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ANALYSIS OF FIRE-PROTECTED LOAD-CARRYING AIRCRAFT STRUCTURES FOR ELECTRIC POWERTRAINS

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Abstract

Fire in aviation is a significant safety hazard to aircraft and their occupants. New electric powerplant technologies and the increased use of flammable fibre composite materials in aircraft structures have directed more attention to fire protection. Great effort was made in developing materials for improving the fire resistance of fibre composites.

This paper concentrates on potential fire sources in aircraft and characteristics of different fire protection materials for fibre composites and their lightweight potential. Therefore, various lightweight fire protection designs for engine compartments were analyzed. To evaluate these designs, fire tests on unprotected and protected fibre composite structures under load were conducted. Therefore, this paper presents the test device and the experimental results. Furthermore, recommendations on designing fireproofed lightweight structures under EASA certification requirements for engine compartments are given.

Keywords

electric flight; fire protection; fire tests; lightweight design; fibre composites

1. INTRODUCTION

Electric propulsion systems in general aviation offer great potential for reducing emissions and improving the overall efficiency of aircraft. The main goal of the project EDARIT (Electrical Drive And Recuperation In-Flight Test) is to design and test an electric power train for General Aviation aircraft with the ability to produce thrust and efficiently regenerate energy during descend flight phases. For this purpose, the electric power train will be integrated into a wing pod underneath an aircraft's wings to conduct flight tests.

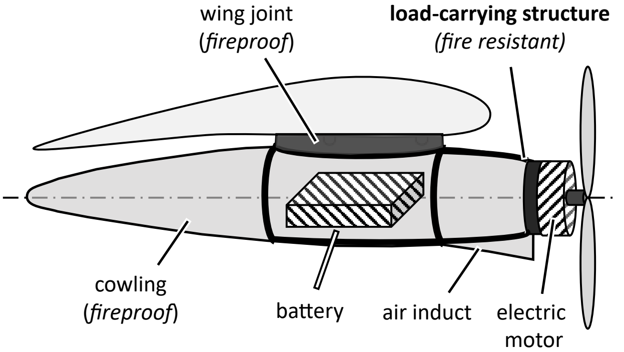

FIG 1. Electric power train and it's load-carrying structure in the wingpod

For this application, the load-carrying structure needs to be designed lightweight and safe. To meet the certification requirements of the CS-23, the structure must carry all loads safely and protect the wing from heat fluxes and potential fire outbreaks induced by electric components [1] [2]. These various requirements lead to a conflict of interest between weight and safety issues. Therefore, research on fire behavior of load-carrying structures needs to be done, to develop a method for designing fire-protected lightweight structures.

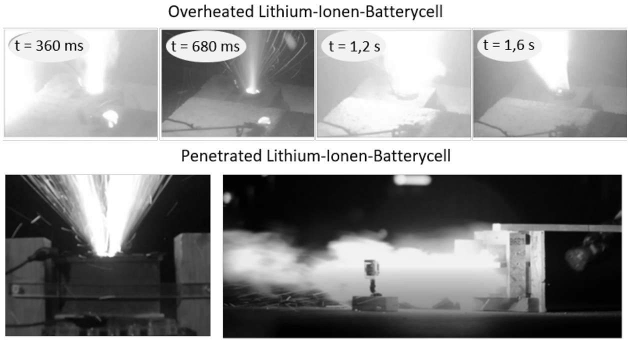

FIG 2. Exploding Lithium-Ion-Battery cells [2] [3]

Aircraft need to be protected from various fire hazards; Current propulsion systems, which use fuel and oil, are highly ignitable whereas electric systems like cables, engines and batteries might overheat or cause a short-circuit. The cause of fire might occur due to a technical failure (in-flight fire) or due to an external force (post-crash fire). Statistic of aviation accidents during 1992 and 2001 show a death toll of 4.9 % due to in-flight fire. Between 20 - 40 % of

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fatalities in impact-survivable aircraft crashes are due to post-crash fire [4].
The danger of overheating and exploding of Lithium-Ion-Batteries is today's threat in electrifying aviation. Figure 2 shows an exploding battery cell due to external penetration by force as well as by thermal overheating. The rapidly appearing flames can reach temperatures of up to 700 - 800 °C [2] [5].

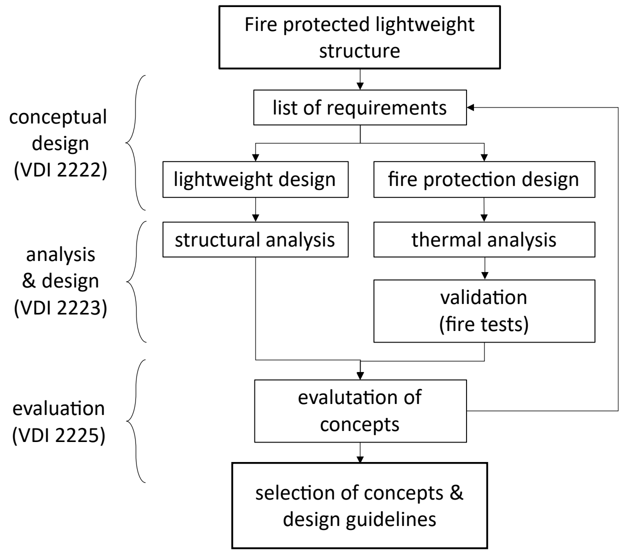

FIG 3. Flow diagram of the approached design process based on the guideline VDI 2221

In order to find an optimal fire-protected structural design for the engine compartment, different load-carrying structure and fire protection designs were investigated (see Figure 3). Theoretical analysis of various architectures, lightweight materials and fire protection materials was performed and validated by experiments. To conduct these experiments, a test device was developed and fire tests on load-carrying fiber composites, covered by different fire protection materials, were performed. The design process was systematically accomplished by following the guideline VDI 2221 [6]. Finally, the different concepts are evaluated and design guidelines for fire-protected lightweight structures are given.

2. STATE OF THE ART

The EASA's certification specification CS-23 demands essential safety requirements concerning fire protection of small aircraft: A sealed fire wall must isolate the fire-zone in order to avoid a spread of flames and, thus, prevent hazards to the rest of the aircraft and its occupants. Critical components, like flight controls or load-carrying structures, located in designated fire-zones, must be capable of withstanding a fire for 15 minutes (fireproof) [7]. For non-critical components, located in fire-zones, it is sufficient to withstand a fire for 5 min (fire-resistant).
According to the certification specification CS-23, fireproof components have to withstand the application of heat by a flame for a time of 15 minutes. The material is then considered to be equally fireproof as steel or titan. The flame must have a temperature of 1100 °C and a heat flux density of 116 kW/m², which is equivalent to a fully grown hydrocarbon fire [8]. Fire safety requirements are defined as the following:

- fireproof: 1100 °C for 15 min
- fire-resistant: 1100 °C for 5 min

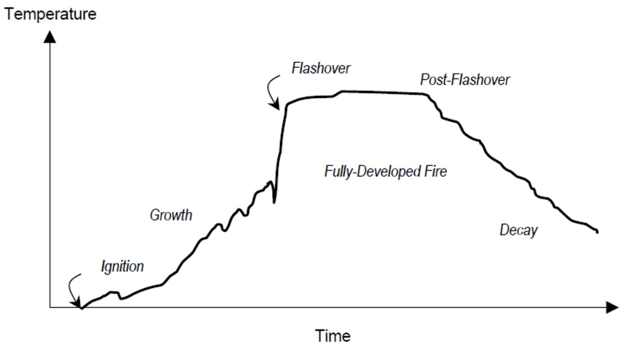

FIG 4. Growth stages of polymer materials in a compartment fire [4]

Epoxy resin is the most used matrix system in aircraft structures, thanks to its excellent mechanical properties. However, epoxy resin is highly flammable and has a low heat resistance, which leads to a rapid loss of strength when exposed to heat. While heating up, the resin releases combustion gases, which will feed and, thus, spread the fire in combination with atmospheric oxygen [4]. As seen in Figure 4, a compartment fire of unprotected fibre composites, made from Epoxy resin, is a self-sustaining process, where temperature and fire grow after ignition and decay after all combustible material is burned. Hereby, temperatures of up to 850 °C can occur [9]. Thus, to avoid a spread of flames and to maintain the mechanical integrity of load-carrying structures, it is necessary to prevent the resin from heating up and igniting.

3. CONCEPTUAL DESIGN

In the following section, the conceptual design process is described. A preselection of promising concepts is possible by separating the design process into a structural analysis and a simplified thermal analysis. First, each lightweight design and their specific structural mass is compared, followed by an explanation of various fire protection concepts. A thermo-mechanical analysis of different fire protection materials allows the identification of three promising isolation materials.
The projects and certifications main requirements for the engine compartment's design are the following:

- integration underneath the wing
- carry all flight, ground and propulsion loads
- fire protection of the wing
- structural mass limit: 35 kg
- room and openings for maintenance work

3.1. Lightweight design

Several structural design concepts promise good lightweight properties for the engine compartment. Figure 5 shows different, applicable lightweight designs (LD). The most common design for engine mounts in General Aviation is the truss design, made from steel tubes (LD 1), which is widely accepted by certifying agencies. All acting loads are carried by the truss structure, while the cowling is not carrying significant loads. Instead of steel, tubes made from pultruded carbon fiber can also be used, which have lower specific mass. Thus, a truss design made from composite materials (LD 2) promises more significant lightweight potential.

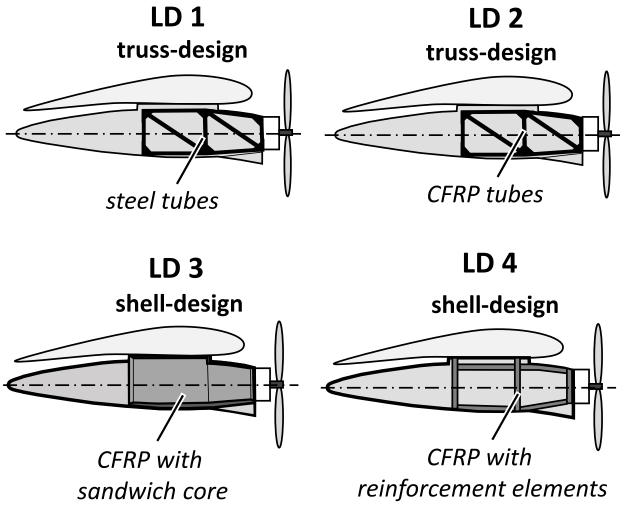

FIG 5. Lightweight design (LD) concepts for the load-carrying structure

As the cowling's only function in LD 1 and LD 2 protects the electrical components from environmental conditions, the skin structure of the shell design concepts (LD 3 & LD 4) carries all acting loads. By combining multiple functionalities, and using carbon fiber reinforced plastics (CFRP), the shell design promises great lightweight potential. However, due to the low wall thicknesses of these shell structures, stability issues, like buckling, can occur. Therefore, additional stiffening elements are required. As seen in Figure 4, either sandwich materials or local reinforcement elements, like stringers, can be used.

By keeping the wingpod's geometry (diameter and length), as well as acting loads constant, a mass specific comparison between each concept can be achieved. An analytical and numerical structural analysis of each load-carrying structure showed that low wall thicknesses of 1.0 - 1.5 mm are sufficient for carrying all flight-, ground- and propulsion-loads safely. The estimated safety factors of each design, concerning strength and stability failure, are sufficiently large and can be considered conservative. Table 1 sums up each component's specific wall thickness.

lighweight design	thickness	masses
LD 1		**6.2 - 6.6 kg**
cowling (CFRP)	1 mm	1.8 - 2.2 kg
tubes (steel)	12 mm	4.4 kg
LD 2		**3.6 - 4.4 kg**
cowling (CFRP)	1 mm	1.8 - 2.2 kg
tubes (CFRP)	12 mm	0.8 kg
nodes (thermoset)	25 - 28 mm	1.0 - 4.4 kg
LD 3		**3.0 - 3.6 kg**
shell skin (CFRP)	1.5 mm	2.7 - 3.3 kg
sandwich (foam)	5 mm	0.3 kg
LD 4		**3.0 - 3.7 kg**
shell skin (CFRP)	1.5 mm	2.7 - 3.3 kg
reinforcements (CFRP)	5 x 5 mm	0.3 - 0.4 kg

TAB 1. Wall thicknesses and structural mass of each lightweight design concept

Additional to the load-carrying structure's mass, cowling and connection nodes have to be taken into account. Therefore, Table 1 shows the determined mass of each design concept, including fluctuations due to uncertainties in the manufacturing process. Both shell designs show the lowest mass, whereas the steel made truss design shows the greatest. As can be concluded, innovative structural designs, like truss or shell structures made from CFRP, offer more significant lightweight potential in comparison to the commonly used steel truss design. To compare different fire-protected lightweight structures fairly, their specific isolation material's mass needs to be taken into account.

3.2. Fire protection

As mentioned above, flight essential components and occupants need to be protected from heat and fire. Thus a promising fire protection concept, applicable on each structural design, has to be found. Different approaches on how to protect an aircraft from fire are discussed, followed by a simplified thermal analysis of various fire protection materials. Their specific masses and required isolation thicknesses are compared based on a simplified thermal analysis.

3.2.1. Fire protection concepts

One way of ensuring fire protection in aircraft is to locally isolate each potential fire source by fireproof cowlings or boxes. In this case, the firewall needs to be non-flammable and have excellent thermal isolation properties, to protect the aircraft and its occupants from flames, smoke and heat.

Figure 6 shows the fire-zone of an unprotected aircraft wing as well as different fire protection design approaches. Fire protection concept 1 (FP 1) locally isolates the fire source by a fireproofed battery box, whereas FP 2 protects the aircraft wing by a fireproofed cowling that works as a firewall. In case of FP 2, all propulsion systems and structural components are located in the fire-zone. According to the certification specification CS-23, non-critical components need to have at least fire-resistant properties. Suppose flight-essential components are located in designated fire zones: In that case, an occurring fire needs to be either extinguished or each critical component needs to be fireproof and, thus, have to maintain its mechanical properties. Fire protection concept 3 (FP 3) not only isolates the fire-zone by a fireproof cowling, but also maintains their structural integrity during fire.

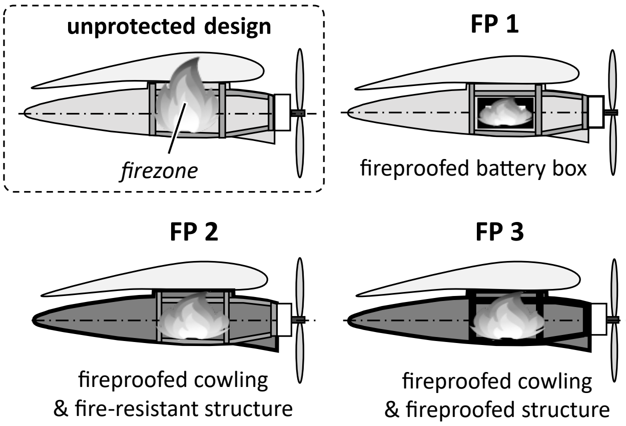

FIG 6. Different fire protection concepts for the engine compartment

Fire extinguisher systems stop fires by replacing oxygen rich air by oxygen-free gas. Due to weight limitations, only a limited amount of extinguisher gas can be carried in an aircraft. Besides the weight limitation, the extinguisher gas can be ineffective if an airstream is going through the fire-zone. In case of an oxygen-free battery fire, the extinguisher gas would not stop the fire. Due to these reasons, a fire extinguisher does not meet the requirements and is not considered further.

For making fiber composite structures flame retardant, you can either use a non-flammable matrix, like phenolic resin or a thermoset matrix, like Polyetherketoneketone. According to Mouritz et al. [4], adding flame retardant fillers (inert or thermally active) into the epoxy resin can also improve flammability behavior of CFRP. Unfortunately, both methods reduce the mechanical properties of the matrix material and, thus increases the aircraft's structural mass.

In order to improve the flammability behavior of load-carrying structures, made from epoxy resin, it is common practice to use surface protections. By applying a non-flammable insulation coating on the composite's surface, it is possible to maintain their excellent mechanical behavior [10]. There are four major classes of insulation coatings: flame retardant polymers, passive thermal barriers and thermally active coatings with ablative or intumescent behavior. Figure 7 shows post-fire properties of surface protected composites, from which the effectiveness of different surface protection materials can be concluded. According to Mouritz et al. [4], thermally active coatings and phenolic skin seem to be promising isolation materials. Fire retardants need to be an excellent thermal isolator and need to have a low density, to be as thin and lightweight as possible. In order to find a promising fire protection material with good lightweight properties, a simplified thermal analysis of various materials needs to be conducted.

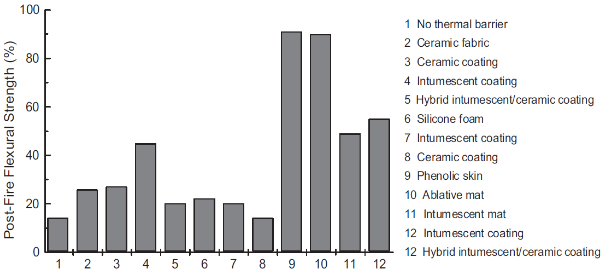

FIG 7. Post-fire strength of load-carrying composite materials protected by different fire retardants

3.2.2. Thermo-mechanical analysis

The goal is to find a combination of surface protection and structural design, which provides mechanical integrity during a fire, while being as lightweight as possible. Therefore, promising surface protection materials for the truss design (CFRP tubes) and the shell design (CFRP plates) need to be found.

In case of the firewall, CFRP plates are considered fireproof, if flames do not burn through the cowling and if the heat on the backside of the wall does not endanger following aircraft components. If cowling (shell structure) or tubes (truss structure) are also carrying critical loads, the mechanical integrity of the CFRP components must be maintained. Therefore, fire protection materials have to be excellent isolators, in order to keep the resin temperature below the critical glass transition temperature [11].

To describe the exact structural behavior of fiber composite structures during a fire, complex relations between thermochemistry, thermomechanic and airflow dynamics needs to be known. To compare of different fire protection materials, a simplified thermal analysis has to be used and assumptions have to be made. By investigating the component's temperature profile, each isolation thicknesses, required for keeping the resin's temperature low, can be determined. The resulting isolation's masses allow the evaluation of different fire protection materials and their lightweight potential.

It is assumed that the fire's heat is transferred into the structural components stationary by convective heat flow and in the out-of-plane direction. Thus, the advective heat flow $\dot{Q}_{adv,body}$ [W/m²] inside the solid body and the convective heat flow $\dot{Q}_{conv}$ [W/m²] between air and solid body, are in equilibrium (see equation (1)).

$$(1) \qquad \dot{Q}_{\mathrm{conv,in}} = \dot{Q}_{\mathrm{adv,body}} = \dot{Q}_{\mathrm{conv,out}} = \dot{Q}$$

Equation (2) describes the stationary, one-dimensional heat transfer of a flat solid body, consisting of different layers with its specific thickness δ_{i} [mm] and coefficient of thermal conductivity λ_{i} [W/mK]. The flat body approach represents a simplification of fire wall application and the shell structure. Heat flow $\dot{Q}$ [W/m²], and the component's temperature profile, can be determined by the flame's temperature T_{flame} [K], diameter d_{flame} [m] as well as the specific heat transfer coefficients α [W/m²K] of flame and air. Based on the coefficients of thermal conductivity, known from material data sheets, and the required temperature profile, resulting from T_{air} [K] and the critical glass transition temperature of the CFRP plate $T_{\mathrm{g,CFRP}}$ [K], the required isolation thickness $\delta_{\mathrm{iso,req}}$ [mm] can be determined by equation (2).

$$(2) \qquad \dot{Q} = \frac{0.25 \;\; \pi \;\; d_{\mathrm{fire}}^{2} (T_{\mathrm{fire}} - T_{\mathrm{air}})}{\frac{1}{\alpha_{\mathrm{fire}}} + \sum_{i=1}^{n} \frac{\delta_{\mathrm{i}}}{\lambda_{\mathrm{i}}} + \frac{1}{\alpha_{\mathrm{air}}}}$$

Unlike the carbon fiber plate's linear temperature profile, the tube's temperature gradient shows logarithmic behavior. Equation (3) describes the stationary heat transfer of a tube, which depends on the specific properties of fire, air and fire protection material as well as the structural material. The temperature changes logarithmic in radial direction r [mm] and is strongly dependent on the tube's and the isolation's thickness $\delta_{\mathrm{iso,req}} = r_{\mathrm{outside}} - r_{\mathrm{inside}} - \delta_{\mathrm{tube}}$ [mm] as well as its thermal isolation properties λ_{iso} [W/mK].

$$(3) \quad \dot{Q} = \frac{2 \;\; \pi \;\; d_{\mathrm{fire}} \;\; (T_{\mathrm{fire}} - T_{\mathrm{inside}})}{\alpha_{\mathrm{fire}} \;\; r_{\mathrm{outside}} + \frac{1}{\sum_{i=1}^{n} \frac{1}{\lambda_{\mathrm{i}}} \;\; ln \frac{r_{\mathrm{i+1}}}{r_{\mathrm{i}}}} + \alpha_{\mathrm{air}} \;\; r_{\mathrm{inside}}}$$

In addition to the simplifications mentioned above, further assumptions have to be made. It is assumed that the following parameters are constant for the environmental condition and present temperature range:

- coefficient of thermal conductivity: $\lambda_{\mathrm{isolation}}$ = const.
- heat transfer coefficient: $\alpha_{air} = \alpha_{flame}$ = 60 W/Km² = const.
- temperature conditions: T_{fire} = 1100 °C, T_{air} = 20 °C
- CFRP glass transition temperature: $T_{\mathrm{g,CFRP}}$ = 100 °C

Figure 8 shows the estimated layer thicknesses of different isolation materials and their specific surface weight, required to keep the CFRP plates temperature below its critical temperature. Various non flammable isolation materials, like thermal barriers (Stonewool, Aerogel, Aerogel fibermat, ceramic fibermat) as well as thermally active materials (intumescent paint, intumescent textile) were analyzed. As seen in Figure 8, the intumescents promise the lowest isolation thickness, while the aerogel materials and the intumesents show the lowest mass and, thus, promises the most significant lightweight potential. Since the Aerogel in its pure form is unsuitable for application to surfaces, it cannot be used for fire protection applications. As can be concluded, the following materials seem to be suitable for surface protection of plate-shaped components: Aerogel fiber mat, intumescent paint coatings and the intumescent textile.

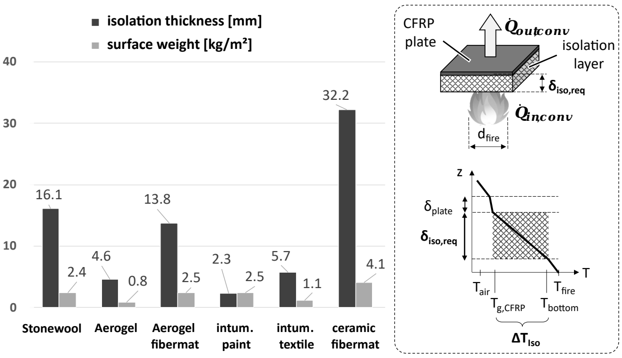

FIG 8. Estimated isolation thickness of different fire protection materials for plate-shaped components and their specific surface weight

Due to the simplified equations and assumptions, made in the thermal analysis, experiments on most promising fire protection materials must be conducted. By applying these materials on structural CFRP components, their specific thermal properties can be studied and the thermal analysis can be evaluated. Furthermore, ire tests can proof the demanding certification requirements.

4. FIRE TESTS

To evaluate the thermal analysis and to test the material's feasibility, three promising surface protection materials were selected and experiments were carried out on different structural components. In this section, the tested materials are characterized, followed by an overview of the most common fire test methods and a description of the developed test device. Finally, the main results of these fire tests are presented, discussed and conclusions on the fire protection design of lightweight structures are made.

4.1. Sample materials

In the conducted experiments, two different fire-protected structural components and the feasibility of the selected isolation material's were tested. For evaluation of the fire wall application and the shell design, fire tests on carbon fiber plates with and without surface protection were carried out. Furthermore, experiments on compression loaded carbon fiber tubes (truss structure) were conducted. Both, the carbon fiber plate and the carbon fiber tubes, are made of epoxy resin with a temperature resistance of $T_{g,\mathrm{CFRP}} = 120$ °C and a wall thickness of $t = 1$ mm [12]. As described in the truss design concept above, the tubes have a diameter of 12 mm [13].

Table 2 sums up the materials used in the fire tests. The most promising fire protection materials (Aerogel textile [14], intumescent paint [15], intumescent textile [16]) were applied on the CFRP surfaces and tested in the developed test device. The intumescent textile tested in its dry form as well as impregnated with resin that is more robust and has a smoother surface. Furthermore, a combination of Aerogel textile and paint coating was tested. In addition, Table 2 shows layer thicknesses as well as the surface weight of each fire protection material. In order to ensure statistic significance in the experiment's results, five samples of each material were tested.

CFRP plate	
Epoxy resin	$T_g = 120$ °C
dimensions	240 x 200 mm
thickness	t = 1 mm
CFRP tube	
Epoxy resin	$T_g = 120$ °C
length & diameter	l = 310 mm, d = 12 mm
thickness	t = 1 mm
compression strength	497 MPa
Aerogel textile	
"Superwool 607"	2 layers, t = 6.0 mm
surface weight	1.2 kg/m²
intumeszent paint	
"Pyrosafe DG-HF"	t = 1.3 mm
surface weight	1.30 kg/m²
intumeszent textile	
"Tecnofire E8AI mat"	1 layer, t = 1.3 mm
surface weight (dry)	0.26 kg/m²
surface weight (resin)	1.04 kg/m²
Combination	
"Superwool 607"	3 layers, t = 9 mm
"Pyrosafe DG-HF"	t = 1.0 mm
surface weight (total)	1.8 kg/m²

TAB 2. Dimensions, thickness and surface weight of the tested materials as well as the CFRP tube's compression strength [12] [13] [17] [15] [16] [14]

4.2. Test device

The multi-functional test device was designed in accordance to standardized test methods, which were specifically developed for fiber composite materials. There are several standardized fire test methods like the "Heat-Release Cone-Calorimeter", "Flame Spread Test" or "Burn-Through-Test" [4]. In General Aviation, on the other hand, fire test methods are not specified in detail. Neither, the test device nor the test material, are specified. In the certification specification CS-25 for passenger aircraft however, fire test methods, like the "Powerplant Penetration Test", are specified more detailed [18]. For fire testing of truss or shell structures under mechanical load, currently no standardized test method exists.

For the conducted experiments, a combination of these test methods was used: The heat was applied by a flame, while the position of the material sample's was set in accordance to the "Powerplant Penetration Test" and the "Flame Spread Test". Due to the lack of existing fire test methods for load-carrying structures, a new test device was developed.

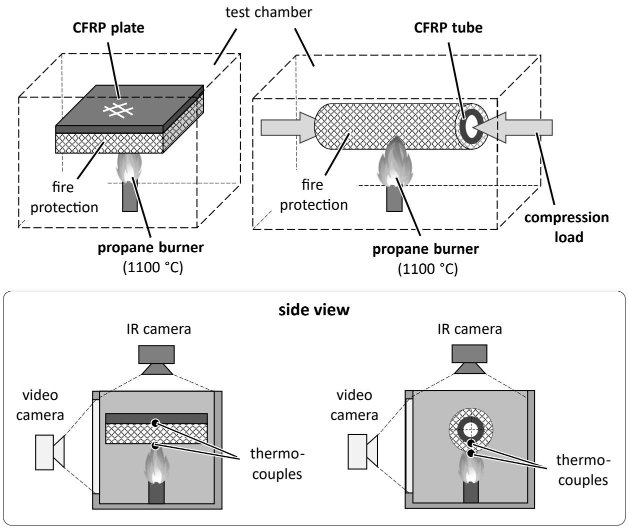

FIG 9. Fire tests on surface protected CFRP plates (left) and carbon fibre pultruded tubes under compression load (right)

As seen in Figure 9, all fire tests were carried out in a test chamber, while heating the sample materials with a propane gas burner from below. In order to evaluate the thermal behavior, the sample materials' temperature profile was measured by several thermocouples and an infrared camera [19] [20]. Furthermore, a video camera was installed in front of the test chamber, to record the materials' and flame's behavior. By applying a constant compression load on the tube samples, the critical case of the observed CFRP truss structure was tested.

Figure 10 shows the manufactured test device. A test chamber was developed that allows the positioning of the plate as well as the tube samples. Propane gas burner and CFRP tubes can be inserted through holes, while the CFRP plate can be placed inside the test chamber [21]. To ensure the vision for the video camera and the infrared camera, a glass window on the front and an opening on the top was realized.

In case of the tube samples an additional device for load input, allowing fire testing of load-carrying CFRP tubes, was developed. Test load can be applied directly on the specimen, by use of a local weight on a rotating lever arm (length L_1 and L_2). Figure 11 shows a sketch of the design measures

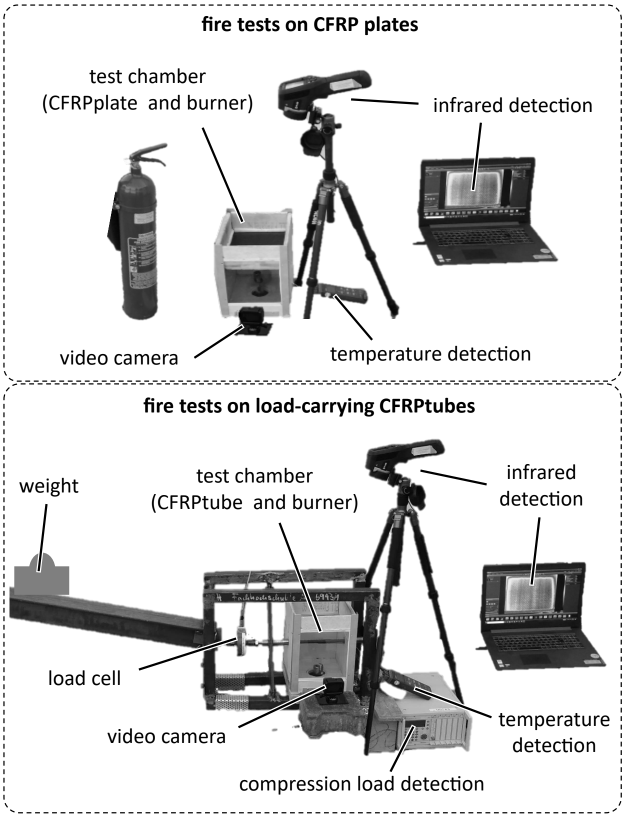

FIG 10. Test device for fire testings of CFRP plates (top) and compression loaded CFRP tubes (bottom)

and their functionality. Using angle compensating bearings and fitted specimen holders, the intended compression load could be applied without any tilting of the tube or disturbing bending loads. Furthermore, the test device's frame structure was developed to be as stiff as possible, to avoid unwanted deflections and to ensure optimal test load conditions. To detect the exact test load, a load cell was used.

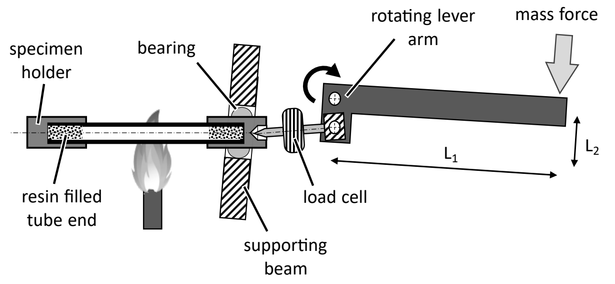

FIG 11. Cross section of the load-inducing test device and the specimen holders

Prior to the fire test, the propane burner's flame was calibrated thermally, to examine the flames temperature profile and its hottest spot. During this calibration, local temperatures of maximum 1000 °C were measured. Contrary to the manufacturer's specification, the intended flame temperature could not be reached by the propane burner. Furthermore, five compression strength tests on the CFRP tubes were conducted, to test the devices functionality and to examine the required test load. An ultimate load of 15.85 kN and, thus, compression strength of 495 MPa (+/- 87 MPa), was measured at failure.

In conclusion for the fire tests, a constant test load of 10 kN, which is equal to the limit load, needed to be applied on the CFRP tube. By adding weight on the lever arm, the test load was enforced and measured by the load cell. Once the constant compression load of 10 kN was applied, the propane gas burner was ignited and the CFRP tube's thermal behavior as well as their times to failure were observed.

4.3. Test results

The materials' flammability behavior and their individual thermal properties and the CFRP tubes time to failure are described below. By analyzing the material-specific temperature profile, conclusions on its specific thermal isolation efficiency can be made. Figure 12 shows each material sample and the CFRP plate's temperature plot. Each plot shows the average of all five samples and, thus, statistical differences between the tested fire protection materials can be analyzed. Heating up of the tested materials was seen after 15 minutes so that stationary temperatures could be measured.

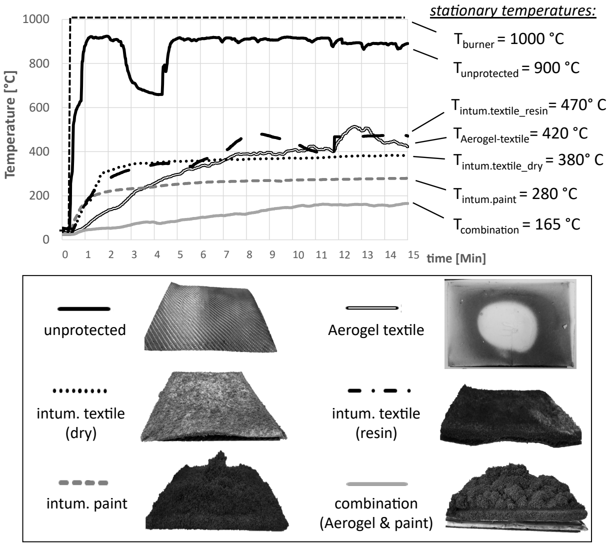

FIG 12. Temperature plots of the CFRP plates during fire testing (top) and material samples after the experiment (bottom)

In case of the unprotected CFRP plate, an ignition of the epoxy resin, followed by a quick spread of flame was observed, which lead to high temperatures of 900 ° C. Although, all epoxy resin on the plate's downside burned off completely, no burn-through behaviour was seen. By using thermally isolating fire protecting materials, lower temperatures could be reached (see Figure 12). With an average of 165 °C, the lowest stationary temperatures were measured while testing the combination of Aerogel textile and intumescent paint. The pure Aerogel textile however, heats up to a temperature of 420 °C. Both intumescent materials, paint as well as dry textile, showed good thermal isolation behavior. As seen in

Figure 12, a significant swelling of the thin isolation layer was observed and low temperatures of 280 °C and 380 °C were averagely measured. Nevertheless, for the resin-filled textile, neither ignition nor burn-through behavior was seen while testing all fire protection materials. In case of the resin-impregnated fibers, ignition of the epoxy resin was noted, leading to a significant increase in temperature of 470 °C.

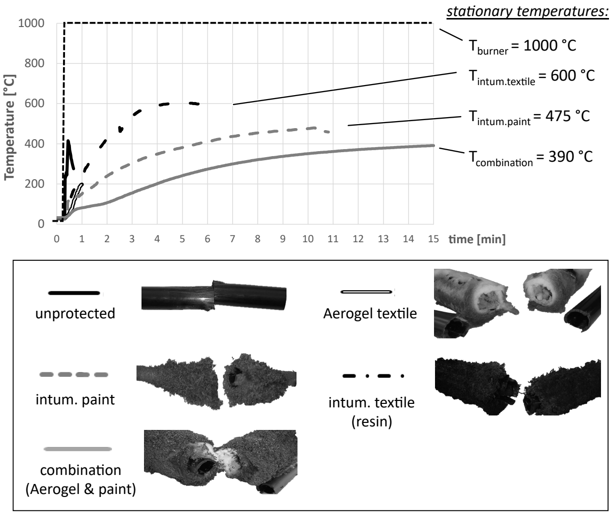

FIG 13. Temperature plots of the CFRP tubes during fire testing (top) and material samples after the experiment (bottom)

Figure 13 shows pictures of each fire-protected CFRP tube sample and their measured, averaged temperature plot. Hereby, similar flammability behavior was seen: The samples with epoxy resin, directly in contact with the flame, ignited quickly, while the others were thermally isolated by the surface protection. Nevertheless, the intumescent materials were heated up to stationary temperatures of 390 - 600 °C and failed quickly under the applied compression load. Despite their excellent thermal isolation properties, heating up of the load carrying tubes and consequently, a loss of strength, could not be avoided. However, the CFRP tube's flammability behavior was improved. Their heating-up to the critical temperature T_{crit} could be significantly lowered by using the tested fire protection materials. Consequently, their time to failure could be significantly improved. Compression failure was seen at a temperature of T_{crit} = 80 °C and therefore, way below the glass transition temperature of T_g = 120 °C. The following times, until failure occurred, were observed during fire testing:

- Without protection: 1 - 1.5 seconds
- Intumescent textile (resin infused): 3 - 7 seconds
- Intumescent paint: 8 - 11 seconds
- Aerogel textile: 16 - 24 seconds
- Combination: 38 - 44 seconds

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It should be noted that isolation layer thicknesses of the tested materials were largely different (1 - 9 mm). Therefore, a direct comparison of each material, on the basis of the measured temperatures, is not possible. In order to fairly compare these materials, and to evaluate their lightweight potential, their specific thermal coefficient of conductivity needs to be determined. Thanks to the measured temperature profile of the plate experiments (flame, isolation layer, CFRP, air) and the coefficients of conductivity of the Aerogel textile, known from the manufacturers data sheet, the stationary heat flow $\dot{Q}$ and α_{air} can be determined. An heat transfer coefficient of $\alpha_{air,test}$ = 50 W/Km² was determined, which is assumed to be prevailing for all experiments. By the convective heat flow and the measured temperature profile of each fire protection layer, the following coefficients of conductivity were estimated:

- **Aerogel textile**:
  λ = 0.18 W/mK (data sheet for T_m = 700 °C)
  $\alpha_{air,test}$ = 50 W/Km²
- **Intumescent textile** (dry):
  λ = 0.22 W/mK (+/- 0.01 W/mK)
  for T_m = 690 °C [ΔT = (380 - 1000) °C]
- **Intumescent textile** (resin):
  λ = 0.29 W/mK (+/- 0.12 W/mK)
  for T_m = 735 °C [ΔT = (470 - 1000) °C]
- **Intumescent paint**:
  λ = 0.25 W/mK (+/- 0.40 W/mK)
  for T_m = 640 °C [ΔT = (280 - 1000) °C]
- **Combination**:
  Aerogel textile:
  λ = 0.1 W/mK (data sheet for T_m = 400 °C)
  intumescent paint:
  λ = 0.2 W/mK (+/-0.005 W/mK)
  for T_m = 283 °C [ΔT = (165 - 400) °C]

4.4. Conclusion

After investigating each material's flammability behavior and validating their specific thermal coefficients, trustful isolation thicknesses for the fire protection design can be determined. However, it should be noted that the measured material coefficients are valid only for the specific temperature range from the experiment, listed above. Therefore, it is assumed that the measured thermal coefficients from the experiments (165 - 1000 °C) are the same for the required temperature range from $T_{CFRP,crit}$ = 80 °C to T_{flame} = 1100 °C.

4.4.1. CFRP plates (shell structure)

Figure 14 shows the temperature profiles of each fire protection materials that are required to keep the CFRP plates temperature below the measured critical temperature $T_{CFRP,crit}$ = 80 °C. With its strong dependency from the temperature, the Aerogel-textile has a non-linear temperature gradient (see Figure 14). For high temperatures, its isolation efficiency decreases significantly and, thus, a large thickness of up to 63 mm is needed.

By combining Aerogel textile and intumescent paint, the required thickness can be decreased effectively by a factor of three. Hereby, synergy effects between both materials can be used: As soon as the flame gets in contact with the paint, it swells up, while the Aerogel textile's temperature stays relatively low and isolates thermally well.

The lowest surface layer thicknesses of 4.25 mm was estimated for the paint. Nevertheless, this would lead to swollen layer thicknesses of up to 85 mm that has, at this state, low adhesion and foam stability. Thus, to ensure effective fire protection, lower coating thicknesses of a maximum of 2 mm should be used for the paint. The intumescent textile's required thickness of 9.35 mm is comparable low and can be manufactured well.

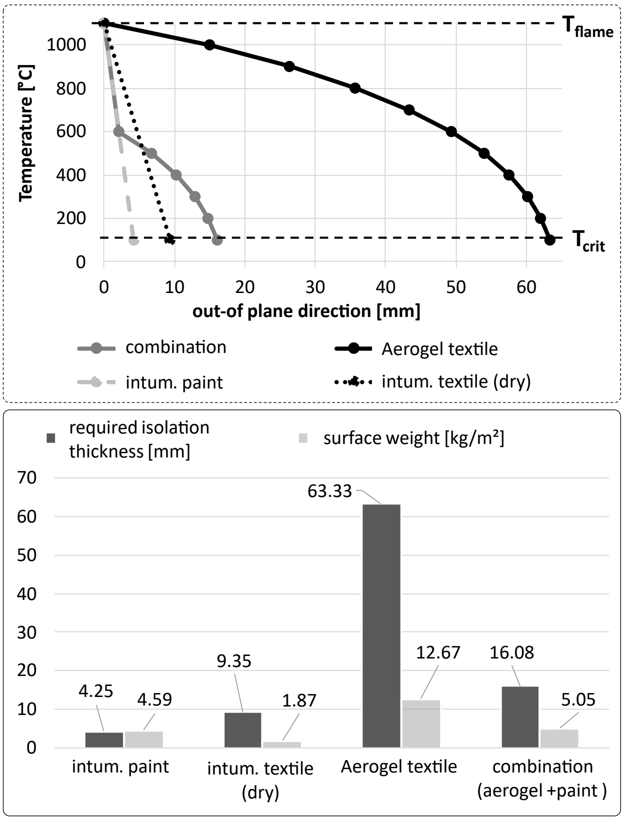

FIG 14. Temperature profile and required isolation thickness of each surface protection layer (top) and their specific surface weight (bottom)

In order to design a fire-protected structure with good lightweight properties, low surface weight is required. In the bottom of Figure 14, the surface weight of each isolation layer, required to protect load carrying firewalls or shell structures, is shown; The intumescent textile, with a surface weight of 1.87 kg/m², seems to have the lowest mass and, thus, promises the best lightweight potential. Intumescent paint as well as the combination of Aerogel textile and paint, have similar surface weight of 4.59 kg/m² and 5.05 kg/m². In conclusion, the most promising material is the intumescent textile for the fire protection design of load carrying plate-shaped structures.

4.4.2. CFRP tubes (truss structure)

Fire tests on CFRP tubes showed that maintaining of the structural integrity of load-carrying structures during a fire is not possible. Although heating up could be effectively delayed by the isolation materials, stationary temperatures way above the glass transition temperature were measured. Due to the lack of a cooling heat flow inside the tubes, layer thicknesses of more than 100 mm would be needed.

Nevertheless, improvement in terms of time-to-failure, in comparison to steel tubes, can be expected. Steel has a temperature stability of about $T_{steel,crit}$ = 400 ° C and, thus, compression failure of load-carrying steel tubes in a fire will occur as well [steel]. During non-stationary heating, the material's specific thermal mass has the greatest influence on the tube's temperature. Due to its greater density ρ, specific heat capacity c and temperature stability T_{crit}, steel can resist a heat flux for a longer period of time, then CFRP. According to this simplified estimation, a steel tube would experience a compression failure after 16 seconds. For the CFRP tubes, protected by the combination of Aerogel textile and intumescent paint, times-to-failure of 38 - 44 seconds were observed. In conclusion, the surface protected CFRP tube has, most likely, equal or even better fire resistance compared to steel.

However, in order to validate this hypothesis, fire tests on compression loaded steel tubes have to be conducted. As these experiments have not been carried out yet, final compliance of the certification's fire protection requirements could not be shown.

5. FIRE-PROTECTED STRUCTURAL DESIGN

After analyzing different structural designs and various applicable fire protection materials, all concepts can be evaluated and most promising solutions for the engine compartment can be selected. By determining the total mass of each fire-proofed structural design, their lightweight potential can be evaluated and design recommendations can be given. Finally, the performed structural and thermal analysis as well as the conducted experimental results are discussed.

5.1. Evaluation of concepts

As mentioned above, fire-protected engine compartments can be designed differently, depending on the level of fire protection and the selected structural design. By the validated materials' thermal coefficients, the most promising fire protection materials for each design according to the level of fire protection be selected.

For firewall application and non-critical components (FP 2) inside of fire-zones, a thin layer (1 mm) of intumescent paint or intumescent textile is sufficient for fire-resistant behavior.

If fireproofed behaviour of critical load-carrying structures is required (FP3), a higher level of fire protection and, thus, larger isolation layer thicknesses are needed. Figure 15 shows suitable solutions, resulting from the analyzed structural designs and their applicable fire protection design. Hereby, already certified solutions are presented as well as innovative fireproofed structural designs.

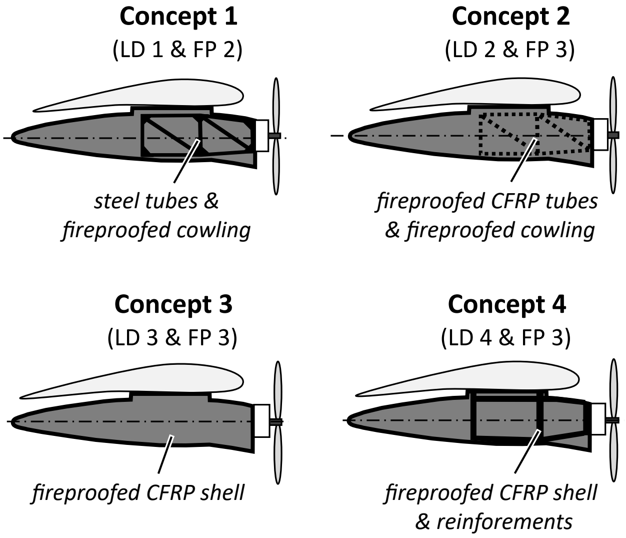

FIG 15. Fireproofed lightweight concepts for the engine compartment

Concept 1 is the reference case, which is widely used in General Aviation. Steel truss designs are considered as fireproof by the certification agencies, whereas the cowling functions as a firewall. An intumescent paint layer of 1 mm on the cowling's inside surface, sufficient for the firewall application, has a mass of 1.4 kg. Thus, the reference case has a total mass of 7.6 - 8.0 kg and can be compared to innovative concepts.

While steel does not require surface protection, the CFRP tubes of concept 2 need to have equivalent fire behavior and, therefore, need to be fire protected. In addition to the cowling's paint layer, the whole truss structure needs to be protected. The combination of both, Aerogel textile and paint, proved to be most effective for the truss application. Due to the additional isolation material, its total mass of 8.2 - 9.0 kg is more significant, then the reference design, and is also more complex in terms of the manufacturing process.

The sandwich reinforced CFRP shell structure of concept 3 can be fireproofed effectively by a 9 mm thick layer of intumescent textile. By applying the fire protection material on the inner surface, not only firewall function is ensured, but also its load-carrying properties can be maintained during fire. An additional mass of 2.4 kg is needed, leading to a total mass of 5.4 - 6.0 kg. The same isolation layer is required for the shell and the local reinforcements of concept 4, leading to to a similar total mass.

As seen in Table 3, both shell structure designs, in combination with the intumescent textile, promise the best lightweight potential. In conclusion, concept 4 seems to be the most promising design for the EDARIT project, as it is the lightest and allows the integration of openings for maintenance work. As the engine compartment's structure is not critical for a safe flight, the load-carrying structure does not necessarily need to be designed fireproof. Firewall function of the cowling and fire-resistant behavior of the load-carrying structure is sufficient. Thus, a 1 mm thick layer of intumescent paint is sufficient and would decrease the total mass.

Concept 1	
1 mm paint coating (cowling)	1.4 kg
no protection (steel tubes)	———
fire-proofed structure	**7.6 - 8.0 kg**
Concept 2	
1 mm paint coating (cowling)	1.4 kg
15 mm combination (CFRP tubes)	3.2 kg
fire-proofed structure	**8.2 - 9.0 kg**
Concept 3	
9 mm intum. textile (shell structure)	2.4 kg
fire-proofed structure	**5.4 - 6.0 kg**
Concept 4	
9 mm intum. textile (shell structure)	2.3 kg
9 mm intum. textile (reinforcements)	0.3 kg
fire-proofed structure	**5.5 - 6.1 kg**

TAB 3. Total mass of each fire-proofed lightweight design, including its structural and specific fire protection material mass

However, concept 4 has disadvantages in terms of low robustness, high costs, poor modifiability and complex manufacturing process. On the other hand, the steel truss structure is beneficial in these aspects, even though concept 1 has a large weight.

5.2. Design guidelines

After evaluating all concepts and different fire protection designs, general recommendations on designing fire-protected lightweight structures are given. There are two different approaches on how to fire protect an aircraft:

1. Local isolation of the fire threat:
If technically possible, the fire source should be thermally isolated by a fireproofed box with a 1 - 2 mm layer of intumescent paint or intumescent textile. This approach has the most significant lightweight potential.

2. Global isolation of the fire-zone:
However, in case the of an air-cooled battery, local isolation is not possible and the fire-zone needs to be isolated globally. The firewall can be made of 0.45 mm steel plate that needs to be thermally isolated in order to avoid heating up the rear firewall surface. Due to the steel's large mass, it is recommended to use lighter CFRP that is protected by 1 - 2 mm thick layer of intumescent material.

2.1. Non-critical structural components: In addition to the firewall, components, which are not essential for a safe flight, must be fire-resistant. For this purpose, CFRP shell structure, protected by 1 - 2 mm coating thickness or the classic steel truss design, is recommended.

2.2. Critical structural components: These components have to meet higher fire protection regulations: In here, they must be fireproofed and retain their load-carrying functionality in the event of a fire. In view of the lightweight construction potential, the CFRP shell structure and the use of thickly applied fire protection materials is recommended. Hereby, air flow on the aerodynamic surface cools the outer skin and increases the isolation material's effectiveness. For the fire protection material, a 9 mm layer thickness of the intumescent textile is sufficient. Neither steel, nor CFRP truss structures are advised to use, as preservation of the mechanical integrity, without additional cooling measures inside the tubes, is not possible.

In addition to the aspects mentioned above, a structural design should differentiated between the following fire sources: In the case of electrical drive technologies and fiber composites, maximum fire temperatures of 850 °C can be expected. For conventional fuels, such as kerosene or petrol, temperatures of up to 1100 °C can occur. Thus, aircraft with electric propulsion would require less protection, which would lead to a lower mass increase. However, such an approach would have to be coordinated with the certification authorities, since the certification regulations require a demonstration of critical temperature of 1100 °C.

5.3. Discussion

As seen in the temperature plots presented above, the measured temperatures varied over time and for each sample. Therefore, this can be reasoned in the burner flames' oscillating temperature (700 - 1050 °C) due to weather-related movements in the air and fluctuations of the air's temperature. Furthermore, it should be noted that the flame's calibrated temperature was 1000 °C in average and, thus, lower then required. Another factor for the variance of the measured data, is the dynamic thermal and swelling behavior of the intumescent materials.

Nevertheless, the presented results can be considered as safe and conservative, as the worst-case scenario was simulated within the experiments. In a battery fire, temperatures of not more then 850 °C can be expected, which is way below the tested temperature of 1000 °C. Furthermore, no direct contact of flame and structural element is expected to occur due to the batteries position in the compartement's center. Lastly, air streams outside the cowling as well as inside the engine compartment will cool down and most likely, extinguish the flames.

6. CONCLUSION AND OUTLOOK

In this concept study, promising fire-protected lightweight structures for the engine compartment were found. General recommendations for designing fire-protected lightweight structures, regarding specific fire threats and the required safety level, were given. In addition, valid thermal material properties of a wide range of fire protection materials were determined and their material behavior was studied. Furthermore, practical proof of the demanding certification requirements was shown by the conducted tests series.

In order to increase the accuracy of the thermal design, further tests should focus on different insulation layer thicknesses and varying temperature should be carried out. For this purpose, an optimized testing device should be used to set the burner's temperature exactly and maintain of constant laboratory conditions during the experiments. Furthermore, failure behavior of steel tubes in fire should be validated by experiments in the future to proof compliance of the CFRP truss structure design.

Since several assumptions and simplifications were made in this concept study, a more detailed structural and thermal analysis should be performed. More knowledge of the strength failure during the transient heating behavior is required, to dimension load-carrying structural components during fire more accurately. Therefore, more detailed observations on the thermo-mechanical behavior of load-carrying CFRP components should be carried out.

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References

[1] European Union Aviation Safety Agency (EASA). *Certification Specifications CS-23*. Amendment 5 edition, 2020.

[2] Airbus. *Schlussbericht HEMEP - Technologieentwicklung und Validierung für ein flugtaugliches Batteriesystem*, 2017.

[3] Flugwissenschaftliche Vereinigung Aachen e.V. *Zwischenbericht - Entwicklung des Hybrid-Elektrischen Motorseglers FVA 30*, 2019.

[4] A. Mouritz and A. Gibson. *Fire properties of polymer composite materials*. Springer, 2006.

[5] Siemens. *Schlussbericht HEMEP*. 2017.

[6] Verein Deutscher Ingenieure. *VDI 2221 - Methodik zum Entwickeln und Konstruieren technischer Systeme und Produkte*, 2018.

[7] European Aviation Safety Agency (EASA). *Certification Specifications CS-23*. Initial issue edition, 2003.

[8] European Aviation Safety Agency (EASA). *Definitions and abbreviations used in Certification Specifications for product, parts and appliances*. 2007.

[9] Dietmar Hosser. *Leitfaden - Ingenieurmethoden des Brandschutzes*. 2013.

[10] S. Feith A. Mouritz Z. Mathys A. Gibson. *Fire Structural Modeling of Polymer Composites with Passive Thermal Barrier*. 2010.

[11] Fachverband der Kunststoffrohr-Industrie. *Glasübergangstemperatur*. 2013.

[12] R&G Faserverbundwerkstoffe. *Datasheet CFK-Platten ECOTECH*, 2020.

[13] R&G Faserverbundwerkstoffe. *Datasheet CFK-Rundrohre pultrudiert*, 2020.

[14] RS Components. *Datasheet Calcium-Magnesium Silicate Thermal Insulation Sheet "Superwool 607"*, 2013.

[15] SVT Unternehmensgruppe. *Datasheet "PYRO-SAFE DG-HF"*, 2020.

[16] Tecnical Fibre Products. *Datasheet - Tecnofire E8AI Mat*, 2020.

[17] R&G Faserverbundwerkstoffe. *Prüfbericht CFK-Rohre*, 2020.

[18] Federal Aviation Administration (FAA). *Aircraft Materials Fire Test Handbook*, 2000.

[19] TC-Direct. *Datasheet - Mineral Insulated Thermocouples and Fire Testing Copper Disc Thermocouple*, 2020.

[20] Flir. *"FLIR E60" Infrared Camera Manual*, 2013.

[21] Bochem. *Datasheet - Sicherheitsbrenner mit Propangas*, 2020.