Project No. FP7-2010-265612-CP-FP

AircraftFire

Fire Risk Assessment and Increase of Passenger Survivability

FINAL SUMMARY REPORT

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PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
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1. Executive Summary

Safety aboard aircraft is one of the main concerns of aircraft manufacturers and airline companies. For 20 years, the fire threat in aeronautics has been decreasing, but, the intensive use of polymer composites in new generation aircraft (A350 or B-787 families), for weight reduction and energy saving purposes, causes the fire scenarios to evolve in terms of threats. The global aim of AircraftFire (AcF) was to contribute to clarify these fire threats linked to the substitution of aluminium by composite materials in major aircraft structures. The methodology adopted by AcF is outlined according to the following five topics.

Fire Threat Analysis: From a database analysis of aircraft incident/accident caused by fire or causing fire in the last 20 years, major generic fire scenarios have been identified (In-flight fire, Post-crash fire ...).

The Fire Prevention: Flammability and burning composite materials characterisation

After A350-like materials were selected for testing, a complete experimental database on the flammability, burning, thermo-physical properties, smoke formation and toxicity of composites was built.

Fire scenario: In-flight fire

Fire detection: the project has contributed in defining required characteristics of composite burning for early detection using new advanced sensors.

Hidden fires: experimental and numerical studies of the fire-spread mechanisms have been developed for assessing containment and propagation of the fire into the cabin and cockpit.

Fire Extinction: suppression technologies are perceived to be mature except on the subject relative to halon replacement, but no new progress was proposed in this project on this matter.

Fire scenario: Post-crash fire

Crash: a complete structural analysis of a composite aircraft during crash was performed, to define the initial state of the aircraft before a potential fire ignition.

Fire threat: a kerosene pool-fire, ignited consecutively to a spreading of kerosene was simulated to evaluate the thermal and chemical impact of the flames on the aircraft fuselage.

Fire resistance of composites: a new device at laboratory scale has been qualified to evaluate and understand the efficiency of the flame barrier by the composites, in representative fire conditions.

Model and data integration

From the data gained from the experiments on the new materials and from the study of the fire scenarios, existing simulation software for fire growth and evacuation have been upgraded and coupled to simulate a complete fire from the source to the consequences on the occupants' evacuation in post-crash fire scenarios.

Synthesis of key results

- Without post-crash fuselage rupture, the composite fuselage offers a much better fire protection regarding penetration and better evacuation environment than the conventional aluminium fuselage.
- But due to thermal fluxes composite materials degrade on the rear side with potential release of toxic, highly irritant and flammable compounds into the cabin;
- Post-crash fuselage ruptures during the impact may result in a flashover within the cabin, severely reducing survivability.
- When assessing the impact of fire on passenger survivability, it is essential to perform combined fire and evacuation analysis.

Recommendations

Main advances and recommendations have been provided to the manufacturers and to the regulatory agency to help them to take better into account the impact of fire in the future aircraft design and rulemaking and to enhance fire safety without significantly deteriorating the aircraft performance.

2. Description of the project context and objectives

Safety aboard aircraft is one of the main preoccupations of aircraft manufacturers and airline companies. For 20 years, the threat in aeronautics has decreased (Figure 1), but because the fatality rate on the world fleet has shown little improvement in the last ten years, more efforts are still necessary to reduce the incident/accident rate and increase the passenger and crew survivability despite the anticipated increase of the aeronautic traffic.

A statistical analysis of accident databases shows that, in the aircraft world fleet, impact remains a major survivability factor in accidents, but due to the highly flammable fuel load aboard aircrafts fire is a major threat leading to the reduced escape possibilities. Nevertheless the accident rate and the survivability of people have been overall reduced over 40 years (Figure 2).

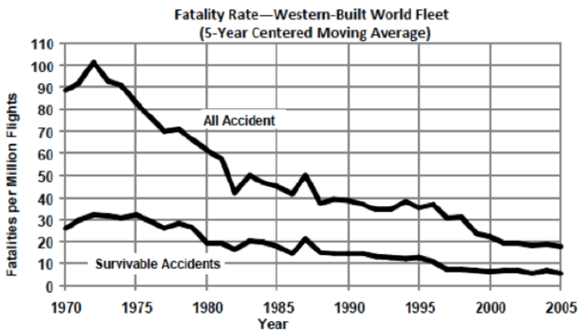


Figure 1: Fatality rate – All accidents and survivable Accidents – World fleet

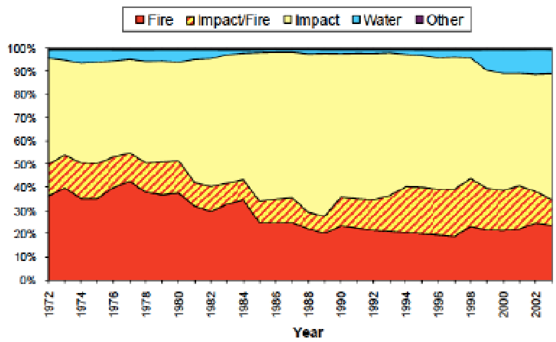


Figure 2: Proportion of fatalities by cause in a survivable accident – World fleet

In the new generation of aircraft (A350 or B-787 families), to save energy, the reduction of the aircraft weight has been considered as major economic driver. This is the reason why composites are now intensively used in all means of transportation (aeronautics, land and sea transportation), for weight reduction purpose as well as for their good mechanical properties. For many years, the aircraft designers have been increasing the use of polymer materials for interior panels and equipment; in addition, composites also replace metallic parts in the structures (fuselage, structures, wing, engine cowling, etc.). In the A350, composite materials represent around 53% of the airplane mass, consequently, the fuel load aboard (kerosene, oil, composites, etc.) is considerably increased and the fire scenarios are changing. This requires a re-evaluation of the hazards, to reduce the fire incident/accident rate and to increase the survivability of the passengers and crew during accident involving fire.

The forty five months AircraftFire (AcF) project was focused on the fire safety in new generation of aircrafts characterised by an intensively use of composite materials. The objective was to highlight all feasible contributions to reduce the impact of in-flight (cabin or engine fires) or post-crash fires on the accident rate and on the survivability of people. To reach this aim, upstream researches in partnership with aeronautical actors were developed to get additional basic and technological knowledge.

The global aim of AircraftFire (AcF) was to contribute to the evaluation of the evolution of the fire threat linked to the substitution of aluminium by composite materials in major aircraft structures, mainly for fuselage in the present context, and its consequences on the survivability of occupants in the new generation of aircrafts.

The cabin wall must be a safe and efficient barrier to the flame penetration and propagation into the passenger compartment up to the aircraft landing and evacuation.

To effectively contribute to the reduction of the accident rate despite the use of the flammable composites, the AircraftFire project has concentrated its resources on the construction of a database of thermo-chemical and thermo-physical properties of materials for the engineering requirements and on the numerical simulation of the main fire scenarios to evaluate the consequences of fire on the survivability of occupants during an accident.

To reach these objectives, suitable diagnostics and tests have been performed to address the severe lack of data both on thermo-physical properties of composites and cabin materials, and on their availability for numerical tools to assess the fire safety enhancement through technical investigations.

AircraftFire methodology

- The methodology adopted in this project is outlined in 5 parts (the organisation chart is given in Figure 3)

Objectives:

- To construct a complete database on the flammability, burning, thermal and mechanical properties of the major composites as used in current or future composite aircraft;
- To model generic major fire scenarios in A350 type aircraft (wide body);
- To predict, by means of numerical simulation tools, the consequences on the fire threat including the complete fire scenario modelling, from the fire source to the impact on the passenger survivability.

Part 1: Fire Threat Analysis

From a database analysis of aircraft incident/accident caused by fire or causing fire in the last 20 years, major generic fire scenarios have been identified highlighting the causes and consequences on the aircraft control.

Relevant fire scenarios and materials have been selected for the AircraftFire project.

Part 2: Aircraft Fire Prevention.

From adapted and specific metrologies, a complete database on the flammability, burning, thermo-physical properties, smoke formation and toxicity of selected aircraft materials (fuselage, wing and structure skins, thermo acoustic insulation, cabin panel materials, cabling, ducting, carpet and seats) were determined for modelling and predicting the fire threat and its consequences on the fire development.

The list of required properties for modelling and data processing was considered by all partners.

Part 3: Aircraft Fire Protection: Modelling of generic Fire Configurations

- Inflight Fire

Most of the in-flight aircraft fire scenarios require the protection of vital components of the aircraft. Fire containment is the essential protection to maintain the fly home capability, avoiding the uncontrollable fire situation that can be catastrophic in less than 15 minutes, to protect the cabin and to ensure the survivability of occupants.

Fire detection: In the cabin, the occupants detect the fire that the crew can promptly fight. In cargo zones, although automatic protection systems are available and operational, research is still necessary to develop efficient technologies (including the replacement of halon). The project has contributed to define the required specificities for burning composite detection using new advanced multi-criteria sensors. Special data fusion algorithms provide the essential functionality to such system or fire and smoke detection which fuses the data generated by all the heterogeneous sensors. The concept of a decision support system was developed that generates warnings as early as possible in case of real incidents, while at the same time the number of false alarms should be minimized.

Hidden fires: To evaluate the burning characteristics of the cabin materials in **hidden zones** (inaccessible area), where no protection is generally present, experimental and numerical studies of the fire-spread mechanisms have been developed, to reduce the risk of fatal outcome, by better assessing containment and propagation of fire into the cabin and cockpit.

Fire Extinction: Suppression technologies are perceived to be mature except on the subject relative to halon replacement, but no new progress was proposed in this project.

- Post-crash Fire

Crash: An aircraft structural analysis of the composites during crash is essential to define the initial state of the aircraft before a potential fire ignition: are there ruptures, cracks or does the fuselage remains intact?
Fire threat (source): After crash, a kerosene pool-fire is generally ignited following the release of kerosene from damaged fuel tanks. A numerical study was developed to evaluate the thermal and chemical impact of flames on the aircraft fuselage.
Fire resistance of composite: The fuselage must be a safe barrier to flame penetration in the cabin. Specific tests were performed to evaluate the efficiency of the flame barrier provided by the composite in representative fire conditions. The data processing developed in large conditions of thermal, pressure or load stress, has provided original information on composites during fire. The data were integrated by the modelling to simulate a complete fire from the source to the consequences for the occupant evacuation.

Part 4: Aircraft Simulation Tools: Modelling of the fire growth and passenger evacuation

Model and data integration in a global post-crash fire simulation: From the academic data gained from the experiments on the new materials and technical skill obtained from the study of the identified specific fire scenarios, a global post-crash fire software has been upgraded in order to enhance the modelling and the simulation of fire evolution in an aircraft to adapt the modelling to new risks and materials found in new generation of aircrafts.

Part 5: Aircraft fire safety improving: Synthesis of the results of the project

A synthesis of new knowledge on composite behaviour during fire and an informed opinion for aircraft fire safety improvement was provided by aircraft engineers.

All experimental and numerical results were integrated in a data base. The findings and conclusions will be disseminated to provide decision support for the choice of materials based on their mechanical, flammability, burning and toxicity properties.

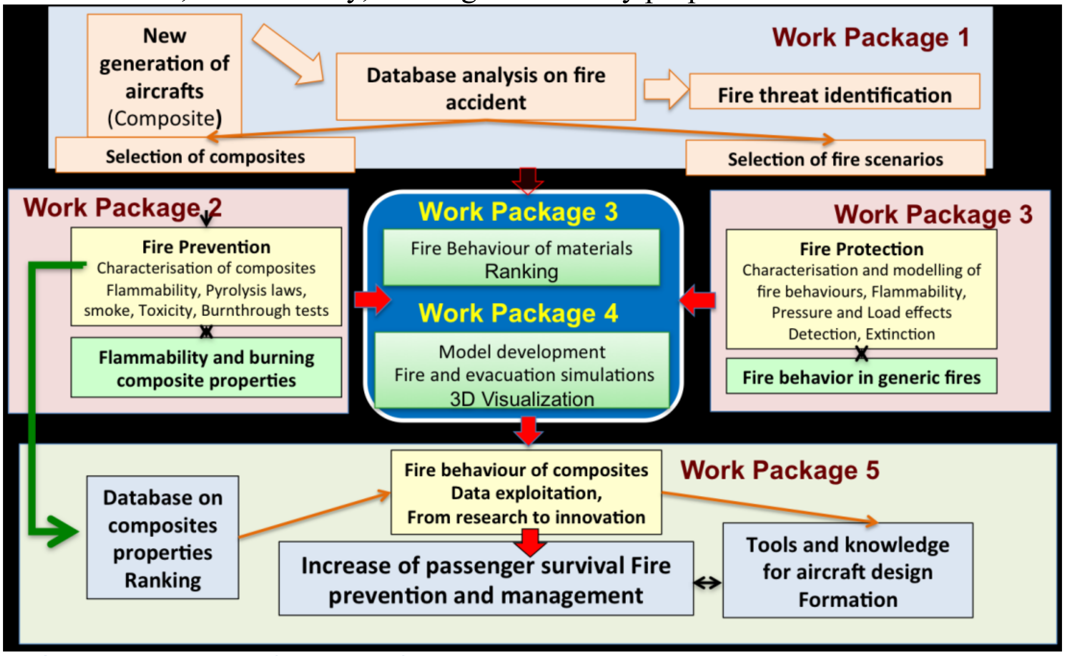


Figure 3: Organisation chart of the AircraftFire project

Conclusion and recommendations

Main advances and recommendations have been provided to the manufacturers to help them to take into account the impact of fire in the aircraft design and to enhance the fire safety without deteriorating the aircraft performances.

3. Description of the main S&T results/foregrounds

3.1. Fire Threat Analysis from fire issues to knowledge for research strategy and safety enhancement

Leader CAA

3.1.1. Fire/Smoke Occurrence database analysis

Involved partner: CAA, Fraunhofer

The UK Civil Aviation Authority (CAA), together with other aircraft safety regulatory agencies around the world maintains databases of safety related aircraft incidents. In the case of CAA this data has been collected for almost 40 years and at the time of writing over 17,000 incidents are reported each year. A team of 12 CAA staff enter data into a database for detailed analysis.

There are four issues that this analysis sought to investigate:

- An analysis of 10 years of CAA fire related incident data.
- The possibility of combining databases from different sources to enhance the reliability of analysis by widening the amount of data.
- The use of text analysis, which can potentially automatically analyse text to infer meaning. A particular use of this technique could be used as a quality control tool for incident databases.
- The use of data mining tools to identify relationships that were previously unknown. It is important to ensure that these identified relationships have practical significance for safety purposes.

The main objectives of the analysis of the CAA data were to:

1. Confirm the scenarios selected in AircraftFire
2. Find causes for fire in the past
3. Locate aircraft areas where fires occur often
4. Find previously unknown knowledge by examining the data

This work set the scene for AircraftFire and provided the context for the studies. The majority of fires is associated with ovens, Auxiliary Power Units (APU) and brake systems. Oven fires are usually relatively innocuous, although all fires have the potential for serious harm. Of particular concern are fires in the hidden zones of the cabin, behind the walls and above the ceiling where typically electrical-fault ignited dust or lint can lead to a large fire before being detectable in the cabin (there are at the time of writing no detectors required in the hidden zones of the cabin). Gaining access to the area to fight the fire can be quite difficult for the cabin crew.

The work on automatic text analysis, data combination and data mining has produced useful results, which have resulted in additional investigations outside of the AircraftFire project. Essentially these techniques are likely to have a part to play in either automated or semi-automated safety data analysis.

The applied process has consisted to the identification of likely fire scenarios for composite-based aircraft in terms of data has of course to be based on aircraft of conventional construction. There are clearly two major delineations, in-flight and the post-crash situation.

Most of the aircraft fire scenarios require the protection of vital components of the aircraft and the containment of the fire to stop its propagation to the cabin (survivability of passengers) or the protection of essential parts of the aircraft in a way that the fire does not grow to an uncontrollable situation that could be catastrophic. The main objective is to contain any potential propagation up to a safe landing.

Two general situations have been identified:

- One deals with in-flight fire dynamics within aircraft in contained zones, particularly in hidden areas of the aircraft not accessible for the crew other than dedicated cargo areas.
- The other concerns fire dynamics outside the aircraft and during post-crash, that affect aircraft and passenger safety (survivability of occupants - fire safety, mechanical resistance of structure during fire, and evacuation – smoke formation and visibility in the cabin, engine fire). For that, a better knowledge of the composite behaviour is essential.

As result of discussion based on data and subject-matter input, the following specific fire scenarios, of interest to AircraftFire, have been identified in order to be specified and studied:

In flight fire scenarios:

- Hidden zone fire;
- Engine fire - Effect of altitude on a combustion product jet.

Post crash fire scenarios:

- Crash and kerosene fire with the integrity of the hull maintained
- Crash and kerosene fire with fuselage break
- Cross-cutting: Effect of load on the flammability properties of material

Methodology for automatically extracting information out of database

The aim of the database analysis was to develop a methodology for automatically extracting important information out of aircraft incident reports and turning this information into new knowledge. The sources of the information are different databases of incident reports, like CAA's MOR (Mandatory Occurrence Report) database

As a first step, a large number of available databases was examined by Fraunhofer and a set of common attributes was defined together with the CAA. It was decided to have a relational database system to store the reports from the source databases.

In the next step, a large number of reports were automatically read and analyzed to identify which information given in these reports can be extracted to fulfil the work packages aims. Some information, like the aircraft make and model, are available as structured information which can immediately be processed.

Obviously, the most important information is contained in free texts, as there is only little structured information in each incident report. It turned out that the type of incident (fire/smoke/fume) and the location within the aircraft the incident originated can be found in these free texts, as well as a causal factor for the incident.

After that, Fraunhofer investigated the opportunities and available tools to support the text mining. The GATE toolkit was chosen due to its long history, extensive features, comprehensive documentation, and open source license. Together with the CAA, a complex set of keywords and rules was defined, which is able to extract semantic information from these free texts and turn them into a machine readable form. A close collaboration between the CAA and Fraunhofer was necessary, as knowledge in aviation and computer science had to be combined.

The machine learning toolkit WEKA was used. It is the de-facto standard in data mining, and heavily used in both research and industry. Besides, it is also available under an open source license. Given all the features extracted as described above, like the type of fire incident or the location of the fire within the aircraft, statistical interrelations could be found.

The results of the data mining done by Fraunhofer were also carefully examined by the aviation experts from the CAA to ensure their correctness. It could be shown that the results indeed have a high validity.

The work which has begun in this project is continued in cooperation with EASA[1]. The aim of this study is to quickly extract key features such as the aircraft make/model or the registration from a large number or incident reports. As these are not pre-filtered for fire incidents, in a first step a classification was done to determine the primary cause of the incident described in the text. One of the possible next steps is to perform data mining on these reports.

3.1.2.FST Scenarios and Materials Selection

Contributions: Airbus Group Innovation, Airbus SAS)

Two general fire situations were identified. These are the in-flight fires (hidden zone fires in the cabin and engine fire) and the post-crash fires (full-scale fires with burning kerosene including the integrity of the hull and fuselage break). Another point is the effect of load on the flammability properties of the materials. For these scenarios the specifications and the research strategies were defined with regard to the used materials.

The state of the art of fire testing was collected. Based on these data the laboratory scale fire configurations were defined so that the testing methods reflect **the three scenarios selected (hidden zone fire, engine fire and post-crash fire) and contribute to the understanding of the fire behaviour of the selected materials**.

Moreover, the materials used in present or near future aircrafts were collected and assessed by AGI[2]. **The relevant materials were identified in relation to the defined scenarios**. From these materials were the twelve most important materials representatively selected[3] and categorized into the three application areas cabin materials, structural materials and equipment. These twelve materials include 7 thermoset and thermoplastic types (fuselage, wings and structure), 1 thermoacoustic insulation and 4 cabin materials (seating, cabling, ducting wall). Also the dimensions and amount of the materials were defined for the testing methods and the partners for the tests were selected. For this purpose Airbus Group provided manufactured composite materials.

3.2. Characterisation of the thermo-chemical properties of composites and cabin materials, Smoke specificities

The aeronautic regulations require standard passed/failed tests to certify the aircraft materials. These tests might not be as appropriate for the new fire threats and their consequences as they are for conventional aircrafts. Despite previous FP6 studies, progress depends on determining

1 European Aviation Safety Agency, Cologne
2 Airbus Group Innovations
3 see Deliverable D.1.4

the composites flammability and burning properties required to enhance the fire prevention and protection to increase of passenger survivability. The AircraftFire approach is based on a better knowledge, obtained experimentally and numerically, of the main fire origins and on the development of individual and global events involved during aeronautical fires and on the efficiency of fire management and passenger evacuation.

3.2.1. Characterisation of materials

Contributions: University of Ulster-FireSERT, Pprime and University of Patras

The objective of this task was to characterize the ignition and flammability behaviours of various materials used aboard aircraft. This work was carried out at three organisations, namely FireSERT at the University of Ulster, Pprime and University of Patras. FireSERT and Pprime tested the fuselage materials (AcF1, AcF2, AcF3, AcF6 and AcF7) whereas University of Patras the cabin materials (AcF8, AcF9-1, AcF9-6, AcF9-7a, AcF9-7b, AcF10, AcF11-1, AcF11-2 and AcF12).

Tests were conducted using a range of apparatus including thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), Fourier transform infrared spectroscopy (FTIR), attenuated total reflectance (ATR), tube furnace, burn-through test in an indicated furnace and cone calorimeter. TGA tests provide the degradation temperature, residue and kinetic parameters for pyrolysis. DSC measured the specific heat and the heat of pyrolysis. FTIR and ATR coupled with TGA and cone calorimeter allow identification of the pyrolysis gases and also solid structure in the residue.

Cone calorimeter tests were conducted for all the materials. The width and length of the samples were always 10cm × 10cm, whereas the thickness varies from 1.2 to 20 mm depending on the materials. Measurements include time to ignition, mass loss rate, heat release rate, and production of smoke, CO and CO_2. From the time to ignition tests, the critical heat flux/ignition temperature and effective conductivity and specific heat were deduced. The average effective heat of combustion was calculated by dividing the total heat released by the total mass lost and then used to find the stoichiometric ratio of a given material, and subsequently the smoke point height with the use of smoke yield.

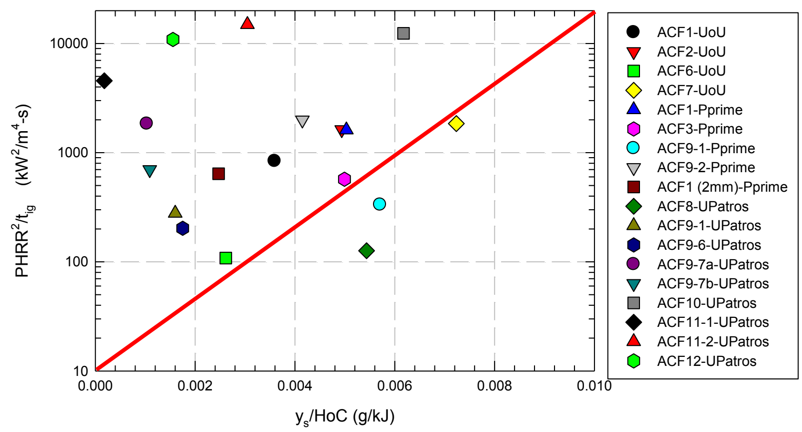


Figure 4: Flame spread parameter plotted against smoke parameter

Based on cone calorimeter and TGA measurements, three parameters were deduced which could be used to classify flammability of materials: one related to fire growth, one to smoke and one to gas toxicity. In addition as a supplement, we also can use the mass of the remaining residue and a parameter for thermally thin conditions. Figure 1 plots the fire growth parameter against the smoke parameter for all the materials. It can be seen that the thermoplastic resin (AcF6) composite has the best performance in terms of fire growth whereas AcF10 (cable) produce significant amounts of heat release rate and smoke.

Tube furnace was coupled with FTIR, and tests were conducted for selected cabin materials: AcF9-6, AcF9-7, AcF11-1, AcF11-2 and AcF12. The results show that there is a sudden increase in the yields of toxic gases, including CO, HCN and SO_2, when the ventilation condition changes from fuel- to ventilation-controlled. Furthermore, the CO yield obtained from tube furnace for well-ventilated tests is similar to that measured in the cone calorimeter.

Burn-through tests were conducted for AcF2 (4mm) and AcF7 (3mm). Samples were placed in a test frame having dimensions of 500mm x 460mm. The temperature of the furnace was programmed to follow the standard ISO834 curve. Both materials produced a significant amount of smoke. It was also found that both the thickness of the panel and the exposed time have a significant impact on the burning behaviour: AcF7 (thickness: 3mm, exposed time: 40 minutes) completely collapsed, whereas the residue of AcF2 (thickness: 4mm, exposed time: 30 minutes) remains in the test frame after the test. The pyrolysis of the resin lasts about 200s for heat fluxes over $80kW/m^2$ and the oxidation of the carbon fibres, followed by burn-through, lasts about 1800s for a heat flux of $80kW/m^2$ (furnace test). It is estimated based on order of magnitude heat transfer analysis that for a heat flux of $180kW/m^2$ (the FAA test conditions) burn-through will occur in 1800/5= 360 seconds.

3.2.2. Characterisation, at laboratory scale, of intrinsic material flammability and burning properties

Contribution: University of Patras

3.2.2.1. *Cone calorimeter measurements*

The flammability and burning performance of thermoplastic and composite materials, previously selected for the study, is determined. Reaction to fire tests is accomplished using a dual cone calorimeter based on ISO 5660, ASTM E1354 standards. The cone calorimeter (close to OSU apparatus) is one of the most significant bench scale instruments in the field of fire testing because it measures important real fire properties of materials under a variety of preset conditions. Flammability characteristics of the combustible solid materials will be determined at small scale. Results will include time to ignition, heat release rate (average, peak, total), mass loss, and chemical composition of the combustion products such as CO, CO_2, Oxygen residuals and smoke production.
The Cone calorimeter in a standard atmosphere provides a measurement of the heat release rates and burning velocity (or mass loss) of composites (mass thermal output power during burning) and the chemical composition of the combustion products. Special calorimeter (Universal Flammability Apparatus UFA), allows assessing combustion in under ventilated conditions and evaluating tendency for dripping and charring strength by performing experiments in vertical orientation.

3.2.2.2. *Thermogravimetric Analysis (TGA) and High Resolution TGA (hi-res TGA) measurements*

These diagnostic methods are a type of testing that is performed on samples to determine, with high precision, changes in weight in relation to temperature and temperature change. This technique of TGA is employed to determine characteristics of materials such as **degradation temperatures** of materials. The hi-res TGA allows a greater accuracy in the derivative curve peaks. In this method, temperature increase slows as weight loss increases. This is done so that the exact temperature at which a peak occurs can be more accurately identified.

3.2.2.3. *Differential scanning calorimeter (DSC) measurements*

This thermoanalytical method is a technique in which the difference in the amount of heat required to increase the temperature of a sample and reference are measured as a function of temperature. Both the sample and reference are maintained at nearly the same temperature throughout the experiment. The reference sample should have a well-defined heat capacity over the range of temperatures to be scanned. The main application of DSC is in studying phase transitions, such as melting, glass transitions, or exothermic decompositions. These transitions involve energy changes or heat capacity changes that can be detected by DSC with great sensitivity. This technique, coupled with TGA provides the solid degradation in mg scale in order to determine the **heat of pyrolysis** (TGA) and simultaneously the **specific heat capacity** (DSC) of the material.

3.2.2.4. *Fourier Transform Infrared Spectroscopy (FTIR)*

The FTIR technique is based on the absorption of an Infrared radiation by the analysed material or gases. It allows, from detection of characteristics vibrations of the chemical bonds, to provide the analysis of the chemical functions in the material or gas. The coupling of TGA devices and FTIR provides the analysis of gas composition. This technique is used to determine the gaseous combustion products in mg scale for toxicity and ignition kinetics.

3.2.3. Pyrolysis mechanisms and models in CFD codes

Contributions: INSA-CORIA, University of Patras

The modelling of the pyrolysis based on small scales tests is useful in order to understand the phenomena that occur during the degradation processes, to perform sensitivity analysis for varying external heat fluxes (EHF) and to determine physical and chemical parameters that are difficult to measure, in particular during the degradation process at high temperatures. With the modelling of the pyrolysis, indirect determination is still possible. The idea is to use an optimization procedure of the parameters that are unknown by comparing theoretical and measured values of the mass loss rate (MLR) of the material occurring during cone calorimeter tests. For composites, it is important to consider that heat and mass transfers occur both at the exposed surface and inside the material. This is not straightforward, and it is important control a large number of parameters.

For the present work the THERMAKIN model developed by Stoliarov (Comb. & Flame 2009) has been used. The 1D geometry has been considered, corresponding to the case of a planar material for which the parameters vary only as a function of depth. It is assumed that this is close to the experimental conditions encountered in the cone calorimeter experiments. The parameter estimation needs an optimization method to find the best parameter values. The principle is based on an iterative procedure which compares the calculated MLR values, which are function of the parameters to estimate, to the experimental data. Shuffled Complex Evolution (Duan, J. Optimization Theory and Appl., 1993) has been chosen in this study. It has been assumed that the thermo-physical parameters[4] ρ, Cp , λ and ε of the composite constituents do not depend of the temperature, and that these parameters (ρ_f, $C_{p,f}$,λ_f) are known for the fibres. Accordingly, nine parameters have been optimized, the four thermo-physical parameters of the resin, the emissivity of the fibre, the three parameters of the chemical degradation, and the flux F emitted by the flame and received by the material.

Results have been obtained for 4 thermosets (AcF1, -2, -7, -9_1) and 1 thermoplastic (AcF 6). It has been found that it is possible to estimate the most important parameters (among the previous ones). It is recommended to use in the optimisation procedure the MLR data

[4] density ρ, heat capacity Cp , λ and emissivity ε

obtained at several EHF, for example ranging from 30 to 70kW/m2. It is important to note that the MLR values must be measured with accuracy otherwise no reliable parameters can be estimated. In particular if the MLR values are too low and less than about 0.005kg/s, the optimization of the parameters is difficult. This is the case in the present work for the thermoplastic AcF6 and the thermoset AcF9_1.

Some assumptions have been taken in order to carry out the modelling. In particular the mass transfer is assumed to be very fast inside the material. However, after a certain time, the resin disappears, a layer composed by a residue (char) and the fibres remains. So the resin pyrolysis front is inside the material at the interface between this layer and the virgin material, this layer acting as a barrier for the mass transfer (and also the thermal transfer). Further works are needed to improve the modelling of the mass transfer inside composites during their degradation.

A similar approach using the GPYRO software (Lautenberger C., Gpyro - Technical Reference, 2009) was undertaken for several cabin and hidden zone materials, including AcF9-1 Phenolic, AcF9-6 Sidebar, AcF9-7b Ceiling, AcF11-2 Seat Foam and AcF12 Carpet. Experimental tests in TGA and Cone Calorimeter have been processed using 0D and 1D approaches respectively. One and two step reaction mechanisms have been considered, implying that the initial "virgin" material degrades to a "residue" (char) either directly or through an "intermediate" material. A Genetic Algorithm scheme is utilized for estimating, through successive generations, the unknown parameter values which provide a convergent solution. A typical set of estimated parameters comprises the reaction pro-exponential factor, Z, activation energy, E, and order, n, the residue material density, $\rho_{residue}$, the fraction of the bulk density difference between condensed phase species that is converted to gases, χ, the virgin and residue materials' conductivities, k_{virgin}, and $k_{residue}$, emissivities, ε_{virgin} and $\varepsilon_{residue}$, and specific heat capacities, c_{virgin} and $c_{residue}$, and the volatiles part of heat of reaction, DHV. **The evaluation of the results shows that fitting of the experimental curves is better for higher External Heat Flux levels experiments. Although the Two Step Reaction Model provides better prediction of the thermophysical and reaction properties, the One Step Reaction Model is in most cases quite adequate for large-scale simulations.**

3.2.4. Characteristics of the emitted smoke, opacity of the pyrolysis gases and combustion products

Involved partner: INSA-CORIA

In order to understand and to improve the behaviour of the composite materials exposed to high fluxes, tests at small scales, during which the thermal fluxes are controlled, are recommended. Complementary to TGA and cone calorimeter tests, smoke chamber tests allow to determine the properties of smokes emitted during degradation. In particular, the optical properties have to be known because of their influence on the visibility which can be reduced during the evacuation of passengers and the crew interventions. In addition, the size and mass concentration of smoke particles have been also measured.

A smoke chamber has been installed in the CORIA laboratory to realize the measurements of transmittance and optical density of smokes on the visible wavelength spectrum as recommended by the standards ASTM E-662 and ISO 5659. The CORIA laboratory has also determined the size, the mass and the number concentration of the smoke particles. Results have been obtained for AcF1/AcF2/AcF3/AcF6/AcF7/AcF9-7/AcF9-6/AcF12 materials.

- For some composite materials, the particle emission inside the smoke chamber is very strong. So the initial size 72x72 mm^2 was reduced to 36x36 mm^2.
- The mass concentration values are high, greater than $10g/m^3$.

- The optical densities are very high,
- The diameters of particles are less than one micrometer, and the modal diameter of the particle size distributions is greater than 100nm, and for most cases close to 200nm.

The typical value of the specific extinction coefficient is σ_{ext}= 4.5 m^2/g.

3.2.5. Thermophysics properties measurements

Involved partner: I2M-TREFLE

Analysis of thermophysical properties of composite samples versus temperature, damage and stress.

This study was mainly devoted to a first approach of a systematic analysis of the thermal behaviour of composite samples versus temperature, damage and stress, through the study of the thermal diffusivity.

Such thermal diffusivity is obtained from the analysis of the transient temperature response of a sample to a radiative heat pulse. It is possible to implement such a method at different temperatures, on large samples (healthy or delaminated) and also when the sample is under a mechanical stress (tensile test). It is also possible to estimate several mappings of transverse properties (mapping of transverse diffusivities) or local values of the in plane diffusivity.

The results and remarks are here itemized:

The main part of the study was focused on the comparison of mappings of diffusivities related to healthy and damaged composite samples.

The Healthy Composites samples ACF1, ACF2, ACF3 are:

- Non isotropic (transverse diffusivity about 10 time lower than in-plane diffusivity)
- The in-plane diffusivity is non strictly homogeneous at the millimeter scale (in-plane diffusivity varying from 2.5 x 10^{-6} to 4 x 10^{-6} m^2/s, versus samples and scales)
- The behaviour of healthy samples is valid only at ambient temperature. All the samples at temperatures higher than 100°C drip. The transverse thermal diffusivity of ACF5 and ACF6 is decreasing versus temperature (maybe from partial delamination).

The main properties of damaged (delaminated by fire) composites samples ACF1, ACF2, ACF3, ACF6 are:

- Transverse diffusivity much lower than healthy samples (from 4x10-7 to 1x10-7 m2/s)
- Transverse diffusivity depending on temperature (radiation/dilatation), but less than metallic homogeneous samples (Armco Iron)!
- ACF3 becomes very heterogeneous (with ondulated delamination)
- The in-plane diffusivity is logically of the same order of magnitude as healthy samples (only ACF2 and ACF3 tested)
- The temperature variation of the thermophysical properties of fully delaminated samples is lower than the variations of Armco iron (reference metallic sample). The thermal diffusivity is generally increasing versus temperature when the thermal diffusivity of Armco iron is decreasing.
- The first trials on Samples ACF2 and ACF3 under cycling tensile tests show that the thermal properties are only slowly varying under mechanical stress (less than under fire stress, from 4.5 x 10-7 to 4.2 x 10-7 m2/s for ACF3)

The main result is that a damaged delaminated composite is thermally more insulating. It is an advantage of composite materials under fire, compared to metallic samples.

3.2.6. Robust methodology for material ranking and development of a scaling laws

Contributions: University of Iceland and University of Ulster-FireSERT

Using scale modeling in fire research can be a very good complement to other investigative methods such as analytical modeling and numerical modeling. Scale modeling can also be very useful in scaling down full-scale experiments. The strategies of immediate interest to the AircraftFire project were mainly of two types. The first issue is scale modeling of aircraft fire experiments. A scale model of a part of an aircraft hull to evaluate thermal attack and fire spread due to an external fire. The second scaling strategy addresses methods for scale modeling of material flammability, where the aim is to use results from material bench scale tests to assess material flammability and fire growth in full-scale. These results were then used to develop a methodology for material ranking.

Manufacturers of interior aircraft materials are constantly looking for improvements in their engineered formulations. With regard to life safety linked to fire threat, the best material formulations would be those materials that are difficult to ignite, allow very slow flame spread and therefore low fire growth, produce very limited toxic gases and relatively thin smoke so that visibility is acceptable.

The objective of material ranking was to develop the absolutely simplest of such methods; where data from small-scale tests would be used to directly predict material ranking with regard to fire hazard in full scale. Considerable work of this type has earlier been carried out for construction products but no full scale testing philosophy has been developed for fires in aircraft cabins. Therefore the aim was to develop and utilize a very simple methodology when assessing the flammability of building materials while using new knowledge of modern aircraft interior material characteristics.

The ranking method developed here is based on measurements performed in the Cone Calorimeter at an external heat flux of 50kW/m^2. Three parameters are mainly used for the ranking: the main parameter is related to fire growth, a second to smoke and a third parameter to gases toxicity. The fire growth parameter is determined by the following relation, based on measurement performed in the Cone Calorimeter at an external heat flux of 50kW/m^2:

$$\textbf{Fire}\text{ Growth Parameter} = \frac{PHRR^2}{t_{ign}} \qquad (1)$$

Here, *PHRR* is the peak heat release rate per unit area and t_{ign} is the time to ignition. This is the main parameter for ranking, since it gives an indication of how quickly a material ignites, how quickly it releases heat and how rapidly it will spread flame. Also, the faster the flame spread and the heat release rate, the faster one expects the production of soot and toxicity to be. However, some materials may produce unusually toxic or sooty smoke and therefore it is important to screen for these quantities. This is done by determining the “Smoke parameter” and the “Toxicity parameter”.

The ranking methodology was applied to carbon fiber composite materials used in modern aircraft. The materials tested by FireSERT were designated as ACF1 (epoxy resin), ACF2 (epoxy resin), ACF6 (PEEK resin) and ACF7 (epoxy resin), all 4 mm thick. Some additional materials, designated as ACF3 and ACF9 were investigated by PPRIME, CNRS, but that laboratory also tested material ACF1 at two thicknesses: 4mm and 2mm.

Results showed that the far best material tested by FireSERT is the thermoplastic resin composite (AFC6), which gives more than a 100 times lower Fire Growth Parameter than the thermoset materials (AFC1, AFC2 and AFC7). At the same time, AFC6 gives reasonably low values for smoke and toxicity. We conclude with considerable certainty that AFC6 will perform much better than the other materials in a full-scale fire situation.

Therefore, we conclude that further work should be done on increasing reproducibility of small scale test methods for material flammability (especially for the Cone Calorimeter) and a "round robin" (where the same materials are tested in different laboratories and results compared with the aim of increasing reproducibility) should be carried out. Work on pyrolysis models for the small scale scenario should be coupled to such an exercise. Also, the real scale fire threat should be considered further, a limit state should be determined and efforts to use pyrolysis models for full scale numerical simulations should be increased. Finally, full scale fire experiments of an aircraft hull, possibly coupled with quarter scale fire experiments, should be carried out.

Therefore, the ranking scheme presented in the AircraftFire project cannot be compared to any bench-mark, cannot be fine-tuned in any sense and must be seen as being a very rough indication of material hazard. However, the process has shown the way forward and indicated some desirable avenues in future fire research work into interior aircraft materials.

3.3. AircraftFire Fire Protection: 1st part: In-flight fire

Most of the in-flight aircraft fire scenarios require the protection of vital components of the aircraft to do not alter the fly home capability, protect the cabin and to assume the survivability of occupants. In hidden zones where no protection is generally present, fire detection and suppression must be adapted to the composite burning and the fire-spread mechanisms must be prevented to avoid fatal outcome by containing the fire. It's the objective of the following work.

3.3.1. Flammability limit of kerosene or oil leak

University of Edinburgh

An accidental release of aircraft fuel in the presence of an ignition source (e.g. hot surfaces or electrical arcing due to damaged wires) is likely to result in a large fire in a matter of minutes. Understanding the properties of such a fire is therefore of great importance. The AircraftFire project studied the evaporation, ignition and burning rate of kerosene for fuel spillage scenarios. It was found that each of these parameters depends heavily on the thermal and physical nature of the surface(s) that the fuel spills onto, so it is impossible to generalise kerosene flammability behaviour across a range of different locations within an aircraft, or outside of the aircraft.

However, kerosene spillages may be treated as conventional pool fires (as described in many standard texts in the literature) and it has been shown that the impact of the surface materials can be accounted for simply, but effectively, by introducing an efficiency factor, χ. This can be calibrated for any specific surface material / location using a simple experimental test.

3.3.2. Fire Ignition and Propagation in Hidden Zone

University of Patras

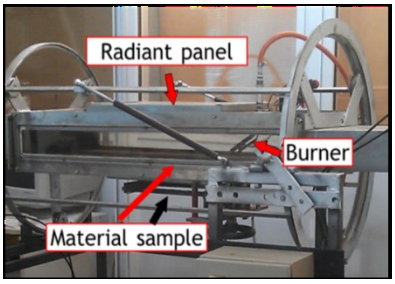
Objective - Fire scenario

An important class of in-flight potential fire-hazards is that of hidden zone fires, i.e. fires in areas not easily accessible to the crew, where a fire cannot be clearly identified and becomes more challenging to extinguish.

This work aimed to evaluate the consequences of hidden fires taking into account real-life incidents and identifying new potential risks related to the introduction of novel materials in aircrafts.
A scenario involving ***a hidden fire occurring in the void above the cabin ceiling, spreading forward from an ignition source located in the aft of the aircraft and resulting in leakage of gases and smoke into the cabin*** was investigated in and used for large scale simulations in this project. Relevant materials comprised the AcF9-7b ceiling panel and AcF10 Cable. Besides flammability properties, flame spreading characteristics had to be estimated experimentally.

Development of a generic experimental apparatus - Hidden Fire Apparatus (HFA)

The Hidden Fire Apparatus (HFA), a small scale thermally insulated combustion wind tunnel, operated under free or forced flow conditions was designed with reference to hidden fire scenarios and standard tests. Flame spreading was studied over specimens 0.29x0.19m^2, irradiated with a uniform heat flux. Instrumentation included a digital video camera and thermocouples. Flue gases were analysed with Cone Calorimeter (CC) instrumentation and an FTIR analyser. HFA tests contribute to assessing Hidden Fire behaviour, as follows:



- Monitoring material behaviour in controlled Hidden Fire conditions.
- Establishing a new flame spreading estimation technique providing experimental results and generic characteristics such as the critical heat fluxes for fire spreading and for ignition, the flame spread parameter and the ignition parameter.
- Cone Calorimeter instrumentation provides information on Heat Release Rate, O_2, CO, CO_2 and Smoke production in HFA conditions, whereas FTIR is used for flue gas composition analysis.

The experimental results obtained with the HFA:

- Complement current material flammability measurement techniques with information on hidden fires.
- Provide verification data for the evaluation of numerical codes and models
- Identify and provide material properties needed in numerical models
- Enhance our knowhow for the development of physical or simplified numerical models

Collection of relevant information on fire behaviour of specific materials in Hidden Fire conditions

Extensive experimental campaigns have been undertaken for the materials AcF9-7b Ceiling Panel and AcF10 Cable in horizontal orientation and free flow conditions, at several heat fluxes and preheating times.

- AcF9-7b Ceiling panel tests were performed at incident heat fluxes 25, 28, 30, 32, 35kW/m^2 (no fire spreading for 25 and 28kW/m^2). Preheating times had negligible effect and results focus on those of 30s. A technique has been developed to derive production rates per infinitesimal area from CC instrumentation and FTIR results, complementing typical CC test and FTIR results. The AcF9-7b had a rather positive behavior in HFA experiments.

Properties were handed over to UoG[5] for numerical simulations of the fire growth and evacuation.
- AcF9-10 cable tests were accomplished for heat fluxes 15, 16, 17.5, 20kW/m^2 using preheating times 30, 150 and 250s (no spreading for 15kW/m^2). The presence of materials having different thermal and flammability properties and the formation of continuous cavities resulted in phenomena such as intermittent pyrolysis gas release and significant internal heat conduction along the wire material.

Numerical modelling and extensive simulations with FDS were used to support: the hidden fire scenario selection, the design of HFA, the assessment of orientation effects, the selection of experimental conditions and the analysis of the results.
Extensive hidden fire scenario simulations were used to assess burn through behaviour of the material AcF9-7b, to evaluate the adequacy of models to correctly predict fire behaviour in hidden zones and in the development of a technique for numerically assessing flame spreading velocity. Developed models based on material properties were able to predict the behaviour of the ceiling panel material in most cases. The use of models incorporating experimentally estimated characteristics, such as the spreading velocity in hidden fire conditions, implemented in SMARTFIRE by the team of the University of Greenwich[6], was also successful.

3.3.3. Contained fire detection

University of Edinburgh

Historically, the aim of all fire detection systems in buildings as well as aboard aircraft has been to identify a fire as quickly as possible after ignition. Currently, in aircraft, this is achieved using a variety of different systems and sensors, deployed in different parts of the aircraft, in accordance with current aircraft regulations. While minor advances have been made in the field of detection technologies in recent years, current systems all still rely on the same principles as the systems in use last century.

If detection on aircraft is to be achieved significantly earlier than is currently possible, this cannot be achieved through refinements of existing technologies. A new approach to detection is required.

The scientific advances achieved in the Aircraft Fire project derive from the fact that ignition is not the first step in the fire process. In order for ignition to occur, there must have been a chain of events prior to this which brought about the conditions necessary for flaming ignition. The AircraftFire project focused on detection of these pre-ignition events.

If these earlier stages of fire development can be detected, then it will be possible to detect potential fires before ignition and, assuming appropriate suppression or mitigation technologies are available (see below), it will be possible to prevent such ignitions from occurring. The aim of future detection systems must be to prevent fires before they happen, not respond to them after they are burning.

Ignition of any fire requires the generation of a flammable gas/air mixture in the locality of an energy source sufficiently strong to ignite the vapours. In the AircraftFire project, the research was focused on identifying the pre-ignition pyrolysis gases before they are sufficiently accumulated to generate a flammable gas/air mixture.

[5] AircraftFire partner University of Greenwich-FSEG
[6] AircraftFire partner University of Greenwich-FSEG

This part of the project studied the gases which were evolved before ignition conditions were achieved when each of the project materials was subjected to external radiant heating. All of the project materials along with some other typical cabin materials were tested and their ‘pyrolysis signatures’ were defined. The only evolved gases common to all materials prior to ignition (with the exception of one cable material which did not ignite) were Sulphur Dioxide (SO_2) and Carbon Monoxide (CO). **Thus it is proposed that future detection systems for aircraft should be specifically designed to detect Sulphur Dioxide and Carbon Monoxide.**

A simple algorithm was developed which should ensure detection of most of the ignitable materials prior to the onset of flaming ignition. A threshold level of 20 ppm of SO_2 or of 50 ppm of CO should be established. Any detection of these gases above these levels could indicate a potential fire situation.

A more advanced detection device could then analyse the other trace gases and hence identify, by means of the ‘pyrolysis signature’ exactly what material is in danger of reaching ignition conditions. If the system had details of the various component materials used in the aircraft, and their locations, it would be able to precisely identify the location of the problem and deploy an appropriate response before ignition occurs.

3.3.4. Developing a concept of a data and information fusion system

Fraunhofer

One objective of this work was to develop the concept of an information fusion system able to process data from a greater number of different sensors in the aircraft to derive real-time in-flight warning or threat alarms. This implies a decision support system generating warnings as early as possible in case of real incidents, while at the same time the number of false alarms should be minimized.

Special data fusion algorithms provide the essential functionality to such system which fuses the data generated by all the heterogeneous sensors monitoring the status of an aircraft. In order to be able to develop such algorithms for fire and smoke detection a review of the existing and currently applied sensor technologies was done and the number of sensors and their placement in aircrafts have been analysed. The development process of data fusion algorithms usually consists of a training phase and an application phase in which the trained knowledge is applied (Figure 5). In the training phase models are derived from a set of recorded real data. Each model represents one of the possible output cases of the considered application, in this case fie or smoke detection. A rather simple model would consist of a level for the case of an alarm and a level for the case of no alarm. In the application phase the newly incoming data is then compared with the learned models to distinguish between alarm and no alarm. A simple decision rule is given by a threshold.

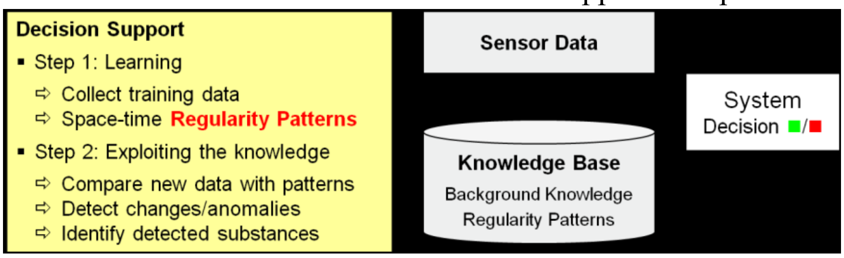


Figure 5: Derive patterns from training data to be used for change detection

3.3.5. Extinguishing systems for composite: Suppression technologies

University of Edinburgh

For several decades, halon gases have proved to be an excellent means of suppressing fires in aircraft. However, following the Montreal Protocol in 1987, these gases are being phased out and suitable alternatives need to be developed. This project focused on assessing the suitability of test methods for quantifying the ability of Halon replacement systems to effectively suppress fires. Some Halon replacement systems were also considered and reviewed.

After it was found that current 'standard' test methods are inadequate for assessing the true ability of gaseous systems to suppress fires in inaccessible locations (e.g. the 'hidden zone'), it was intended to develop a more robust test method for testing and ranking alternative suppression systems. However, it was found that a suitable test methodology was proposed by NIST over a decade ago, and reviewed by Gann in 2007, but has not been adopted into practice by the industry. This method is the most suitable method for assessing the suppressing abilities of gaseous flooding systems in complex geometries. This test methodology is adequately defined and fully developed, yet has not yet been accepted by the appropriate regulatory authorities. The AircraftFire project recommends that this existing test method be considered by the aircraft safety regulators.

3.4. AircraftFire Fire Protection: 2^{sd} part: Post-crash Fire

The post-crash scenario is compared to the in-flight fire scenario the one where it is most likely to save passengers and crew. The objective of this work is to study the crash and the consequences of the induced kerosene pool fire on the aircraft. The fuselage must be a safe barrier to the flame penetration in the cabin. To that aim, the fire resistance and the mechanical properties of composites must be characterised in representative conditions of fire by adapted diagnostics.

3.4.1.Report on concepts for cabin integrity during crashes

Impact Comparison of Metallic and Composite Aircraft
TU Delft

Crashworthiness is typically judged based on the evaluation of acceleration and damage of vertical drop tests. Simulation and experimentation focus on the vertical drop tests of 'typical' fuselage sections, primarily, but can include complete fuselages. But survivable crashes never occur with velocity components perpendicular to the ground only, so fixed-wing aircraft impacts should be analysed with horizontal speed included.

A selection of incident reports focuses on survivable mid-range civil transport aircraft incidents such as the Airbus A320 and the Boeing B737 series, and within the FAA database at the time contained only 44 such incidents. Some of these incidents involve fire that spread before crews could photograph the aircraft and obfuscate the damage done by impact, rather than fire or the combination of impact and fire. These incident reports show that the majority of damage due to collision or impact occurs near structural discontinuities, for example, immediately ahead and aft of the wing box, where the longitudinal stiffness is suddenly increased.

Impacts that involve aircraft on its landing gear and rolling into another object, such as a ditch, a barrier, or trees, often have damage contained in the forward sections, around what is often the business class area, just aft of the cockpit. As the impact speed increases, or there is a combination of forward and vertical velocities, often two fracture or cleavage sites are observed. In one case, in which there was a roll angle, a diagonal fracture across the fuselage over the wing is observed. These aircraft incidents are included in the current study as inputs, and can be used to validate the simulations of the full metallic fuselage crash scenarios.

Drop tests involve typical sections of approximately 3 m lengths of the aircraft hull. The comparison between the metallic aircraft structure and the composite aircraft structure was performed through the analysis of the section drop tests. The metallic section was modelled as an elasto-plastic material with minimal damage (decreasing stiffness) and true ultimate strain failure. The composite fuselage model was performed in two ways: once as a quasi-isotropic model and once as a ply-by-ply laminate model. The quasi-isotropic model was an elastic model with brittle failure and abrupt damage, whereas the laminate model used Hashin damage and failure. The results of these tests were that the metallic model showed the lowest magnitude of acceleration pulses, then the quasi-isotropic, then the laminate model. The plasticity of the frame near the floor, in the metallic model, was negligible in the composite models because of the lack of plasticity in the composite frame. Instead, plasticity occurred in the floor spar itself. **The consequence is that the floor spars become susceptible to failure, rather than the frame; this means that the floor may detach from the frame**. Also, damage was negligible in the metallic model, but accounted for 0.8% and 1.5% of the energy dissipation in the quasi-isotropic and ply-by-ply models.

The full A350-like aircraft models show higher accelerations and greater damage, compared to the drop test simulations. With the inclusion of fuel mass, stabilizers, landing gear, etc, the aircraft model has manifests greater contact forces than experienced in the certification drop tests. The amplified contact forces cause more damage and deformation to both the metal and composite models, compared to the typical section, especially in the cargo area and along the cabin floor. In the full aircraft model, damage accounted for up to about 1% and 16% of the deceleration energy in the metallic and composite structures, respectively. Both the metal and composite models show that the plasticity of the floor can be a survivability concern in a crash. Accelerations may be fatal in some areas of the cabin, and these are also located in areas that correspond to the cleavage zones for a typical metal aircraft. There is greater plastic deformation in the metal aircraft, but damage is visible in both models. **The clearest difference between the models is the appearance of a large cleavage in the composite model, which occurs near the wing box edges**. In general, there were greater numbers and sizes of openings or gaps in the skin of the composite model than in the metal model. This has consequences for the AircraftFire study, since the inflow of noxious fumes and flame will be faster with an increased rupture surface area.

The primary result of including the mass of the wing box (and fuel stored in the wing) is that the local deformation is great enough to cause the brittle fracture of the composite structural elements nearby. It is unsurprising that the fracture is vertical in this case, as opposed to the metal stress concentrations that extend away from the wing box along non-circumferential curves. Due to the nature of the stringer/frame arrangement, there is no interference from structural reinforcement. That is to say, that the crack does not extend towards the frames on either side of the cleavage, and the skin and stringers are insufficient to halt the crack growth.

The maximum accelerations seen by various locations along the longitudinal axis of the A350-like aircraft were plotted on the Eiband plot. The Eiband plot gives a good visual example of the limits of the human tolerance to acceleration, with respect to acceleration magnitude and duration. Empennage accelerations were unreasonably affected by the tearing away of the floor spars from the frame near the location of the accelerometers, and therefore not included.

The impact of the drop test on an A350-like aircraft seems to cause moderate injury in both the composite and metal variants. The composite aircraft average accelerations according to the Eiband plot is slightly higher magnitude, but also slightly shorter in duration. In fact, the average magnitude of the floor level acceleration for the metal aircraft is about 29 g, whereas the composite average is about 36 g. However, the average duration of the metallic impulses is 84 ms, but the average composite impulse duration is only 72 ms. This means that the average acceleration impulse lies on the borderline of moderate-to-severe injury for both the metallic and composite aircraft.

Simulations show that the effect of angle of attack is more damaging than including the forward velocity for these aircraft. However, it should be noted that this is only for aircraft on rigid grounds, where ploughing and the compression of the soil is not considered. **Both angle of attack and forward velocity effects should be taken into account when performing the crashworthiness certification of an aircraft.**

3.4.2. Report on modelling of large scale kerosene pool fire during post-crash fire scenario

Pprime

This numerical study focuses on the fire phenomenology associated with the presence of a full scale aircraft immersed, at one location and orientation, within a large aviation-fuel fire in a moving fluid medium. The CFD approach is much more realistic when dealing with the characteristics of the wind-induced interaction of fires and large objects. The wind deviations in speed and direction are erratic in nature and contribute to the large spatial and temporal variations of the flame shape and heat flux on the fuselage skin.

The basis of the analysis is the conservation equations of mass, momentum, energy and species, a set of three-dimensional elliptic, time-dependent Navier-Stokes equations. Turbulence is modelled using a standard Smagorinsky sub-grid scale model in a Large Eddy Simulation. The combustion model is based on an Eddy Dissipation Concept. A radiative transfer equation is solved and the effect of soot concentration on radiation is included by adding the radiation coefficient of soot into that of gas. The pyrolysis rate of condensed fuel can be derived from the mass transfer number which is a dependant parameter on the heat of combustion, the local oxygen concentration and the fuel latent heat.

The prediction indicates that interaction between aircraft and fire environment combined with the influence of wind conditions affects dramatically location of the continuous flame zone, and consequently, the heat flux on the fuselage skin. With a weak crosswind speed, a quiescent pool-like fire is attached to the kerosene pool and the magnitude of the wind speed is insufficient to direct the flame towards the fuselage due to the dominant buoyancy forces. The fire propagation assisted by a strong crosswind is the most devastating, and causes the flame zone to impinge on the bottom surface of the fuselage. When the aircraft moving direction is parallel to the wind direction, the cold air flow exists between the pool fire and the fuselage, and there is evidence of the lowest heat flux on the fuselage skin. The peak in heat flux to the fuselage skin to a high crosswind is up to 340 kW/m^2, a factor of 3 increase of that to a low wind speed, in particular when the wind direction is perpendicular to the aircraft moving direction. For the natural convection reacting flow, the peak in heat flux on the fuselage skin becomes significant when the pool size exceeds 30m. For the low speed of 2m/s, the peak in heat flux on the fuselage skin becomes strong starting from the pool size of 20m. For the high wind speed, an increase of the peak in heat flux from 200 to 340kW/m^2 is brought about with an increase of the pool size from 10 to 20m due to an increase in heat release rate.

Moreover, for a composite-type aircraft (A350-like) immersed even within a quiescent fire, there is an excess of fuel from the pyrolysis of the fuselage skin, and this situation induces an increase in the thermal plume volume. The presence of a wind speed induces an increase of the flame cover on the upper leeward side of the fuselage, resulting in the higher temperatures (about 700°C) there. As compared to the aluminium-type aircraft, the presence of a composite-type aircraft in fire does not affect significantly the distribution of the temperature and CO production at the exit openings outside of aircraft as the liquid pool diameter is below 20m. This is mainly due to the fact that the pyrolysis of the composite material occurs only in the high heat flux zone covered by the flame from the kerosene pool. As the latent heat of the composite material is great, the flame spread over the fuselage skin is limited due to the weak mass transfer driving force.

3.4.3. Report on a new laboratory scale burnthrough apparatus to determine the fire resistance, flammability and burning properties of composites under representative fire conditions

Pprime

To protect the aircraft occupants, the fuselage must be a safe barrier to the flame penetration in the cabin. To quantify this efficiency, the burnthrough test, defined by the FAA norms, foresees to submit the materials to the impingement of a calibrated flame to measure the burnthrough time (BTT):

- engine fire (AC 20-135 norm), the heat flux at the material surface is fixed to 106 kW/m^2 with a gas temperature of 1093 ±83°C;
- post-crash fire (AC 20-107B norm), the heat flux at the material surface is fixed to 182 kW/m^2 with a gas temperature of 1160 to 1200 ±93°C.

The objectives of this work on the fire resistance of composites were to measure the evolution of the Mass Loss Rate (MLR) and the value of its peak PMLR (proportional to the Peak of Heat Release Rate PHRR), and of the surface temperatures, to determine both the fire resistance of the composite, its flammability and burning properties under the conditions equivalent to FAA norms.

For that, an original experimental device, the Material Fire Resistance Test System (MFRTS), has been realised to mimic, at laboratory scale, the standard burnthrough test.

From the test results, it is shown that:

- The observed burnthrough time (BTT) of the composites was never within the 15 minutes duration time of the test. This behaviour can be explained by the role of the radiation heat flux emitted by carbon fibres, at the gas temperature, once the resin has been pyrolysed. Thank to this radiative emission of the carbon fibres, the net heat flux penetrating into the composite decreases, which finally increases the BTT.
- When the composite slab backside temperature T_b reaches the degradation temperature of the resin, the resin of this backside is pyrolysed, emitting degradation products into the cabin side with the potential of poisoning occupants and propagating fire. The off-gassing time is around 1 to 2 minutes corresponding to the order of magnitude of the aluminium BTT.
- The thickening of the sample does not modify the PHRR itself, but the **PHRR time** is increased, reducing both the fire risk and the value of the fire growth parameter.
- No effects of the fibre arrangement (1D or woven fabric) are observed on PMLR, PMLR or other properties. But woven fabric composites conserve after the resin pyrolysis the composite structure and they are less sensitive to a destructive erosive effect;
- The decrease of the ambient pressure (altitude simulation) increases PHRR (direct effect of pressure on the pyrolysis rate interpreted by a smaller gas resistance to the pyrolysis gas injection in the environment). The fire risk is rather increased;

- For all incident heat fluxes, the epoxy resin is completely burnt and PHRR (energy released by the combustion of the degradation products), related to PMLR, is independent of the incident heat flux: the diffusion processes control the resin pyrolysis rate. For thermoplasts, the PEEK resin is not completely burnt and droplets stay anchored to the fibres. The PHRR (energy released by the combustion of the degradation products) increases with the incident heat flux: the resin degradation rate is controlled by the pyrolysis law;
- The composite ranking, based on the fire growth parameter FIGRA, shows that the thermoplasts present a better fire resistance to a fire stress than phenolic resin/glass fibre thermosets, and finally than epoxy resin/carbon fibre thermosets (better heat resistance and a slower pyrolysis kinetic law for thermoplasts);
- After test, the woven laminate composite samples, particularly in reduced pressure, present a swelling that retains its braided structure despite the formation of gas pockets between the fibre layers. The gas conductivity is much less than the plastic one, and as consequence this enhances the heat blocking.

The Strength of the composites fire resistance:

BBT is greater than 15 min for the studied composites. This fire resistance is attributed to the re-radiation of the carbon fibre curtain. Consequently, their fire performances are already fair, but higher degradation temperature and activation energy could still enhance their fire resistances. **If the composite itself satisfies the BTT norms, the interest of the thermo-acoustic insulation mattress for burnthrough becomes inessential.**

The weakness of the composite fire resistance:
Composite are an efficient fire barrier, but:

- ✓ The resin warming destroys the cohesion between carbon fibres, which changes the mechanical properties of the composite. A mechanical stress can break the fibres as soon as the first layers of fibres are decorrelated;
- ✓ The fast heat penetration in the composite induces an off-gassing of pyrolysis products, **potentially toxic** (intoxication of the occupants) **and flammable** (gas ignition) with a potential fire propagation in the cabin after few tens of seconds.

The new MFRTSystem presented in AircraftFire is a performant tool to characterise the fire resistance and to determine flammability and burning properties of composites under representative fire conditions. An adapted **dissemination** should propose for rule making the concept of the MFRTSystem as a tool for composite qualification.

Due to the high fire performances of the carbon curtain after the resin degradation, the composites present a better fire resistance to burnthrough than aluminium fuselage. The fire post-crash fire scenarios are safer but the **off-gassing in the cabin of toxic and flammable** degradation products can have a **fatal effect** on passengers and crew survivability.

Obviously, all these results suppose the absence of cracks and ruptures in the fuselage skin during the crash, allowing the flame to rush directly in the aperture and propagates the fire in the cabin.

3.4.4.Behaviour of composite materials under thermal and mechanical stress conditions

Pprime

The aim of this study was to characterize the mechanical behaviour of different structural composite material submitted simultaneously to a flame attack and a mechanical stress in order to:

- evaluate the coupled effect of the stress and heating source on the material behaviour,
- compare the behaviour of different materials submitted to such thermal aggression and stress loading,
- describe the failure modes

For this purpose a mechanical testing machine has been set up. The equipment allows 3 or 4 points bending test and is coupled with a burner or a cone calorimeter. It has been designed by Pprime specifically for the experiences developed for the AircraftFire program. During the test, the load or the displacement can be controlled and the temperatures at three locations on the back side of the specimen were recorded. Two different fiber stress states in front of the flame could be achieved (tension or compression).

The burner design allows a hot jet gas which is similar to a fire of kerosene from a large post-crash. The main features of the burner are a wide range of heat flux up to 200kW/m² over a diameter of 3.5cm, and a maximum temperature gas exhaust of 1200°C.

Four structural materials were tested combining different layup and type of matrix (AcF1, -2, -3 and -6) in two different thicknesses (2 and 4mm). During the tests, four heat fluxes were chosen in the range from 75 to 200kW/m². All the tests were performed in the deflection control mode where the deflection is constant all over the test so the heat flux on the specimen remains constant too. For the 2mm thickness specimen, two different deflections have been used (15 and 30 mm) while for the 4mm one, only the 15 mm deflection has been applied.

The main experimental results are:

- The combination of the load and the thermal aggression leads to a failure of the specimen while the specimen doesn't break when the load only is applied
- In the case studied, the specimens fail systemically before the ignition time of the composite material
- The fiber stress state (tension vs compression) leads to two totally different failure modes leading to greater failure time in compression than in tension
- The failure time decreases while the heat flux increase
- The matrix type (thermoset vs thermoplastic) has a strong influence on the failure time
- The failure occurs only with few plies pyrolysed

Tomography on failed specimens shows that the failure mode is driven by buckling mechanism of the plies in compression whatever the stress field of the fibers exposed to the flame. Due to the variety of stacking sequence and fibers orientation, the stress in each ply can only be achieved by computer simulation. Some simulation works were performed on AcF2 in order to evaluate the stress field at mid span of the specimen and the effect of the temperature increase. The thermo mechanical simulation taking into account, the 3D temperature evolution in the specimen and the mechanical properties evolution with the temperature shows that, part of the load decrease during the test is related to the increase of the temperature but up to now the model developed do not describe accurately the sudden failure of the specimen.

3.5. Aircraft simulation tools: modelling of the fire growth and passenger evacuation

Fire can penetrate into the passenger compartment by a variety of paths (fuselage skin; windows, sidewall, cheek area and baseboard return air grills). Tests on fire resistance of materials are performed on the individual components to qualify the fire barrier efficiency, but not on the complete fuselage shell system. A complete simulation, from the description of the fire source to the passenger and crew evacuation, shall allow quantifying the efficiency of the protection for increasing the survivability.

3.5.1.Results of SMARTFIRE and EXODUS Simulations

University of Greenwich-FSEG

The primary objective of Work Package 4 was to investigate the impact of post-crash and in-flight fire on passenger survivability for the new generation wide-body passenger aircraft composed of a significant amount of composite materials through the use of fire and evacuation simulation based on the material data and properties deduced from the works on material and fire scenario analysis. As part of this work, the state-of-the-art fire and evacuation tools, SMARTFIRE and airEXODUS were extended and enhanced to address issues associated with the combustion of composite materials and used to simulate 22 fire scenarios and 31 coupled fire/evacuation scenarios. Key findings of this work include:

- The most critical finding is that, without a post-crash fuselage rupture, the composite fuselage results in a much better evacuation environment than the conventional aluminium fuselage resulting in improved passenger survivability.
- However, simulations suggest that composite materials with a low yield of highly irritant compounds such as SO_2 should be used in aircraft construction.
- Post-crash fuselage ruptures may result in the occurrence of flashover within the cabin severely reducing survivability, especially if the rupture occurs in the vicinity of monuments. This suggests that the fuselage should be strengthened or protected to decrease the likelihood of rupture especially in areas near interior monuments.
- It is suggested the aviation industry consider using a more challenging and representative exit combination for evacuation certification than the current approach.
- When assessing the impact of fire on passenger survivability, it is essential to perform coupled fire and evacuation analysis rather than an analysis of only the fire or only the evacuation, or separately consider the fire and evacuation. It is only when a coupled fire/evacuation analysis is undertaken a realistic assessment of the impact of fire on passenger survivability can be achieved.
- The size and location of fuselage ruptures is a significant factor in determining survivability in post-crash fires with and without wind. It is therefore essential to determine how composite fuselage aircraft are likely to rupture in the event of a crash and to undertake coupled fire and evacuation analysis of the ruptured fuselage.
- The presence of wind is a significant factor in determining the spread of the internal fire and exit availability and hence passenger evacuation and survivability. A detailed study investigating sensitivity of these factors to wind magnitude and direction should be undertaken.

3.5.2.Results from the visibility simulation

Airbus Innovation Group

The visibility simulation performed by Airbus Group Innovations (former EADS Innovation Works) is separated into two phases. First a method was developed, which was able to simulate the influence of smoke on the light distribution. This simulation must be physically correct to enable the comparison of results with reality. Additionally, it is important to calculate the light distribution in three dimensions, to simulate the influence of smoke to spatial light distribution. The open source software PBRT (www.pbrt.org) was selected as basis of this work, because it delivers an adequate infrastructure for the physically correct simulation of the light distribution. In this work package, the PBRT software is extended by a smoke model.

The smoke model contains a probabilistic approach, which expresses the probability of light-ray interaction with smoke-particles. Additionally the smoke-particle size distribution is considered, to include the type of particles in the smoke. The information about smoke particle distribution can be derived from the experiments performed by the CORIA institute. This information is combined with a model for the physical light scattering and light absorption effects that considers the different particle sizes.

The smoke density distribution is derived from the SMARTFIRE CFD fire simulation conducted by the University of Greenwich-FSEG. Therefore, the CFD Fire Model can be utilized as geometrical input. The results from the CFD fire simulation contain also a finite-volume mesh which includes the information about the smoke density distribution. This mesh is utilized to transfer the information about the smoke density to the light simulation, too.

At the end it is possible to simulate the lighting in a room under smoke conditions.

As a result of the simulation, an image was rendered. These images represent the view from an observer and contain the numerical information about brightness and color for each pixel.

Secondly, the numerical information from the rendered images is assessed regarding visibility. This is enabled by the prediction of human perception, which is based on the Weber–Fechner law. For the assessment of the results, the image was separated into different parts. These parts are derived from detectable image objects. Finally detailed contrast analyses of the image parts are performed, to express the visibility level and the perceivable brightness levels.

3.6. Synthesis of the results

Airbus SAS

In the past 20 years, the fire threat in aeronautics has been drastically reduced. However, there is a need to go beyond the minimum level of safety ensured by certification of new generation aircraft with increased use of composites instead of metallic structural elements, is not an option.

AircraftFire project has investigated how this innovation may influence the understanding of fire risk and can therefore influence the fire safety approach for passenger and crew safety and survivability during fire incidents or accidents.

The project enabled an evaluation of the impact of fire on aeronautical composites used in aircraft design and its impact on the associated aviation regulations by bringing external scientific points of view and knowledge to the aeronautic industry, including Airbus.

The project focused on the main physical phenomena involved in aeronautical fires to derive experimental and numerical methodologies developed by AircraftFire comparing them, where possible, with the current standards used for aircraft certification.

A key aim of AircraftFire was the determination of the flammability and burning properties of aeronautical composite materials (used in fuselage, wings, structures, fuel tank walls, cabin materials) and their influences on the mechanical behaviour.

The project further investigated relevant fire scenarios by considering the effects of the materials' fire behaviour on the fire growth in the cabin, as well as procedures for increasing the survivability of aircraft occupants during in-flight and post-crash fire.

Many findings/recommendations of the project are of significant interest for direct or future implementation, among them but not only:

- the study of mechanical approach of composite under flame
- the study of thermal diffusivity in damaged samples (burnt ones for examples)
- the conclusions on cabin material flammability
- the approach of coupling fire growth and evacuation principle

These areas of improved knowledge, methodology demonstration and modelling are enablers to optimize design keeping same safety objectives and for discussions of their implication with airworthiness authorities (passengers evacuation, composites performances under fire and load,..) for safety improvement.

The extrapolation of the new knowledge to industrial applications, the potential evolution of standard tests and the needs for training on fire safety in aviation has also been described through the deliverables of the project.

Finally the strengths and weaknesses of the project have been underlined, as well as perspectives on future fire safety research activities in aeronautics

3.7. Conclusion

AircraftFire is an ambitious project covering such key topics for fire safety in aircraft. The scientific theme is wide; it requires the contribution of multidisciplinary experts from chemistry, combustion, heat transfer, physics, mechanisms, and modellers. A strong collaborative research on tasks was required between the 13 partners in order to reach the objectives of the project by exchanging their skills, their needs, by sharing data to improve their advices on fire safety in aeronautics.

This project allows for developing, from more than one thousand reports mostly from pilots, cabin crew, firemen, technicians and other aeronautical experts, an original statistic study on the main causes, types, frequency and consequences of incidents and accidents[7]. The automatically extraction tools of safety information out of the reports established in AircraftFire proved to be comparable to the manual analysis for many purposes. Furthermore data-mining tools showed to have a certain potential for further analysis[8]. Thus, the frame of fire scenarios in aeronautics relevant for the AircraftFire project was verified[9,10].

The experimental and numerical methodologies used, were based on experimental characterisations of the flammability, burning, thermo-physics properties and of the pyrolysis law of composites and cabin materials[11,12,13,14,15]. This approach is an already proven technique in the area of prevention building of fires. It allows adding a complementary scientific aspect to results of standard passed/failed certification tests required by FAA and EASA.

Using these material fire properties, the study of the scenarios was essential to determine a global fire threat and its consequences on the survivability of aircraft occupants during in-flight or post-crash fires. The characterisation of the material behaviour in under-ventilated hidden fire condition[16] provided a complementary approach for the fire prevention in the cabin coupled with the criteria for an adapted fire detection and suppression[17]. The post-crash scenario is the one where it is most likely to save passengers and crew. The aircraft structural

[7] CAA
[8] Fraunhofer
[9] Airbus Innovative Group
[10] Airbus SAS
[11] University of Ulster, FireSERT
[12] University of Patras
[13] INSA-CORIA
[14] Pprime
[15] University of Iceland
[16] I2M, TREFLE
[17] University of Edinburgh

analysis of the crash impact[18] notes a great sensitivity of the fuselage composite to strain energy and Hashin, a less plasticity of the material and greater rupture chance. The modelling of a large-scale kerosene pool fire[19] provides the characterisation of the heat fluxes and chemical species along the aircraft fuselage. An experimental study is highlighting the fire resistance of composites under representative post-crash and engine fire conditions[20]. From the observations, it notes the substantial fire resistance of the fuselage to flame penetration in the cabin from a fire zone (APU) or outside kerosene pool-fire. This fire performance of composites is attributed to the pyrolysis of the resin and to the re-radiation effects of the high temperature fibre network naked after the resin degradation. The heat transfer to the cabin is reduced and the fire propagation through the fuselage seems less likely. This optimistic conclusion on the survivability must be moderated by, on the one hand, the off-gassing of toxic, highly irritant and flammable degradation products in the cabin from the composites rear side, and, on the other hand, by the potential rupture or the formation of cracks in the fuselage skin allowing the flame penetrating the cabin and propagating the fire inside[21, 22].

The experimental data and the global post-crash fire simulation generated using the SMARTFIRE[23] CFD fire model and evacuation simulation generated using the airEXODUS[24] evacuation model including the external pool fire source, flame and heat penetration in the cabin, fire growth, visibility[25] and occupant evacuation procedure provides a synthesis of the progress of AircraftFire on fire safety. Key findings of this work include:

- Without a post-crash fuselage rupture, the composite fuselage results in a much better fire protection and evacuation environment than the conventional aluminium fuselage resulting in improved passenger survivability;
- Experimental results suggest that composite materials are degraded on the rear side of the composite, with the emission of toxic, highly irritant and flammable compounds in the cabin;
- Original experimental results on the composite behaviour under high flux flame and mechanical stress show a short failure time of the material, as soon as the first layer or fibre layers degraded;
- Post-crash fuselage ruptures during the impact may result in the occurrence of flashover within the cabin severely reducing survivability, especially if the rupture occurs in the vicinity of monuments. This suggests that the fuselage should be strengthened or protected to decrease the likelihood of rupture especially in areas near interior monuments.
- It is suggested that the aviation industry considers using a more challenging and representative exit combination for evacuation certification than the current approach;
- When assessing the impact of fire on passenger survivability, it is essential to perform coupled fire and evacuation analysis rather than an analysis of only the fire or only the evacuation, or separately consider the fire and evacuation. It is only when a coupled fire/evacuation analysis is undertaken that a realistic assessment of the impact of fire on passenger survivability can be achieved.

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18 TUDelft
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22 University of Greenwich-FSEG
23 University of Greenwich-FSEG
24 University of Greenwich-FSEG
25 Airbus Innovative Group

4. Potential Impact and the main dissemination activities and exploitation of results

4.1. Introduction

The project AircraftFire was an ambitious collaborative project co-funded by the EU-FP7. AircraftFire aimed at increasing passenger survivability in the case of fire aboard aircraft, focused on the next generation of aircraft and had the objective to make an important and significant contribution to the evaluation of fire risk for aircraft of the new generation such as the A350 or B787 families. In both types of aircraft as well as in other new generation aircraft composite materials are used significantly for structural parts allowing for reduction of weight and of fuel consumption. The increasing use of composite materials and other combustible materials in order to reduce the weight of the aircraft or to increase passenger comfort raise the fire load significantly. By addressing these safety topics related to persons and assets, AircraftFire was active in an extremely practical yet commercially sensitive domain regarding the aeronautics sector, which is one of the most significant of the European industry creating value, employment and growth.

This type of new generation aircraft has been certified now by the regulation authorities, consequently, it is recognised that its level of safety is demonstrated to be, as far as is practicable, at least equivalent to that of conventional aircraft having elements of structure from aluminium. Although these composite materials have passed the certification tests, it is a newly-emerging area of technology with potentially substantial benefits in studying and assessing fire risks for relevant areas, specific zones of the aircraft and the entire aircraft. The impact of the project is to understand why their level of resistance to the fire is already at the high level of that of conventional aircraft and if it is still possible to augment it.

Existing and validated simulation tools have been further developed and adapted in the project. AircraftFire has increased the knowledge of fire propagation and evacuation simulation in aeronautics through material property studies and fire behaviour data. The relevant data necessary for the advanced simulations have been gained by experiments. Beside the provision of physical and chemical data a sound analysis of existing data bases maintained by aviation authorities and aircraft manufacturers in order to identify and classify the relevant fire related scenarios for in-flight and post-crash fires provided the additional basis for the improved simulation. The project investigated the necessary sensing capacities and deployment of the relevant sensors aboard aircraft. This, together with the results of the simulation of fire propagation and of advanced evacuation allow recommending improvements for the aircraft operation and mitigation activities in case of fire related incidents. The consortium composed of aircraft manufacturer, aviation authority, research establishments and universities undertook the necessary efforts to make the knowledge gained available to all relevant parties to promote the results and achieve the objectives of the project.

AircraftFire covers a broad spectrum of complementary disciplines such as physics, heat and mass transfer combustion, mechanics of fluids and of solids. This required a close collaboration between the different partners. The first purpose was the improvement of knowledge on the behaviour of the structure in conditions of extreme heat flux during a fire and consequently, to be able to improve further the limits of safety of the composite elements by a better resistance to fire.

AircraftFire was a project with predominantly academic character where the co-ordinator and most partners (9/13) belonged to the university domain. Consequently the impact of project was first and foremost the publication of the results of research through high ranking scientific international journals or symposia. Nevertheless AircraftFire results and findings can influence the design of the next generation of aircraft with respect to fire prevention, protection and fire management.

The organisation and the development of research, especially thanks to industry (Airbus) and regulator (CAA) presence in the consortium, allowed the work to remain focused on the practical development of methodologies for the approach to the fire phenomenon in aeronautics. Many meetings allowed to tie and to maintain uninterrupted relations between the partners, the members of the External Advisory Board (EAB) of the project, industry networks and scientific societies to disseminate knowledge and results generated through the work performed by the consortium.

4.2. Improvement of fundamental knowledge

4.2.1. Composites: heterogeneous and not well known materials

Thanks to its small weight and its rigidity to stress and load, the main interest to use a composite material is to improve the material quality for the specific purpose. The properties of the composite explain the increasing use in different industrial sectors. Composites can be used in an environment of high temperature and they have found applications in areas of very high technical nature, as air transport (civil and military), maritime, road, railway, aerospace, building, chemistry (high pressure gas tanks), nuclear technology (containers), ammunition, etc. as well as sports and leisure, notably thanks to their good mechanical behaviour, comparable to homogeneous materials as steel, and to their low density. Nevertheless, their detailed and in depth description remains complex with regard to mechanical, thermal, chemical and physical properties because of the non-homogeneity of these materials.

The impact of the work performed in the AircraftFire project is of relevance for a wide spectrum of industries.

The project AircraftFire was mainly centred on evaluation and identification of physical-thermochemical phenomena initiated during the attack of a composite material by a strong flux of heat representative of those to be encountered during a fire. Up to now, the composite materials used despite their very high economic costs must have better physical properties than conventional materials in term of use, fatigue, safety and reduced weight that is generally linked to a reduction of energy consumption. In the field of fire safety, which concerns the majority of the industrial sectors, **AircraftFire developed a new and original methodology based on the experimental characterisation of the properties of flammability, of combustion and physical-thermal behaviour of such composite materials likely to be used in aircraft**. This approach allows increased understanding of why their fire resistance is very good and to quantify their shielding effect to fire spread and the expectations in terms of mechanical stability.

In a fire, generally only a small fraction of the casualties are related to burns, mostly **smoke and gases are responsible for fatalities** as result of **their toxicity** causing loss of consciousness and/or reduced human functionality and their capacity of **causing hindrance for escape** (e.g., low visibility). **In this domain AircraftFire gave essential information for the selection of materials, for the conception of locations and about heat transfer in confined or semi-confined areas.**

Impact of AircraftFire:

- Provision of a database of the properties of certain composite materials;
- Classification of materials in relation to fire behaviour, smoke emission and toxicity of emitted gases;
- Evaluation of the fire risk and its consequences for the protection of persons and assets;

for industry and regulators.

4.2.2. Development of diagnostic tools

4.2.2.1. *Characterisation of composite properties*

The methodology deployed to qualify materials used in the building industry was adapted to composite materials used for aircraft structure. Results showed the interest of this academic approach to provide essential information on fire behaviour of polymeric materials and of their capability to contain a fire.

The composite producers currently tend not to characterise their products much beyond commercial imperatives, which tend to relate to mandatory performance aspects. Regulation generally requires the successful presentation of materials to so called "passed/failed" standard tests and there is rarely more consideration of holistic, more performance based tests in a more system-based philosophy. Sometimes reproducibility of test results is low and there is a strong inherent potential to give less consideration to certain phenomena (ageing, etc.).

The impact of AircraftFire is to deepen the reflections about the criteria of certification at the regulatory level.

4.2.2.2. *Proposal of tests for the characterisation of the composite materials in representative fire conditions*

To be approved, the fuselage must show resistance to the fire penetration into the cabin from an external pool fire during the evacuation of the aircraft. The criterion of the test is the surpassing of a timely threshold of intrusion:

burnthrough time > 4 minutes, which is superior to the certification test time limit of evacuation, which is 90 seconds to evacuate all crew and passengers.

AircraftFire developed diagnostics allowing not only for identifying the burnthrough time of composites, but also the characterisation of the main properties of flammability and of combustion of composites (resin burning rate evolution, burning time, off gassing time and flow rate, etc.) in conditions representative of standard tests or of large scale fires.

This test concept for the composites is now seen as interesting by research centres (ONERA), manufacturers (SAFRAN, ZODIAC, IRSN, CEA) and test centres like DGA AS, Toulouse. This test concept will be in the centre of a short term research project initiated by CORAC[26].

This concept of test bench is a tool of diagnostics, probably essential to determine the fire resistance of a composite. It will have to be improved for becoming an approved device accompanied by the definition of appropriate thresholds.

[26] Council for Civil Aeronautics Research (COnseil pour la Recherche Aéronautique Civile)

4.2.2.3. *Thermo-mechanical test bench*

A new tool of characterisation of the mechanical load capacity of a composite was presented. It allows determining mechanical properties of a composite under load and thermal stress. The thresholds for breaks are determined in function of thermal and mechanical stress.

The impact of the preliminary results is important. It is of interest for academia as well as for industries in all the fields of application identified before.

4.2.2.4. *Test bench for hidden fires*

A specific experimental tool was developed to characterise the development of a composite fire in an inaccessible area of the cabin (hidden zone). This test bench, in our knowledge unique, reproduces a scenario and conditions representative of standard tests and of real fires, but with powerful and adjustable means of diagnostics. It allows understanding phenomena coming into effect during fire growth in a confined area by not reducing itself to the determination of exceeding a threshold of a "passed/failed" test.

Impact: The concepts related to the presented experimental methodology are at the disposal of the academic community for the study of behaviour of composite subjected to strong thermal fluxes, of the industry wanting to improve their product quality and of authorities to help evolving regulation in the domain of fire prevention and protection.

4.2.3. Development of numerical tools

4.2.3.1. *Text and data mining tool*

The aim of the database analysis was to develop a methodology for automatically extracting important information out of aircraft incident reports and turning this information into new knowledge. The sources of the information were different databases of incident reports, like CAA's MOR (Mandatory Occurrence Report) database. A large number of available databases was examined and a set of common attributes was defined. The type of incident (fire/smoke/fume), its location within the aircraft as well as a causal factor for the incident can be found in free text reporting. From the feature extracted as described above statistical interrelations could be found. The results of the data mining were carefully examined by aviation experts showing a high level of validity.

Impact: The experience and the knowledge gained in AircraftFire by the successfully undertaken development of a methodology for automatically extracting important information out of aircraft fire incident reports and turning this information into new knowledge can be used in other domains than fire safety and other areas as aeronautics in order to provide valuable support in an automatic way to human analysts investigating incident reports.

4.2.3.2. *Simulation of a large scale pool fire*

Fires include an infinite range of scenarios (geometric configuration, influence of aero thermal parameters - forced convection (intensity and wind direction), weather conditions, and location of the target relative to the fire). Numerical simulation of a large kerosene pool fire subsequent to a post-crash could inform fire fighters about the fire behaviour and fire growth depending on weather conditions and about consequences induced on the aircraft to refine the specific choice of the firefighting procedure. Unfortunately, the detailed simulation is currently incompatible (difficulty of use, prohibitive calculating time) for real-time use or vocational training, but it may have already now **impact for technical or legal expertise to determine the causes of fire**.

4.2.3.3. *Coupled fire-evacuation simulation*

A coupled simulation of fire / heat transfer behind a heat shield / fire development and growth in a confined space / evacuation of people was conducted which is an important capability in the evaluation of aircraft evacuation procedures in the event of post-crash fire. This work has demonstrated that simply considering fire and evacuation performance separately may lead to inappropriate conclusions concerning the level of safety achieved in a particular scenario. The simulation approach and modelling tools demonstrated in AircraftFire should be recognized by the regulatory authorities as a pre-certification and recommendation tool for crew training. **It could be used in some cases for the qualification of equipment following a minor modification of the aircraft which would avoid costly and difficult to implement tests.**

4.3. Contributions to changes in the regulation of aviation safety

Without acting directly on the Description of Work of the project, EASA and AircraftFire consortium shared their expectations in terms of regulation and responses that can be given. The principal orientations and issues are in common and overlapping and thus AircraftFire can provide some of the answers to the regulators, but some important differences could be noted. Hereafter some examples of topics related to the issues of EASA follow, where AircraftFire may help to support EASA rulemaking by an appropriate response:

- Resistance to flame propagation and resistance to flame penetration through the material ;
- Enhancement of type III exits evacuation capability ;
- Composite structure designs should not decrease the safety level relative to metallic designs ;
- In flight fire and external fire should be assessed related to metallic A/C including toxicity ;
- EASA.2008.C19 : Burnthrough resistance of fuselage ;
- Research on the identification of potential evacuation issues on airplanes with multiple stairways between decks ;
- Research on the technologies for locating available exits in low visibility conditions (post-crash fire smoke) ;
- Bleed contamination from Engine/APU fire : Fumes/Smoke migration into the cabin/cockpit generates risk of toxicity/reduced visibility ;
- Composite fuel tank explosion risk.

EASA was interested in learning more about the flammability and burning properties of composite materials used for aircraft manufacturing, as there is an increasing trend in the use of these materials for new products applying for an EASA certification.

EASA estimated that improving the knowledge in this domain is important in order to better assess the protection of occupants that can be expected and demonstrated when certifying a composite aircraft. Mechanical behaviour and flammability of composites in presence of fire is crucial, but also the toxic emissions associated to burning materials, are domains on which we are particularly interested to learn from this project.

EASA also appreciated the effort of the project in modelling emergency cabin evacuations.

EASA noted that AircraftFire conducted a review of available modern smoke and fire detection means, including potential solution for early detection before fire spreading.

In its conclusion, EASA estimated that AircraftFire has potentially useful tools to bring adequate knowledge and recommendations permitting improved engineering practices with regard to protection of occupants in composite aircraft.

EASA would also welcome suggestions with regard to existing certification standards which would aim at mitigating any identified concern specific to the use of composite structures, or to further upgrade the existing standards. When making such suggestions, it is expected that an impact assessment is performed to characterize the associated safety benefit against its cost.

A major part of the AircraftFire research addressed the regulatory concerns above but a continued effort must be developed to give accurate answers to the regulator problem areas to enhance the fire safety in aeronautics. Thus AircraftFire has allowed a comprehensive understanding of many potential regulatory concerns but the subject is far from completely covered, the work has certainly identified new areas of potential research.

The need for basic research results developed by AircraftFire was strongly confirmed by the European officer of the EC in charge of the project and is perfectly in line with the expectations of industry and national and European policies. At the end of AircraftFire project, an additional effort was required for researchers to participate in thematic and technical meetings between EASA and the consortium to find the resources to transform new knowledge and to meet the technological and normative expectations of the regulator. A further objective will be to adapt and to determine safety levels for composite fire during standard testing.

The potential impact of AircraftFire for EASA is significant for changes in regulations which currently focus on a simple adaptation of existing certification tests of conventional aircraft to the new generation of aircraft with composite materials in use.

4.4. Means of dissemination

4.4.1. Academic Impact: Publication in international journals and symposia or conferences

The first impact carrier of results of academic research is the **publication of results and interpretations in magazines, journals, papers or presentations at conferences and meetings**. Laboratories are currently in the drafting stage of publications for dissemination of results in the area of fire as well as in the fields of mechanics and of aviation.

4.4.2. Impact in the consortium: CAA, Airbus and Airbus Group

The second natural way for dissemination of knowledge and new technologies is within the consortium and their individual business activities. Airbus has recognized the value of inputs the project has given and disseminated the results widely within its group.

The direct impact on partner institutions is achieved within each of the groups and departments. It was noted the strong participation of engineers of Airbus group, even off-site at the AircraftFire conference and final workshop.

4.4.3. Impact on student training and advanced training of engineers

Direct impact on the training is given for students, interns, PhD and Post PhD students.

4.4.3.1. *The AircraftFire School « Fundamentals and state of the art in fire safety in aeronautics »*

A series of courses on the **"Fundamentals and state of the art in fire safety in aeronautics"** presented general principles for understanding fire safety; it was provided during the first day of AircraftFire Colloquium in July 2014 in Brussels. It was followed by some PhD students, but especially by manufacturers (Airbus group, Airbus, IRSN-CEA, LNE, SAFRAN, ONERA, CLARIAN, SOGERMA, DGA SA, Paris Airport, Lyon Airport, Fraport, CTAERO, etc.) who were informed about the complex of problems and on the methodology developed in holistic approach system.

4.4.3.2. *The consortium and engineer schools*

Another impact is initiated to prospect new contributions to the training of **aeronautical engineers**, to be built from the works and results of AircraftFire. These engineers receive a classical education in particular in fluid mechanics and aerodynamics, combustion, heat transfer, solid mechanics, material sciences..., and master thus the prerequisites adapted to the scientific basis of AircraftFire research. Internal discussions involving engineering schools showed that the problem of fire safety aboard aircraft or during a crash becomes more critical with the development of new generation aircraft involving more and more composite materials.

A possible program based on the main lines of AircraftFire: accidents typology, scenarios, combustion science, material properties, fire growth, evacuation procedures…, with classical (in the field of mechanical engineering) prerequisites like mechanics (solid / fluid), combustion, heat transfer, material science, might be an example of basis to start with.

In terms of education, the knowledge brought by AircraftFire might also be very useful to help to inform the **passengers** but also all the citizen about the real level of risk, to avoid misunderstandings about new generation of aircraft.

A last suggestion might also consist in providing to **insurance companies** objective basis concerning these new aspects of fire safety problems for which they lack reference data.

The impact to engineering education is being developed. The concept of a thematic school is supported by the majority of the partners, but the integration of a new school in an existing student curriculum is long and requires a local objectives assessment.

4.4.4. The AircraftFire Workshops

Two workshops for the dissemination of research results obtained by AircraftFire were held in July and September 2014 in Brussels and Toulouse (Airbus). The first was mainly focused on the identification of the principal "New issues for fire safety in aeronautics". It attracted fifty engineers from industry, research centre and university. Experts from the AircraftFire project presented the main physical phenomena involved in aeronautical fires as well as the experimental and numerical methodologies developed by AircraftFire.

The second workshop was used to present a synthesis and long-term vision of topics to be continued in a future project: “AircraftFire and beyond: Discussion panel on follow-up activities for fire safety in aviation”. Areas such as the fire retardants, the mechanical strength of burning composites and ignition by equipment devices are not in the focus of the AircraftFire project. External experts have shared their experience to identify the remaining lack of knowledge and understanding in these domains. An open panel discussions has addressed topics of aeronautics fire safety related to batteries, seat foam, thermo-acoustic blankets, engine fires, avionics equipment, fuel tank inerting, oxygen threat (masks and fuel cell), firefighting. Presentations outlining the current regulations and the physical aspects of certification tests for the materials completed the holistic approach of this event. This approach has taken researchers to share their knowledge with industrial, political and regulatory actors and vice versa in order to identify the new challenges on materials and modelling to improve further the fire safety in aeronautics.

Increasing the knowledge on the interdependencies and mechanisms related to the fire threat in new generation aircraft helps to express more easily the medium and long term needs for research and innovation and to identify break-through technologies to reach the "Holy Grail" of fire safety.

The impact of these two workshops as means for dissemination of knowledge and deployed methodology was extremely effective. Unanimously, the participants appreciated the quality of interventions and the contribution of the presentations focused on topics of future.

4.4.5. The External Advisory Board (EAB)

In the Description of Work of the project, it was proposed the creation of an external advisory board with following objectives:

- To express opinion and eventually deliver advices on technical subject related to the fire safety in aeronautics;
- To help, through exchanges, to transform AircraftFire academic results into innovations and then towards their respective organisms, institutes or companies;
- To contribute to strengthen the AircraftFire consortium, in order to consider it as an expert group on aircraft fire safety and promote a new fire safety strategy and highest common standards of safety for new aircrafts.

The EAB typology covers members from end-users and regulation (aircraft manufacturers, OEM (*Original Equipment Manufacturer)*, technical and test centres (FAA, DGA AS), regulation (EASA)), research (AircraftFire Governing Board) and education (Universities and Schools) to evaluate the research progress during the project.

The impact of EAB was significant for the definition of research orientations. This resulted from feedback based on industrials' and firefighters' experience on the still poorly understood complex issues. In return, members of the EAB are important dissemination carriers within their establishment. In this group, the information from airport firefighters was strongly appreciated.

4.4.6. Impact on the French research group on Aeronautics with an European vocation

CORAC (http://www.aerorecherchecorac.com/) is the Council for Civil Aeronautics Research (COnseil pour la Recherche Aéronautique Civile), a French initiative of the aeronautical manufactures (aircrafts and equipments). It was created in July 2008 following commitments made in late 2007 during the Grenelle Environment Forum. Established according to the ACARE(*) model, it brings together, under the impetus of DGAC and GIFAS, all of the French players in the air transport sector, meaning the aviation industry, airlines, airports, ONERA, and relevant institutions and ministries. The implementation of CORAC represents a desire to ensure the consistency of research and innovation efforts in the aviation sector, especially in terms of preservation of the environment and sustainable development. Among its first achievements, it created the technological road map for aeronautics research, serving as the foundation for the implementation of an ambitious and coordinated research strategy focusing on objectives for management of the environmental footprint of air transport by 2020. AircraftFire contributed to the CORAC fire roadmap.

The methodology and results developed by AircraftFire have been used to elaborate a research program in the field of aeronautic fire. French partners of AircraftFire have taken an important role in the definition of the first program and will be involved in upcoming activities. The project starts in the first months of 2015 with an ambition to be widening towards a European project.

The impact of AircraftFire to all manufacturers in the aerospace sector is undeniable, strengthened by their strong participation in the workshops of Brussels and Toulouse.

4.5. Socio-economic impact

AircraftFire structured a scientific and industrial community bringing together researchers and engineers with different expertise in the fields of aeronautics, mechanics of solids and fluids, combustion, thermal and evacuation. They were able to communicate and complement the complex topic of fire safety. The discussions helped to understand the issues and to identify the interactions between the experimental tasks and the numerical modelling with its important need for physical data not accessible by the results of standard tests. AircraftFire, through the participation of its members in meetings with FAA and EASA on cabin safety and through the knowledge of academic and industrial actors working in the fields of fire and aeronautics, was able to identify and engage the R & I (Research and Innovation) forces possessing the skills and competences to meet the European challenges in the field of fire safety in aviation.

4.6. Social Impact

The AircraftFire social impact in terms of created jobs was also notable. PhD students and post-doctoral students participated in AircraftFire research. Some have joined the professional world, others have had their contracts renewed or have been recruited by another consortium member giving them a good chance of sustaining employment as researchers.

4.7. Conclusion

The AircraftFire project has developed fundamental research in the field of fire behaviour and resistance of aeronautical composites and the consequences on the survival of the passengers and crew members during in-flight or post-crash fires. The process of dissemination of methodology and results was early started during the project and is ongoing with a strong impact on proposals for future research programs. CORAC will be the first initiative that will fund French researchers in that context. It should also contribute to the inclusion of the fire safety topic in the next European work programmes. The coordinator of AircraftFire will exert influence that the consortium will be fully involved in project submissions to the EC.

For this AircraftFire **has demonstrated a significant increase of knowledge as a result of the work and associated safety benefits**:

• a mastered and proven methodology, powerful diagnostic tools, digital simulation codes reliably validated with experimental data,

• a network of competent partners willing to continue collaborative work, a broad vision of complex of issues, an ability to innovate, trusted contacts with manufacturers of aircraft and aircraft equipment, recognition by test and research centres.

To conclude, the **best AircraftFire assets** are the synergy that has developed during the project in the consortium, the excellence in interdisciplinary research conducted, the ability to combine experimentation and simulation, and the ability to communicate within the group.

For all these reasons, the **main attraction of the AircraftFire consortium** is its dynamism to prepare, submit and continue research in a new collaborative project on aeronautical safety in cooperation with manufacturers and aircraft manufacturers, developers and producers and composites testing centres. Such project will have to convince the European Community taking into account the safety interests in transport being developed in close relationship with the regulator, considering the industrial and commercial objectives, and finally being focused towards acquisition and transfer of knowledge to industry, research and education to increase its full impact on the European economy through the creation of wealth, business and jobs.

5. Address of the project public website

Address Web site of the Project: www.aircraftfire.eu

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