and optics to mention a few items, and was dubbed "Doctor Admirabilis" because of his extensive knowledge.

For his efforts to put knowledge on a verifiable basis, the curious friar was accused of necromancy, heresy, and black magic by the chiefs of his order. He was confined to a monastery for ten years in Paris so that he could be watched. He attempted to persuade Pope Clement IV to allow experimental science to be taught at the university. However, his efforts failed.

After Pope Clement IV died, he was imprisoned for another ten years by the next pope, Nicholas III. Nicholas III also specifically forbade the reading of his papers and books. This was somewhat moot, however, since his work had generally been banned from publication anyway. Some scholars believe that Roger Bacon was the original inspiration for the Doctor Faustus legend.

Why all the fuss over a friar who wants to play in the laboratory? Because it threatened the "correctness" of theories promulgated by the church. At the time of Bacon, the doctrine of *a priori*sm was the accepted basis for inquiry. *A priori*sm is the belief that the underlying causes for observed effects are already known, or at least can be deduced from some first principles. Under *a priori*sm, if a person's observations conflict with the accepted theory, then somehow the person's observations must be imperfect. They may even be the product of the Devil tempting a foolish mortal.

For example, in Bacon's time it was assumed *a priori* that the sun revolved about the earth and that all celestial motions followed perfect circles. Thus, all other theories concerning the universe and the planets had to encompass these *a priori* assumptions. This led, of course, to many inaccuracies and difficulties in accounting for the motions of the planets. Why then were these things assumed to be correct in the first place? It was because they were deemed reasonable and compatible to accepted religious dogmas. In fact, various Bible verses were cited to "prove" these assumptions.

Because holy scriptures had been invoked to prove that the earth was the center of the universe, it was then reasoned that to cast doubt upon the assumption of the earth being at the center of the universe was to cast doubt by inference upon the church itself. Because the holy scriptures and the church were deemed above reproach, the problem was considered to lie within the person who put forward such heretical ideas.

Fortunately, we no longer burn people at the stake for suggesting that the sun is the center of our solar system, or that planets have elliptical orbits. The modern scientific method does not accept the *a priori* method of inquiry. The modern scientific method works as follows. First, careful and detailed observations are made. Then, based upon the observations, a working hypothesis is formulated to explain the observations. Experiments or additional observations are then made to test the predictive ability of the working hypothesis.

As more observations are collected and studied, it may be necessary to modify, amplify, or even discard the original hypothesis in favor of a new one that can account for all the observations and data. Unless the data or observations are proven to be inaccurate, a hypothesis is not considered valid unless it accounts for all the relevant observations and data.

1.6 Applying the Scientific Method to Forensic Engineering

In a laboratory setting, it is usual to design experiments where the variable being studied is not obscured or complicated by other effects acting simultaneously. The variable is singled out to be free from other influences. Various experiments are then conducted to determine what occurs when the variable is changed. Numerous tests of the effects of changing the variable provide a statistical basis for concluding how the variable works, and predicting what will occur under other circumstances.

In this way, theoretically, any accident, failure, crime, or catastrophic event could be experimentally duplicated or reconstructed. The variables would simply be changed and combined until the "right" combination is found that faithfully reconstructs the event. When the actual event is experimentally duplicated, it might be said that the reconstruction of the failure event has been solved.

There are problems with this approach, however. Foremost is the fact that many accidents and failures are singular events. From considerations of cost and safety, the event can not be repeated over and over in different ways just so an engineer can play with the variables and make measurements.

It can be argued, however, that if there is a large body of observational evidence and facts about a particular accident or failure, this is a suitable substitute for direct experimental data. The premise is that only the correct reconstruction hypothesis will account for all of the observations, and also be consistent with accepted scientific laws and knowledge.

An analogous example is the determination of an algebraic equation from a plot of points on a Cartesian plane. The more data points there are on the graph, the better the curve fit will be. Inductively, a large number of data points with excellent correspondence to a certain curve or equation would be proof that the fitted curve was equal to the original function that generated the data.

Thus, the scientific method, as it applied to the reconstruction of accidents and failures, is as follows:

- a general working hypothesis is proposed based on "first cut" verified information.
- as more information is gathered, the original working hypothesis is modified to encompass the growing body of observations.
- after a certain time, the working hypothesis could be tested by using it to predict the presence of evidence that may not have been obvious or was overlooked during the initial information gathering effort.

A hypothesis is considered a complete reconstruction when the following are satisfied:

- the hypothesis accounts for all the verified observations.
- when possible, the hypothesis accurately predicts the existence of additional evidence not previously known.

- the hypothesis is consistent with accepted scientific principles, knowledge, and methodologies.

The scientific method as noted above is not without some shortcomings. The reality of some types of failures and accidents is that the event itself may destroy evidence about itself. The fatigue fracture that may have caused a drive shaft to fail, for example, may be rubbed away by friction with another part after the failure has occurred. Because of this, the fatigue fracture itself may not be directly observable. Or, perhaps the defective part responsible for the failure is lost or obscured from discovery in the accident debris. Clean up or emergency repair activities may also inadvertently destroy or obscure important evidence. In short, there can be observational gaps.

Using the previous graph analogy, this is like having areas of the graph with no data points, or few data points. Of course, if the data points are too few, perhaps several curves might be fitted to the available data. For example, two points not only determine a simple line, but also an infinite number of polynomial curves and transcendental functions.

Thus, it is possible that the available observations can be explained by several hypotheses. Gaps or paucity in the observational data may not allow a unique solution. For this reason, two qualified and otherwise forthright experts can sometimes proffer two conflicting reconstruction hypotheses, both equally consistent with the available data.

1.7 The Scientific Method and the Legal System

Having several plausible explanations for an accident or failure may not necessarily be a disadvantage in our legal system. It can sometimes happen that an investigator does not have to know exactly what happened, but rather what did not happen.

In our adversarial legal system, one person or party is the accuser, prosecutor, or plaintiff, and the other is the accused, or defendant. The plaintiff or prosecutor is required to prove that the defendant has done some wrong to him, his client, or the state. However, the defendant has merely to prove that he, himself, did not do the wrong or have a part in it; he does not have to prove who else or what else did the wrong, although it often is advantageous for him to do so.

For example, suppose that a gas range company is being sued for a design defect that allegedly caused a house to burn down. As far as the gas range company is concerned, as long as it can prove that the range did not cause the fire, the gas range company likely has no further concern as to what did cause the fire. (“We don’t know what caused the fire, but it wasn’t our gas range that did it.") Likewise, if the plaintiffs cannot prove that the particular gas range caused the fire, they also may quickly lose interest in litigation. This is because there may be no one else for the plaintiffs to sue; there is insufficient evidence to identify any other specific causation.

Thus, even if the observational data is not sufficient to provide a unique reconstruction of the failure, it may be sufficient to deny a particular one. That may be all that is needed.

1.8 *A Priori* Biases

One of the thornier problems in the reconstruction of a failure or catastrophic event is the insidious application of *a priori* methodology. This occurs when legal counsel hires a forensic engineer to find only information beneficial to his client's position. The counselor will not specifically state what findings are to be made, but may suggest that since the other side will be giving information detrimental to his client, there is no pressing need to repeat that work.

While the argument may seem innocent enough, it serves to bias the original data. This is because only beneficial data will be considered and detrimental data will be ignored. If enough bad data is ignored, the remaining observations will eventually force a beneficial fire or explosion reconstruction. Like the previous graph analogy, if enough data points are erased or ignored, almost any curve can be fitted to the remaining data.

A second version of this *a priori* problem occurs when a client does not provide all the basic observational data to the forensic engineer for evaluation. Important facts are withheld. This similarly reduces the observational database, and enlarges the number of plausible hypotheses that might explain the facts.

A third variant of *a priori* reasoning is when the forensic engineer becomes an advocate for his client. In such cases, the forensic engineer assumes that his client's legal posture is true even before he has evaluated the data. This occurs because of friendship, sympathy, or a desire to please his client in hopes of future assignments.

To guard against this, most states require that licensed professional engineers accept payment only on a time and materials basis. Unlike attorneys, licensed engineers may not work on a contingency basis. This, at least, removes the temptation of a reward or a share of the winnings.

Further, it is common for both the adversarial parties to question and carefully examine technical experts. During court examination by the attorneys for each party, the judge or jury can decide for themselves whether the expert is biased. During such court examinations, the terms of hire of the expert are questioned, his qualifications are examined, any unusual relationships with the client are discussed, all observations and facts he considered in reaching his conclusions are questioned, etc.

While an expert is considered a special type of witness due to his training and experience, he is not held exempt from adversarial challenges. While not perfect, this system does provide a way to check such biases and *a priori* assumptions.

1.9 The Engineer as Expert Witness

To the lay public and even to many engineers, engineering is often considered an objective science. This is perhaps fostered by the quantitative problem-solving methods used by engineers in design work. People hire engineers to tell them exact answers to their questions. For example, how many cubic meters of earth must be dug out, how much steel is required, or what size bearing is needed?

The undergraduate training of engineers also emphasizes exact problem-solving techniques. Students spend many hours calculating the correct answer to a specific problem, learning the correct fact, or applying the correct theorem to answer their homework problems. Where there is doubt, often the correct answer is found at the back of the textbook.

Engineers often refer to their discipline as a “hard” science: one that provides a “hard” or exact solution to a problem. This is in contrast to disciplines like psychology, sociology, or economics, which are sometimes considered “soft” sciences because of their inability to supply exact or specific answers. While an engineer can calculate when a beam will break because of excessive load stress, a sociologist is unable to similarly calculate the date when a community will riot because of analogous social stress.

Because of this traditional bias, some engineers are wholly taken aback when they present their case findings and conclusions in a courtroom for the first time. Their well-reasoned, scientifically sound investigation of an accident, failure, or catastrophic event may be pronounced unsound or fallacious, and may even be dismissed out of hand.

In fact, their qualifications, which may impress colleagues, will be belittled. Their experience, which may be considerable, will be minimized or characterized as inappropriate. Their character and professionalism, no matter how impeccable, will be questioned and doubted. It is not unknown for the experience to be so unpleasant to some that they never again undertake a forensic assignment.

In a courtroom, extremely well-qualified and distinguished professional engineers may testify on behalf of one side of an issue. They may radically disagree with another set of equally well-qualified and distinguished engineers who may testify on behalf of the other side of the issue. Bystanders might presume that the spectacle of strong disagreement among practitioners of such a hard science indicates that one side or the other has been bought off, is incompetent, or is just outright lying.

While the engineering profession is certainly not immune from the same dishonesty that plagues other professions and mankind in general, the basis for disagreement is often not due to corruption or malfeasance. Rather, it is a highly visible demonstration of the subjective aspects of engineering. Nowhere else is the subjectivity in engineering so naked as in a courtroom. To some engineers and lay persons, it is embarrassing to discover, perhaps for the first time, that engineering does indeed share some of the same attributes and uncertainties as the soft sciences.

Because of the adversarial role, no attorney will allow another party to present evidence hurtful to his client's interests without challenging and probing its validity. If the conclusions of a forensic engineer witness cause his client to lose $10 million, it is a sure bet that the attorney will not let those conclusions stand unchallenged! This point should be well considered by the forensic engineer in all aspects of an investigation. It is unreasonable to expect otherwise.

It is not the duty of the attorney to judge his client; that is the prerogative of the judge and jury. However, it is the attorney's duty to be his client's advocate. In one sense, the attorney is his client: the attorney is supposed to do for his client what the client would do for himself had he had the same training and expertise. When all attorneys in a dispute present their cases as well as possible, the judge and jury can make the most informed decision possible.

An engineer cannot accept a cut of the winnings or a bonus for a favorable outcome. He can only be paid for his time and expenses. If it is found that he has accepted remuneration on some kind of contingency basis, it is grounds for having his professional engineer's license suspended or revoked. The premise of this policy is that if a forensic engineer has a stake in the outcome of a trial, he cannot be relied upon to give honest answers in court.

Attorneys, on the other hand, can and do accept cases on a contingency basis. It is not uncommon for an attorney to accept an assignment on the promise of 30–40% of the take plus expenses if the suit is successful. This is allowed so that poor people who have meritorious cases can still obtain legal representation.

However, this situation can create friction between the attorney and the forensic engineer. First, the attorney may try to delay paying the engineer's bill until after the case. This is a version of "when I get paid, you get paid" and may be a *de facto* type of contingency fee arrangement. For this reason, it is best to agree beforehand on a schedule of payments from the attorney for service rendered. Follow the rule: "would it sound bad in court if the other side brought it up?"

Secondly, since the lawyer is the advocate for the case and may have a financial stake in the outcome, he may pressure the engineer to manufacture some theory to better position his client. If the engineer caves in to this temptation, he is actually doing the attorney a disservice.

A forensic engineer does his job best when he informs the attorney of all aspects of the case he has uncovered. The "other side" may also have the benefit of an excellent engineer who will certainly point out the "bad stuff" in court. Thus, if the attorney is not properly informed of the "bad stuff," he cannot properly prepare the case for presentation in court.

1.10 Reporting the Results of a Forensic Engineering Investigation

There are several formats used to report the results of a forensic engineering investigation. The easiest is a simple narrative, where the engineer simply describes all his investigative endeavors in chronological order. He starts from when he received the telephone call from the client, and continues until the last item in the investigation is complete. The report can be composed daily or piecewise when something important occurs as the investigation progresses, like a diary or journal. Insurance adjusters, fire investigators, and detectives often keep such chronological journals in their case files.

A narrative report works well when the investigation involves only a few matters and the evidence is straightforward. However, it becomes difficult for the reader to imagine the reconstruction when a lot of evidence and facts must be considered, along with test results, eyewitness accounts, and the application of scientific principles. Often the connections among the various items are not readily apparent, and the chronology of the investigation often does not logically develop the chronology of the accident itself.

Alternately, the report could be prepared like an academic paper, replete with technical jargon, equations, graphs, and reference footnotes. While this type of report might impress colleagues or the editors of technical journals, it is usually unsatisfactory for this application. It does not readily convey the findings and assessment of the investigation to the people who need to read it to make decisions. They are usually not professional scholars.

To determine what kind of format to use, it is often best to first consider who will be reading the forensic investigation report. In general, the audience includes the following.

1. **Claims adjuster:** The adjuster will use the report to determine whether a claim should be paid under the terms and conditions of the insurance policy. If he suspects there is subrogation potential, he will forward

the report to the company's attorney for evaluation. In some insurance companies, such reports are automatically evaluated for subrogation potential. Subrogation is a type of lawsuit filed by an insurance company to get back the money they paid out for a claim by suing a third party that might have something to do with causing the loss. For example, if a wind storm blows the roof off a house, the insurance company will pay the claim to the homeowner, but may then sue the original contractor because the roof was supposed to withstand such storms without being damaged.

2. **Attorneys:** This includes attorneys for both the plaintiff and the defendant. The attorneys will scrutinize every line and every word used in the report. Often, they will inculcate meaning into a word or phrase that the engineer-author never intended. Sometimes the engineer-author will unadvisedly use a word in an engineering context that also has a specific legal meaning. The legal meaning may be different from the engineering meaning. Lawyers are wordsmiths by trade. Engineers as a group are renown for being poor writers. This disparity in language skill often provides the attorneys for either side plenty of sport in reinterpreting the engineer's report to mean what they need it to mean.
3. **Technical experts:** The report will also be read by the various technical experts working for the attorneys. They will want to know on what facts and observations the engineer relied, which regulations and standards he consulted and applied, and what scientific principles or methodologies were used to reach the conclusions about the cause of the loss or failure. The experts for the other side, of course, will challenge each and every facet of the report that is detrimental to their client and will attempt to prove that the report is a worthless sham. Whatever standard the engineer used in his report will, of course, be shown to be incorrect, incorrectly applied, or not as good as the one used by the other side's technical expert. One common technique that is used to discredit a report is to segment the report into minute component parts, none of which, when examined individually, are detrimental to their side. This technique is designed to disconnect the interrelationships of the various components and destroy the overall meaning and context. It is akin to examining individual heart cells in a person's body to determine if the person is in love.
4. **The author:** Several years after the report has been turned in to the client and the matter has been completely forgotten about, the forensic engineer who originally authored the report may have to deal with it again. Court cases can routinely take several years for the investigating engineer to be involved. Thus, several years after the original investigation, the engineer may be called upon to testify in deposition or

court about his findings, methodologies, and analytical processes. Since so much has happened in the meantime, the engineer may have to rely on his own report to recall the particulars of the case and what he did.

5. **Judge and jury:** If the matter does end up in trial, the judge will decide if the report can be admitted into evidence, which means that the jury will be allowed to read it. Since this is done in a closed jury room, the report must be understandable and convey the author's reasoning and conclusions solely within the four corners of each page. Bear in mind that the members of an average jury have less than a 12th grade educational level. Most jurors are uncomfortable with equations and statistical data. Some jurors may believe there is something valid in astrology and alien visitations, will be distrustful of intellectual authorities from out of town, and since high school, their main source of new scientific knowledge has consisted of television shows and tabloids.

In order to satisfy the various audiences, the following report format is often used, which is consistent with the pyramid method of investigation noted previously. The format is based on the classical style of argument used in the Roman Senate almost 2000 years ago to present bills. As it did then, the format successfully conveys information about the case to a varied audience, who can chose the level of detail they wish to obtain from the report by reading the appropriate sections.

1. **Report identifiers:** This includes the title and date of the report, the names and addresses of the author and client, and any identifying information such as case number, file number, date of loss, etc. The identifying information can be easily incorporated into the inside address section if the report is written as a business letter. Alternately, the identifying information is sometimes listed on a separate page preceding the main body of the report. This allows the report to be separate from other correspondence. A cover letter is then usually attached.
2. **Purpose:** This is a succinct statement of what the investigator seeks to accomplish. It is usually a single statement or a very short paragraph. For example, "to determine the nature and cause of the fire that damaged the Smith home, 1313 Bluebird Lane, on January 22, 1999." From this point on, all the parts of the report should directly relate to this "mission statement." If any sentence, paragraph, or section of the report does not advance the report toward satisfying the stated purpose, those parts should be edited out. The conclusions at the end of the report should explicitly answer the question inferred

in the purpose statement. For example, "the fire at the Smith house was caused by an electrical short in the kitchen ventilation fan."

3. **Background Information:** This part of the report sets the stage for the rest of the report. It contains general information as to what happened so that the reader understands what is being discussed. A thumbnail outline of the basic events and the various parties involved in the matter are included. It may also contain a brief chronological outline of the work done by the investigator. It differs from an abstract or summary in that it contains no analysis, conclusions, or anything persuasive.
4. **Findings and Observations:** This is a list of all the factual findings and observations made related to the investigation. No opinions or analysis is included: "just the facts, ma'm." However, the arrangement of the facts is important. A useful technique is to list the more general observations and findings first, and the more detailed items later on. As a rule, going from the "big picture" to the details is easier for the reader to follow than randomly jumping from minute detail to big picture item and then back to a detail item again. It is sometimes useful to organize the data into related sections, again, listing generalized data first, and then more detailed items. Movie directors often use the same technique to quickly convey detailed information to the viewer. An overview scene of where the action takes place is first shown, and then the camera begins to move closer to where things are going on.
5. **Analysis:** This is the section wherein the investigating engineer gets to explain how the various facts relate to one another. The facts are analyzed and their significance is explained to the reader. Highly technical calculations or extensive data are normally listed in an appendix, but the salient points are summarized and explained here for the reader's consideration.
6. **Conclusions:** In a few sentences, perhaps even one, the findings are summarized and the conclusion stated. The conclusion should be stated clearly, with no equivocation, using the indicative mode. For example, a conclusion stated like, "the fire could have been caused by the hot water tank," is simply a guess, not a conclusion. It suggests that it also could have been caused by something other than the hot water tank. Anyone can make a guess. Professional forensic engineers offer conclusions. As noted before, the conclusions should answer the inferred question posed in the purpose section of the report. If the report has been written cohesively up to this point, the conclusion should be already obvious to the reader because it should rest securely on the pyramid of facts, observations, and analysis already firmly established.
7. **Remarks:** This is a cleanup, administrative section that sometimes is required to take care of case details, e.g., "the evidence has been moved

and is now being stored at the Acme garage," or, "it is advisable to put guards on that machine before any more poodles are sucked in." Sometimes during the course of the investigation, insight is developed into related matters that may affect safety and general welfare. In the nuclear industry, the term used to describe this is "extent of condition." Most states require a licensed engineer to promptly warn the appropriate officials and persons of conditions adverse to safety and general welfare to prevent loss of life, loss of property, or environmental damage. This is usually required even if the discovery is detrimental to his own client.

8. **Appendix:** If there are detailed calculations or extensive data relevant to the report, they go here. The results of the calculations or analysis of data is described and summarized in the analysis section of the report. By putting the calculations and data here, the general reading flow of the report is not disrupted for those readers who cannot follow the detailed calculations, or are simply not interested in them. And, for those who wish to plunge into the details, they are readily available for examination.
9. **Attachments:** This is the place to put photographs and photograph descriptions, excerpts of regulations and codes, lab reports, and other related items that are too big or inconvenient to directly insert into the body of the report, but are nonetheless relevant. Often, in the findings and observations portion of the report, reference is made to "photograph 1" or "diagram 2B, which is included in the attachments."

In many states, a report detailing the findings and conclusions of a forensic engineering investigation are required to be signed and sealed by a licensed professional engineer. This is because by state law, engineering investigations are the sole prerogative of licensed, professional engineers. Thus, on the last page in the main body of the report, usually just after the conclusions section, the report is often signed, dated, and sealed by the responsible licensed professional engineer(s) who performed the investigation. Often, the other technical professionals who worked under the direction of the responsible professional engineer(s) are also listed, if they have not been noted previously in the report.

Some consulting companies purport to provide investigative technical services, investigative consulting services, or scientific consulting services. Their reports may be signed by persons with various initials or titles after their names. These designations have varying degrees of legal status or legitimacy vis-à-vis engineering investigations depending upon the particular state or jurisdiction. Thus, it is important to know the professional status of the person who signs the report. A forensic engineering report signed by a person without the requisite professional or legally required credentials in the particular jurisdiction may lack credibility and perhaps even legal legitimacy.

In cases where the report is long and complex, an executive summary may be added to the front of the report as well as perhaps a table of contents. The executive summary, which is generally a few paragraphs and no more than a page, notes the highlights of the investigation, including the conclusions. A table of contents indicates the organization of the report and allows the reader to rapidly find sections and items he wishes to review.

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Wind Damage to Residential Structures

2

> You know how to whistle don't you? Just put your lips together and blow.
>
> **— Lauren Bacall to Humphrey Bogart, in *To Have and Have Not***
> *Warner Bros. Pictures, 1945*

2.1 Code Requirements for Wind Resistance

Most nationally recognized U.S. building codes, such as the Unified Building Code (UBC) and the Building Officials and Code Administrators (BOCA) code require that buildings be able to withstand certain minimum wind speeds without damage occurring to the roof or structure. In the Midwest, around Kansas City for example, the minimum wind speed threshold required by most codes is 80 mph. For comparison, hurricane level winds are considered to begin at 75 mph.

According to the National Oceanic and Atmospheric Administration (NOAA) weather records, the record wind speed to date measured at the weather recording station at Kansas City International Airport is 75 mph. This occurred in July 1992. Considering together the Kansas City building code requirements and the Kansas City weather records, it would appear that if a building is properly "built to code" in the Kansas City area, it should endure all winds except record-breaking winds, or winds associated with a direct hit by a tornado.

Unfortunately, many buildings do not comply with building code standards for wind resistance. Some communities have not legally adopted formal building codes, and therefore have no minimum wind resistance standard. This allows contractors, more or less, to do as they please with respect to wind resistance design. This is especially true in single-family residential structures because most states do not require that they be designed by licensed architects or engineers. Essentially, anyone can design and build a house. Further, in some states, anyone can be a contractor.

It is also likely that many older buildings in a community were constructed well before the current building code was adopted. The fact that they have survived this long suggests that they have withstood at least some

Plate 2.1 Severe wind damage to structure.

severe wind conditions in the past. Their weaker contemporaries have perhaps already been thinned out by previous storms. Most codes allow buildings that were constructed before the current code was adopted and that appear to be safe to be "grandfathered." In essence, if the building adheres to construction practices that were in good standing at the time it was built, the code does not require it to be rebuilt to meet the new code's requirements.

Of course, while some buildings are in areas where there is indeed a legally adopted code, the code may not be enforced due to a number of reasons, including graft, inspector malfeasance, poorly trained inspectors, or a lack of enforcement resources. Due to poor training, not all contractors know how to properly comply with a building code. Sometimes, contractors who know how to comply, simply ignore the code requirements to save money. In the latter case, Hurricane Andrew is a prime example of what occurs when some contractors ignore or subvert the wind standards contained in the code.

Hurricane Andrew struck the Florida coast in August 1992. Damages in south Florida alone were estimated at $20.6 billion in 1992 dollars, with an estimated $7.3 billion in private insurance claims. This made it the most costly U.S. hurricane to date. Several insurance companies in Florida went bankrupt because of this, and several simply pulled out of the state altogether. Notably, this record level of insurance damage claims occurred despite the fact that Andrew was a less powerful storm than Hugo, which struck the Carolinas in September 1989.

Plate 2.2 Relatively moderate wind caused collapse of tank during construction due to insufficient bracing.

Andrew caused widespread damage to residential and light commercial structures in Florida, even in areas that had experienced measurable wind speeds less than the minimum threshold required by local codes. This is notable because Florida building codes are some of the strictest in the U.S. concerning wind resistance. Additionally, Florida is one of the few states that also requires contractors to pass an examination to certify the fact that they are familiar with the building code. Despite all these paper qualifications, however, in examining the debris of buildings that were damaged, it was found that noncompliance with the code contributed greatly to the severity and extent of wind damage insurance claims.

The plains and prairie regions west of Kansas City are famous for wind, even to the point of having a "tall tale" written about it, the *Legend of Windwagon Smith*. According to the story, Windwagon Smith was a sailor turned pioneer who attached a ship's sail to a Conestoga wagon. Instead of oxen, he harnessed the wind to roam the Great Plains, navigating his wind-driven wagon like a sloop.

An old squatters' yarn about how windy it is in Western Kansas says that wind speed is measured by tying a log chain to a fence post. If the log chain is blowing straight out, it's just an average day. If the links snap off, its a windy day. In fact, even the state's name, "Kansas," is a Sioux word that means people of the south wind.

According to a publication from Sandia Laboratories (see references), Kansas ranks third in windy states for overall wind power, 176.6 watts per square meter. The other most windy states with respect to overall wind power are North Dakota (1), Nebraska (2), South Dakota (4), Oklahoma (5), and Iowa (6). Because of Kansas' windy reputation, it is hard to imagine any contractor based in Kansas, or any of the other windy Midwestern or seaboard states for that matter, who is not aware of the wind and its effects on structures, windows, roofs, or unbraced works in progress.

2.2 Some Basics about Wind

Air has two types of energy, potential and kinetic. The potential energy associated with air comes from its pressure, which at sea level is about 14.7 pounds per square inch or 1013.3 millibars. At sea level, the air is squashed down by all the weight of the air that lies above it, sort of like the guy at the bottom of a football pile-up. Like a compressed spring, compressed air stores energy that can be released later.

The kinetic energy associated with air comes from its motion. When air is still, it has no kinetic energy. When it is in motion, it has kinetic energy that is proportional to its mass and the square of its velocity. When the velocity of air is doubled, the kinetic energy is quadrupled. This is why an 80-mph wind packs *four times* the punch of a 40-mph wind.

The relationship between the potential and kinetic energies of air was first formalized by Daniel Bernoulli, in what is now called Bernoulli's equation. In essence, Bernoulli's equation states that because the total amount of energy remains the same, when air speeds up and increases its kinetic energy, it does so at the expense of its potential energy. Thus, when air moves, its pressure decreases. The faster it moves, the lower its pressure becomes. Likewise, when air slows down, its pressure increases. When it is dead still, its pressure is greatest.

The equation developed by Daniel Bernoulli that describes this "sloshing" of energy between kinetic and potential when air is flowing more or less horizontally is given in Equation (i), which follows.

$$\text{total energy} = \text{potential} + \text{kinetic}$$

$$[P_{atmos}/\rho] = [P/\rho] + v^2/2g_c \tag{i}$$

where P_{atmos} = local pressure of air when still, ρ = density of air, about 0.076 lbf/ft^3, P = pressure of air in motion, v = velocity of air in motion, and g_c = gravitational constant for units conversion, 32.17 ft/(lbf-sec^2).

It should be noted that Equation (i), assumes that gas compressibility effects are negligible, which considerably simplifies the mathematics. For wind speeds associated with storms near the surface of the earth and where

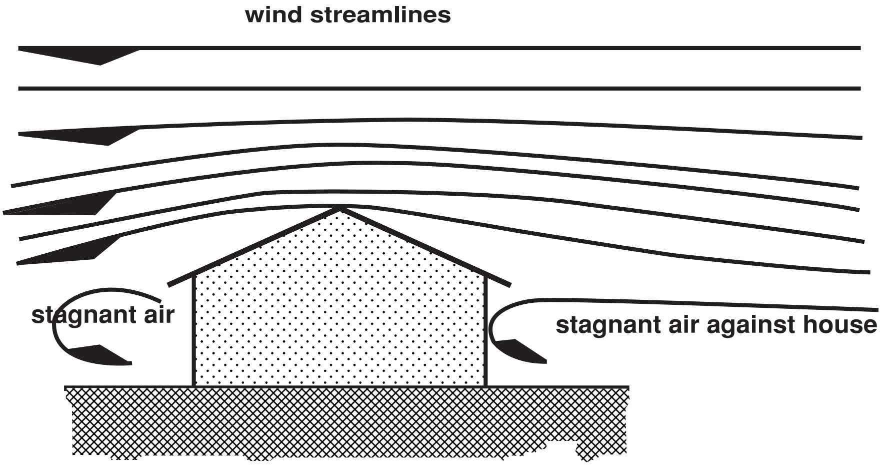

Figure 2.1 Side view of wind going over house.

air pressure changes are relatively small, the incompressibility assumption implicit in Equation (i) is reasonable and introduces no significant error.

Wading through the algebra and the English engineering units conversions, it is seen that a 30-mph wind has a kinetic energy of 30 lbf-ft. Since the total potential energy of still air at 14.7 lbf/in^2 is 27,852 lbf-ft, then the reduction in air pressure when air has a velocity of 30 mph is 0.0158 lbf/in^2 or 2.27 lbf/ft^2. Similarly at 60 mph, the reduction in air pressure is 0.0635 lbf/in^2 or 9.15 lbf/ft^2.

What these figures mean becomes more clear when a simplified situation is considered. Figure 2.1, shows the side view of a house with wind blowing over it. As the wind approaches the house, several things occur.

First, some of the wind impinges directly against the vertical side wall of the house and comes more or less to a stop. The change in momentum associated with air coming to a complete stop against a vertical wall results in a pressure being exerted on the wall. The basic flow momentum equation that describes this situation is given below.

$$P = k\rho(v^2) \tag{ii}$$

where P = average pressure on vertical wall, k = units conversion factor, ρ = mass density of air, about 0.0023 slugs/ft^3, and v = velocity of air in motion.

Working through the English engineering units, Equation (ii) reduces to the following.

$$P = (0.00233)v^2 \tag{iii}$$

where P = pressure in lbf/square feet, v = wind velocity in ft/sec.

Table 2.1 Perpendicular Wind Speed Versus Average Pressure on Surface

Wind Speed ft/sec	Resulting Pressure lbf/sq ft
10	0.23
20	0.93
30	2.10
40	3.73
50	5.83
60	8.39
70	11.4
80	14.9
90	18.9
100	23.3
120	33.6
150	52.4

By solving Equation (iii) for a number of wind speeds, Table 2.1 is generated. The table shows the relationship between a wind impinging perpendicularly on a flat surface and coming to a complete stop, and the resulting average pressure on that surface.

In practice, the pressure numbers generated by Equation (iii) and listed in Table 2.1 are higher than that actually encountered. This is because the wind does not fully impact the wall and then bounce off at a negligible speed, as was assumed. What actually occurs is that a portion of the wind "parts" or diverts from the flow and smoothly flows over and away from the wall without actually slamming into it, as is depicted in Figure 2.1. Therefore, to be more accurate, Equation (ii) can be modified as follows.

$$P = k\rho(v_1^2 - v_2^2) \text{ or } = C\rho(v_1^2) \tag{iv}$$

where P = average pressure on vertical wall, k = units conversion factor, ρ = density of air, about 0.0023 slugs/ft^3, v_1 = average velocity of air flow as it approaches wall, v_2 = average velocity of air flow as it departs wall, and C = overall factor which accounts for the velocity of the departing flow and the fraction of the flow that diverts.

In general, the actual average pressure on a vertical wall when the wind is steady is about 60–70% of that generated by Equation (iii) or listed in Table 2.1. However, in consideration of the momentary pressure increases caused by gusting and other factors, using the figures generated by Equation (iii) is conservative and similar to those used in actual design.

This is because most codes introduce a multiplier factor in the wall pressure calculations to account for pressure increases due to gusting, building geometry, and aerodynamic drag. Often, the end result of using this multiplier is a vertical wall design pressure criteria similar, if not the same, as that generated by Equation (iii). In a sense, the very simplified model equation ends up producing nearly the same results as that of the complicated model equation, with all the individual components factored in. This is, perhaps, an example of the *fuzzy central limit theorem* of statistics at work.

Getting back to the second thing that wind does when it approaches a house, some of the wind flows up and over the house and gains speed as it becomes constricted between the rising roof and the air flowing straight over the house along an undiverted streamline. Again, assuming that the air is relatively incompressible in this range, as the cross-sectional area through which the air flows decrease, the air speed must increase proportionally in order to keep the mass flow rate the same, as per Equation (v).

$$\Delta m/\Delta t = \rho A v \tag{v}$$

where $\Delta m/\Delta t$ = mass flow rate per unit time, A = area perpendicular to flow through which the air is moving (an imaginary "window," if you please), ρ = average density of air, and v = velocity of air.

Constriction of air flow over the house is often greatest at the roof ridge. Because of the increase in flow speed as the wind goes over the top of the roof, the air pressure drops in accordance with Bernoulli's equation, Equation (i). Where the air speed is greatest, the pressure drop is greatest.

Thirdly, air also flows around the house, in a fashion similar to the way the air flows over the house.

Lastly, on the leeward side of the house, there is a stagnant air pocket next to the house where there is no significant air flow at all. Sometimes this is called the wind shadow. A low pressure zone occurs next to this leeward air pocket because of the Bernoulli effect of the moving air going over and around the house.

A similar effect occurs when a person is smoking in a closed car, and then opens the window just a crack. The air inside the car is not moving much, so it is at high pressure. However, the fast moving air flowing across the slightly opened window is at a lower pressure. This difference in relative pressures causes air to flow from the higher pressure area inside the car to the low pressure area outside the car. The result is that smoke from the cigarette flows toward and exits the slightly opened window.

If a wind is blowing at 30 mph and impinges against the vertical side wall of a house like that shown in Figure 2.1, from the simplified momentum flow considerations noted in Equation (iii), an average pressure of 4.5 lbf/ft^2 will be exerted on the windward side vertical wall.

If the same 30-mph wind increases in speed to 40 mph as it goes over the roof, which is typical, the air pressure is reduced by 4.0 lbf/ft^2. Because the air under the roof deck and even under the shingles is not moving, the air pressure under those items is the same as that of still air, 14.7 lbf/in^2 or 2116.8 lbf/ft^2. The air pressure under the roof and under the shingles then pushes upward against the slightly lower air pressure of the moving air going over the roof. This pressure difference causes the same kind of lift that occurs in an airplane wing. This lifting force tries to lift up the roof itself, and also the individual shingles.

While 4.0 lbf/ft^2 of lift may not seem like much, averaged over a roof area of perhaps 25 × 50 ft, this amounts to a total force of 5000 lbf trying to lift the roof. At a wind speed of 80 mph, the usual threshold for code compliance in the Midwest, the pressure difference is 16 lbf/ft^2 and the total lifting force for the same roof is 20,000 lbf.

If the roof in question does not weigh at least 20,000 lbf, or is not held down such that the combined total weight and holding force exceed 20,000 lbf in upward resistance, the roof will lift. This is why in Florida, where the code threshold is 90 mph, extra hurricane brackets are required to hold down the roof. The usual weight of the roof along with typical nailed connections is not usually enough to withstand the lift generated by 90 mph winds.

It is notable that the total force trying to push the side wall inward, as in our example, is usually less than the total lift force on the roof and the shingles. This is a consequence of the fact that the area of the roof is usually significantly larger than the area of the windward side wall (total force = ave. pressure × area). Additionally, a side wall will usually offer more structural resistance to inward pressure than a roof will provide against lift. For these reasons, it is typical that in high winds a roof will lift off a house before a side wall will cave in.

Lift is also the reason why shingles on a house usually come off before any structural wind damages occur. Individual asphalt shingles, for example, are much easier to pull up than roof decking nailed to trusses. Shingles tend to lift first at roof corners, ridges, valleys, and edges. This is because wind speeds are higher in locations where there is a sharp change in slope. Even if the workmanship related to shingle installation is consistent, shingles will lift in some places but not in others due to the variations in wind speed over them.

Most good quality windows will not break until a pressure difference of about 0.5 lbf/sq in, or 72 lbf/sq ft occurs. However, poorly fitted, single pane glass may break at pressures as low as 0.1 lbf/sq in, or about 14 lbf/sq ft. This means that loosely fitted single pane glass will not normally break out until wind gusts are at least over 53 mph, and most glass windows will not break out until the minimum wind design speed is exceeded.