LIGHT WEIGHT FIRE BARRIER MATERIALS FOR AIRCRAFT FUSELAGE THERMAL/ ACOUSTICAL INSULATION

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Abstract - Light-weight ceramic and polymeric materials including silica, alumino-silicates, melamine- and aramid-based, and hybrid organic/inorganic materials in fiber, felt, paper, or fabric form have been examined for the aircraft thermal/acoustical insulation blanket application. The burn-through property of the materials was determined using a small-scale burn-through testing apparatus which can produce a turbulent premixed flame at 1000-1100 ?C with a heat flux of 170-1100 kW/m^2. This method is intended to model an aircraft post-crash fuel fire scenario. Experimental results indicate that the insertion of these flame resistant materials into a fiberglass insulation blanket can increase the burn-through time from 2 to 6 minutes in this test. A comparative investigation of the heat flux behavior of these materials was presented.. The factor of burn-through time-to-areal density (mass per unit area) ratio $R = t_b/d_a$ was introduced for the description of the burn-through performance and the applicability of materials.

I . Introduction

Presently, fiberglass batting is the principal material for the fabrication of thermal/ acoustical insulation strips or blankets that are installed inside and along the fuselage structure of commercial air transportation vehicles. These blankets are intended to provide a noise and thermal barrier. The fiberglass battings are mainly made of borosilicate glass fiber bonded by phenol-formaldehyde resin and treated with water-repellant materials. These battings are light, soft, and can be shaped flexibly in the blanket manufacturing process. They can provide optimum thermal and acoustical insulating performance for applications up to 230 ?C. The density of these battings is usually standardized at 5.45 kg/m^3 (0.34 lbs/ft^3), 6.7 kg/m^3 (0.42 lbs/ft^3), 8.0 kg/m^3 (0.5 lbs/ft^3), 9.6 kg/m^3 (0.6 lbs/ft^3), 19.2 kg/m^3 (1.2 lbs/ft^3), and 24 kg/m^3 (1.5 lbs/ft^3). The thickness of the battings can be 9.65 mm (0.38 in.), 12.7 mm (0.5 in.), or 25.4 mm (1 in.).

Typical blankets for aircraft insulation are encased in a polymeric film bagging material such as metallized and non-metallized polyvinyl fluoride (PVF), metallized and non-metallized polyethylene teraphtalate (PET), or polyimide (PI). The metallized PET film is being replaced due to its flame spread property [1]. Although the film material itself is primarily intended to hold the fiberglass and act as a moisture barrier, it should be also a flame retardant/resistant material.

In case of a post-crash fuel fire aircraft incident, the fiberglass strips/blankets are expected to provide a degree of protection as a fire barrier to inhibit the penetration of fire to the cabin interior. The burn-through resistance capability of such an insulation blanket is identified by their burn-through properties such as the burn-through time and the rear heat flux. There are typically three barriers that an external fuel fire must penetrate in order to burn through to the cabin interior: the aluminum-alloy skin, the thermal/acoustical insulation blanket, and the honeycomb composite interior side-wall or the floor panel structure. A recent report indicated that the external fuel fire could burn through this fuselage structure in about 2 minutes [2] if the insulation blankets are made only of layers of fiberglass batting, assuming that these blankets are not yet damaged in their expected location. Such short a period of time is clearly insufficient for the evacuation of all passengers.

To provide additional time for evacuation and enhance survivability of the passengers, a longer burn-through time for the fuselage structure of at least 6-8 minutes is preferred. Of the three fuselage members involved in a post-crash burn-through accident, focus on improving the burn-through performance of the insulation blanket is the most practical and cost-effective approach. A burn-through standard for thermal/acoustic insulation blanket materials on commercial aircrafts, therefore, has been proposed [3]. Using high-temperature bagging film material like polyimide can increase the burn-through time for the blankets, but this increase was still not sufficient. A solution is to insert a light-weight flame-resistant polymeric or ceramic sheet into the fiberglass battings. Test results showed that some of these materials can offer further protection for cabin occupants against the penetration of external ground fires up to 6-8 minutes or more [4].

This paper introduces firstly some ceramic and polymeric fire barrier materials in fiber, felt, or fabric form that are either commercially available or still in the development stage. These materials are being considered for commercial aircraft thermal/acoustical blanket applications. The paper then presents the burn-through characteristics of the insulation blankets that are inserted with a fire barrier layer. The experimental measurements from this work provide useful data for the development of a database of fire blocking materials. Finally, we introduce a burn-through time-to-areal density ratio factor R for the comparison of the burn-through performance and applicability of the thermal/acoustical insulation blankets on commercial aircraft.

II. Materials

Ceramics-based materials

The fire barrier ceramic layers are mainly made of Al_2O_3, SiO_2, and/or B_2O_3. The thickness of a layer is in the range of 0.15 – 5 mm and the areal density is around 50 – 150 g/m^2. The continuous temperature use of these sheets is from - 250 ºC to more than 1100 ºC. Silica-based ceramics melt at 1050 – 2200 ?C depending on the composition and also operate successfully under high pressure and humidity. These materials are resistant to most organic and mineral acids except hydrofluoric and phosphoric acids, and other chemical reagents. These ceramic compounds are expected not to be burned or melted by a fuel flame.

Polymer-based materials

The polymeric flame-resistant materials of interest include oxidized polyacrylonitrile-based (PAN) felt, aramid-based felt, melamine-based fabric, or hybrid aramid/inorganic fiber/felt.

Fiber-grade acrylonitrile (CH_2 ??CHCN) materials are usually produced by reacting propylene (CH_2 ??CH - CH_3) with ammonia (NH_3) and oxygen in the presence of catalysts. The reaction is called the ammoxidation of propylene. Acrylonitrile is polymerized to poly-acrylonitrile through suspension methods using free-radical or anionic initiators. PAN-based fiber can be blended with other fibers and be needle-felted to produce a wide variety of felted materials for fire burn-through protection applications.

Aramid is an abbreviation for aromatic polyamide. The chemical composition of a commercial aramid is poly-para-phenylene-terephthalamide, and it is more commonly known as a para-aramid. Aramid fibre is a man-made organic polymer produced by spinning a solid fibre from a liquid chemical blend. The bright golden yellow filaments produced have high strength and low density giving very high specific strength. The aramid materials do not ignite, melt, or drip; but decompose at about 425 ?C in air. They are highly flame-resistant with high tensile strength. Aramids are unaffected by a small amount of water vapor.

Melamine is a common name for 2,4,6-triamino-1,3,5-triazine. It condenses with formaldehyde to give a thermosetting resin. Melamine-based fiber is structured to enhance the performance of fire blocking materials. It exhibits excellent heat insulation properties with low thermal conductivity. Additionally, the distinct diameter distribution of non-round fibers can trap insulating air and further increases the heat blocking characteristics of fire blocking fabrics.

Hybrid aramid/inorganic fiber

Another type of fire barrier fiber material resulting from the combination between aramid material and ceramic oxides is the hybrid aramid/inorganic fiber. This material is usually formulated with the Nitrile Rubber (NBR) binder and exhibits a high strength, low thermal conductivity, and excellent fire resistance.

III. Experimental

The blanket specimens for the burn-through tests were fabricated using 1 or 2 layers of the fiberglass batting commercially obtained. The thickness of each layer is 25.4 mm and the density is 9.6 kg/m^3. Covering film for the blankets was made of scrim reinforced PET material.

Experimental specimens include a reference sample (A), samples with ceramic fire barrier layer (B-E), and samples with polymeric fire barrier materials (F-I)

(A) blankets containing 2 layers of fiberglass only. This is the reference sample. The areal density for 1 fiberglass layer is 245 g/m^2.

(B) blankets containing 2 layers of fiberglass and a ceramic layer of 0.5 mm thickness. This ceramic layer is in fiber paper form and is made of B_2O_3, Al_2O_3, and SiO_2 (BAS). The areal density of the fiber paper layer is 75 g/m^2.

(C) blankets containing 2 layers of fiberglass and a glass-silica ceramic paper of 0.15 mm thickness. The areal density of the paper layer is 50 g/m^2.

(D) blankets containing 2 layers of fiberglass and a silica felt layer with 3-5 mm thickness and 50 g/m^2 areal density.

(E) blankets containing 2 layers of fiberglass and an alumino silicate fabric with 1 mm thickness and 145 g/m^2 areal density.

(F) blankets containing 1 layer of oxidized PAN fiber with 2.54 cm thickness and 250 g/m^2 areal density.

(G) blankets containing 1 layer of fiberglass and 1 layer of pre-oxidized polyacrylonitrile felt. The thickness of PAN layer is 0.4 cm and the areal density is about 400 g/m^2.

(H) blankets containing 1 layer of fiberglass and 2 layers of melamine-aramid felt. The areal density of the aramid felt is about 900 g/m^2.

(I) blankets containing 2 layers of fiberglass inserted with 1 layer of hybrid aramid/inorganic fiber. The inserted layer has an areal density of 170 g/m^2.

All sample blankets have a same dimension of (80 cm x 90 cm). For each burn-through experiment, a set of 2 blankets is required. These two specimens are installed on a steel frame. All specimens were conditioned at room temperature for at least 24 h before the burning process in order to stabilize the moisture content. If one fiberglass layer is used then the fire barrier layer is placed facing the flame. The burn-through experiments are performed in a test cell under a large fume hood with a temperature controlled at 20-21 ºC and a relative humidity of 50-55%.

The burn-through apparatus is described in Figure 1. The thickness and the areal density of the fire barrier materials are given in Table 1.

Figure 1. Burn-through apparatus and the flame it generated .

Table 1. Reference material and fire barrier materials inserted into specimen blankets.

Materials	**Thickness (mm)**	**Areal Density d_a (g/m^2)**
Fiberglass	25.4	245
Ceramic Fiber paper (BAS)	0.4-0.5	75
Ceramic Paper (Silica Glass)	0.15	50
Silica Felt	3-5	50
Alumino Silica Fabric	0.5-1	75-150
Oxidized Poly-Acrylonitrile Fiber	25.4	~ 250
Pre-oxidized Poly-Acrylonitrile Felt	~ 4	400
Melamine/Aramid Felt	3.8	900
Aramid/Inorganic Fiber	12.7	170

As shown in Figure 1, the burner generates a large flame that entirely covers the set of two blankets. This is a turbulent premixed flame that yields an average flame temperature in the range of 1000-1100 ºC and a front heat flux of 170-175 kW/m^2. The temperature of the flame was measured by means of a set of seven thermocouples horizontally mounted at about 10 cm from the center point of the burner cone. The actual temperature of the flame from the burner could be higher than the value recorded due to potential errors including surface reactions, radiation, and stem loss. Details of the apparatus configuration, calibration process, and testing procedure are described elsewhere [3]. Test is stopped if either (i) a burn-through failure occurs, or (ii) the blanket is not burned through after 5 or 6 min., or (iii) a failure occurs because the rear heat flux exceeds 23 kW/m^2.

IV. Results and Discussion

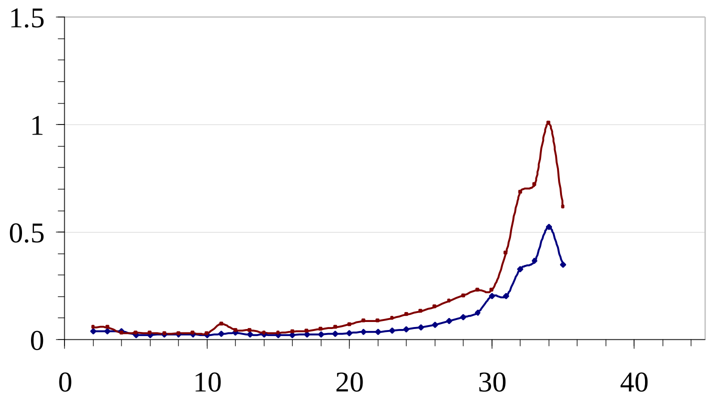
Prior to a burn-through test, the temperature and the front heat flux profiles of the flame generated by the burner were recorded using a computerized data acquisition system. The flame reached the stabilized value in about one minute after the burner had been turned on. The temperature of the flame averaged over all seven thermocouples is 1058 ºC. The average front heat flux is 172 kW/m^2. These values are close to those generated in a large-scale fuel fire test on a real aircraft fuselage [5]. During tests real time data for the burn-through time and the rear heat flux Q were recorded using two back-side calorimeters. Table 2 showed the results of the test for all samples from A to I.

Table 2. Burn-through results for all samples (1 $Btu/s.ft^2$ ~ 11.3 kW/m^2).

Materials	**Burn-through Time and/or Maximum Rear Heat Flux (kW/m^2)**
Fiberglass (Reference sample)	Burned through after 29-32 s.
Ceramic fiber paper (BAS)	Not burned through at 6 min., Q =17.3
Ceramic paper (Silica Glass)	Not burned through at 4 min., Q = 23
Silica Felt	Not burned through at 5 min., Q = 23
Alumino Silica Fabric	Not burned through at 6 min., Q = 16
Oxidized Poly-Acrylonitrile Fiber	Burned through at 175 s
Pre-oxidized Poly-Acrylonitrile Felt	Burned through at 120-180 s
Melamine/Aramid Felt	Burned through at 120 s
Aramid/Inorganic Fiber	Not burned through at 6 min., Q = 15

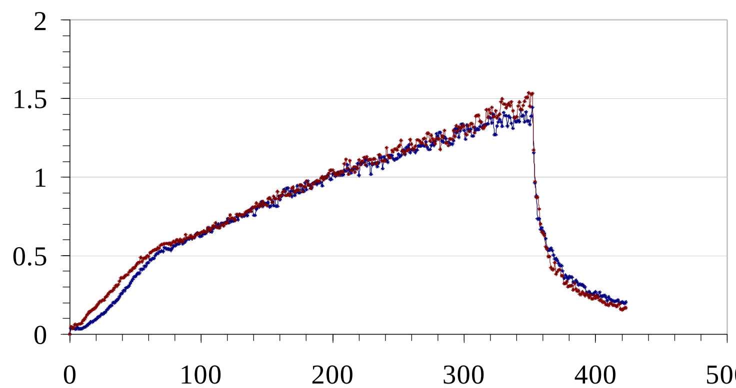
Blankets A containing only two fiberglass layers were burned-through in 29-32 seconds with holes of about 25 cm diameter on both blankets. The rear heat flux as shown in Figure 2 was nearly zero for first 20 seconds, then increased slowly to 3 kW/m^2 (0.26 $Btu/s?ft^2$) before the burn-through occurred, and finally increased sharply at the burn-through point to 11.5 kW/m^2 (1 Btu/s?ft^2) or more.

Heat Flux (Btu/s?ft^2)



Time (s)

Figures 2. Rear heat flux of fiberglass reference sample (A).



Figures 3. Rear heat flux of sample with BAS ceramic fiber paper layer (B).

Blankets B were not burned through after 6 minutes. The rear heat flux was described in Figure 3. The heat flux increased with two linear stages of different slopes and reached 17 kW/m^2 (1.5 Btu/s.ft^2) at 6 minutes. The fiberglass and cover film layers behind the ceramic sheet were melted away due to heat transferred from the ceramic sheet. No shrinkage of the specimen was observed. The ceramic sheet changed its color from white to light brown after being burned, indicating a complete burnout of binder materials. This fire barrier ceramic sheet blocked the fire effectively.

Blankets C, inserted with a silica-glass ceramic paper sheet, were not burned through after 4 minutes. However, the blankets failed since the fire barrier sheet rapidly became red-hot after 60 seconds, causing the rear-side heat flux to exceed the failure limit of 23 kW/m^2. The rear heat flux curve shown in Figure 4 was almost zero for first 20 seconds, then increased sharply to the failure value in the next 40 seconds. Residues after burning included a brown brittle paper layer.

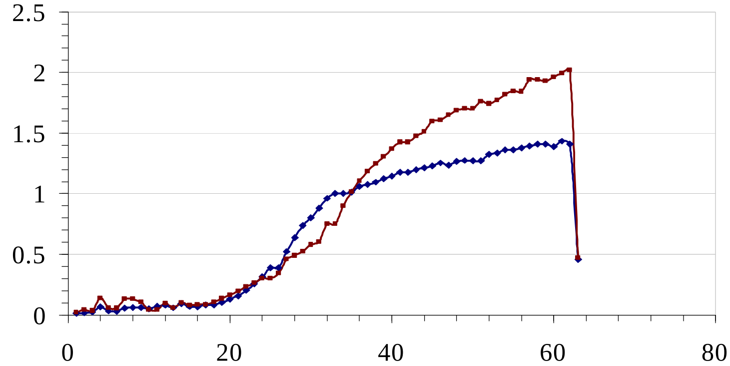


Figure 4. Rear heat flux of sample with silica glass paper layer (D).

Blankets D with a layer of silica felt was not burned through after 6 minutes; but the rear heat flux also reached the failure value after about 5 minutes as seen in Figure 5.

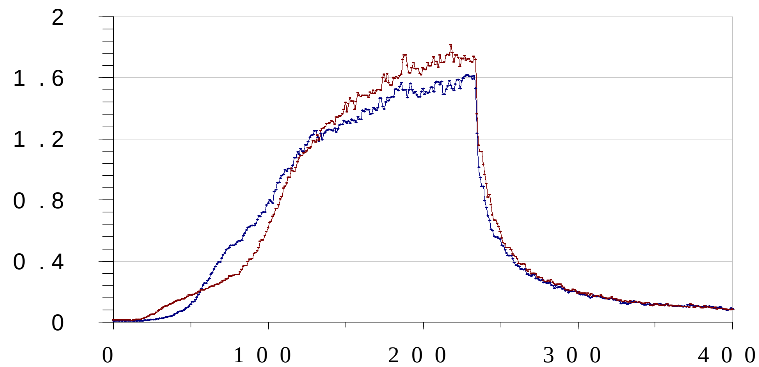


Figure 5. Rear heat flux of sample with a silica felt layer (D).

The shape of curves in Figures 3 and 5 are similar, showing typical burn-through behavior of silica-based fire barrier fiber material. The heat flux rate of material in paper form increased faster than that in the felt form.

Blanket E includes an alumino silicate fabric sheet which successfully blocked the flame after 6 minutes and the rear heat flux reached only 16 kW/m^2. As observed in Figures 2 and 6,

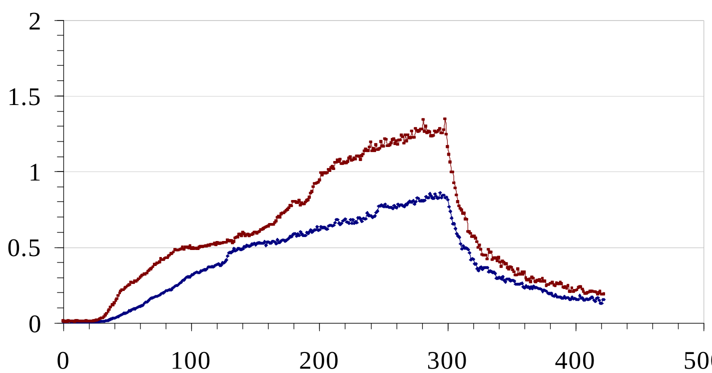


Figure 6. Rear heat flux of sample with an alumino-silicate fabric layer (E).

the presence of alumina significantly lowered the rear heat flux and altered the shape of the heat flux curve. The fact that the rear heat flux of the alumino-silicate is lower than that of amorphous silica and silica glass can be interpreted by their different thermal conductivity values. The thermal conductivity of the former compounds are smaller (~0.11 W/m?K) compared to the latter ones (~1.4 W/m?K) so they provide lower heat losses and accordingly lower outer surface temperature on the external casing.

Figures 7, 8, and 9 described the heat flux of blankets F, G, and H. Samples F with one layer of oxidized polyacrylo-nitrile fiber were burned through after 175 s. The rear heat flux increased linearly from 0 to 0.35 Btu/s.ft^2 (4 kW/m^2) and then to 0.6 Btu/s.ft^2 (7 kW/m^2) at the burn-through point as shown by a sharp increase of heat flux in Figure 7. The thickness and density of this layer F is close to those of a fiberglass layer but the burn-through time is 6 times longer than fiberglass.

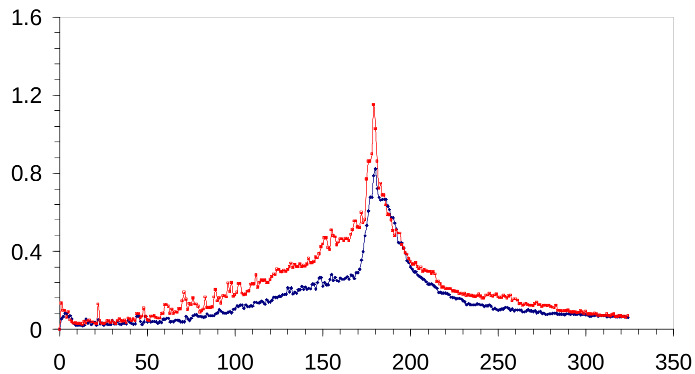


Figure 7. Heat flux curve of sample with a layer of oxidized-polyacrylonitrile fiber (F).

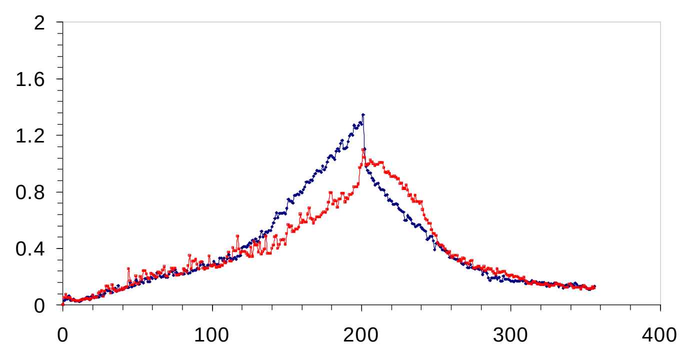


Figure 8. Rear heat flux of sample with a pre-oxidized polyacrylonitrile felt (G).

Blankets G contain fiberglass and 1 layer of pre-oxidized poly-acrylonitrile felt which burned through at 120-180 s. The maximum heat flux at burn-through point is close to that of blanket F. Blankets H containing 2 layers of aramid felt were burned through at about 115-120 seconds. The rear heat flux, as shown in Figure 9, increased slowly from 0 to 3.5 kW/m^2 after 90 s, then sharply increased to the failure value when burned through at 115 s. The behavior is similar to that of blankets A and F.

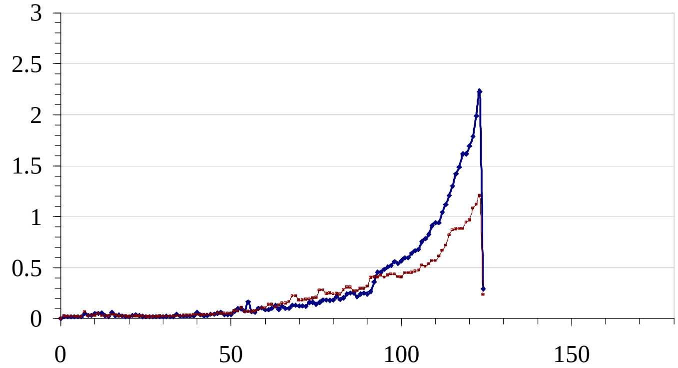


Figure 9. Rear heat flux of sample containing 2 layers of aramid felt (H).

Finally, blankets I with a hybrid aramid/inorganic fiber were not burned through after 6 minutes. The rear heat flux shown in Figure 10 increased gradually from 0 and reached 15 kW/m^2 after 5 minutes. This value is still smaller than the failure limit of 23 kW/m^2.

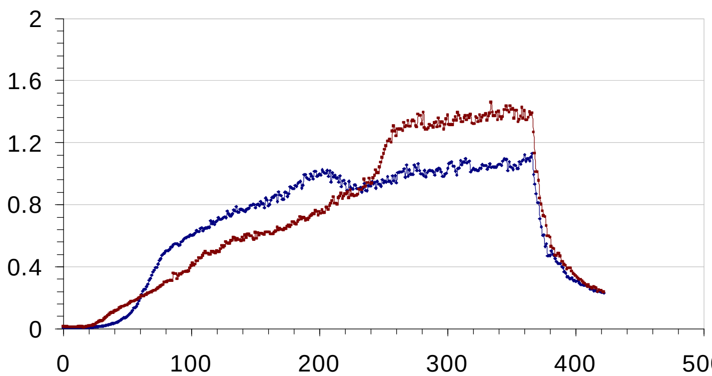


Figure 10. Rear heat flux of sample with a hybrid aramid/inorganic layer (I).

Burn-through time-to-areal density factor (t_b/d_a)

In addition to a longer burn-through time, light weight is also a requirement for materials inserted into aircraft insulation blankets. Therefore, the burn-through time itself alone is not sufficient for the description of both the burn-through performance and their applicability. A more appropriate factor for the description of the burn-through performance and the applicability of aircraft insulation blankets is the *burn-through time to areal density ratio* in which the weight of the materials is also taken into account. For a determined burn-through system, that ratio can be defined as

$$R = t_b/d_a \tag{1}$$

where t_b is the burn-through time (s) of the blanket and d_a is the areal density (g/m^2) of the inserting layer. R is measured by $s \cdot m^2/g$. For a burn-through configuration, a blanket with higher value of R has a better burn-through performance and is more suitable for the application. According to the currently proposed standard, a burn-through experiment is stopped if the blanket specimen is not burned-through after t_M = 4-6 minutes (240-360s); therefore, when applied to the circumstances in which blankets were not burned through after 4 min. the factor *R* becomes t_M/d_a. In order to be considered applicable as a fire barrier layer, the areal density of a material should be smaller than 245 g/m^2 which is the density of a fiberglass layer, and it is not burned through after at least 4 minutes. Therefore *R* value should approximately be ? 1. This factor is not applicable to circumstances in which blanket fails by exceeding the rear heat flux of 23 kW/m^2 or by a visual burn-through before 4 minutes. Table 3 shows the value of *R* for the blanket samples from A to I.

Table 3. Burn through to density factor of fire barrier materials.

Materials	**Burn-through time (s)**	**Burn-through factor *R***
Fiberglass	29-32 s	N/A
Ceramic fiber paper (BAS)	Not burned through after 6 min.	4.8
Ceramic paper (silica-glass)	Not burned through after 4 min. (exceeded heat flux at 60 s)	N/A
Silica Felt	Not burned through after 5 min. (exceeded heat flux at 5 min.)	6.0
Alumino silica fabric	Not burned through after 6 min.	2.4-4.8
Oxidized Poly-acrylonitrile fiber	Burned through after 175 s	N/A
Pre-oxidized acrylonitrile felt	Burned through after 120-180 s	N/A
Melamine/Aramid felt	Burned through after 120 s	N/A
Aramid/Inorganic fiber	Not burned through after 6 min.	2.1

A reciprocal factor *T* defined by the areal density to burn through ratio ($g/m^2 s$) can also be used for the same purpose. In this case, the smaller value of *T* the better the burn-through performance of the sample.

$$T = d_a/t_b \quad (2)$$

V. Conclusion

Burn-through properties of light weight ceramic/ polymeric fire barrier materials have been examined for aircraft thermal/acoustical insulation blanket applications. These materials include SiO_2-based ceramics and fire-resistant polymers such as oxidized polyacylonitrile, aramid, melamine-based, and hybrid aramid/inorganic materials. The above materials were inserted into fiberglass blanket samples. These specimens were burned using a medium-scale burn-through apparatus. The burn-through time of many of these sample blankets is larger than 4 minutes, which is much longer than that of currently used fiberglass/foam blankets. The ratio of burn-through time to areal density was introduced for the comparison of the applicability and burn-through resistance performance of aircraft thermal/acoustical insulation blankets. Burn-through test results showed that blankets containing an alumino-silicate ceramic sheet or a hybrid aramid-inorganic felt layer have high *R* factor, indicating their excellent burn-through resistance. These materials are considered potential materials for the next generation of aircraft thermal insulation blankets.

Acknowledgements

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