Progress in Fire Science

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ABSTRACT

A reflection and a projection of views are presented on the general state of fire research and its relationship to design, investigation, and education. The field of fire science is a relatively new discipline and its scope is likely to expand, and its impact is likely to be felt more significantly in the new 21st century. Examples are given to suggest the trends taking place in education, fire investigation, and fire safety design methodology for regulation. The significant scientific and societal obstacles to advancing fire science will be discussed. As an indication of educational progress, examples of the author's research with his master of science students will be presented. This includes models for the prediction of burning rate, flame spread and fire growth in rooms, and fire plume characteristics.

INTRODUCTION

The level of fire science used in applications to safety and investigation processes is relatively weak compared to other engineering disciplines and areas of technology. Moreover, the science knowledge-base for fire is undeveloped but growing. Therefore, the current use of fire science is consistent with this base of knowledge and its dissemination. Consequently, the practice of fire safety and fire investigation is empirical, and based on established practices that have stood the test of time and the consensus of it practitioners. Despite this current state, there is a growing awareness and appreciation of fire science, a growing use of engineering analysis in fire applications, and a growing interest in the pursuit and development of fire safety engineering education. The seeds of fire science have been planted during the later half of the 20th century, and the 21st century is surely to see a complete restructuring of how fire issues are considered. Moreover, the advancement of mathematical computing methods will make complex problems such as those of fire more tractable as computers become faster, larger, and easier to use.

HISTORICAL DEVELOPMENTS

In order to understand the evolution of fire science, it is useful to examine its historical development. Despite the fact that some might consider fire and combustion as separate domains, fire is combustion without the normal constraint imposed by power generating devices. Therefore, in order to make progress in the science of fire, a foundation of appropriate knowledge must exist to support it. Some dates are suggested in Table 1 for the birth of significant science disciplines which were necessary for the development fire science to commence. All of the subjects listed, preceding fire, were needed in order for the subject of fire to even be considered for study. For those who study fire, it is soon realized that the fluid mechanics is the key to understanding the combustion phenomena as well as the general motion of air and smoke. Fire research activities may have begun as early as 1920 but these were insignificant to the large scope of the field. These early studies were focused on the establishment of engineering design practices to insure the adequate fire resistance of building structural elements. Examination of the literature probably places 1950 as the nominal starting

Table 1. Suggested Dates for the Development of Modern Science Disciplines

Date	Discipline
1780	Chemistry
1850	Thermodynamics
1890	Fluid Mechanics
1920	Heat Transfer
1930	Combustion
1950	Fire

date of the birth of modern fire science and research. The studies from this period began to address the dynamics of the fire and the movement of smoke. Damage to people and contents were now considered more important than just the building structure.

Several noteworthy pioneers are significant for launching the study of fire.Scientists in Japan were early leaders in this field due to the extreme sensitivity to occurrence of fire with earthquakes, and the deadly Tokyo quake of 1923. Kawogoe (BRI) stands out as the most significant pioneering fire scientist from Japan. Beginning in the early 1950's in England, at the Fire Research Station, P. H. Thomas and David Rasbash were key leaders in British fire research. At about' the same time, Prof. Howard Emmons (Harvard), encouraged by Prof. Hottel (M. I. T.), began to demonstrate and advocate for basic research in the field of fire. This effort coupled with the existing fire research program under A. F. Robertson at the National Bureau of Standards eventually stimulated government support for a wide spread program of fire research in the USA. The USA program began to grow at about 1970. It is very likely that significant work went on in Russia and the Soviet Union countries during this period since Russia was the seat of pioneering studies in combustion and the source of several translated textbooks on fire; however, this author is not familiar with the history of fire science in those countries.

If we examine the motivation of these fire research efforts we would probably find it due to natural or war-time disasters, or the recognition of societal problems and ability of government to devote funding to the study of fire safety. In Japan, it is very likely that the style of traditional housing and the risk of conflagration was their motivator for studying fire. Indeed, the source of most fire research activity in Japan is among architects, and they have a fire science handbook for reference which was published in the early 1980's. The U. K. effort in fire research began as early as 1939 at the Fire Research Station and was soon involved in wartime fire issues. Following World War II a Fire Research Board was established in November 1946 to resume research on peacetime fire research needs.[1] The research of this laboratory is prominent in the literature, and pioneered many of the key fire problems, with very likely counterpart work occurring in Japan. In the USA a presidential commission report, America Burning, outlined the needs of the fire service, the fire problem in the USA, and its research needs [2]. The commission's study was prompted by the high perceived death rate due fire in the USA which was then thought to be as high as 11,850 per year (1971). However, this number was later found to have been in error due to a misplaced decimal place in fire deaths in auto accidents: 395 instead of 3950. This report, in a time of an acute consumer interest in the safety of products, brought fire research to the forefront in the USA. It established a fundamental grants program of $ 2 million per year, an a Center for Fire Research at the National Bureau of Standards that employed nearly 125 at its peak. But at about 1983, the US program came under attack i due to changing government policies, and the fundamental grants program dropped to $ 1.3 million where it stands today. Fire research and safety has suffered accordingly as government attitudes change and funding wanes.

One motivator of fire research is the perception of society about the risk posed by fire. Figure 1 shows a recent review of fire death statistics from developed countries. It should be noted that the recent political and economic changes affecting Russia have accounted for about a 3 fold increase in their death rate to its current astounding high level. It is not know what are the causes of these statistics, and why countries differ. Some speculate on the cultural differences, another reason suggested is the effects introducing new technologies and products. New technologies bring unforeseen problems to fire safety. These problems are not anticipated because fire safety is not commonly part of the design and development processes in manufacturing. Usually society reacts to fire disasters. When society has the means and the time for thoughtful deliberation, the usual outcome is the advancement of fire science knowledge and its dissemination.

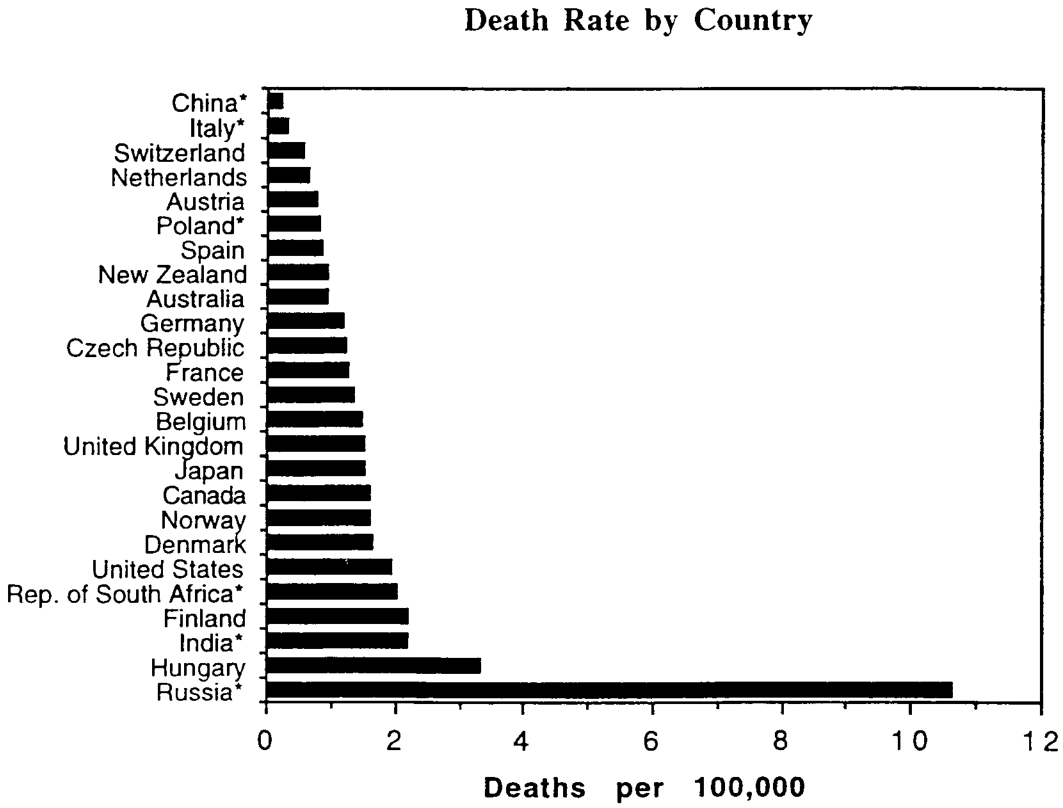

Figure 1. Annual Fire Death Rate of Developed Countries [3,4]

We can look forward to much more rapid progress in fire science in the next century since a good base of knowledge has already been established. However, the advancement of fire research and safety will always be tied to good economic times and an enlightened society. It is not part of the normal practices used to advance technology since these practices are driven by driven by positive economic factors leading to profit and the increase in the gross domestic product. On the other hand, fire safety is a perceived drag on the economy. Hopefully by the end of the 21st century, society will have the ability to look beyond its needs of survival and comfort, and issues of safety will take a more dominant focus.

STATE OF FIRE SCIENCE

The state of fire science can be measured by the ability to present consistent and generalized explanations for its phenomena, and to be able to predict important variables with generalization. A general documented review is not possible here, but a perusal of the few texts and handbooks in the field can display the scope of the accrued knowledge base [e.g. 5, 6,7].

Two computational strategies have emerged for treating smoke movement within buildings: (1) *zone modeling* which treats the stratified regions of smoke and air layers as well mixed and uniform in properties, and (2) *field modeling* which considers pointwise solutions to the basic turbulent conservation equations of mass, momentum, energy and species. The expanding speed and size of computers has made the latter approach much more feasible. Surely, in the 21st century this capability will expand well beyond our imagination. Once the fundamental transient equations can be solved without recourse to turbulent and combustion models and with sufficient resolution of scale to capture the small scale diffusion effects in combustion, then their results will be better than the best experiment that can be done today. Such a field modeling approach will be relevant to many other scientific problems as well, and fire science will benefit by these computational advances. However, it will still be necessary and practical to use zone modeling for large complex buildings and structures. Moreover, the description of individual fire phenomena will still need analytical presentations to illustrate and directly present the important variables. These formulas will come from simplified theories and correlations based on detailed experimental and computational data. We are just beginning to learn how to take advantage of these tools.

Progress over the last half of the 20th century has laid a good foundation to demonstrate that fire research can lead to a wide range of engineering methods for prediction with a sound scientific base. Current knowledge will allow the prediction in the following areas:

1. Dynamics of fire plumes for simple geometries.
2. Dynamics of smoke flow under ceilings.
3. Dynamics of room fires and flashover.
4. Dynamics of fire effects on simple structural elements.
5. Dynamics of the effects of fire and products of combustion on people.
6. Dynamics of ignition, flame spread and burning rate for simple geometries.
7. Primitive results for the suppression of fire and its agents.
8. Smoke movement in simple building geometries from room to room.

Given sufficient funding in fundamental research, prediction accuracy in these areas can be improved and their scope expanded. But fundamental research must be systematically conducted or the knowledge-base will weaken due to its limited scope and accuracy.

Table 2. Barriers to Fire Science Limiting Prediction

Phenomena	Ability to Predict
Turbulence	Flow, Combustion
Buoyant flows	Entrainment, Air supply
Flame Structure	Heat transfer, radiation
Chemical kinetics	Combustion products
Decomposition	Burning rate of solids

In the near future, empirical and experimental based formulas will be the most practical method to advance the state of the art. Although current computational and instrumentation based results can yield much detail about fire phenomena, there are limitations to their generalization. These limitations are due to barriers in our current state of knowledge and techniques that preclude the solution to key complex fire phenomena from first principles. These barriers to our capability have to be by-passed by more approximate engineering methods. In Table 2 some of these current barriers are listed along with their effect on our predictive ability. We have developed methods to compensate for each of these limitations. Empirical entrainment rules are applied, and experimental data supplies the means to develop dimensionless correlations for fire induced turbulent buoyant flow phenomena. Measurements can give us heat transfer results from flames, but these are not generalized to real fire scenarios. Data from material tests have presented chemical data in the form of *yields* which give the energy and species mass per unit mass of the volatile fuel generated. It has been found [e.g. 8] that these yields are approximately constant when enough air is present, and markedly change which the air supply drops below its required stoichiometric supply. No simple general models exist for the description of transient burning of materials in terms of easily determined material properties. And no burning rate models exist for the evaluation of materials currently regulated by fire codes, or for commercial products and items generally of concern to fire safety. These issues pertaining to material and product flammability are still relegated to a collection of empirical tests which vary around the world.

FLAMMABILITY TESTING

There is no uniformity in the methods to assess the flammability of materials. Tests vary between countries, and even within government agencies. In the USA the flammability tests and criteria for assessing the performance of commercial aircraft cabin interior furnishings substantially differs from the tests used to assess the furnishings in rail cars, and passenger transit vehicles. The aircraft tests have been based on specific accidental fire scenarios of concern, while the others have been established based on availability, judgement, and tradition. Rarely can a scientific rationale or fire scenario connection can be made to the flammability test method. There is no universal criterion established to assess flammability, nor can it be separated from the fire scenario of relevance. This is a serious and a complex problem. Scientists work on idealizations of products and materials, and regulators demand robust, reproducible tests. This is an area that demands more science and more connection to reality.

Over the past 10 years the problem of the best flammability test for construction materials has been an acute issue among the nations of the European Community (EC). Most countries regulate the flammability of construction materials: namely, products for lining the walls and ceilings of buildings. The tests vary in size and in the measurements made. The results are expressed in relative indices which only truly show the ranking of the material in the test. In order to establish some meaning to these rankings, full-scale tests have been used to check their performance. Some full-scale tests have taken the form of a room-corner test in which a wall and ceiling mounted material is subjected to a corner ignition burner. The room-corner testing strategy was originally proposed in ASTM, and is currently standards of the International Standards Organization (ISO 9750) and the Uniform Building Code in the USA (UBC No. 42-2).

The frustration of the EC to establish a universal flammability test format is illustrated in Figure 2 where the test results displayed have been forced into a 4 class basis to enable them to be plotted against the 4 classes proposed for ISO 9750 [9]. The attempt to amalgamate the "Three Sister Tests" of Germany, France and England did not lead to harmony. A further attempt to use the Cone Calorimeter (ASTM E 1354) failed, probably because its measurement capability is a function of the prescribed heat flux, and regulators were now confronted by the need to relate measurement data to realistic fire conditions. Of course, these are not the only reasons. Such confrontations of fire testing, regulation, and product classification become embroiled in technical, political and economic issues. Fire science can not ignore these confrontations, but must provide a path to their solution that allows science and the public interest to not be sacrificed. These are complex problems that need rational solutions. The EC has an opportunity to advance the art and science of fire testing due to their quest for unification. But all countries and manufacturers share this responsibility. Fairness in safety and marketing must be based on science, not opinions.

Currently, the EC strategy is to consider a new test entitled, "The Single Burning Item Test". This test consists of a corner configuration of a scale of roughly 1 m to 1.5 m with a gas burner ignitor. It seeks to measure the material characteristics of ignition, flame spread, energy release, and smoke opacity. The Roland Test, of similar scale, uses a radiant panel to initiate piloted ignition on a vertical specimen, recording flame spread in three directions, energy and smoke. The former test can be considered *scenario* based, and the latter *property* based. For such tests to be useful in engineering analysis, they must produce useable data for predictive models. They can not just produce arbitrary numerical rankings. The EC process will have profound impact on how fire science is perceived and how it relates to real world fire safety issues.

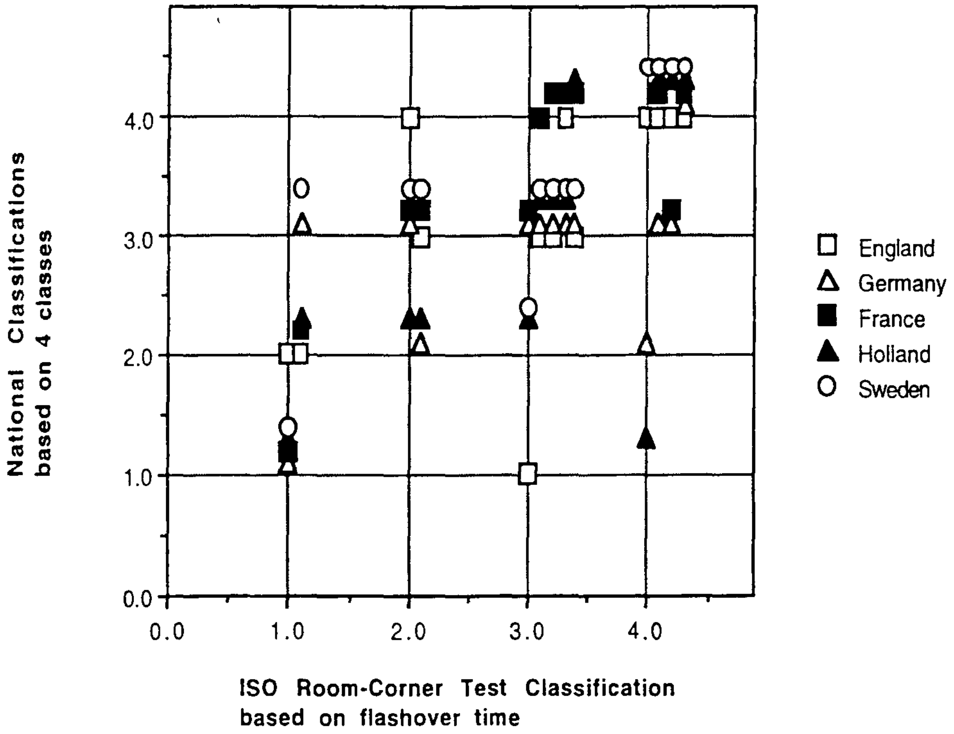

Figure 2. Comparison of the ISO Room Corner test with five national European tests [9].

FIRE SAFETY DESIGN

There has been increasing interest by regulators and standards organizations to embrace the use of engineering methodology in fire safety design. Most regulatory codes provide for an alternative to the prescriptive requirements if equivalence can be demonstrated. This is a challenge for the engineer, and is becoming a bigger part of the dialogue between the fire protection engineer and the authority responsible for administering the regulations. The knowledge-base of fire science has become more disseminated in terms of its ability and desire to use it. Motivating factors for including engineering methods in fire safety design are (1) the reduction of cost, (2) the maintenance of architectural integrity, and (3) the out right elimination of constraining regulations. Government policies on deregulation have led to legislation in the United Kingdom and in New Zealand to promote the seeking of alternatives to the specific fire regulations. This has opened the door to engineering as an alternative. Australia is also considering the establishment of an engineering-based *performance code* to replace its current traditional prescriptive code. In Japan, studies by the Building Research Institute under the Ministry of Construction (MOC) led to alternative engineering methods to assess the fire safety of people in buildings. This technology was supported by the Japanese construction industry which facilitated its widespread use. Under Article 38 of the [Japanese] Building Safety Law the number of applications for equivalency approvals using the MOC Total Fire Safety Design System of Buildings has grown from a few per year before 1987 to nearly 100 as reported by Tanaka in 1994 [10]. In the USA there has been significant discussion about the concept of performance codes, and the three major building codes in the USA are seeking to merge which could more easily facilitate the use of engineering methods.

Just as with the measurement of product flammability, there is a challenge here for fire science. The current fire science knowledge-base has demonstrated and has stimulated the use of engineering methods. In the USA, the litigation of claims in fire accident damage suits have encouraged a progressive view of engineering methods for fire. This is a natural consequence of the fire science becoming available and the legal parties recognizing that valid scientific expertise could help them. Unfortunately, the legal community does not contribute to open research. The ability for the performance code process to grow and have economic and safety, benefits can be a catalyst for more needed fire research.

FIRE INVESTIGATION

Fire science expertise has been recognized to help explain fire accidents and crimes of arson. Governments have convened boards of inquiry which have included fire scientists to help understand fire tragedies of significant public impact. Examples include the fires following the earthquake in Kobe, the Kings Cross fire in London, and the recent TWA 800 explosion. In the USA the National Transportation Safety Board (NTSB) has the authority to investigate any significant transportation accident. Some include fire issues. The NTSB has unique authority for investigating such accidents. In recent years the Bureau of Alcohol Tobacco and Firearms (ATF) was given the federal authority to investigate arson crimes, and as a consequence has established a trained nationwide team that can immediately respond individually or in force to a fire scene. Their fire investigation expertise is now being recognized beyond just fires of arson, and they have sought to educate their team and others in the science of fire. They have found that fire predictive formulas and scientific principles of fire behavior have enhanced their ability to analyze the cause and origin of fire. My own personal experience with them has led to a book for non-engineers on the principles and predictive methods pertaining to fire [11]. Their interest in fire science has culminated in recent federal funding of the ATF National FIRE Center (Fire Investigation, Research and Education Center). Scheduled for completion in 2001, it would become the first national laboratory for the study of fire pertaining to investigation needs.

FIRE ENGINEERING EDUCATION

Institutions formally granting degrees in fire safety (protection) engineering, or providing special subprograms in fire engineering, appear to be increasing around the world. Table 3 is an ad hoc listing of programs known to this author. It is noteworthy to consider the number begun after 1990. Our program at the University of Maryland has graduated about 700 with a BS degree since 1956 and about 45 MS students since 1990. I am told that the fire program at the University of Lund is the most popular curriculum in Sweden, apparently due to its career path into officer positions in the fire service. Unfortunately this is not a view shared by all, but it is clear that the general support for fire safety engineering education is growing. Yet as an engineering discipline it has a challenge to demonstrate its scientific competence and market its profession into traditional and new career paths. While in some countries the fire service is recognizing the need for trained scientific personnel, in general the fire service has lagged in its appreciation of fire safety engineering. There are exceptions and I am emphasizing the US attitude. Russia and the old Soviet bloc nations have a long tradition of formal scientific education for the fire service in an advanced tier of educational institutions leading to the BS through Ph. D. degrees. Also in South America, the education of the officers in the police and fire services come through military-style university educational systems. Moreover, in the USA there are approximately 150 "fire science" 2 and 4 year college programs populated by students associated with careers in the fire service. As these professional programs introduce more advanced science and engineering into their curriculum they will undoubtedly stimulate developments in fire science and enrich the US fire service with engineering expertise.

To dramatize the challenge facing fire safety education, I point out that it is a fledgling discipline founded on science that must grow. Texts are limited or nonexistent, and few engineering educators exist. Those that have worked in fire research with engineering and science backgrounds appreciation the value and credibility of a fire safety engineering discipline, but this is not shared by the mainstream of academics. Last year a review of graduate programs at the University of Maryland by a diverse faculty team recommended canceling our MS program because of its small size and a perception that uniqueness suggested other institutions did not wish to have such a program. This review was partly motivated by a decreasing university budget. Our response, helped by those that understand the value of fire science and its study, was overwhelmingly persuasive in eliminating this threat. The support we received was not just based on our competence, but on the vision by those that understand the needs in this field. It will take special efforts to maintain fire protection engineering programs in cultures where their value might be questioned.

Several years ago, encouraged by Vilhelm Sjolin , a group of educators lead by S. E. Magnusson of Lund University established a model curriculum for fire safety engineering[12]. This was published as a guidance document to describe to others the scope of the subject material and how it justified a unique branch of engineering. An outline of the model curriculum along with current courses offered in the Department of Fire Protection Engineering at the University of Maryland is shown in Table 4. It can be seen that the some of the core subjects are common to other engineering branches, but the specialized areas are unique to fire. The establishment of respected texts for these curriculum subjects will go a long way to promoting the field among other educators.

STUDENT FIRE RESEARCH

Over the last eight I have been attempting to educate students in fire protection engineering; trying to bring the subjects of heat and mass transfer, fluid mechanics and combustion to this curriculum. Having only a master of science level graduate program, we have not had the ability to have our students develop deep specialties. However, I have been very pleased with the level of accomplishment made by students who have worked with me. I would like to briefly share some of that work with you. The first area is in the development of analytical burning rate models. We have worked with the Cone Calorimeter mass loss apparatus, and have developed predictions for that configuration involving non-charring materials [12,13,14]. Figure 3 gives an example of the accuracy of the analysis for polypropylene. Results showed that the flame heat flux in the cone apparatus is approximately

Table 3. Programs in Fire Safety Engineering

Program	Degree	Year Established
1. Department of Fire Protection Engineering University of Maryland, USA	BS,MS	1956,1990
2. Department of Fire Safety Engineering Lund University, Sweden	BS,PhD	1986
3. Fire Protection and Safety Engineering Technology Oklahoma State University	BS	1937
4. Department of Chemical Engineering South Bank University, UK	BS, Ph. D.	
5. Centre for Research in Fire and Explosion Studies Department of the Built Environment University of Central Lancashire,UK	BS	
6. Department of Fuel and Energy University of Leeds, UK	BS	
7. Fire Safety Center University of New Brunswick, Canada	BS,MS,Ph.D	1967
8. Unit of Fire Safety Engineering Department of Civil Engineering University of Edinburgh, UK	MSc	1974 (ended 1983)
9. Centre for Firesafety Studies Worcester Polytechnic Institute, USA	MS, Ph.D	1979, 1995
10. Fire SERT Centre University of Ulster, No. Ireland	MS, Ph. D (DPhil) (D.Eng) Fire Safety Eng	1991 1998
11. Interdisciplinary Graduate Program in Fire Safety Engineering Science University of California,Berkeley,CA,USA	MS,Ph.D.	1972
12. Department of Civil Engineering University of Canterbury, New Zealand	MS, PhD	1994
13. Centre for Environmental Safety and Risk Engineering Victoria University of Technology, Australia	MS,PhD,Grad.Dipl,Cert.	1992,92,92,94
14. Department of Chemical Engineering University of British Columbia, Canada	MS	1995
15. Department of Safety Engineering Yokohama National University, Japan	BS, MS, Ph. D.	
16. Building Fire Safety Engineering Department of Architecture Science University of Tokyo, Japan	M. S., Ph. D.	
17. Department of Building Services Engineering Hong Kong Polytechnic, Hong Kong	Ph. D	
18. State Key Laboratory of Fire Science University of Science and Technol. of China P.R. China	BS, MS, PhD	1996,84 90
19. Departments of Architecture in Japan	Dr. Eng.	Traditional
20. Higher Engineering Fire Technical School Moscow, Russia	B.S, Ph. D.	
21. Greenwich University, Fire Safety Engineering Group	M. Sc, Ph. D.	1992
22. Department of Fire Safety Engineering/ Industrial Research Center, Hoseo University, Korea	B.S-Ph. D.	1996
23. Stord/Haugesund College, Dept. Of Safety Engr,Norway	Eng.	1990

Table 4. Fire Safety Engineering Curriculum

MODEL PROGRAM (Magnusson, S. E., et al.[13] BACKGROUND COURSES(ex.Math,Chem, Phys)	UNIVERSITY OF MARYLAND
Thermodynamics (chemical)	ENME 320 (from Mechanical)
Fluid Mechanics (buoyancy)	ENFP 300 Fire Protection Fluid Mechanics
Heat and Mass Transfer (diffusion)	ENFP 312 Heat and Mass Transfer
Sold Mechanics (beams,columns)	ENES 102,221,220 Statistics, Dynamics, Materials
	ENFP 251 Introduction to Fire Protection Engineering ENFP 416 Problem Synthesis and Design (Capstone)
FUNDAMENTAL COURSES	
Fire Fundamentals (premixed, diffusion flames, ignition, flames spread, spontaneous ignition, burning rate, laboratory)	ENFP 415 Fire Dynamics ENFP 649J Topics in Fire and Combustion ENFP 630 Diffusion Flames and Burning Rate Theory ENFP 620 Fire Dynamics Laboratory
Enclosure Fire Dynamics (fire growth, plumes, ventilation, heat transfer, chemistry, computer models)	ENFP 425 Fire Modeling* ENFP 625 Advanced Fire Modeling ENFP 611 Fire Induced Flows ENFP 624 Causative Analyses (case studies)
Active Fire Protection (detection, signals, suppression, smoke control)	ENFP 255 Fire Alarm and Special Hazards Design ENFP 310 Water Based Fire Protection Systems ENFP 411 Fire Protection Hazard Analysis (smoke) ENFP 649M Smoke Management Systems Design ENFP 489M Advanced Fire Suppression
Passive Fire Protection (building construction, code processes, structural fire resistance)	ENFP 320 Fire Assessment Methods and Laboratory ENFP 405 Structural Fire Protection ENFP 431 Building Safety and the Law* ENFP 455 Fabrics and Furnishings Flammability* ENFP 621 Analytical Procedures for Structural Fire Protection
People and Fire (combustion products, human behavior, egress, communication, fire safety training)	ENFP 421 Life Safety and Risk Analysis ENFP 455 Technology and the Law* ENFP 612 Toxicity Evaluation and Analysis ENFP 614 Egress Characteristics and Design
APPLIED COURSES	
Risk Analysis (hazard/risk, event/fault tress, probabilistic design methods)	ENFP 411 Fire Protection Hazard Analysis ENFP 622 Fire Prot. Engineering Hazard Analysis
Industrial Fire/Explosion Protection (flammability of gas/liquids, gas/dust explosions, industrial processes, environmental impact)	ENFP 489E Fire Protection and the Environment

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* Undergraduate electives

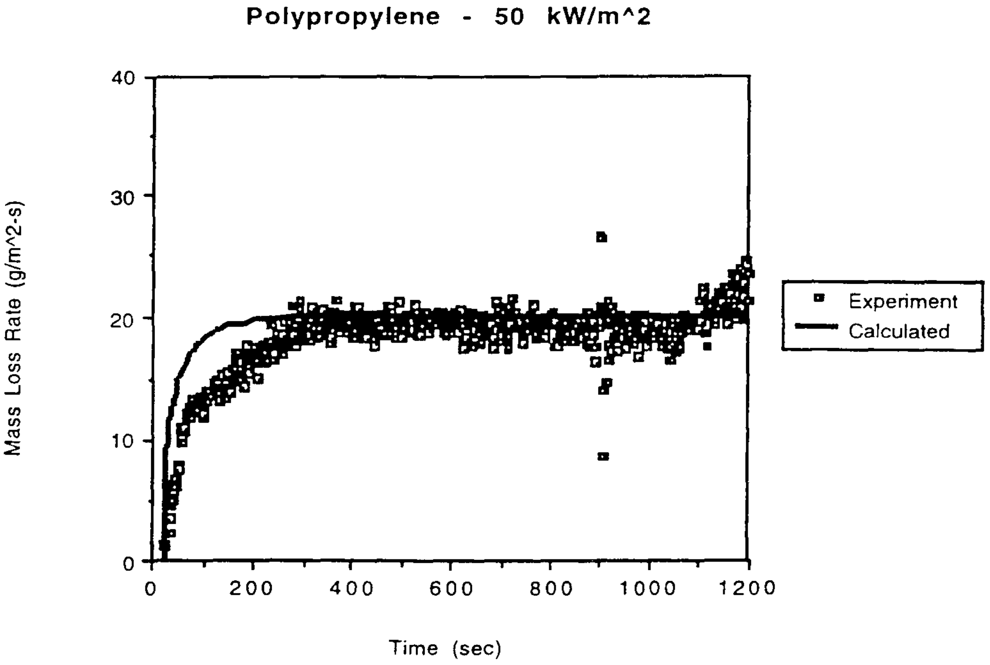

Figure 3. Example of Cone Calorimeter burning rate prediction [13].

constant as long as its height is more than twice the base diameter. Further applications of the model investigated the heat flux from pool fire flames [15,16]. Recently we have succeeded in obtaining approximate solutions to the charring problem as well but have not yet demonstrated its comparison to data [17]. Our goal has been to develop methods to use the Cone Calorimeter as a means to develop material property data consistent with the models. The application of this approach is to synthesize models for the ignition, flame spread and burning rate into fire growth predictions. Partial success has been achieved in simulating room-corner results [18,19,20] and other aspects of flame spread due to large ignition sources [21]. Other work has included studies on spontaneous ignition related to fire incidents involving the storage of plastic materials and cotton waste from an industrial polishing process [22]. Recently we have developed new correlations for the properties of fire plumes which explicitly include the effect of the base geometry [23]. All of these studies seek to offer analytical relationships and experimentally derived material properties for the prediction of fire growth phenomena.

CONCLUSIONS

Much progress in fire science has taken place over the last 50 years of the 20th century, and this has led to increased interest and activities in fire engineering education and the applications of engineering methods to administering the process of fire safety regulations. This progress has been based on societal needs for the pursuit of fire research as motivated by social, cultural, and economic factors. However, the research funding for fire science has not been consistent and is not always focused on fundamentals, two ingredients needed for the continued advancement of the field. Fire research dissemination is greater as manifested by this international meeting, and many in the profession of fire safety and investigation who are becoming aware of its benefits. Although disasters may motivate fire research, it will be an enlightened society and economic factors that will motivate its sustained support. The 20th century progress has laid a solid foundation for significant impact of fire science in the 21st century.

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