Use of CFOAM® Vitreous Carbon Foam as a Fire Resistant Material

Case Study: AeroDelft Phoenix FS Aircraft Firewall

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GM and CTO

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WHAT IS CFOAM®?

CFOAM LLC manufactures a highly engineered carbon foam from coal.

Our facility is located in Triadelphia, WV, USA.

<u>CFOAM LLC owned by CFOAM Corp</u>

- 75% CFOAM Ltd, Perth, Australia
  - Australian Stock Exchange (CFO)
- 25% CONSOL Energy, Canonsburg, PA, USA

CFOAM LLC is the **only** commercial scale producer of coal-based carbon foam in the world.

PRODUCTION FACILITY

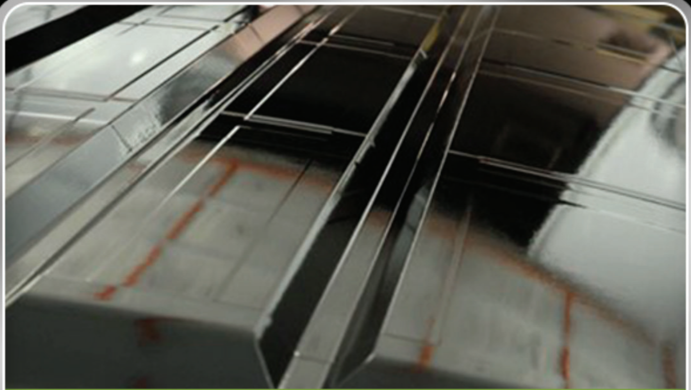
Current capacity of ~ 500 m^3 annual

Standard panel size of 46 x 96 x 5 cm

FOAM

KEY MARKETS

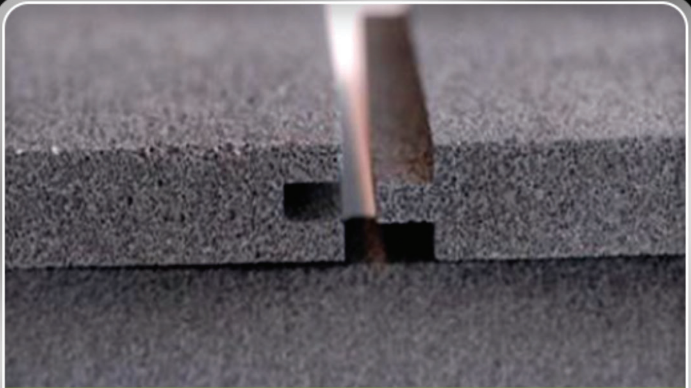
AEROSPACE



COMPOSITES AND COMPOSITE TOOLING

DEFENSE

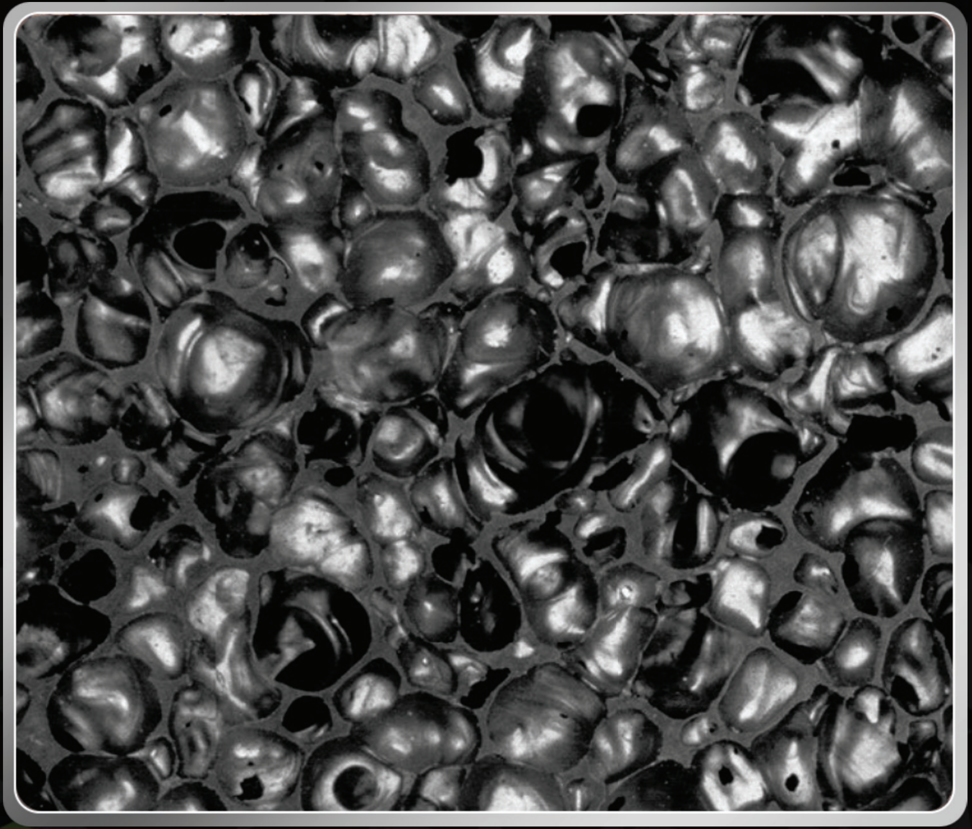
HIGH TEMPERATURE INSULATION



THERMAL CONDUCTOR

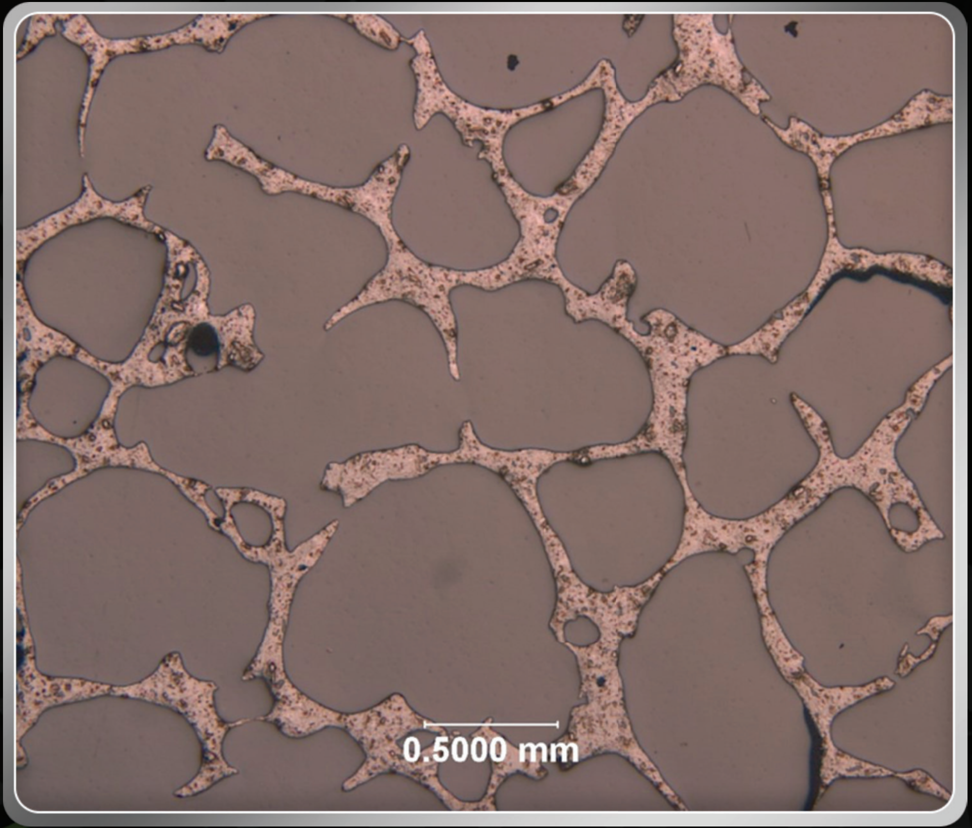
FIREPROOF STRUCTURES

What can CFOAM® do?



- Composed of vitreous carbon
- Fire resistant
- Lightweight
- Easily machined to shape
- Not attacked by rot, mold, or mildew
- Corrosion resistant
- UV resistant

CFOAM® STRUCTURE



- Open Cell Foam
- Full Density Range
  - 0.25 – 1 g/cc (15 – 65 pcf)
- Current Manufacturing Range
  - 0.27 – 0.56 g/cc (17 – 35 pcf)

PHYSICAL PROPERTIES

CFOAM® Typical Properties (Metric)					
Property	**Test Method**	**Units**	**CFOAM20**	**CFOAM25**	**CFOAM30**
Nominal Density	ASTM D 1622	g/cc	0.32	0.40	0.48
Compressive Strength	ASTM C 365	kPa	6,037	10,337	16,042
Compressive Modulus	ASTM C 365	MPa	1,665	2,121	2,586
Tensile Strength	ASTM C 297	kPa	2,250	3,573	5,214
Tensile Modulus	ASTM C 297	MPa	1,708	1,996	2,266
Shear Strength	Torsion Shear	kPa	1,310	1,690	2,065
Coefficient of Thermal Expansion	ASTM E 228	ppm/°C	5.0	5.0	5.0
Thermal Conductivity	ASTM E 1225 / Laser Flash	W/m-K	25°C: 0.3 500°C: 0.7 1000°C: 1.0 2000°C: 4.0	25°C: 0.4 500°C: TBD 1000°C: TBD 2000°C: TBD	25°C: 0.5 500°C: 0.9 1000°C: 1.1 2000°C: TBD
Maximum Operational Use Temperature	*Application Dependent*	°C	Extended Use: 370 - Air 3,040 – Inert	Extended Use: 370 - Air 3,040 – Inert	Extended Use: 370 - Air 3,040 – Inert
Electrical Resistivity	ASTM D 4496	ohm-cm	Std. Product: $7x10^{-2}$ Tailorable from $2x10^{-3}$ to $2x10^{6}$	Std. Product: $6x10^{-2}$ Tailorable from $2x10^{-3}$ to $2x10^{6}$	Std. Product: $5x10^{-2}$ Tailorable from $2x10^{-3}$ to $2x10^{6}$
Fire Resistance	ISO 1182 ASTM E1354. E119 IMO FTP Pt I & III UL1709	N/A	PASS	PASS	PASS

FIRE RESISTANCE

NON-FLAMMABLE + NON-COMBUSTIBLE

NON-FLAMMABLE

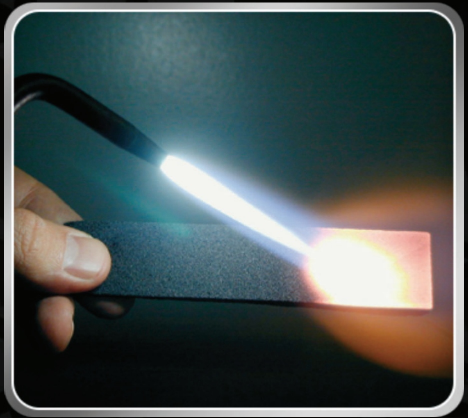
> 850ºF (455ºC) in Oxygen

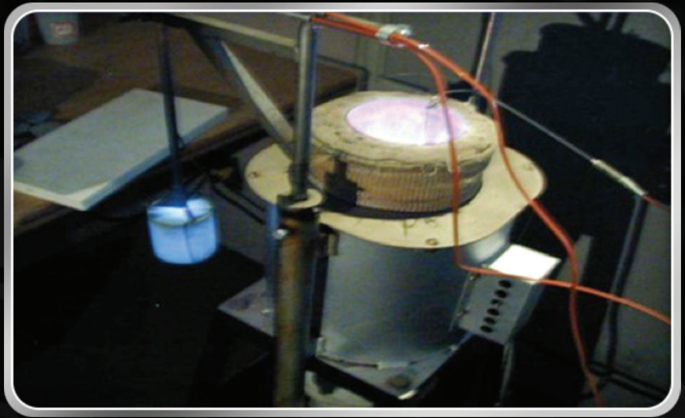
- Resists Ignition
- Oxidizes Slowly
- Slow Smoke Release
- Low Toxicity

NON-COMBUSTIBLE

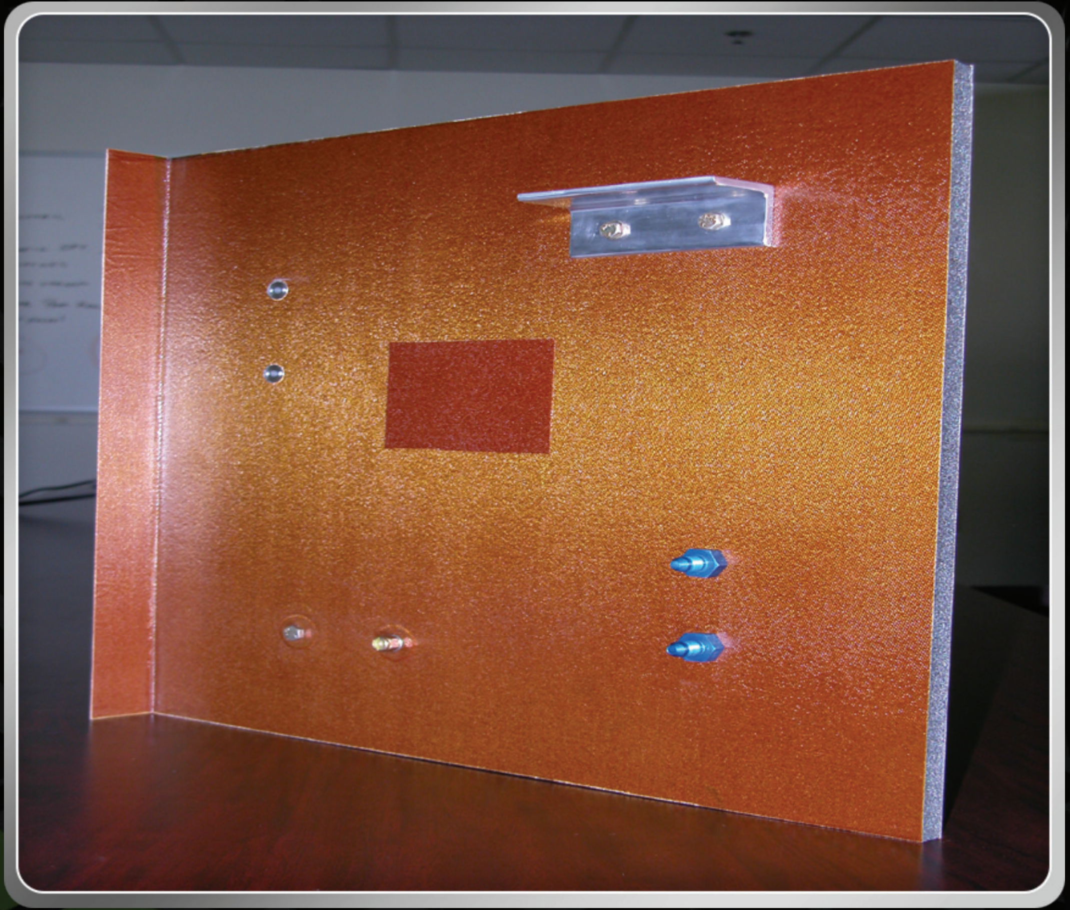
PASSES THE FOLLOWING:

- ISO 1182 - 750ºC for 30 minutes
  Certified “non-combustible”
- ASTM E1354 (Cone Calorimeter)
  Heat and Visible Smoke Release
- ASTM E162 (Radiant Panel)
  Surface Flammability

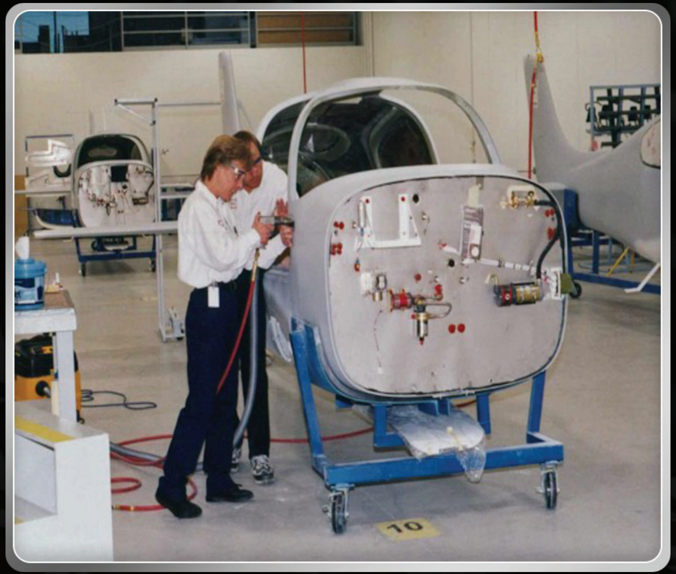




FIRE RESISTANCE



Early Touchstone Design

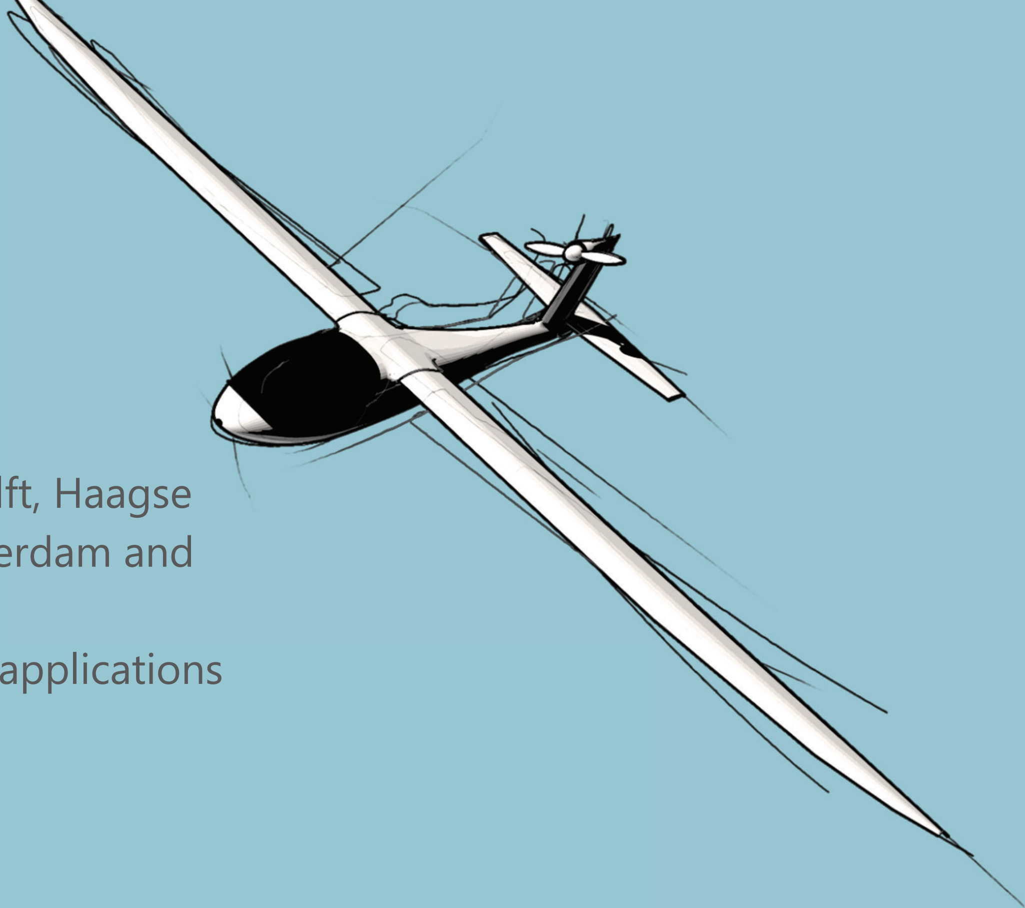


Firewall Design

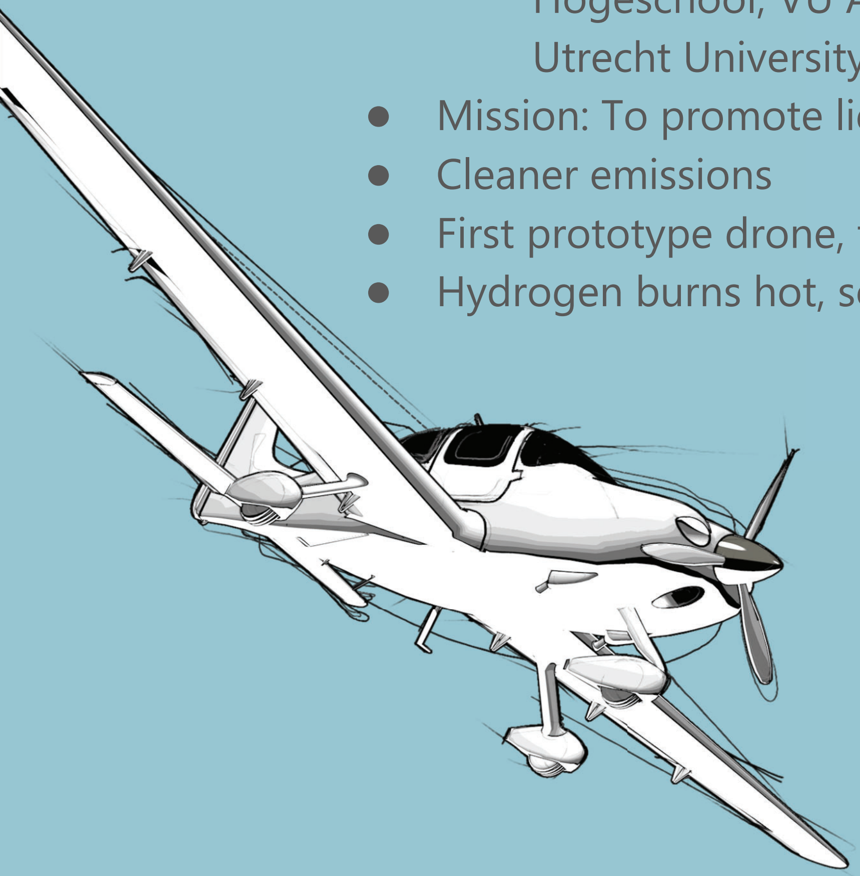
AeroDelft Phoenix FS

AeroDelft

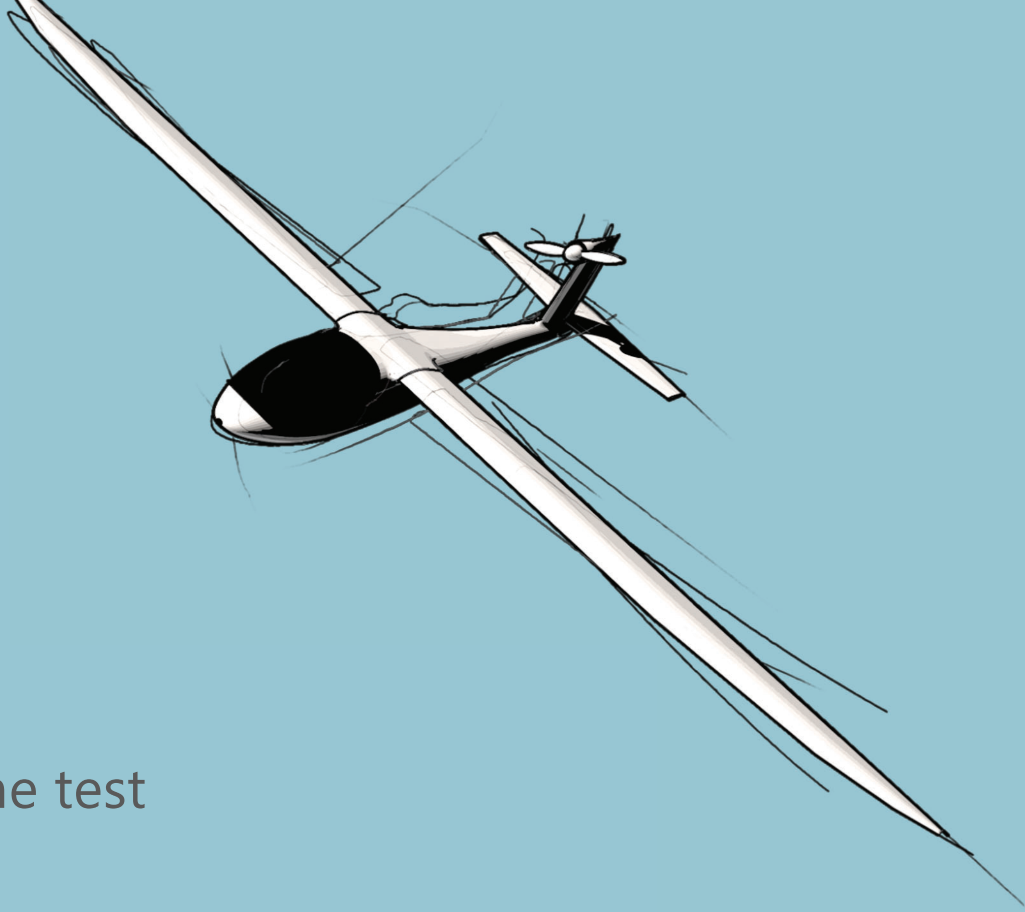
AeroDelft



- Non-profit organization (~ 47 students and 6 universities)
  - TU Delft, Willem de Kooning Academie, InHolland Delft, Haagse Hogeschool, VU Amsterdam, Erasmus University Rotterdam and Utrecht University
- Mission: To promote liquid hydrogen for use in aerospace applications
- Cleaner emissions
- First prototype drone, then prototype manned aircraft
- Hydrogen burns hot, so need a good firewall…



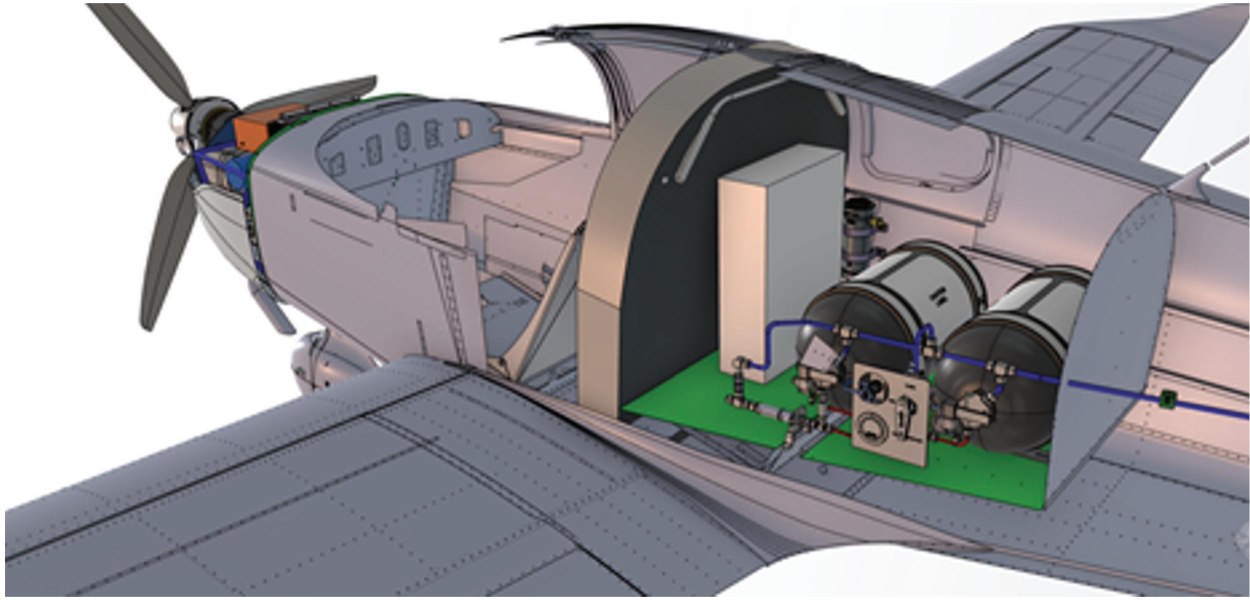
CONTENT



01 Aircraft information
02 Firewall requirements
03 Coupons design
04 Heat transfer model
05 Firewall coupons flame test
06 Results
07 Conclusion and future steps

PHOENIX FS

- Sling 4 Aircraft (retrofit 2 seats for hydrogen)
- Liquid hydrogen to electric power
- MTOW: 920 kg
- 84.5 kW engine
- Fly from Amsterdam to London



Aircraft information

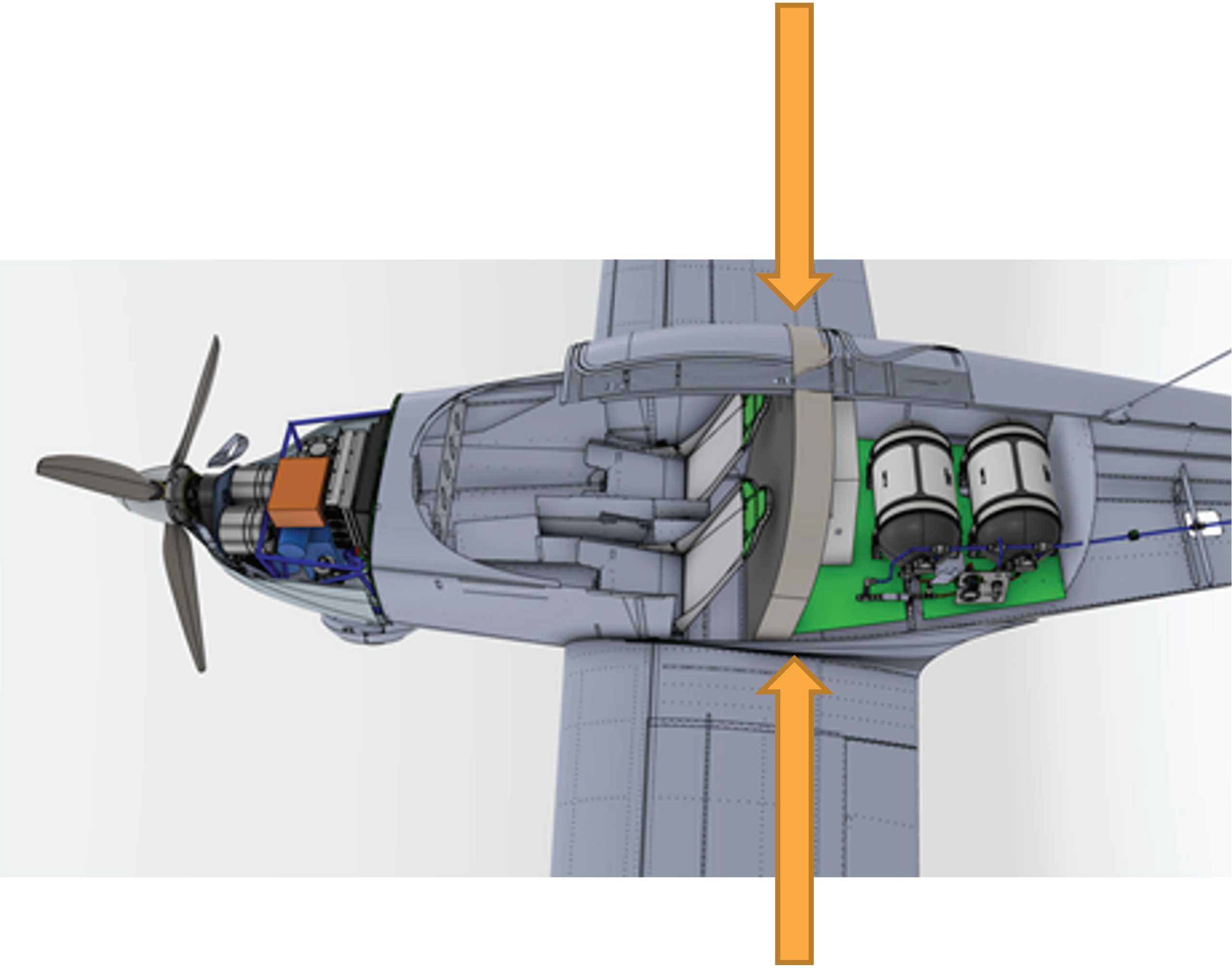
SYSTEMS ARCHITECTURE

Hydrogen area

- 125 kW fuel cell
- Hydrogen tanks
- Firewall to cope with 2000°C fire

Nose

- 20 kW Battery system
- Electric motor



Need for a firewall

- Hydrogen ignites easily at a concentration as low as 4%
- Safety systems must allow the pilot 15 minutes for an emergency landing
- Firewall must withstand hydrogen flames and protect the pilot in case of hydrogen leak and consequential flame
- Hydrogen flames reach 2045°C in air (3713°F)

Requirements of firewall for heat resistance and permeability

Regulation CS-23.1191 – Firewalls

- Compliance with the criteria for fireproof materials or components must be shown as follows:
  - The flame to which the materials or components are subjected must be 1,093 ± 83°C.
  - Sheet materials approximately 10 inches square must be subjected to the flame from a suitable burner.
  - The flame must be large enough to maintain the required test temperature over an area approximately 5 inches square.
- Firewall materials and fittings must resist flame penetration for at least 15 minutes.

Internal requirements:

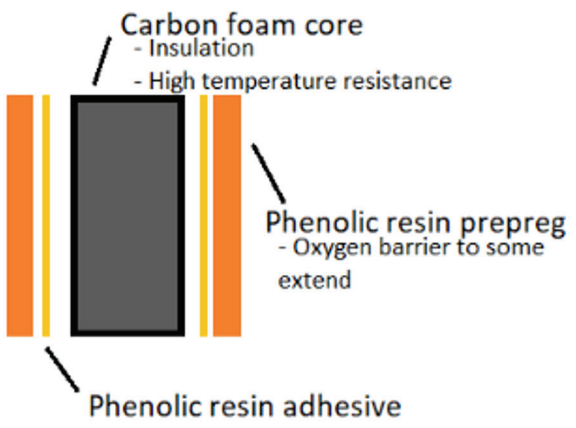
- Maximum temperature on pilot side of firewall = 120°C

First firewall test: Begin with natural gas flame (temperature of 1500°C).

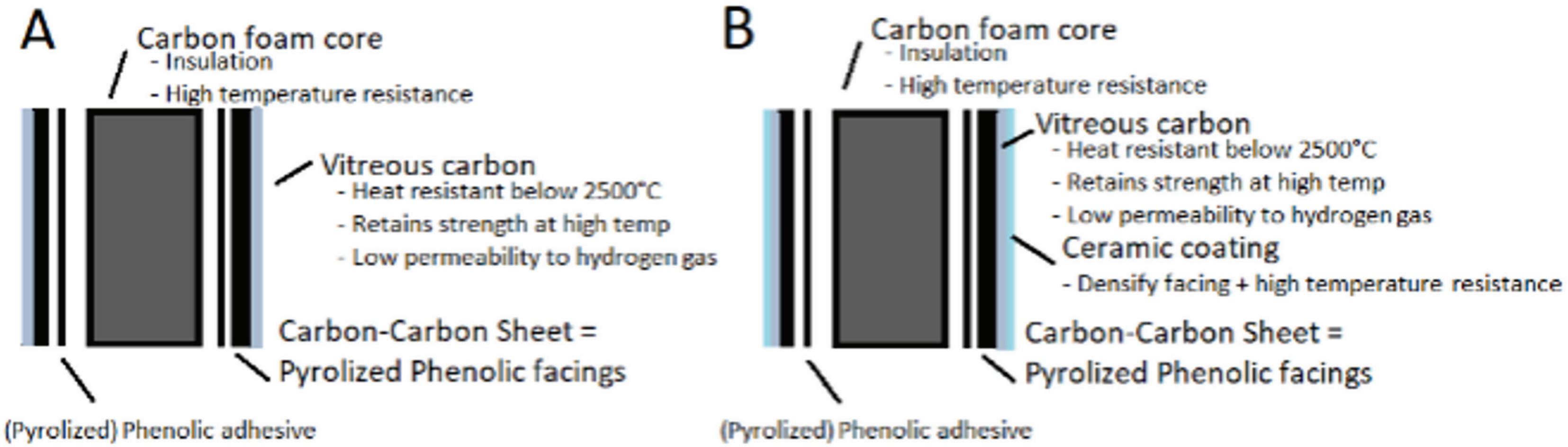
Coupon concepts

Visuals of coupons concepts:

Concept 1



Concept 2



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Coupon design

Design alteration

The two concepts were discussed with CFOAM.

Two simplified concepts were suggested for initial testing:

- Concept 1.1: Carbon foam core with a phenolic/glass fiber laminate surface bonded by phenolic resin (similar to early Touchstone design).
- Concept 2.1: Carbon foam core with a ceramic surface composed of aluminosilicate powder bonded by silica glass (same CTE as CFOAM).

Dimensions of firewall coupons

- Surface area: 45.7 cm x 45.7 cm (18 inch x 18 inch)
  - Meets the test requirement of 25.4 cm x 25.4 cm (10 inch x 10 inch)

- CFOAM required thickness to be determined through experiments and modelling.
  - Conduct heat transfer simulations to build model and optimize thickness.

- Mass budget calculations
  - 20 kg → 4.6 cm of firewall thickness

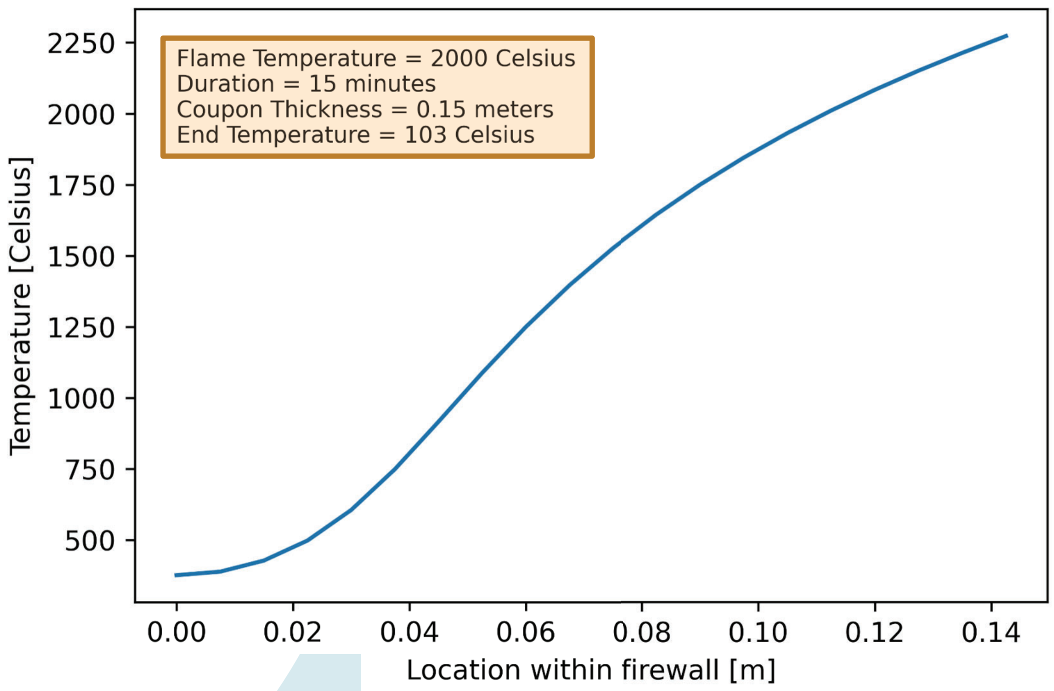
Heat transfer simulation

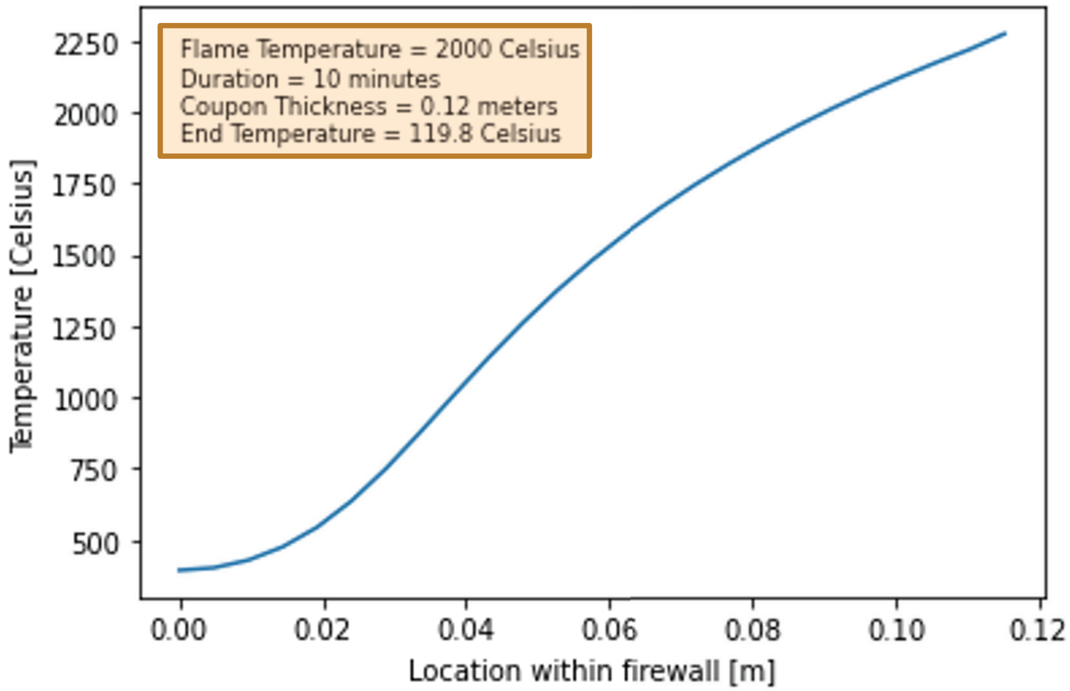
- Porous CFOAM is treated as a one-dimensional problem.

- The heat is transferred by conduction and radiation.
  - Natural convection is neglected due to the foam structure limiting large scale motion of the gaseous phase.

Heat transfer simulation

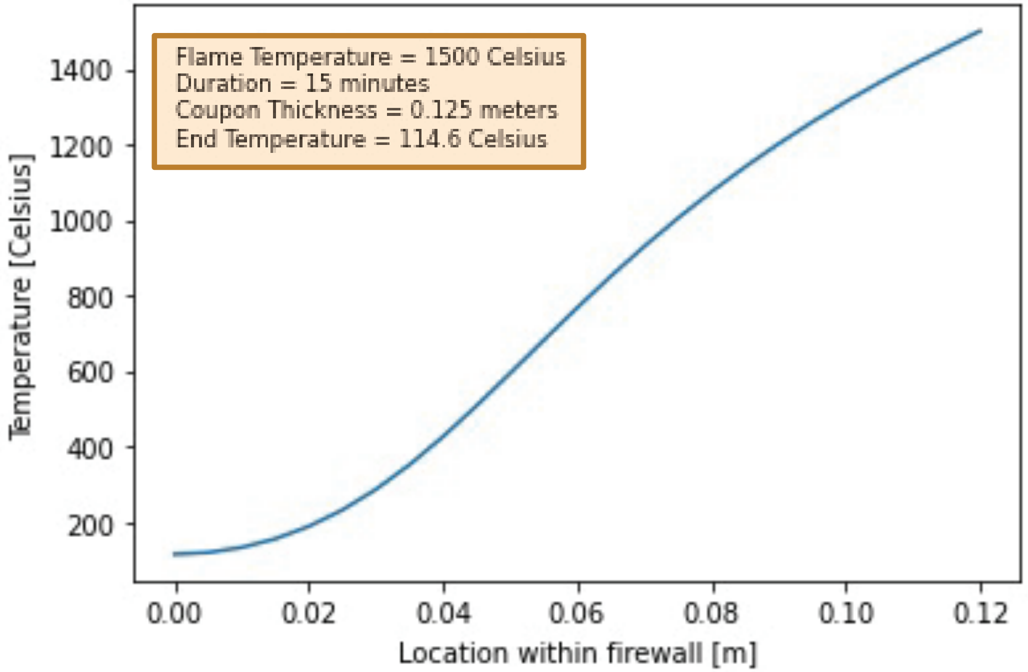
Different combinations of temperature and testing time were used in simulations.





Heat transfer simulation

- Thickness of 12.5 cm achieved 115°C on pilot side when exposed to 1500°C flame for 15 minutes.
- Deemed best thickness for first trials.



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Heat transfer model

Coupons tested

Coupon name	Thickness	Facing
Sample 1	12.5 cm	Phenolic laminate plus a phenolic resin
Sample 2	4.5 cm	Phenolic laminate plus a phenolic resin
Sample 3	4.5 cm	Ceramic coating of aluminosilicate bonded with silica
Sample 4	12.5 cm	Ceramic coating of aluminosilicate bonded with silica

05

Part of AeroDelft team at Peutz laboratory with coupons

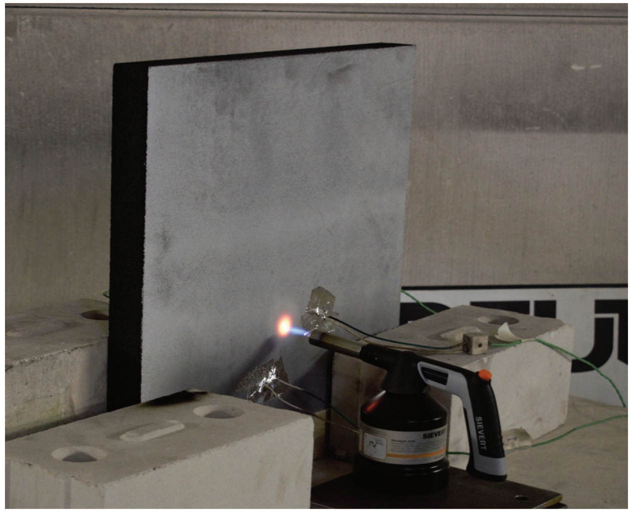
<u>Peutz</u>
Fire resistance and wind tunnel testing capabilities

Firewall coupons flame test

Non-hydrogen flame test

Phenolic skin, 12.5 cm

Ceramic skin, 4.6 cm (no spalling)



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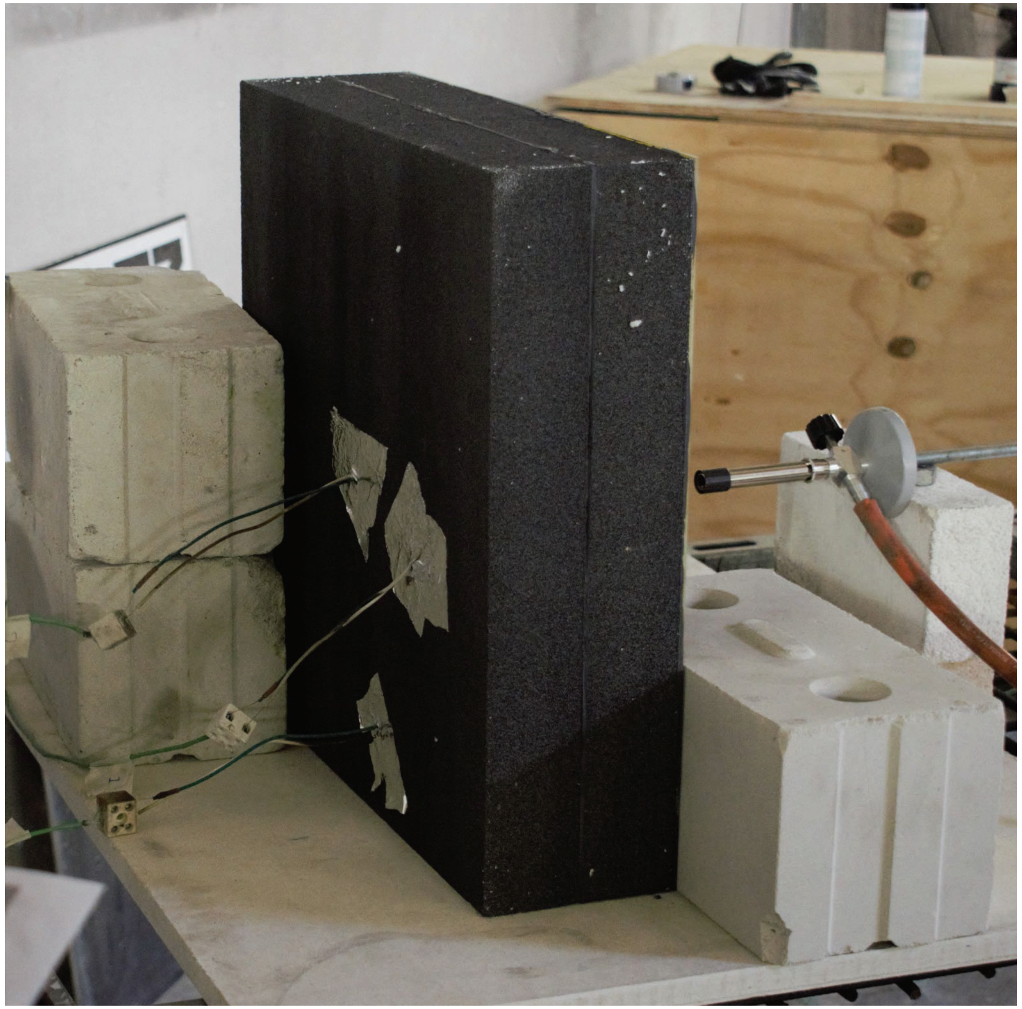
Firewall coupons flame test

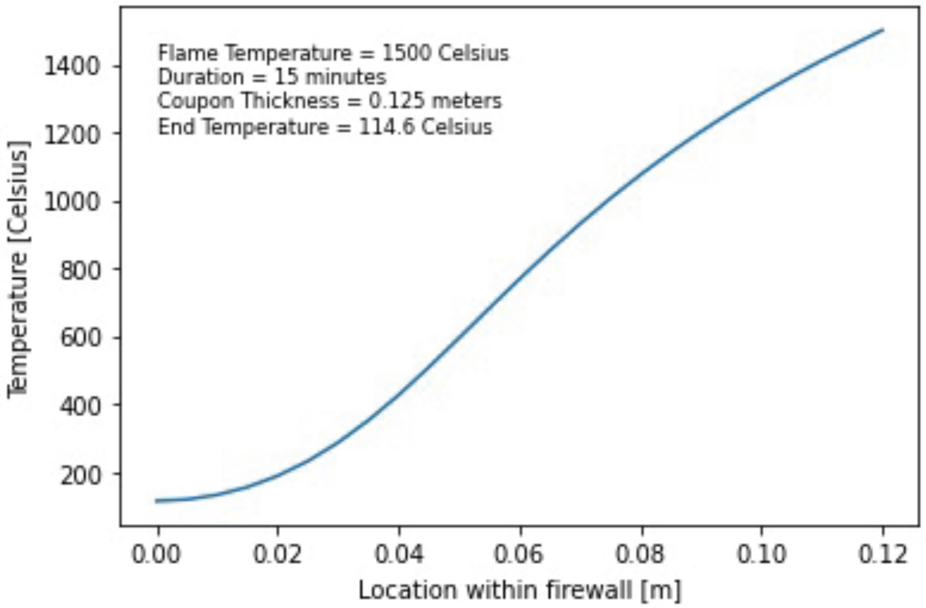
Placement of thermocouples

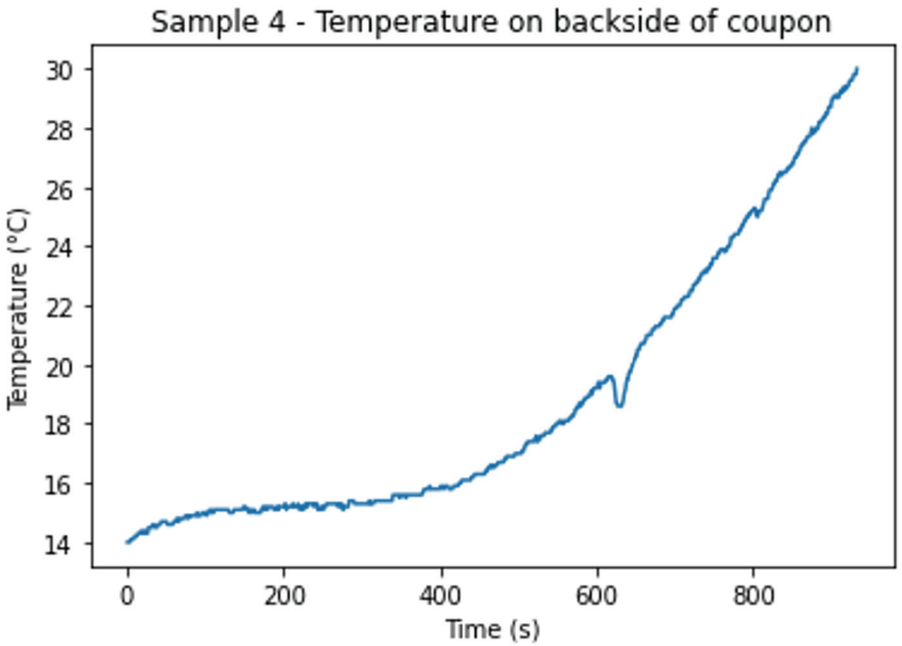


Firewall coupons flame test

Sample 4

Ceramic facing, 12.5 cm thickness, 15 minutes





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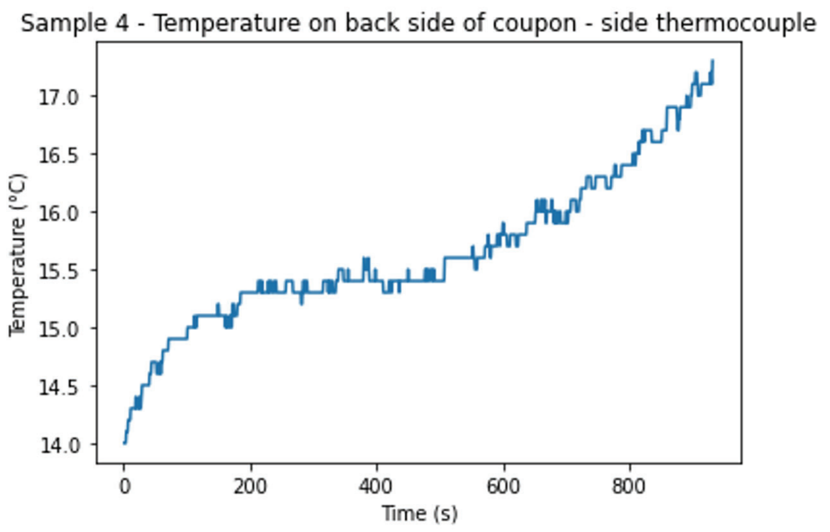
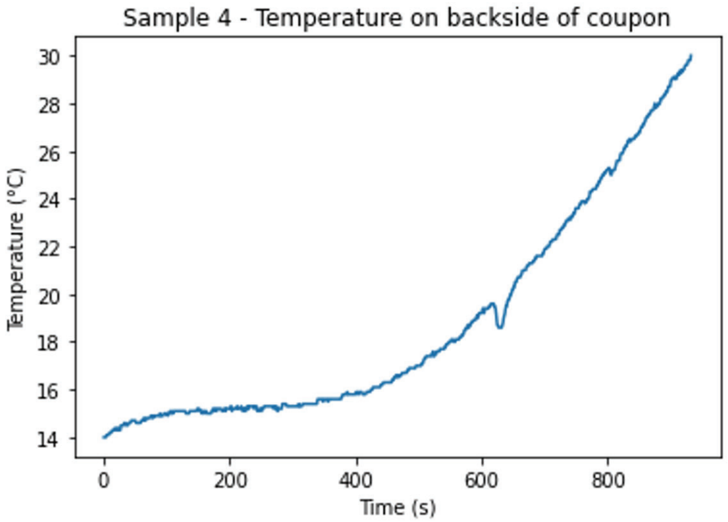
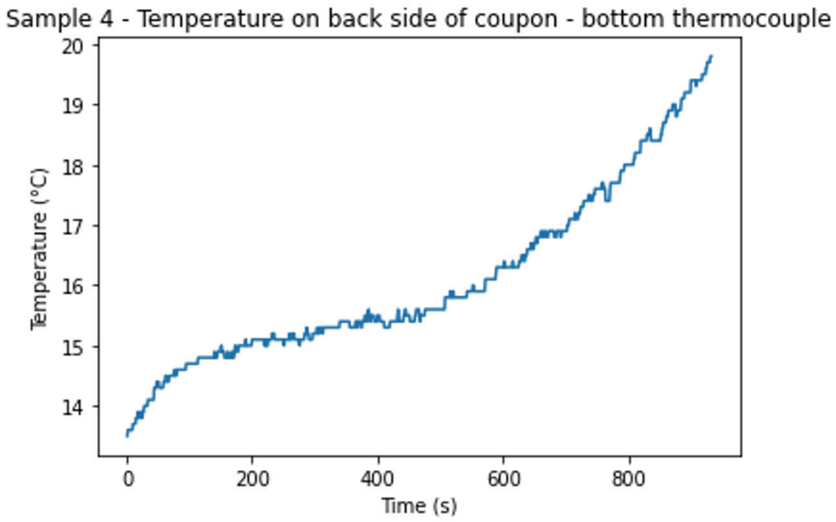
Results

Sample 4


Sample 4 - Temperature on back side of coupon - side thermocouple
Temperature (°C)
Time (s)


Sample 4 - Temperature on backside of coupon
Temperature (°C)
Time (s)


Sample 4 - Temperature on back side of coupon - bottom thermocouple
Temperature (°C)
Time (s)

Conclusion and future steps

CONCLUSION:

- The current design of firewall, according to risk scenarios, exceeds current aviation requirements.

FUTURE STEPS:

- Need to test using hydrogen flame.
- Optimize performance versus weight.
- Test firewall thickness between 12.5 cm and 4.5 cm
- Consider inclusion of a honeycombed material
- Utilize Numeca simulations to help predict performance of new coupon designs

07

CFOAM

Consider the possibilities.

Special thanks to Matthew Dekkers, Silvia Pagnottelli, Annefleur Maat and the rest of the AeroDelft Team!

Thank you to Claudio, Antonio and Octima.

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