Invited Lecture

Fire Research in France: An Overview

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ABSTRACT

This paper is an overview and a summary of the research topics, in the area of fire safety engineering in France, developed by the entities which have a significant contribution in the field. This review concerns mainly open and confined fires, laboratory and large scale studies, compartment and forest fires, empirical, experimental, theoretical and numerical approaches, fundamental and more applied contribution, fire resistance testing to detailed fire physics.

KEYWORDS :fire physics and chemistry, fire engineering, performance-based codes, toxicity, risk assessment, fire regulation.

INTRODUCTION

Fire is certainly one of the greatest discovery in human history. The first productive applications of fire were probably the cooking of food and the heating of caves. It is interesting that anthropologists[1] now believe that the use of fire by homo erectus, 500,000 B.C. in Africa, precedes the evolution of modern species of man. Initially, humans were presumably using biomass fuels, solid fuels, as they were the easiest to gather. Closer to us, as civilisation advanced, as shown at many prehistoric site even in France like in the Dordogne valley, the utilisation of solid fuels extended to the use of metals and to the burning of fossil fuels and various chemical compounds. Properly controlled, the extensive use of fire as an energy source became an economic theme strongly linked to the process of industrialisation. But uncontrolled, it can lead to severe material damage and dramatic loss of life.

In his paper Quintiere [2] mentioned what Eddie Foy wrote as he recounted his experiences on the afternoon of December 30, 1903: *"It takes a disaster to make one cautious"*. Eddie Foy was a well-known entertainer appearing at the Iroquois Theater in Chicago, on that day. In eight minutes, 1825 people sought to escape; 602 did not succeed. Disastrous continue time to time to take their toll. In 1970, a discotheque fire in France, Saint Laurent du Pont disaster near Grenoble, killed 146. In 1973, still in France, a Lycée fire claimed 23 lives. In 1987, the King's Cross Station fire killed also 30 people. 165 more were killed by the fire in the drilling plate-form Piper-Alpha in north sea. Unfortunately, more disasters still randomly occurs around the world every year. In the developed world fire claims the lives of 10-20 people per million of the population each year [3]. The majority of fatal fires occur in occupied buildings. As a result a very strong emphasis in the scientific study has been placed on understanding the growth and spread of fire within enclosures such as building in an attempt to combat this tragic loss of human life. The economic costs are also great and represent all together around 1% of GDP.

All these figures apply to the situation in France where not much work was done on building fires before the seventies. Since the end of world war principally two aspects of fire safety have been of great concern at the "Direction de la Sécurité Civile", (DSC), at the "Ministère de l'Intérieur": the problems related to forest and wildland fires and the development of a regulation to prevent building and also industrial fires. However nearly no basic research was conducted in France prior to the Saint Laurent du Pont disaster where the casualities were linked to the large amount of smoke released by the burning of the lining polymeric materials on the walls and the ceiling of the discotheque. As an illustration of Eddie Foy assertion, during the seventies the " Ministère de l'Education de la Recherche et de la Technology" initiated a research program involving CNRS or University laboratories (Orléans, Poitiers, Lille,....), national technological centers like "Centre Scientifique et Technique du Bâtiment", (CSTB), " Laboratoire National d'Essais", (LNE), etc..., and industrial partners like "Rhône-Poulenc", (RP), "Société Nationale des Poudres et Explosifs", (SNPE), ELF Atochem, Société Bertin, etc..., to get information about the fire resistance characteristics of the various polymeric materials starting to be extensively produced by the industry and then in use in the construction of any kind of new buildings. During this period the research projects were focused mainly on the determination of ignition criteria, of kinetic parameters of the pyrolysis, of the nature, the amount and even the toxicity of the several species released during either the degradation of the materials or their combustion. However it clearly appeared that this holding action even if it led to the adoption of more sophisticated regulation and fire protection system, further major advances in combating wildfire are unlikely to be achieved by continued application of the traditional methods. As clearly explained by Drysdale [4], "*What is required is a more fundamental approach which can be applied at the design stage rather than tacitly relying on fire incidents to draw attention to inherent fire hazards*". According to that several "Ministères" (Education, Recherche et Technology, Logement , Intérieur (DSC),...) in France supported, during the eighties and early nineties, a research program entitled "Feu – Incendie – Sécurité" focused on the development of compartment fire and smoke movement performance-based codes involving CSTB, Société Bertin and six CNRS laboratories (Orléans, Poitiers, Rouen, Paris,...). During the nineties most of the institutions laboratories or industrial groups have been part of one or more research program sponsored by the European community.

The overview below concerns around twenty different research entities, spread all around France, and which sent me enough material to allow a presentation of their activities in the fire safety engineering area. One can consider five different groups as follows:

*National institutes or institutions: CSTB (Centre Scientifique et Technique du Bâtiment), CETU (Centre d'Etudes des Tunnels), CTICM (Centre Technique Industriel de la Construction Métallique), CEA/IPSN (Centre d'Etudes Nucléaires/ Institut de Protection et Sûreté Nucléaire), INERIS (Institut National de l'Environnement Industriel et des Risques), INRA (Institut National de Recherche Agronomique), CNPP (Centre National de Protection et de Prévention), and also CEREN Valabre, LNE, ...

*Large industrial groups: EDF (Electricité de France), GDF (Gaz de France), RP (Rhône-Poulenc), ELF,.....

*Private Institutes: (Sté BERTIN, SCETAUROUTE, ...)

*Organisations directly related to the Ministry , "Interior" DSC (Direction de la Sécurité Civile), "Defense" DGA (Direction Générale de l'Armement) and its research centers,

* University or CNRS laboratories : Poitiers LCD (Laboratoire de Combustion et de Détonique), LET (Laboratoires d'Etudes Thermiques), Marseille IUSTI (Institut Universitaire des Systèmes Thermiques et Industriels), Hopitaux de Paris, Université de Corse - SDME. Some other laboratories are also concerned by research related to fire LEMTA Nancy, IRPHE Marseille, LCSR Orléans, Cethil Lyon, CORIA Rouen, etc...

The research activities of the above laboratories or institutes are of different concern, from basic research at laboratory scale experiment to large scale tests, from empirical approach to detailed field modelling , from compartment fire to forest fire, from confined fire to open and wind-tilted situation , from fire resistance testing to detailed fire physics,.....

OVERVIEW OF THE FIRE RESEARCH ACTIVITIES IN FRANCE

CTICM (Centre Technique Industriel de la Construction Métallique)

The CTICM, a very important institute located 20km south of Paris, developed for years research activities in the field of Fire Safety Engineering which concern mainly three topics:
- development of fires,
-smoke production and movement,
-fire resistance of materials used in the construction of buildings in general.

Their objectives are:
-to develop and test approaches to determine the pyrolysis flow rate of a fire source, and to model the resistance of the structure to fire,
-to elaborate a procedure to test and validate the resistance to fire of building materials,
-to contribute to the development of performance based codes.

Development of fire:
CTICM develops in this area experimental and numerical studies. Large scale fires in large volumes like those of several MW sponsored by the EEC. Moderate scale fires under a hood to test the fire resistance of an exhibition furniture stand, a standard hotel room , car's fires,......About the numerical studies the CTICM is using CFAST and developing a code in collaboration with the "Université de Liège". It also exists a real interest for the establishment of empirical relationships or for the development of a probabilistic method.

Smoke production and movement:
Experimental and theoretical studies of the evacuation of smoke from large atrium and of the efficiency of smoke vents have been developed with the support of EEC . Parallelely the testing of the efficiency of the exhaust fans at high temperature is under progress.

Fire resistance of materials:
A very important part of the activity of CTICM in the fire safety area is related to the fire resistance testing of building elements like, steel and composite (steel and concrete) poles and beams, concrete and composite floor or ceiling elements, and to the testing of stainless steel, of the thermal protection of the elements considered fire resistant (doors, under ceiling, beam protection,.......). Most of these studies have been carried on with European partners again with the support of EEC and will serve as a basis to the definition of the new European standards in terms of fire resistance data base and specification.

Going through the papers listed in the bibliography provides more precise and detailed information about CTICM research activities and especially on the establishment of performance based codes.

INERIS (Institut National de l'Environnement Industriel et des Risques)

In France, INERIS, located 50km north of Paris, is one of the major technical research centres active in the field of industrial safety, covering many aspects of the fire problem. In the field of fire safety science, fire prevention, protection, and technology it has experimental and modelling capabilities originally issued from its former duty regarding fire safety in coal mines. INERIS has turned its skills and devoted its work towards industrial fire safety concerns since the beginning of the 80's. It has implemented numerous links with other national (CSTB, CNPP,.....) and international (Factory Mutual, HSE, TNO, SP,.....) laboratories operating in the field of fire prevention and protection.

INERIS, according to its former duty, is doted of large-scale fire testing facilities including:
-a fire testing gallery fitted with a gas cleaning system which allows large-scale testing of a variety of materials and products including very toxic products, with on line evaluation of the toxicity of the fire plume before safe elimination of the toxic compounds in the gas cleaning unit,
-a 80 m^3 concrete enclosure allowing large-scale experiments regarding under ventilated chemical fires,
-various testing areas capable of welcoming full-scale mock-ups of systems of customised test-rigs sometimes required to study specific fire safety issues.

INERIS is also equipped with lab-scale standard testing equipment for the evaluation of the fire hazard as required for "haz-mat" classification. Recently, a new lab-scale fire calorimeter based of the FMRC 50kw flammability concept devoted to fire research and material approval regarding fire safety has been set up. The activity in this field mainly shares in two domains:
-practical research mainly sponsored by the French Ministry of Environment and some other public bodies (regional or EEC funds),
-tests and other consultancy work for the private industries and other administrations.

A number of real-case studies or research work performed by INERIS by means of experimental approaches, computer modelling exercise or state-of-the-art expertise are listed below:
*experimental evaluation (on a full-scale mock-up) of the fire fighting and fire detection system of the shuttle wagons transporting cars and coaches in the Channel tunnel,
*experimental evaluation of the behaviour commercially-important chemicals in fire conditions (pesticides, nitrogenated solvants, aromatic isocyanates,....),

*field training of undergraduate fire brigade officers in evaluating toxic and thermal aspects of the fire hazard
*design and performance of a customised course regarding the fire hazard and fire prevention techniques pertaining to the related industry for the general technical managers of all factories of a single industrial UK group producing and manufacturing mineral wool as thermal insulation materials,
*design and practice of a large- scale reaction-to-fire test pertinent for the approval of fire performance of roofing materials in use in poultry-farming buildings,
*performances of courses in the field of toxicity of the fire gases and smoke,
*large-scale evaluation of fire resistance of newly developed water irrigated curtains for emergency fire compartmentation of large exhibition halls,
*full-scale testing of fire and explosion proof flammable underground collectors and pipes network designed to make fire fighting feasible or easier in road tunnels by collecting flammable liquid spillages in case of car or truck crash,
*computer simulation of the consequences of a possible fire initiated in the propulsive of a TGV rail in a projected rail tunnel crossing the Alps,
*contribution to various European funded projects in the related field (MISTRAL, FIRETUN, ...),
*consultancy work in the field of public access buildings in matter of fire prevention.
Going through the recent literature released at INERIS by the group working in the field of fire safety engineering gives detailed information about the results obtained on the different topics.

Gaz De France (GDF)

Gaz de France is mainly concerned by natural gas jet or cloud fires related to an accidental release of this gas under pressure (45 to 110 bar) in the atmosphere. The breaking of a pipe or of a tank is of major concern. They are more particularly interested by the following points: gap flow rate, plume shape, overpressure in case of plume ignition, geometry and temperature of the flame, thermal radiation and flux impingement on a target, major threat on the surroundings.

Their approach is focused on the development of a specific methodology, including the choice of the best adapted scientific analysis and the use or design of the required tools , ending by a validation based on experimental observations (real accidental situations or simulation). The most important part of the studies applies to the characterisation of dispersion of the gases and of the transport by radiation. They are developed in collaboration with national (ELF) or European partners (Ruhrgas, Statoil, ENI, SINTEF,...). One of their most important implication is the 3D calculation code called "Kameleon". The Kameleon FireEx is a user-friendly three-dimensional transient simulator for fire and gas dispersion scenarios. The simulator consists of three parts, which are tied together by the graphical user interphase. The preprocessor consists of two major parts, geometry modelling and specification of boundary and initial conditions. The sub-models included are the the k-ε turbulence model, the Eddy Dissipation Concept of turbulent combustion, the Eddy Dissipation Soot Model and the Discret Transfer Model of Radiative transfer. The interactive control part gives the user the opportunity to change operational parameters of the CFD code during run time and to specify what data to look at in a graphical instructive display.

GDF also developped with EDF and SNPEA another very interesting tool: the "Persephone" code. This code is a successful attempt to model large scale liquid natural gas pool fire, however the soot model should be improved. The data for the validation have been obtained during three LNG fire experiments which have been conducted successfully at Montoire, France, under different wind conditions in a shallow 35m diameter bund. Parallely the efficiency of various foam (influence of expansion ratios and flow rates) to extinguish LNG pool fires. The trials conducted demonstrate that certain rules are not adapted since they encourage the use of high expansion ratios to the detriment of safety considerations.

Moreover GDF is now involves in an international collaborative research program on vapour cloud fires (VCF's). This proposal has been developed to carry out a programme to investigate the current state of understanding of VCF's, in terms of both the model describing them and the experimental data used to validate these models, and to reach a consensus on whether the factors which influence the behaviour of a VCF are understood adequately and appropriately modelled.

IPSN (Institut de Protection et Sûretè Nucléaire)

For more than 10 years, IPSN has been carrying out experimental and modelling research programs in order to improve the knowledge on the fire consequences in a nuclear installation. The fire is indeed a major risk for the industrial installations. In the case of a nuclear or reprocessing plant, the consequences of a fire can lead to a possible release of radioactive materials inside the installation and even outside into the environment if the confinement and the filtering devices are damaged. There is so far a large amount of results available from the researches carried out by IPSN. These results are already used within the frame of the safety analysis of the nuclear installations (LWR, laboratories and reprocessing plants). It has to be highlighted that the computer code FLAMME_S assessed in particular on the IPSN experimental data is used to carried out safety analysis, especially in the framework of underway fire related to French PWR 900 MW. The main conclusions are that the improvement of our knowledge on this complex domain is very important and that the research results (especially assessed computer codes) are already used for safety evaluations. However a lot of fire configurations and scenario remain to be studied and some phenomena exhibited so far in IPSN experiments need additional investigations and a better modelling. Research will continue in two complementary ways: a research program addressing safety concerns, which generally ask for a rather quick and global answer, and a more basic research program, dealing with fundamental aspects of the fire, that will be carried out in a tight collaboration with universities and French and foreign research organisations studying combustion and fire. The research programs will continue to help in evaluating the risk connected with a fire in the nuclear installations. The coexistence inside IPSN of safety evaluation and research activities favours a tight dialogue during the definitions of the programs and during the code development and validation. This coexistence allows also a quick and efficient feedback between new safety analysis questions and new scientific knowledge gained by the research. It has also to be underlined that the future research will be also carried out in more fundamental aspects related to the modelling (3-D multifield computer code ISIS) and to the experiments. Moreover, since the fire is not a nuclear phenomenon, the main knowledge and developments gained by means of the IPSN research programs can also be used for the analysis of the fire risk in non nuclear installations. It is also worth to notice that the IPSN has a large range in size (0.3 to 3600 m^3) of experimental facilities very useful for code validation and of course to study the influence of scale.

CSTB (Centre Scientifique et Technique du Bâtiment)

The CSTB's Fire Safety Service is nearly fifty years old. Under the responsibility of the French Ministry of Housing, Equipment and Facilities it hosts two official test laboratories (fire reaction and fire resistance) under the control of the Ministry of Interior. It former research activities have been presented by M. Curtat at the 3rd IAFSS meeting .

The most important part of their activities concerns official tests on fire resistance and fire reaction. Another important part is related to the release of notices to put in agreement with the regulation the renewing of ancient buildings or to design new architectural projects.
The Ministry of Interior has been encouraging them over the late nineties to define a method for regulating the use of some of their software, in two respects: calculation of fire resistance based on the simulation of real fires and definition of smoke removal requirements in public buildings. Widespread use of computation software is made in order to reach a rapid harmonisation of the European standards. The evaluation of fire safety in the real world based on event-oriented models and probabilistic networks is of primary concerns.

The Fire Safety Service is still developing basic research on the modelling of smoke movement and of compartment fire (multi zones models) in parallel to more applied research activities. The former are well illustrated by different papers like the one presented during this meeting by M.Curtat et al.. At the 4th IAFSS meeting they showed the potential flexibility of the use of smoke movement modelling for the purpose of elaborating tables or diagrams specifying in a straightforward way minimal value of ventilation parameters such as vent areas or fan powered flow rates, for the control of smoke flows in case of building fires. More recently they completed their analysis by studying the fan powered extraction of smoke in a room where a fire develops. They compared full-scale experiment results with computer simulations using a zone and a CFD model.

Concerning the later the following list of topics they are involved underlines the great ability of CSTB in the above mentioned field of fire resistance and fire reaction.
*contribution to the elaboration of the European regulation called ISO TC 92, concerning the modelling of building fires, among the association of the "fire testing laboratories" EGOLF .
*contribution to the design and setting of the SBI test (single burning item).
*contribution to the European harmonisation of the fire resistance tests.
*application of the CIFI code to the prediction of smoke movement (Ministry of Interior);
*application of the SOPHIE code (developed jointly with FRS at BRE in England) to model the development of small fires (few kW of output) in a room (relation between the thermal output and the thermal structure of the plume).
*contribution to the comparative study of the performance of different compartment fire models (zone and CFD models) under the CIB authority.
*contribution to the modelling of people evacuation.
*activities of fire consultant for the prediction of smoke movement in large buildings, for the design of efficient thermal protections (radiation curtains), for the elaboration of a new regulation,....
Moreover the CSTB is involved for years in various nation wide or European co-operation with other research laboratories (University, Research centers,...).

SCETAUROUTE

This company located nearby Paris, Saint Quentin en Yvelines and near the Alpes, Annecy, is mainly concerned with the development of fire in tunnels. Their activities are related to large European project , large scale tests, and studies at laboratory scale, including modelling, in collaboration with different Universities.

Concerning European program, SCETAUROUTE has been involved from 1991 to 1995 in the FIRETUN program as a co-ordinator of the French side. The program was shared by 9 countries. Around 20 large scale fires (in real situation: railways cars and wagons, trucks, cars, buses) were carried on. The output power of the fires ranged from 1 to 150MW. Nearly 20 millions of data were collected. This program was very similar to the program launched in the USA, "Memorial Tunnel Project", (95 diesel oil pool fires ranging between 5 and 100MW).

In France , various fires have been set in the Puymorens (in the Pyrénées area) and Chamoise (near Chambéry in the Alpes) tunnels. Again nearly 20 tests were performed and the data from around 100 sensors or probes were recorded. Data analysis provided a lot of information which led to a better understanding of the interaction between the fire plume and the longitudinal flow induced . This data base appeared to be a very useful tool for the validation of the numerical code developed for the simulation of those tests and consequently for the prediction of the requirements for the design of safe and efficient ventilation systems.

SCETAUROUTE also developed studies at smaller scale (1/20), at the University of Marseille first and later at the University of Valenciennes. This research tends to reproduce the influence of the buoyancy forces induced by the fire (injection of air and helium through the floor of the test scale). The results led to the prediction of the critical flow velocity required to prevent backlayering in the tunnel. The present studies are focused on the influence of key parameters like the slope of the road, the shape and size of the cross section on the critical flow velocity and on the establishment of the stratification.

More recently the numerical simulation of the development of a fire in a tunnel has been considered in collaboration with the University of Marseille and through different other research projects on more particular point. It is important to notice that the numerical techniques used for the simulation at laboratory scale have been successfully applied for the design of real project.

CETU (Centre d'Etude des Tunnels)

CETU is presently under the responsibility of the Ministry of Equipment, Transportation and Lodging. This centre is located nearby the city of Lyon. The study of the development of a fire in a tunnel is one of the priorities of the Centre for now 5 years. It obtained a lot of very important results which led to a better understanding of the behaviour of a fire developing in a tunnel and of the smoke control systems. These results provide experimental and numerical data, which can be used as reference base to improve or modify the existing regulation or the recommendations.

Among the important literature published by CETU, the report written under the co-ordination of D. Lacroix for the "PIARC Committee on Road Tunnels" and entitled "Fire and smoke

control in road tunnels", provides the complete state-of-the-art for all those who are interested in road tunnels design, construction, operation or safety. It should give them an overview, recommendations, as well as the background on the way to provide a reasonably efficient and cost-effective protection against fire and smoke in road tunnels. It also gives numerous literature references that should be useful to get further details. The report is composed of eight sections. Each section first mentions past work. According to the case it may then describe physical phenomena or present new research results.. Whenever possible, recommendations are drawn; in other cases reference is made to current practice in a few countries and subjects are suggested for future research. The sections are:
*Objectives of fire and smoke control (physical background and principles, function-based requirements in opposition to detail regulations).
*Fire risk and design fires (frequencies and intensities in road tunnels).
*Smoke behaviour (general information on smoke behaviour).
*Study methods (safety strategies, influence of fire on the tunnel structure and equipment).
*Ventilation for fire and smoke control 'dilution of air pollutants, environmental issues, smoke control).
*Exits and other safety facilities (evacuation routes).
*Tunnel reaction and resistance to fire (reaction to fire of the materials, the resistance to fire of the structure and equipment).
*Fire response management (response to a major fire incident in a tunnel: personal injury or loss of life, damage to properties, disruption to the traffic flow).

CETU is concerned by most of the problems listed among the above eight sections. Among these topics it is possible to briefly notice their work concerning:
*small scale aeraulic study of smoke trap door systems, the problem of smoke and critical velocity in tunnels (smoke modelling, fire tests and CFD modelling of critical velocity behaviour, comparison with Memorial tunnel experiments, recommendations on fire and smoke control i.e. aerodynamics and ventilation of road tunnels....),
*large scale hydrocarbon pool fires and numerical modelling (sensitivity of different modelling techniques and comparison with experimental measures, numerical simulation via field modelling, validation of a 3D code flow through a fire test performed in Ofenegg tunnel,....).

DGA (Délégation Générale à l'Armement)

At the CTSN (Centre Technique des Systèmes Navals) a group entitled "Générateurs de gaz et incendies" is in charge, for now nearly 10 years , of the problem of fire safety aboard the ships and submarines of the French Navy. The problems of major concern are the spread of the fire (through openings, walls and floor or ceiling, ventilation and air conditioning networks, the size of the compartment, the adequacy between, thermal protection, the people in charge of the safety, and the extinction devices. In such a boat two kinds of fire occurring have to be taken into account:
*domestic (furnitures, ...) and industrials (hydrocarbons,...),
*pyrotechnic compounds (propellants, explosives).

The theoretical approach is also divided into two approaches depending if the whole phenomenon is considered (mean temperature , chemistry or mechanics nearby the fire source). This corresponds to global fire safety analysis, or if a more detailed analysis is

required to get information about the prevention of the spreading of the flame. For the prediction of the development of domestic or industrial fires they used:
* either a zone code "ŒIL" validated using data of the literature (CSTB....) or using large scale experimental results (tests aboard the MAYO LYKES) to follow the evolution of the mean characteristics of the hot and cold zone,
*or a field code "2D SAPHIR" which describes the flame structure and includes it in the modelling of the compartment fire and which has been validated using data obtained at CTSN.

To predict the ammunition fire the code (zone model) MEGALO developed at the CTSN and validated using data from other DGA research centres (GERBAM, CAEPE) or from IPSN at Cadarache. This code provides the mean value of the different parameters inside the compartment and the ability of extinction using water sprinklers. A code called ANSWER , a commercial 3D code has been modified to include the heat conduction through the walls and the interaction between the fire source and the water spray liberated by the sprinklers (evaluation of the resistance to fire of the equipment and the structures, optimisation of the flow discharge through the sprinklers). Two other models have also been developed. The code 1D, FLAM2, to evaluate the heating rate of a ammunition and the code, PROPAGAZ, to evaluate the propagation velocity of burnt gases in an air conditioning or ventilation shaft. Moreover, the validation of the codes can be partially performed at CTSN by using 50 m^3 parallelipipedic chamber.

More research related to fire is carried on other research centres inside the DGA. Recently at CEAT they ran tests about the fire resistance of aircraft seat cushions in collaboration with Société BERTIN. The flammability laboratory of CEAT as the agreement to tests materials and equipment used in aircraft, from the military and civilian side . It is the reason why they conducted an experimental program to help towards a better understanding of the fire behaviour of aeronautical seat cushion materials and kerosene standard tests (FAA FAR 25). Extended analysis of the experiments results has enable the identification of parameters strongly influencing standard test results (mainly geometry and positioning of the test seat), and also, for the particular case of fire resistant foams, to derive rules of classification with respect to fire response. These rules provide an improved characterisation of test seat behaviour and highlight important fire resistance parameters (density, latent heat of degradation). GERBAM has been also involved for many years in the testing of resistance and reaction to fire. Their large scale facilities allow testing of large elements like wall panels, doors, floor, ceiling, ... of large military boats and ships, but also of wall paint and wall lining. In the past year they have been very much concern by the fire safety requirements aboard aircraft carrier. Especially considering the storage of ammunitions and other pyrotechnic compounds, the possibility of aircraft landing incident leading to fire from a point of view of preventing fire spreading and the design and development of efficient extinction devices. The coupling of smoke movement with the air conditioning network is also of great concern.

EDF (Electricité de France)

At EDF the study devoted to fire safety are developed at the "Département Transfert Thermique et Aérodynamique" part of the "Direction des Etudes et Recherches". Since 1985 the researches are focused on the improvement of fire safety inside nuclear power plants (experimental and modeling studies of fire in compartments). The development of the code

MAGIC (zone model multi-compartment, global modeling of fire in compartment) is the master piece of the project which contains also an experimental counterpart.

MAGIC software is a classical thermal model of fire in multi-compartment building simulation. Each compartment is divided in two superposed gas layers. The mass and energy balance energy equations carried out on each gas layer, together with the equation of the heat diffusion in the walls meshed according to their layered thickness, allow calculation of aerothermal conditions in the building during the fire. MAGIC also computes the concentration of oxygen and unburned hydrocarbons to anticipate the secondary ignition induced by a sudden input of fresh air. Up to 10 fire sources per room and 24 rooms per building can be handled by the software. Sub-models based on correlation obtained through experiments characterise the various phenomena (pyrolysis, combustion in the gas phase, production of smoke, structure of the thermal plume, heat exchange by radiation , conduction, convection, heat buil-up, ignition,etc....

The experiments concern maily liquid hydrocarbons pool fires and cables fires. A test facility. (PITCAIRN/CALORIMETER), has been design and set up in co-operation with the CNRS (LCSR Orléans) on the base of the calorimeter designed by Tewarson in the USA. EDF , also, developed for several years a collaboration with the CNRS Poitiers (LCD). After studying pool fires (structure, steady state burning, radiation, boilover), smoke production and properties (extinction, visibility, physical parameters), the present study concerns the thermal degradation of cable insulation. At the same time large scale experiment concerning cable fires are conducted by the CNPP (Centre National de Protection et de Prévention) which located between Paris and Rouen.

Société BERTIN

BERTIN is a company which provides technical services to other companies. It has been involved in the field of fire safety for years. Its major fields of competence concern either deterministic studies of accidental fire and explosion scenarios or the reliability of complex systems (industrial or power plants, large buildings, etc....) through probabilistic approaches, event trees, human behaviour and reliability...... Concerning the industrial sector, BERTIN has been involved in the nuclear, chemical and petro-chemical industry, but also within the military sector. The company can offer a support which can range from a very specific advice on a particular, but restricted problem, to the full analysis of the concept of fire safety to be implemented in a large building devoted to any kind of utilisation (production of products or energy, storage, receiving flock of people,...).
The following list gives few of the topics BERTIN has been working on:
*identification of the potential scenarios,
*consequence of some of the most specific scenarios,
*development and utilisation of model of simulation to get quantitative predictions,
*establishment of procedures to prevent the development of fire or the initiation of an explosion and to minimise the consequences,
*definition and realisation of specific experiments to test the resistance and the reaction to fire of different materials (polyurethane foams, turning of metals,....).

The company has a long experience in the fire safety field and was for ten years a partner of the so-called co-operative research program on fire "Fire research group FIS" together with CSTB and CNRS. It has also been involved in European research program. BERTIN developed different software and code like KARATE which is able to predict fire growth, hot gas flows and flare radiation and which has been applied successfully to safety analysis in the offshore oil industry. VESTA and VESTA-PLUS have been developed more specifically to model fire development in nuclear power plants and to perform a risk analysis via the coupling of another code called VULCAIN which is also considered as a fire expert – system. The group also developed a deterministic – probabilistic methodology for risk analysis of fire.

More recently BERTIN has been involved in the study of the interaction between the spray generated by a sprinkler and the fire plume rising above an hydrocarbon pool fire. Also we have to notice, as mention earlier, the collaboration with CEAT (Toulouse) they conducted an experimental program to help towards a better understanding of the fire behaviour of aeronautical seat cushion materials and kerosene standard tests (FAA FAR 25).

INRA (Institut National de la Recherche Agronomique)

This institution is very much involved in the study of forest fires via its laboratory "Unité de Recherches Forestières Méditerranéennes – Equipe Prévention des Feux de Forêts" located in south of France in the city of Avignon. It conducts research in three major directions :
*study of the starting and of the spreading of the forest fire (evaluation of the criteria characteristic of the fire danger, development of model to predict fire propagation and experimental validation by laboratory and large scale tests), relation between humidity content of the fuel and its flammability, combustion modelling at the different scales to be considered,
*impact of fire on the trees (trees reaction to fire, relation between the development of the fire and the damage to the trees,....),
*development of techniques to reduce the combustible load (prescribe burning, selected tree cutting,...).

This laboratory is also involves in a European program on forest fire "Efaistos" especially in collaboration with a research group from IUSTI (Marseille). This collaboration aims to a better understanding and prediction of forest fires propagation and includes model development, testing and experimentation on pine needles fuel bed. Some years ago the INRA group studied the effects of slope and fuel load on fire behaviour. More recent work concerns the influence of heat transfer on fire spread. The testing of two radiative physical models for fire spread through porous fuel beds underlines that even if radiation is predominant, convective heat transfer depending on the gas temperature profile should be taken into account. The simplified physical model, developed for a steady fire spread in the absence of ambient wind , using an approach that considers a forest fire as a compressible, reactive and radiative flow through a multiphase medium, provides results in reasonable agreement with the experimental results obtained with their laboratory scale fire test facility.

IUSTI (Institut Universitaire des Systèmes Thermiques Industriels) Marseille

A group of this laboratory, located in Marseille, is a partner, as noticed above, of the INRA group in the European program EFAISTOS, "Experiments and simulations for improvement and validation of behaviour models of forest fires", in which 7 different states are involved. This group is also a partner of DGA through CSTN and developed basic studies on diffusion flames including the burning of solid propellants or more generally of pyrotechnic compounds, the interaction between diffusion flame and its surrounding conditions. Three papers related to their present work are presented at this symposium.

Concerning forest fire, they developed a multiphase approach which is able to take into account the heterogeneous aspect of the combustible medium (porous aspect) and the basic phenomena which are at the origin of fire ignition and propagation (chemical reactions, oxygen transport, gas motions,....). One of the most important problem concerns the closure of the multiphase equations i.e. what kind of simplification should be done, what kind of sub-models is needed to express new physical terms in the equations characteristic of the multiphase medium and how more simplified model can be established. The general formulation based on a weighting average procedure describes the fire induced behaviour of the reactive, radiative and heterogeneous medium. In the frame of wildland fires, the propagation of a line fire through a fuel bed has been simulated using this approach. Their analysis leads to the determination of the rate of propagation of the line fire through a randomly-packed fuel bed of thermally thin cellulosic particles and the induced hydrodynamics inside and above the litter. The predicted rates of fire spread for several configurations, including cross wind effects, have been successfully compared. Another approach concerns the development of a one dimensional model of reverse combustion which controls the fire spread through a fuel bed of pine needles. Both oxygen and fuel limited regimes have been examined for low flow velocities. Moreover they will be implied with INRA in a research program, called DERF and sponsored by the French Ministry of Agriculture. The objective of this program is to study fuel breaks, that is a modification of the landscape which concerns in cutting a zone of rather dense and continuous vegetation. The break is composed of elements of vegetation arranged discontinuously. The break must be tended regularly. The aim of the break is not necessarily to stop the fire but rather to create a highly propitious zone for firemen to fight the fire. Their objective is to propose models which will be able to describe the behaviour of the fire when reaching such a zone.

They also develop studies related to the development of diffusion flames. One of their numerical studies applies to the description of fire induced flow and temperature field in an enclosure. Two models of fire source description have been examined, namely a volumetric heat source and a flame model resulting from the injection of gaseous fuel in the enclosure. The comparative examination between computed results and available experimental data shows the limits of the volumetric approach particularly near the source and in the ceiling gas layer. However the flame model provides data in agreement with experiments and is able to also predict the four layer structure observed for this type of fire-induced flow. Another numerical investigation concerns the effects of cross-wind on a turbulent methane/air diffusion flame. The results fit a correlation obtained for a pool fire and illustrate how aerodynamic interactions generate significant changes on radiation to external targets. The numerical results show that the buoyant flow above the flame is characterised by the development of large eddies on both sides of the hot gas column. The growth of these buoyancy driven instabilities is also marked by an oscillatory behaviour.

Université de Corte (SDEM)

This team located in Corsica have been studying for several years forest fires, most of the time in collaboration with INRA Avignon, but being also in close contact with the IUSTI's group and IPSN Cadarache. It started to study the dynamic modelling of fire spread across a fuel bed. The reaction-diffusion model use for the determination of the necessary coefficients a method based on the dynamic features of a spreading fire. The numerical study provides the rate of spread, the fire front perimeter and the temperature distribution for line-ignition and point-ignition fires. Furthermore, it allows the estimation of the acceleration of the spread for a point ignition found in its initial stage and the steady state phase. The approach has been improved to include slope effects and successfully tested. The research has been pursued to generate a forest fire simulator. Consequently a resolution algorithm capable of reducing the calculation time has been developed and is able to solve all reaction-diffusion equations which possess a spreading solution. More recently they proposed and validated a two-dimensional model of fire spread across a sloping fuel bed. This approach which also considers the influence of fuel load have been validated with experimental results from INRA but also by comparison with data from other physical models.

Laboratoire d'Energétique et de Mécanique Théorique et Appliquée (LEMTA – Nancy)

This laboratory proposed recently a very interesting approach to predict the motion of a forest fire front . The approach is based on the Richards' one dimensional elliptic growth forest fire propagation so as to find an intrinsic expression of the fire front. An equivalent optical geometric variational formulation of this model is given too. They also proposed a three dimensional analysis considering an homogeneisation by volume averaging and irreversible thermodynamics processes. Simplification leads to a two dimensional model, that deals with principal parameters of the propagation of the forest fire. The shaped of correlation used by the elliptical growth forest fire is then deduced. The non local influence of the radiated flux issuing from fire area that is above the vegetation has also been introduced too. Finally numerical simulation with non local radiation have been performed.

Laboratoire d'Etudes Thermiques (LET – Poitiers)

This laboratory has been involved since the eighties in the fire research. It was a very active member of the program "FIS" (Feu – Incendie – Sécurité) and developed very efficient collaboration with different partners like CSTB, CNPP, Société Bertin and some CNRS laboratories. Its activities were directed towards the study of flows in the presence of heat and mass transfers. Part of the research work in this field has been carried out to study the structure of flows resulting from a fire located in an inhabited room leading onto a corridor open to the outside, with or without a smoke extraction system. The laboratory has a computation code based on the field model and experimental facilities (1/3 scale) with diagnostic techniques to validate the approach. Their work entitled "Study of fan powered extraction of smoke in a room where a fire develops: full-scale experiments and computer simulations using a zone and a CFD model" is an illustration of their contribution onto the field of smoke movement. More work has been performed on the characterisation of smoke and on the behaviour of hot plumes, especially in rooms with high ceilings. More recently they started to study the mechanism of flame spreading in a porous medium (this symposium). A new algorithm for fire spread simulation has been proposed by using a dynamic tool of the flame front change and a local spread model. The progression of fire, represented by a close contour, is based on the determination of a parametric function. A physical model, which is mainly based on the Cekirge model, has been introduced. This takes into account external conditions like wind, the topographic conditions and the fuel characteristics. This model, which provides results with a moving boundary problem can be used to evaluate forest fire propagation in real time. During the past years they developed research on extinction by water spray. Presently they are working with CEA/CESTA on the interaction between an hydrocarbon pool fire and a water spray in collaboration with the LCD Poitiers.

Laboratoire de Combustion et Détonique, (LCD Poitiers)

Involved in the study of reacting flows for 25 years, this laboratory tried to provide at first new insights concerning wall and pool fires. It developed experimental, theoretical and numerical approaches in order to get a proper evaluation of the different transports sustaining the burning phenomena. Their great concern for the convective transport led them to the study of the structure of the reacting flow developing above the burning surface: the structure of a boundary layer diffusion flame for the case of wall fires and of a buoyantly driven diffusion flame or reactive plume for pool fires. The evaluation of the transport by conduction into the condensed phase is shown to be equivalent to an increase in the latent heat of gasification and, consequently, a shift in the flammability limits towards lower oxidizer mass fraction. Concerning radiation, their contribution deals with the determination of the radiative properties of the reacting flow and with the experimental and theoretical or numerical determination of the heat fluxes to the burning surface and to the surroundings. They have also been concerned with the determination of soot formation and by the relation between intermittency and radiative fluxes. Either real fuels have been experimentally tested or their combustion simulated using water-cooled sintered porous metallic burners. It clearly appeared that the mass burning rate and the structure of the reacting flow were related to many parameters. However, only a few are of great importance: fuel properties, oxidizer mass fraction, turbulence intensity, and the scale of the experiment. Concerning modelling, simple models can provide relevant results about mass burning prediction. However, to describe the structure of the diffusion flame above the burning surface, more sophisticated models are required. It is also worth to notice that their contribution is significant only at laboratory scale.

More recently the laboratory has been involved in several new topics like, combustion at different gravity levels, combustion in tunnels, pool fires and boilover, fire and their suppression (water spray, gas generators,...), smoke production and smoke properties, development of fires and flame spreading, and more generally in topics related to fire safety engineering in collaboration with the University of Maryland at College Park. It is clear that reliable prediction of fire processes is required for fire protection engineering. The need for immediate solutions to the fire threat, and the complexity of the fire problem have led them to look for practical engineering solutions, often empirical, for the prediction of fire development and control. However, as it is widely recognised that the reliability of prediction of fire process depends upon the quality and amount of knowledge of the processes, they continued their fundamental approach. A large part of their new involvement is presented during this symposium through seven papers and some posters. Concerning smoke, they tried to explain why the specific extinction area for a given material, which is independent of the burning conditions, is the more appropriate quantity to attempt correlation between small and large scale data. Starting from a small scale study on extinction properties of mixtures of smoke, they established a correlation between the specific extinction areas of the different fuels involved. The agreement between dynamic measurements performed with a flow through system and the theoretical development appears very satisfactory. Previous systematic and comprehensive studies on the burning of thin fuel layer floating on water emphasised the importance of heat transfer in the direction normal to the fuel and sublayer surfaces. They corroborated that boilover is due to the heterogeneous boiling nucleation at the fuel/water interface, in sublayer water that has been superheated. Presently a wide range of boiling points fuels were tested including crude oil, a heating oil, and five single component fuels. Some parameters of the process were varied to observe their effect on the boilover characteristics and, through them, some of the controlling mechanisms were inferred. The influence of the major parameters of the problem, specifically the initial fuel layer thickness, the pool diameter, and the fuel boiling point, on the temperature history of the fuel and water and time to the start of boil over, has been studied. The simple one dimensional, quasi steady heat conduction model developed, even with its limitations, contributes to the understanding of the results of the parametric study.

Their approach of wall and pool fires in confined, fully ventilated or completely unconfined situation is still under progress at Poitiers. More particularly the interaction between a vertical burning wall and a pool fire or a ceiling or another vertical wall has been considered. They developed a three dimensional model to predict the aerodynamic field and the thermal structure of such situations. The model considers the turbulent nature of the flow, the gas phase non premixed combustion, the strong coupling between the pyrolysis rate and the buoyancy induced flow, including the influence of the streamwise pressure gradient for the parallel walls case and a two dimensional adaptation of the Discrete Ordinates Method to estimate the flame radiation energy. The methodology extends previous work by substituting the constant soot radiative fraction approach by the two equations soot model and radiative transfer equation without scattering. A good agreement is observed between calculations and experimental values previously obtained using a large scale facilitated consisting of water cooled sintered porous wall burners stack on each other for the vertical walls or side to side on the floor or ceiling configuration. It appears that their findings have implications for identifying and assessing the risks associated with the bulk storage of materials for different wall or shelves spacing/height ratio. Nearly simultaneously they developed a new, consistent and objective methodology, using a CCD camera to map flame luminosity to get wall flame heights. Experiments were carried out in unconfined and confined situations and for different fuels. Their measurements appear essential for the establishment of a new and more scientific wall flame height correlation that include effects of pyrolysis length, burning width and confinement due to side walls. Moreover there are also works in progress related to the behaviour of a wall fire in a vitiated compartment and to the behaviour of a combustible material located in the upper zone of an opened compartment under fire. Concerning pool fires the influence of confinement and of cross wind have also been considered measured and modelled. Experimental and theoretical study of the buoyancy effect on the pulsation frequency of a pool fire has also been completed by this laboratory at different gravity levels. The flame pulsation frequency is determined both from image processing of the visible flame emission and from spectral analysis of a thermocouple signal. The modelling of the puffing shows that this phenomena is induced by the travelling of three dimensional gravity wave and provides a relevant determination of the characteristic length of the turbulent plume.

Another study, motivated by fire safety concerns and the advent of long term micro-gravity facilities, is also under process for six years. First they simulated using a porous burner the conditions aboard a spacecraft (fuel injection through the porous wall into an oxidising flow typical of the HVAC systems. Then they conducted similar experiments but by replacing the porous burner by a slab of PMMA. Several diagnostic techniques are in use: PLIF, visualisation, PIV, temperature measurement by means of thermocouples and IR camera. For the later the main objective is to obtain a complete temperature field in a short period of time like in micro-gravity facilities. The experiments showed the existence of a low oxidiser stability limit linked to a minimum fuel supply to the flame and related to a decrease in the heat feedback from the flame to the fuel surface. The importance of convective transfer of fuel to the flame is underlined and is evidenced by soot oxidation, yellow flames, as opposed to blue flames where diffusion of fuel is dominant. A qualitative agreement exists with theory. The future research program will deal with the determination of the flammability and combustion criteria of solid fuels expose to a low velocity oxidising flow under micro-gravity in order to qualify a material for use in a space vehicle. This research is part of the collaboration developed with the University of Maryland at College Park were experiments have been performed to determine the effects of scale reduction and transport mechanisms on PMMA piloted ignition. It was observed that the sample size did not affect surface temperature, nor the critical heat flux for ignition. Even the ignition delay appears to be not affected however its characteristic length is a major parameter for the development of the fire. It was determined that the delay is affected by flow characteristics mainly by changing the fuel mass fraction, essentially the limit above it ignition occur.

Others Institutions

A lot of work has been performed on the toxicity of smoke for the human being in different laboratories under the responsibility of Hôpitaux de Paris. They gave a lot of information concerning the influence of combustion products and smoke on the breathing, on lungs but also on blood content. Their analysis leads to a better understanding of blood poisoning, but also brain and heart injury. They also provide information about lethal concentrations of poisoning agents. Concerning smoke, but smoke movement and production, the "CNNP" (Centre National de Prévention et de Protection) has a very large facility which has already been used in collaboration with CSTB in order to collect data to validate numerical code. CNPP also organises training sessions for fire safety engineers and to test new equipment for fire fighters but also for detection and suppression. Rhône-Poulenc, Elf and many others large companies have their own fire safety engineers and develop time to time research in the fire safety field in order to solve their home problems. Concerning the hydrocarbon industry, the organisation called GESIP has large facilities to light large pool fires and to test extinction systems. The "LNE" (Laboratoire National d'Essais) has test facilities and has the ability to deliver certification to different combustible materials. There are also different laboratories or institutions spread all around France which are involved in fire safety studies, like at Rouen, at Ecole Centrale de Paris and de Lyon, INSA de Lyon, Orléans, Paris, Ecole des Mines d'Alès, Marseille, and some others Universités et IUT.

CONCLUSIONS

This review underlines that there are a lot of activities developed in France in the field of fire safety engineering. However this paper deals only with the laboratories and institutions which sent their contribution in that area to the author. Most of them has been contacted but only around twenty, those mentioned above, answered. However, only a very restrictive list of their main papers is given among the references. Anyway a lot of work has been and is still performed all around France but unfortunately with no much link between each other. Since the disappearance of the former "F.I.S research program" the collaboration between the different entities occurred only through European Community Program (STEP, EFAISTOS, BRITE – EURAM,......) and some bilateral co-operations. For sure a better co-ordination between the different research programs should lead to a better efficiency including a greater exchange between fundamental or laboratory scale approaches and applied industrial or large scale researches. Especially an efficient co-operation between academic institutions and more applied research centres or industrial laboratories is required to face the new challenges in the field of fire safety engineering at the French and European Level. A special effort is also required to improve the existing regulation and testing and to move from a purely "regulation approach" up to a more "performance based codes" approach.

We can notice an increasing demand on fire safety at any level, industrial storage and large industrial facilities and plants (even power plants), compartment fires in small and large buildings, forest fires which corresponds to a real threat. Consequently, the level of effort society extends to fight and prevent fire should increase. It can be said, according to J. Quintiere [5] that the level of safety must be administrated consistent with the society and with the tools of science and technology. It can be also said that the general public has not a good understanding of the fire and that fire hazards is not easily understood by technical people outside the scope of fire. This situation seems to stem from a low technical understanding of fire and the lack of quantitative tools for the measure of fire safety and its hazards.

In conclusion to meet the demand a great effort should be made in order to better co-ordinate the different research activities in the field of fire safety engineering in France but also to reinforce the educational aspect of this problem.

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