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FIRE PROTECTION ENGINEERING – SCIENCE OR ART?

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SUMMARY

Engineering is the application of technology to useful ends. Originally, engineering was based entirely on art rather than science. About 200 years ago, science developed sufficiently so that it began to be important in certain technologies. This importance of science accelerated in the nineteenth and twentieth centuries, and today certain branches of engineering are 90% science-based. Fire protection engineering is only 25% science-based today, according to the author's estimate, but the percentage is growing rapidly. Examples are given.

ENGINEERING IN GENERAL:

We are all aware that procedures used in every branch of engineering are based in part on science and in part on art. By art, you should not think of the fine arts, but of the useful arts, such as weaving, pottery making, forming arrow-heads, building log cabins, etc. A useful art, or craft, can be defined as a skill having practical applications, which is acquired by practice and experience, and is often passed down from one generation to another.

Two millennia ago, the Romans practiced military engineering and civil engineering. Military engineering was concerned with weapons, fortifications, siege equipment, transportation of armies, etc. Civil engineering was concerned with buildings, bridges, aqueducts, etc. These various engineering activities were based almost entirely on arts, with virtually no contribution from sciences.

At that time, it is not correct to say that no science existed. While the Romans were not noted as scientists, the Greeks before them made a number of important scientific advances. The names Archimedes, Aristotle, and Democritus come to mind. However, this early science was not sufficiently advanced to lead to many practical applications. Furthermore, these ancient Greek geniuses were primarily interested in pure science, mathematics, and philosophy, and were largely indifferent to practical applications.

After the collapse of the Roman empire, there was a thousand-year period in the Western world marked by relatively few innovations or engineering advances, let alone scientific advances. (Some important inventions were made in China in this period.)

This changed with the Renaissance, in the fifteenth and sixteenth centuries. A great number of inventions appeared, such as the magnetic compass, the mechanical clock, the printing press, gunpowder and cannons, eyeglasses, etc. Simultaneously, and at first independently, important scientific breakthroughs occurred, such as Kepler's discovery of the elliptical orbits of planets, Galileo's establishment of the law governing falling bodies, Torricelli's discovery of atmospheric pressure measurement by means of the barometer, etc. By the seventeenth century, these advances reached a peak when Newton set forth the law of gravitation and the laws of motion. Meanwhile, chemists were beginning to identify chemical elements correctly, and to speculate meaningfully about the identity of molecules. The laws of optics were established by Snell, Newton, and Huygens. Scientific instruments such as the thermometer, the microscope, the telescope, and accurate clocks became available and facilitated research. During this period, social changes provided a more receptive attitude of Western society toward innovation.

As science proved itself capable of providing reasonably accurate quantitative predictions of various aspects of real-world behavior, independently verifiable by the experimental method propounded by Galileo, a great acceleration of interest in science occurred. By the end of the nineteenth century, the laws of thermodynamics had been established, most of the chemical elements had been discovered, biology was transformed by Darwin's concept of evolution and Mendel's genetics, and electromagnetic phenomena were quantified, largely by Faraday and Maxwell. This acceleration of scientific discovery has continued through the twentieth century, with results familiar to us all.

As this body of scientific knowledge accumulated in the eighteenth century, mainly from research in England, France, Germany, and Italy, various findings were found to be useful in technology. Indeed, the technological build-up in the eighteenth and nineteenth centuries, called the Industrial Revolution, was based in a significant way on science. A few key examples will be mentioned.

While the first useful steam engine was empirically devised by Savery and Newcomen in 1712, it was very inefficient and had a low ratio of power to weight. It was not until 1776 that Watt, of Scotland, produced a far better steam engine, which revolutionized many aspects of production and transport. Watt had previously been an instrument maker at Glascow University, where he associated with Professor Black, who was the discoverer of latent heat of vaporization (and condensation) and was the first to measure heat energy quantitatively. Clearly the scientific understanding that Watt acquired (through his association with Black) must have been crucial in his successful invention.

As another example, consider steel-making. The so-called "iron age" dates back more than 3,000 years, but for most of this period, the practitioners had no knowledge of the chemical composition of iron and steel. In the nineteenth century, steel-making was revolutionized by introduction of the open-hearth furnace and the Bessemer converter, both of which were based on the principle of using air to oxidize excess carbon and other impurities in molten iron. Clearly a knowledge of chemistry and an understanding of the oxidation process were crucial to this development.

Even more dramatic, the scientific discoveries about the nature of electricity and magnetism by Volta, Ampere, Oersted, Gauss, Faraday, Maxwell, Helmholz, and others in the first half of the nineteenth century led to a whole series of useful devices in the last half of that century: the electric motor, the electric light, the telegraph, and the telephone, to name the most dramatic. In the twentieth century, radio, television, and electronic computers were invented. The field of electrical engineering obviously did not exist until the above inventions began to appear. Note that these inventions were a direct consequence of the preceding scientific discoveries.

Today, electrical and electronic engineering are based much more on science than on art (or experience). Of course, even in this field, some elements of art remain. For example, discovering which materials are the best insulators, which are good conductors, and most recently, which are superconductors, is primarily done by testing many materials (empiricism), although some guidance is obtained by making predictions based on atomic structure.

In the twentieth century, new subdivisions of engineering appeared which are based almost entirely on science. These include nuclear engineering, aerospace engineering, and, most recently, genetic engineering. Illustrations of the dependence of these areas on science should not be necessary for twentieth century readers.

As we approach the twenty-first century, shall we assume that virtually all engineering will soon be based on science much more than on art or experience? Not so!

As of today, scientists do not yet have adequate understanding of all aspects of physics, chemistry, and biology to supplant experience entirely in many areas. A few such areas are listed:

- long-range weather prediction (more than one week)
- combustion in an engine
- the "feel" or "hand" of a fabric
- odor, flavor, etc.
- treatments for certain diseases

- long-time health effects of trace materials or low levels of radiation
- development of materials with specific physical properties
- Corrosion of metals.

One may hope that future advances in scientific knowledge will ultimately provide all the answers, but, meanwhile, technology must continue with a dual foundation – science and art.

FIRE PROTECTION ENGINEERING:

We have seen that engineering skills applied to certain technologies (e.g., electrical engineering) are largely science-based. On the other hand, there are still many pockets of technology with heavy dependence on art, or experience, or trade secrets, or empirical testing. Let us consider the various elements of *fire protection engineering* in regard to the blend of science and art (or empirical components).

First, let us itemize some scientific questions which are relevant to fire protection engineering:

1. Chemistry

1a. Identification of combustible substances, and how much energy they can release (chemical thermodynamics).
1b. The role of oxygen in a fire.
1c. Establishment of chemical properties controlling ease of ignition, rapidity of flame spread, and magnitude of heat release rate per unit of area involved.
1d. Characterization of smoke and toxic species from fires.
1e. Effects of fire toxicants on humans.
1f. Mechanisms of action of fire retardants and extinguishing agents.

2. Fluid mechanics

2a. The motion of fire gases through a building, as influenced by buoyancy, mechanical ventilation, and wind.
2b. The rate of entrainment of air into flowing fire gases.
2c. Prediction of flame height.
2d. Hydraulics, applied to pipes or hoses.
2e. Sprinkler or spray droplet trajectories.

3. Heat transfer (radiation, convection, conduction)

3a. Radiant energy output of a flame.
3b. Convective and radiative energy transfer from a flame to the adjacent solid or liquid supplying the combustible vapors.
3c. Heat transfer from a flame to the surroundings, including time required to heat nearby combustibles to their ignition temperatures.
3d. Penetration of heat from a fire into the interior of nearby structural elements.
3e. Prediction of the cooling effect of water, applied in various ways to a fire.

Various references are available which provide details on all the above problems[1,2,3,4,5]. However, in most cases the present status of scientific knowledge is incomplete, and answers of high accuracy cannot be obtained.

Now let us look through the other end of the telescope, as it were, and consider various elements of

Table 1. Scientific Basis of Elements of Fire Protection Engineering (estimates)

	1969	1989	2009
Prediction of Fire Behavior	10%	20%	40%
Prediction of Fire Resistance of Structures	50%	60%	70%
Prediction of Human Behavior*	0%	5%	10%
Prediction of Toxic Effects*	10%	30%	50%
Detection System Design*	20%	50%	75%
Suppression System Design*	5%	10%	25%
Smoke Control Design*	5%	25%	50%
Fire Risk Analysis	0%	5%	20%
Average	12.5%	25.6%	42.5%

* for a given fire

fire protection engineering, as listed in Table 1.

After each subject, the author has provided his own rough estimates, for 20 years ago, the current status, and 20 years from now, of the percentage dependence on physical science as opposed to art. The scale is such that electrical engineering scores 90%, and gourmet cooking scores 10%. Some comments on these estimates are in order.

Comments on fire behavior: Present predictions are largely based on either actual fires or full-scale tests (empirical) or empirical correlations and extrapolations of bench-scale test results. A limited degree of scientific understanding of some small-scale tests has been obtained, but successful extrapolation to larger size is hindered by incompletely understood fire radiation and turbulence effects. Present research is leading to substantial advances in understanding. Then, computer programs to calculate fire growth will have a stronger scientific basis and will be more reliable. However, the tremendous complexities caused by composite or heterogeneous materials, elaborate geometric arrangements, melting and dripping, char formation, rupturing and rocketing (aerosol cans), etc., will prevent a fully scientific basis for fire behavior prediction in the forseeable future.

Comments on fire resistance of structures (including internal partitions): Present predictive methods are, generally, well grounded on fundamental scientific principles of three-dimensional transient heat transfer in solids and stress analysis, including thermal stresses. Some art is still required to predict the intensity and duration of heat load. Furthermore, the thermal and mechanical properties of the materials involved must be measured directly, rather than predicted from scientific knowledge of the atomic structure.

Comments on human behavior: For the purposes of this article, science means physical science and does not include psychology. By that definition, knowledge of individual and crowd behavior under stress is an art rather than a science.

Comments on toxic effects: Post-mortems of fire victims have provided important scientific knowledge as to which toxicants (carbon monoxide, hydrogen cyanide) have caused most deaths. Again, the detailed roles of each of these toxicants in preventing oxygen intake by the brain have been established. However, uncertainty remains on the combined effect of these with other toxicants, such as irritants, as well as the incapacitating dose, as contrasted with the fatal dose. More significantly, the fraction of toxicants, especially carbon monoxide, present in fire gases is not yet predictable with any accuracy. Research should improve these gaps, as well as reveal any unknown "supertoxicants."

Comments on detection system design: While a useful scientific basis exists for detector location guidelines, it is somewhat limited by uncertainties associated with turbulent and recirculating motions of fire gases carrying smoke. Future developments in computer modeling and physical modeling of turbulent smoke movement will help. Detector sensitivity depends on smoke particle size as well as on mass fraction of smoke particles in the fire gases, and neither of these can yet be predicted with the needed accuracy. Ultimately, science will lead to more sophisticated detectors which can discriminate more surely between fire-produced particles and other (false-alarm) particles.

Comments on suppression system design: There is a good scientific basis for extinguishment by inerting a compartment. However, by far the most common extinguishment procedure involves water application. The required "delivered density" to extinguish a given fire can only be determined empirically in most cases. Further, the trajectory of water droplets from sprinklers or spray nozzles and their deflection by fire plumes are generally determined experimentally. Computer "field models" are now being developed to calculate droplet histories in fire plumes.

Comments on smoke control: While rational procedures for calculating smoke movement in buildings exist, these are limited by uncertainties concerning the fluid dynamics involved (recirculation, entrainment, interplay of buoyancy and pressure forces). Both physical modeling studies and computer "field models" will expand the scientific basis of smoke control. Uncertainties will remain because of effects of wind and lack of knowledge of which doors are open, when windows break, etc.

Comments on fire risk analysis: This important tool, as currently applied, primarily uses empirical data bases rather than science, often because the needed science is not yet adequately developed. (Obviously, if fire protection engineering was 100% based on science, there would be no need for probabilistic studies; everything would be deterministic. This state of affairs is not foreseeable.) Note that a statistical or probabilistic study of some aspect of fire protection engineering, no matter how formidable the mathematical tools used, still cannot be called science-based if the data base employed is strictly empirical.

FINAL COMMENTS:

1. Fire protection engineering currently has a substantial base in science, but there is a great deal, probably a majority, of empiricism.

2. In the next twenty years, the science portion will be enlarged significantly, but major portions of art will remain.

3. The scientific approach, when available, is more powerful than the approach based on art, especially for dealing with novel situations requiring extrapolation, or for dealing with applications where consistency is important, such as code enforcement or insurance rating.

4. Any engineering design procedure based on science is likely to remain *permanently* useful. Since mankind will always be plagued with unwanted fire, research which expands fire science will always ultimately be justified.

5. This is not to denigrate the importance of empirical knowledge. After all, some of the aqueducts built by the Romans are still functional.

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RECENT PUBLICATIONS

As a service to the readers, the *Journal of Fire Protection Engineering* will publish regularly a list of recently published peer reviewed papers and books relevant to fire protection engineering. Readers are encouraged to submit additional peer reviewed journals for consideration for inclusion in the listing of recent publications. Papers relevant to fire protection engineering from journals which are not fully devoted to fire will be considered. Books and individual papers from journals which rarely contain fire papers may also be included.

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Books

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Acknowledgment of Reviewers

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Subject Index
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