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LIST OF ABBREVIATIONS

ABS	Acrylonitrile butadiene styrene
AFRP	Aramid fibre reinforced composite
Al	Aluminum
ATH	Aluminium trihydrates
Ba	Barium
Br	Bromine
Ca	Calcium
CFRP	Carbon fibre reinforced composite
Cl	Chlorine
Cu	Copper
Cr	Chrome
CS25	EASA Certification Specifications for Large Aeroplanes
D&R	Disposal and Recycle
EASA	European Union Aviation Safety Agency
EoL	End of Life
FAR	Federal Aviation Regulation
FST	Flame, Smoke and Toxicity
GLARE	Glass fibre-reinforced aluminium alloy
GFRP	Glass fibre reinforced composite
HBCD	Hexabromocyclododecane

Hg	Mercury
OEM	Original Equipment Manufacturer
OEW	Operating Empty Weight
PA	Polyamide
PAEK	Polyaryletherketone
PAMELA	Process for Advanced Management of End of Life Aircraft
Pb	Lead
PBDE	Polybrominated diphenyle ether
PBT	Polybutylene terephthalate
PC	Polycarbonate
PEEK	Polyetheretherketone
PEI	Polyetherimide
PEKK	Polyetherketoneketone
PES	Polyethersulfone
PMMA	Polymethylmethacrylate
PPS	Polyphenylenesulfide
PPSU	Polyphenylsulfone
PU	Polyurethane
PVC	Polyvinylchloride
rCR	Recycled carbon fibre
Sb	Antimony

Sn	Tin
TBBPA	Tetrabromobisphenol A
TBPH	Bis-(2-ethylhexyl)-tetraBr-phthalate
TDCPP	Tris (1,3-dichloro-isopropyl)phosphate
TCDPP	Tris(diCl-isopropyl)phosphate
Ti	Titanium
TPC	Thermoplastic composite
TPU	Thermoplastic polyurethane
VTP	Vertical tail plane
XRF	X-ray fluorescence
Zn	Zinc

PROJECT ABSTRACT

CREAToR is focused on process development and demonstration to sort and remove hazardous, already banned bromine containing flame-retardants from waste streams using continuous sorting and purification technologies: LIBS technology for sorting and supercritical CO₂ and natural deep eutectic solvents (NADES) for continuous extraction in twin-screw extruders.

CREAToR will cover the whole value chain, starting from collecting thermoplastic waste streams from building and construction, from waste electrical and electronic equipment and from end of life airplanes. The project will implement ways to collect secondary raw materials, identify the presence of hazardous flame retardants, remove these contaminants from the materials and finally reuse the materials. As case studies they will be reused as valuable secondary raw materials for new B&C insulation panels, closing the circle of economy, for automotive interior application, and for producing 3D printed parts for aerospace applications.

For further increasing the economic feasibility of the approach an optimised logistic concept and a harmonized material quality classification scheme will be developed and applied. CREAToR will create a circular economy solution, transforming waste streams that are currently incinerated into value-bringing secondary raw materials. The economic viability of CREAToR will be validated through material benchmarking and LCA/LCC assessment for the whole value chain resulting in next generation products.

This deliverable focusses on the material inventory of thermoplastic materials in aeronautics and assesses how the plastics' waste stream can be recovered for reuse.

DOCUMENT HISTORY AND CONTRIBUTION OF THE PARTNERS

Table 1: Version management

VERSION NR	REVISER	CONTENT
V0	GKR	Document edition (first draft)
V1	ICT	Revision
V2	GKR	Revision
V3	ICT	Submission

Table 2: Partners' contribution to the deliverable

PARTNER	SHORT NAME	ROLE IN THE WP	CONTRIBUTION TO THE DELIVERABLE
Fundacion Gaiker	GKR	Leader of task 2.3	Assessment of information, editing of the deliverable and lead partner
CoolRec BV	CLR	Participant in task 2.3	Analysis of plastic parts from EoL aircraft at AeroCircular's recycling facilities
Industrial Circularity Lab (AeroCircular)	ICL	Subcontractor (non member of consortium)	Materials inventory in current EoL aircraft and plastic parts for onsite screening

1 INTRODUCTION

A wide range of materials has to be used in the aircraft industry, as specific technical requirements must be fulfilled under the very different conditions that a plane is exposed to. For this reason, various waste streams arise from aircraft dismantling, including plastics. The plastic fraction has increased considerably in large airplanes in recent years, because plastic is up to ten times lighter than the metals commonly used in aircraft and therefore a very attractive lightweight material.

In order to determine the different thermoplastics contained in an aircraft, a material inventory of an end-of-life Airbus 320 has been performed. This report provides information about different airframe structural materials including metals, thermoset composites, cabin interior materials and unreinforced thermoplastics, but excluding batteries, kerosene, technical fluids (oil, toilets, etc.), oxygen bottles, tyres, isolation matting, lifesaving equipment, PU seat cushions and halon-containing fire extinguishers, which are considered out of scope for this study.

After a brief recap of applicable certification requirements for components subject to fire risk, the applied method and a global approach of the results of an on-board measurement campaign are provided. For each of those components the weight per aircraft is estimated, allowing yearly volumes of waste streams to be calculated. For the parts selected, including those containing bromine flame retardants, to be subjected to the next processing step, it has been checked whether additional data (for instance demounting time) would be required to estimate the economic feasibility of the new purification process under development in CREAToR, in comparison with the current treatment.

AeroCircular has supported the execution of this task, which includes a material inventory for aeronautic waste. The company has extensive knowledge of aircraft design and recycling of aircraft as well as the material know how from the actual end-of-life aircraft dismantling.

2 THE AIRCRAFT EOL PROCESS

Worldwide air transportation is growing continuously. Current forecasts predict that the worldwide passenger traffic will grow by an average of 5.1 % and the cargo traffic will grow by an average 5.6 % per year until 2030. To meet this increasing demand for air transportation, 33,500 aircraft are expected to be delivered worldwide over the next 20 years.

Likewise, the number of aircraft retirements has been increasing steadily over the last decades and it is expected that around 6,600 aircraft will reach their end of life (EoL) in the next decade as the number of flying commercial aircraft increases (see Figure 1) [1]. The current rate is about 600 aircraft per year, but with the COVID-19 pandemic, with state aid support requiring a swifter replacement to greener aircraft, combined with severe financial impacts on airlines and leasing companies, it is expected that the numbers will be significantly higher.

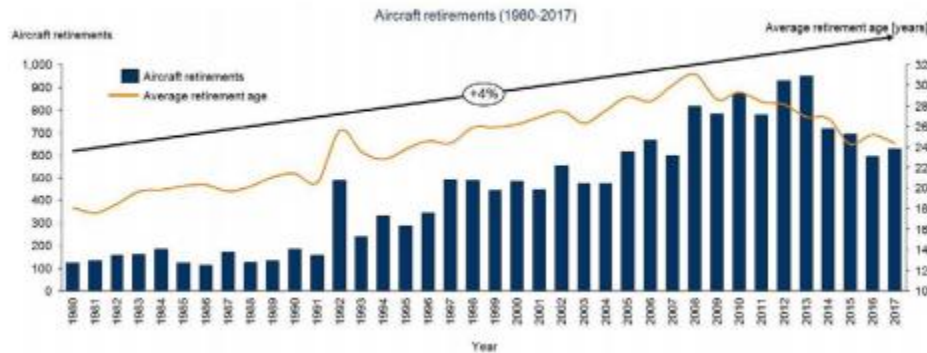


Figure 1: Historical aircraft retirements (1980-2017)[2]

Usually, an aircraft is designed, developed, and operated over a period of about 30 years. In detail, air freighters, with an average retirement age of 32 years, tend to be retired later than passenger aircraft, with an average of 25 years (see Figure 2). Service life is decreasing as older aircraft are replaced with new, more fuel-efficient models. In consequence, the number of end-of-life aircraft is increasing and there is a new need to improve the aircraft design in order to optimise its end of life. This has led to the required development of economically efficient aircraft disposal and recycling (D&R) strategies, involving engineering processes such as dismantling, sorting, and component management.

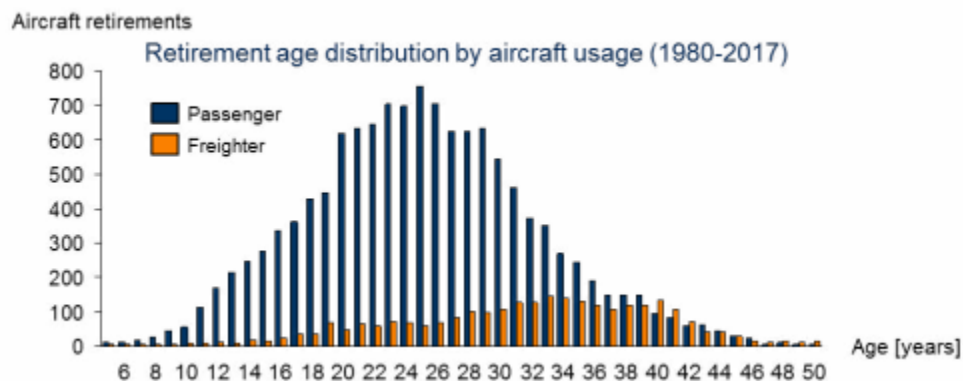


Figure 2: Retirement age distribution by aircraft usage

An aircraft's life cycle consists of seven phases, which are shown in Figure 3:

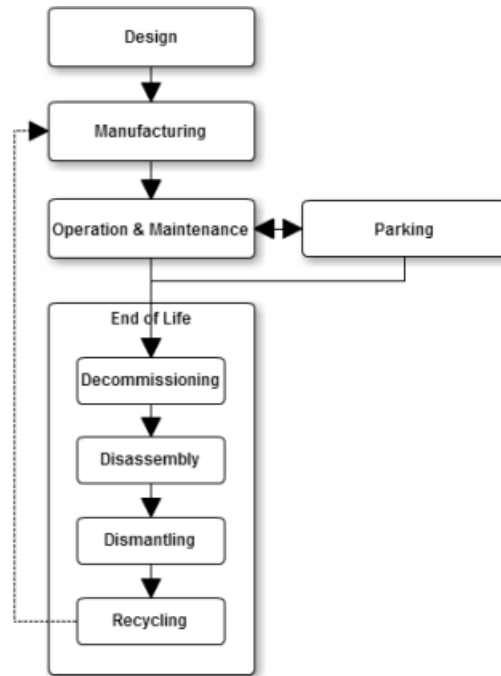


Figure 3: Idealised aircraft life cycle [3]

The EoL of the aircraft starts when it enters the disassembly process with the purpose of removing the valuable components from the aircraft. The removed components, depending on their technical condition, will either return to the aviation market directly or need to be inspected and repaired. These activities are performed by competent and authorized/certified actors in the aerospace sector. Once the aircraft has permanently lost its airworthiness, it will no longer be considered as an aircraft under the state of registry's responsibility and may be considered as waste instead. Through the process of dismantling, some parts of the aircraft can be reused for non-aerospace applications, while the rest of the aircraft will be considered as waste and will be extracted and transferred for further treatment. Recyclable wastes will be processed, batches will be prepared for recycling and the non-recyclable wastes will be prepared for disposal. The overall aircraft EoL process is divided into two phases [1]:

- The first phase includes the processes up to the removal of parts for reuse in other aircraft. This is part of the aviation domain and subject to the related regulations. During this phase, the retired aircraft is still certified.
- In the second phase, which comprises final dismantling and recycling, the retired aircraft has lost its certification, and aviation regulations are no longer applicable.

3 MATERIAL STREAMS FROM EOL AIRCRAFT

Airbus' PAMELA (Process for Advanced Management of End-of-Life Aircraft) project in 2005, has demonstrated that around 85 % weight recovery can be achieved by recycling an A300 aircraft [4]. On average, per aircraft around 800 to 1200 components can be disassembled and recertified for reuse in the aeronautic sector. Those components are sent to homologated companies, where each component is analysed to confirm whether it is suitable for reusing or for recycling for other industrial uses outside the aviation sector. Note that, for a component to be reused on another aircraft of the same model and sustaining of its original function, the component needs to be cleaned, repaired, and recertified to satisfy the regulations of an operational aircraft. Figure 4 shows the aircraft disposal and recycle process model.

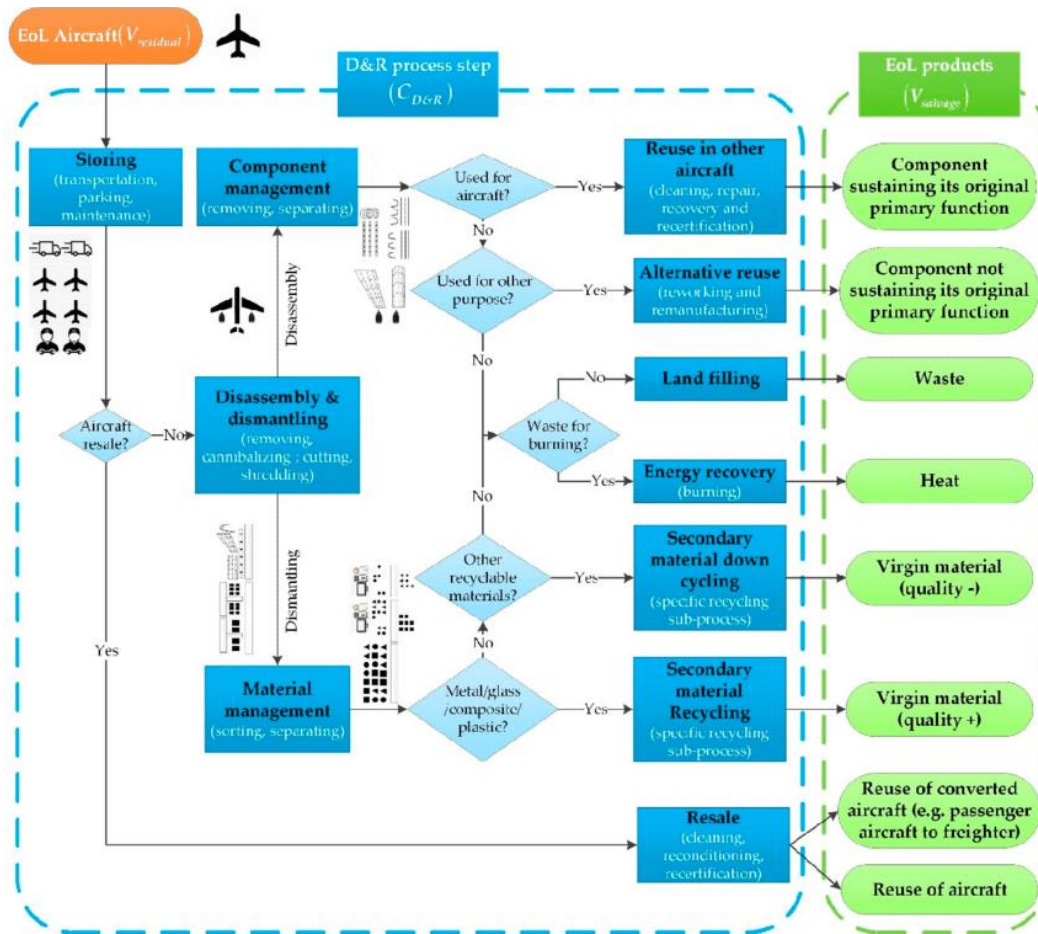


Figure 4. Aircraft disposal and recycle process model [5]

The aircraft dismantling must be a careful process, consisting of ten main steps:

1. Decontamination
2. Extraction of parts (under EASA PART 145)
3. Transfer of the aircraft to the dismantling platform
4. Removal of landing gear
5. Preparation of the materials extraction phase
6. Interior stripping

7. Customer cuts
8. Extraction of specific materials
9. Scrapping
10. Shredding and sorting of the extracted materials.

Overall, the first step is decontamination, which includes cleaning, draining of tanks, and various safety procedures. This is followed by the disassembling process, which involves the removal of equipment and parts from the aircraft body. Once the engine and the landing gear are removed, the aircraft interior is stripped, including the cockpit and the cabin (floor, seats, luggage racks). Windows and doors are then cut, and depending on their composition they can be recovered. The plastic, composite and other wastes separated during interior stripping can be disposed off as non-dangerous waste. Finally, the extracted metals are shredded and sorted by different separation technologies.

In summary, the material types used in the aircraft industry, and therefore found in the waste streams from EoL aircraft, are metals like aluminium, titanium, steel and other alloys; and plastics like reinforced plastic, composite, and carbon-fibre materials.

The aircraft that has been dismantled at the ICL facilities and that will be used within the CREAToR project is the aircraft type Airbus A320. It was designed in the 1980s and has an operating empty weight (OEW) = 42,6 tons [6] (see Figure 5).



Figure 5. A320 aircraft

3.1 METALS

Aircraft construction demands materials to be lightweight, structurally efficient, damage tolerant, durable and able to withstand severe pressures at high altitudes and exposure to the elements, while at the same time being cost effective. The main group of metals used in aerospace structures are aluminium, titanium and steel, with each possessing certain qualities that make them ideal for the specific use [7].

Metals are standard materials in this generation of aircraft, where only 2 wt-% of the real aircraft airframe structure consists of composite materials (in contrast to recent aircraft such as B787 and A350XWB, each having approx. 50 wt-% composite on board).

However, in recent years the use of aluminium has fallen owing to the growing use of fibre-polymer composite materials.

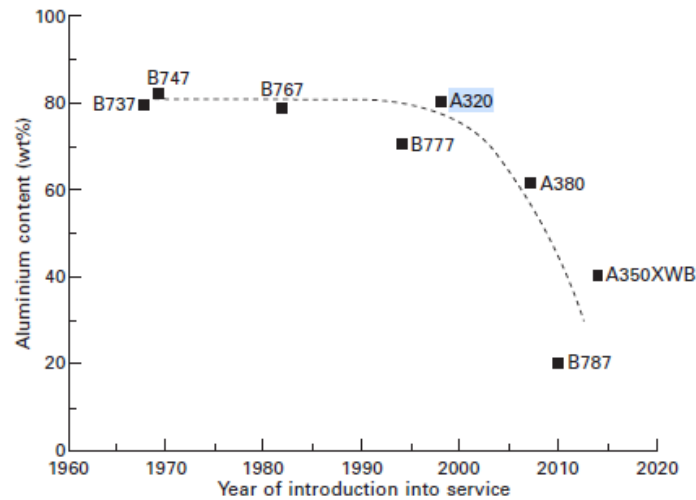


Figure 6. Amount of aluminium used in aircraft

If the entire interior is not considered - i.e. only considering the airframe itself - aluminium takes up 80 wt-% and composites only 2 wt-%. Further details on the composite use are provided in the next chapter.

3.2 COMPOSITES

3.2.1 EVOLUTION OF COMPOSITES USE ON AIRCRAFT

The desire to create faster, lighter, and more fuel-efficient aircraft results in continuous research and development of next-generation materials for this industry.

The use of composites is increasing in commercial transport aircraft due to weight reduction, which enables better fuel economy and therefore lower operating costs, reductions in the number of components, reduced maintenance costs and potential improvements in fatigue behaviour. The first significant use of composite materials in a commercial aircraft was by Airbus in 1983 in the rudder of the A300 and A310, and then in 1985 in the vertical tail fin. In the latter case, the 2,000 parts (excluding fasteners) of the metal fin were cut to fewer than 100 for the composite fin, reducing its weight and production costs. Later, a honeycomb core with a carbon-fibre-reinforced polymer (CFRP) faceplate was used for the elevator of the A310.

Following these successes, Airbus introduced the A320 - the first aircraft in production with an all-composite tail section, which also featured composite fuselage belly skins, fin/fuselage fairings, fixed leading- and trailing-edge bottom access panels and deflectors, trailing-edge flaps and flap-track fairings, spoilers, ailerons, wheel doors, main gear leg fairing doors, and nacelles. In addition, the floor panels were made of glass fibre reinforced polymers (GFRP). In total, composites constitute 28 % of the weight of the A320 airframe.

The A340-500 and 600 feature additional composite structures, including the rear pressure bulkhead, the keel beam, and some of the fixed leading edges of the wing. The latter is particularly significant, as it constitutes the first large-scale use of a thermoplastic matrix composite component on a commercial transport aircraft [8].

The A380 consists of about 20 to 22 wt-% composites and makes extensive use of GLARE (glass-fibre-reinforced aluminium alloy) (see Figure 7).

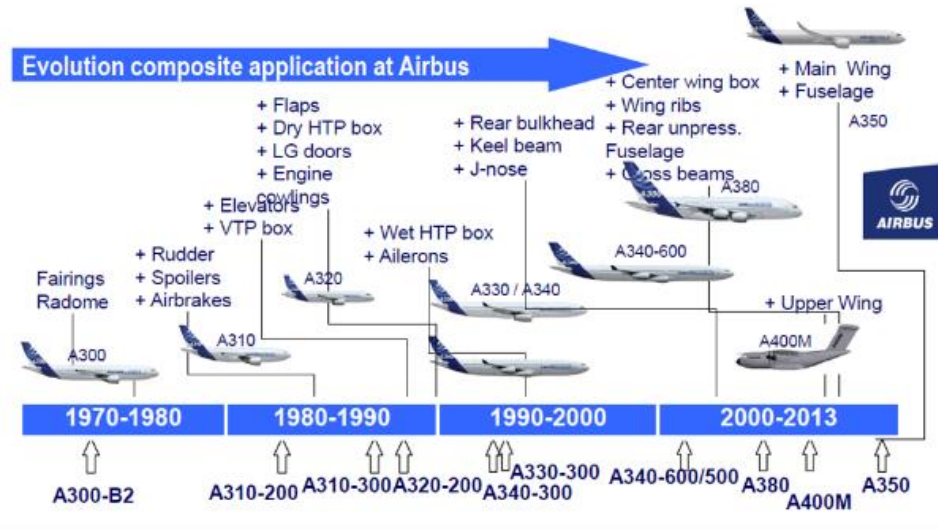


Figure 7: Composite evolution at Airbus [Airbus, 2017]

Composites on board of aircraft are generally divided into following classes:

- Glass fibre reinforced composites (GFRP)
- Carbon fibre reinforced composites (CFRP)
- Aramid fibre reinforced composites (AFRP)

On A320 EoL aircraft, all of these materials use a thermoset matrix. For CFRP and GFRP, this is epoxy-based and for AFRP it is phenolic based. Figure 8 shows the use of CFRP in Airbus aircraft.

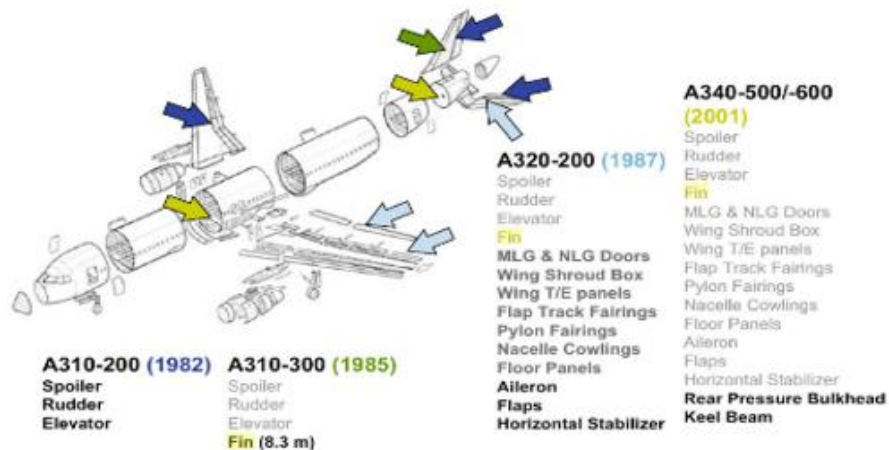


Figure 8: CFRP use on Airbus aircraft, with listed components [Airbus, 2018]

3.2.2 FIBRE-REINFORCED-THERMOPLASTICS ON FUTURE AIRCRAFT

Apart from some exceptions like the Airbus A300 family, which includes thermoplastics in some wing parts, no composites with thermoplastic materials are used on the current EoL aircraft generation.

The evolution of carbon fibre and glass fibre reinforced thermoplastics has only been introduced on airworthy aircraft from the A380 onward. However, as the aerospace industry moves towards composite fuselages and

wings, many of the structural aluminum clips and brackets holding the interior major assemblies are being replaced by thermoplastics composites. These offer a combination of strength, fire resistance and galvanic corrosion resistance that leads to weight and process savings.

In terms of thermoplastic waste management, for all fibre reinforced thermoplastic materials a consensus exists that these are easier to recycle compared to thermoset matrix materials. This is currently an area that attracts considerable research interest and activity across the EU.

Typically semi-crystalline polymers such as PEEK, PEKK and PPS are used on the exterior of aircraft as a result of their inherent resistance to solvents. PEI and polycarbonates are more commonly used in interiors because they are fire retardant, but not necessarily resistant to some of the harsh solvents used on aircraft exteriors and engines. PEI is exceptionally tough and durable and has high heat resistance - it would be found in galleys and stowage bins, while polycarbonates would be more cost competitive for secondary interior structures like window shades, trays, carts and decorative liners and window enclosures [9].

These materials are used either pure or with fibre reinforcement compounded in the thermoplastics (continuous fibres and/or recycled carbon fibre (rCF) in chopped form). Although compounding with glass fibre is an option, most reinforcements in aviation thermoplastics use carbon fibres, in continuous or chopped form.

Figure 9 shows, for example, a PEEK-based composite manufactured by Victrex.



Figure 9: Victrex PEEK bracket design for Safran cabin [VICTREX, 2021]

Glass fibre reinforced plastics (GFRP)

Glass fibres are used to reinforce plastic matrices to form structural composites and moulding compounds, providing the following favourable characteristics:

- High strength-to-weight ratio
- Good dimensional stability
- Good resistance to heat, cold, moisture, and corrosion
- Good electrical insulation properties
- Ease of fabrication
- Relatively low cost.

On current EoL aircraft, GFRP is typically used for impact-driven designs, such as leading edges of aero components. This is due to bird strike strength requirements, demanding some components on the aircraft to be resistant to a pre-defined impact energy and location. Next to bird strike, some components also need to

be able to absorb impact energy from failure cases such as tyre/rim bursts or runway debris. In contrast to the latest models such as the A350, over 50 % of which is built from carbon reinforced composites, the overall GFRP share on an A320 is very modest and negligible compared to the other material streams, even within the total 2 wt-% composite share in the airframe. Of this 2 wt-% composites (again, this is the percentage of composites on the airframe itself, excluding all cabin interior), the vast majority is CFRP.

The following Figure 10 shows an A320 aircraft in which GFRP is used at the leading edge of the vertical fin, along with belly fairing parts.

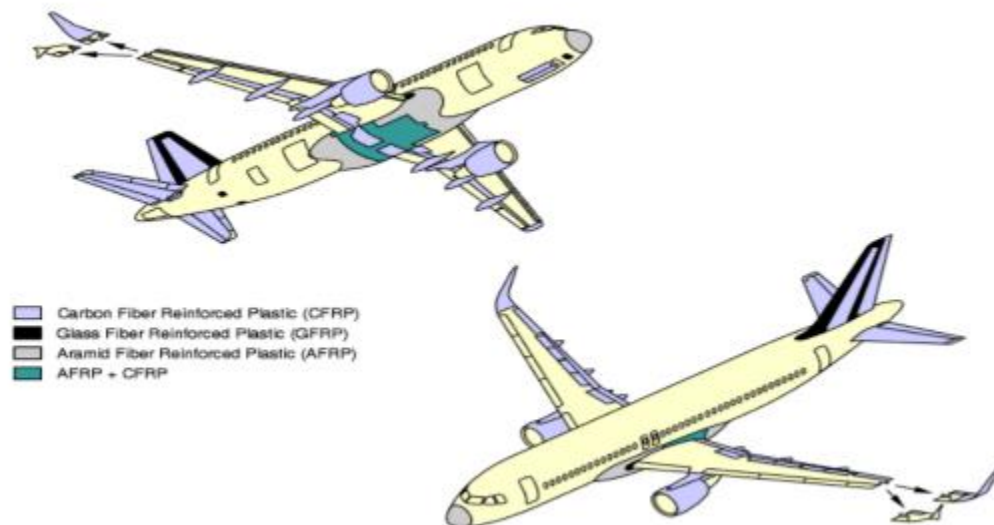


Figure 10: Composite use on A320 aircraft [AIRBUS, 2019]

Recycling GFRP materials is a challenging task, since approximately 75 % of GFRP products are made with thermoset polymers, which have an irreversible structure and do not melt at high temperatures. Currently, most GFRP wastes are landfilled, leading to significant negative environmental impacts. However, several methods for recycling GFRP waste have been developed involving (i) chemical and/or thermal processes for reclaiming the fibres, such as solvolysis, pyrolysis and similar thermal decomposition processes; (ii) incineration and co-incineration, with partial energy and raw materials recovery and (iii) mechanical recycling or size reduction (with reduction to fibrous and/or powdered products) by grinding and milling processes.

Carbon fibre reinforced plastics (CFRP)

Commercial airlines are progressively making a greater use of carbon fibre composites as they have a higher mechanical performance than steel and are lighter than aluminium, resulting in reduced fuel costs, improved aerodynamics, and lower part requirements.

The application of carbon fibre reinforced plastics reached new proportions with the A350 XWB, which boasts a significant application of composites throughout the airplane. For example, most of the A350 XWB's wing is comprised of lightweight carbon composites, including its upper and lower covers. Measuring 32 metres long by six metres wide, these are among the largest single aviation parts ever made from carbon fibre. Nevertheless, carbon fibre reinforced plastics still form a very modest share of the A320 airframe weight.

In contrast to GFRP, CFRP recycling today has economically viable processing routes, leading to recycled output materials with inherent technical value. While several recycling techniques such as pyrolysis, solvolysis, mechanical grinding, chemical depolymerisation, and high voltage fragmentation using different approaches, have shown their feasibility, commercial/industrial applications of recycled carbon fibres are still limited. Recycled fibres are generally of lower quality than virgin fibres due to lack of control in fibre length

and length distribution, diminished surface quality and multiple sources. A lot of research work, however, is still carried out worldwide to improve the quality of the recycling output, trying to maximize rCF fibre length, avoiding rCF fibre sizing etc.

Referring to Figure 7, Figure 8 and Figure 10 carbon fibre reinforced composites are found on the A320 on the vertical tail plane (VTP), left- and right hand horizontal tail plane, fairings and flaps. Smaller amounts are also used as face sheets on floor panels.

Aramid fibre reinforced plastic (AFRP)

Aramid fibre reinforced plastics are used for impact-driven components, such as fairings, engine containing rings, skins, floor panels, landing gear doors, radomes, and other components that need structural efficiency and suitable dielectric properties. This fibre contributes to the durability, lightweight strength, stiffness, and thermal and fire protection (very high melting point $>50^{\circ}\text{C}$) in aircraft composites.

In the case of the A320, ARFP can be found on the radome, belly fairings and some engine pylon fairing panels. The aramid weight per aircraft is negligible compared to the CFRP weight, which seems to have the best strength/cost ratio for a primary load-bearing structure. Figure 11 summarises the use of the above mentioned three fibre grades in aircraft of the Airbus A320 family.

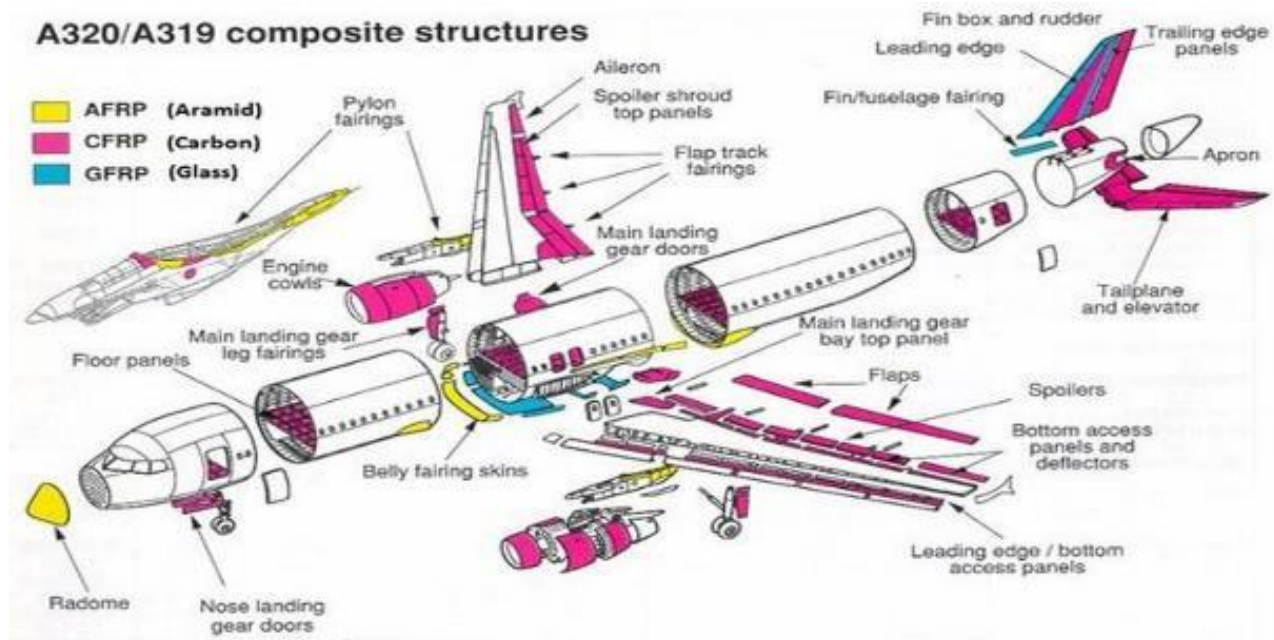


Figure 11: AFRP use on A320 family aircraft, indicated in yellow [AIRBUS, 2017]

3.3 UNREINFORCED THERMOPLASTIC MATERIALS

Unreinforced thermoplastic composites have played an important role in aircraft for decades. Despite current aircraft models such as the Boeing 787 Dreamliner and the Airbus A380, which have been pioneers in using structural thermoset composites in aircraft construction, aircraft interiors remain a significant segment for all composites — with opportunities for thermoplastic composite (TPC) technologies in addition to small components such as brackets and cable hoses.

While thermoplastic parts used inside the cabin do not need to achieve the same structural performance as airframe components, they still have their own set of demanding requirements, including stiffness and strength at low weight, dimensional stability, short process cycles, durable aesthetics, chemical resistance to cleaning solvents, and stringent flame, smoke, and toxicity (FST) restrictions. The materials include the following thermoplastic polymers:

- PVC (polyvinylchloride)
- PA (polyamide)
- PC (polycarbonate)
- PMMA (polymethylmethacrylate)

And in the more recent aircraft, the following high-end engineering thermoplastics:

- ABS (acrylonitrile butadiene styrene)
- PEEK (polyetheretherketone)
- PEKK (polyetherketoneketone)
- PEI (polyethyleneimine)
- PPS (polyphenylenesulfide)
- PAEK (polyaryletherketone)

Table 3 summarises the properties of the most common thermoplastics used in aeronatic applications.

Table 3: Properties of typical thermoplastics used as the resin matrices of thermoplastic composites for aeronautic applications [10]

POLYMER	STRUCTURE	GLASS- RUBBER T _g	TYPICAL SERVICE TEMP.	MELT TEMP. T _m	TYPICAL PROCESSING TEMP. T _p	BENEFITS	LIMITATIONS
PEI	Amorphous	217 °C	149 °C	N/A	332 °C	Processing window Toughness Flammability	Fluid resistance Material cost
PPS	Semi-crystalline	90 °C	100 °C	280 °C	330 °C	Processing window Fluid resistance Flammability Material cost	Service temperature Bonding/painting Toughness
PEKK	Semi-crystalline	159 °C	125 °C	337 °C	380 °C	Processing window Fluid resistance Flammability Toughness	
PEEK	Semi-crystalline	143 °C	121 °C	343 °C	390 °C	Fluid resistance Flammability Toughness	Material cost
PAEK	Semi-crystalline	147 °C	121 °C	305 °C	338 °C	Processing window Fluid resistance Flammability Toughness	Material cost

Based on the latest trends, it is anticipated that the amount of these materials will increase by 200 to 300 % in the coming decade, encroaching on the market share now occupied by metals and thermoset composites. Advances in thermoforming, welding and bonding are opening up new opportunities for thermoplastic compounds in secondary and primary structures, as well as high-volume interior components.

4 AIRCRAFT FIRE, TOXICITY AND SMOKE REGULATION

4.1 APPLICABLE CERTIFICATION REQUIREMENTS FOR CABIN INTERIOR

All cabin interior materials must meet specific regulations with respect to fire resistance, smoke generation and toxicity, often referred to as fire, smoke and toxicity (FST) regulation. This has to do with the requirements to delay fire, smoke, toxic fumes and heat release in case of an emergency fire onboard, allowing a pre-defined and regulated evacuation time for the passengers.

Due to the FST requirements, high temperature and inherently flame retardant thermoplastics are in demand. These include polyetherimide (PEI), polyphenylene sulphide (PPS), polyethersulfone (PES), polyphenylsulfone (PPSU), polyetheretherketone (PEEK), and polyetherketoneketone (PEKK), as well as polycarbonate (PC) and polyamide (PA or nylon). As they have relatively high inherent stiffness, these materials are often used unreinforced in injection moulded or thermoformed covers, window shades, glazing, lighting, and signage.

The relevant specification is the Federal Aviation Regulation Part 25, in short FAR 25, section 853 (www.faa.gov). This is accepted worldwide, and is the most common standard referenced. The European equivalent is the CS25 Appendix F.

In addition to the Aviation Authorities, OEMs have their own company-specific test specifications for fire/smoke/toxicity testing [11]. Table 4 shows the specifications for Airbus and Boeing.

Table 4: Company-specific test specification for fire/smoke/toxicity testing

AIRBUS	BOEING	
ABD0031	D6-51377	BSS 7322
ATM2-0002/4/5/6/7/8/38	BSS 7230 F1/F2/F3/F4	BSS 7238
	BSS 7324	BSS 7239
ATM3-0005	BSS 7303	BSS 7230

4.2 USE OF FLAME RETARDANTS

Flame retardant additives are added to the different aircraft cabin materials in order to meet the fire, smoke and toxicity (FST) requirements. Typical flame retardants used are:

- PBDE (Polybrominated diphenyl ether), in penta, octa and deca-variant depending on the number of Br atoms attached. Penta- and OctaBDE are banned in EU since 2004 due to toxicity and environmental risk. Since 2010, DecaBDE falls under the EU REACH regulation.
- ATH (Aluminium trihydrates): is a low-cost compound, found abundantly in nature and most widely utilised across plastics in aerospace applications, but required in high addition levels (60 wt-%).
- TDCPP tris (1,3-dichloro-isopropyl)phosphate.

Several newer and commercially important flame retardant chemicals are now being incorporated into products to replace the PBDEs. These include brominated flame retardants (tetrabromobisphenol A [TBBPA] and hexabromocyclododecane [HBCD]), chlorinated phosphates (tris(diCl-isopropyl)phosphate [TCDPP]), and brominated phthalates (ethylhexyl-tetraBr-phthalate and bis-(2-ethylhexyl)-tetraBr-phthalate [TBPH]). Figure 12 shows flame retardants used in the aerospace applications in North America between 2012 and 2022. Toxicologic evidence suggests that these compounds may have an impact to human health. For example, the chlorinated phosphate flame retardant used today is similar to the brominated phosphate

flame retardant used in children's pyjamas in the late 1970s which was found to be mutagenic [12]. Limited information is currently available regarding exposure to flame retardants on commercial aircraft.

North America flame retardants for aerospace plastics market, by product, 2012 - 2022
(Tons)

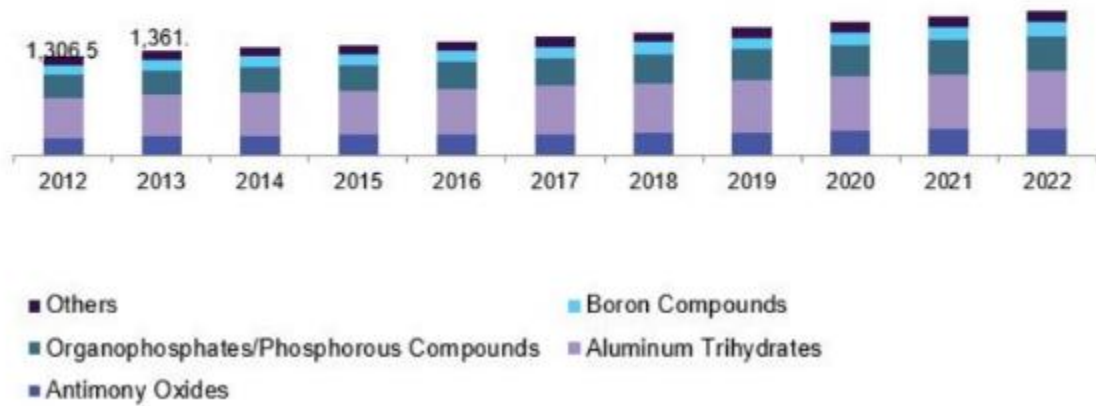


Figure 12: Overview of North American flame retardants market for aerospace applications [13]

5 THERMOPLASTIC TEST CAMPAIGN

For an Airbus A320 aircraft that has been dismantled at ICL facilities, a selection of thermoplastic components was made (e.g. passenger window panels) to measure chemical composition using an XRF handheld analysis system supplied by Coolrec. The aim was to detect non-fibre-reinforced thermoplastic components equipped with a brominated flame retardant as a waste stream to be purified by the CREAToR technology. Those components came from 3 different Airbus A320 aircraft. In order to align the results with the aircraft age and manufacturing practices and the chemical flame retardants used, the following delivery dates to the initial airliner were recorded:

- 14/12/1990
- 20/10/1989
- 14/01/1992

Regarding the measurement method, all components were wipe cleaned with a cloth before analyzing them. Measurements were carried out using an XRF Hitachi XMET handheld analyser, and a desktop NIR setup from Coolrec for wavelength monitoring (see Figure 13). Measurements were carried out by Coolrec on-site at Aeircircular Ostend on 16/02/2021.

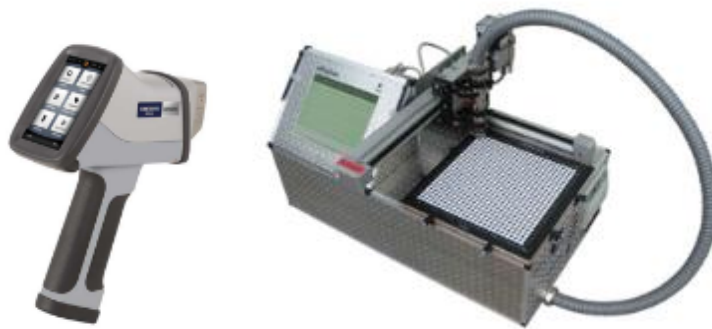


Figure 13: XRF Handheld and NIR desktop measurement device from Coolrec, as used in the test campaign

XRF analysers determine the chemistry of a sample by measuring the fluorescent (or secondary) X-rays emitted from a sample when it is excited by a primary X-ray source. Each of the elements present in a sample produces a set of characteristic fluorescent X-rays ("a fingerprint") that is unique for that specific element, providing a qualitative and quantitative analysis of material composition. This makes it ideal for incoming inspection and quality control of different components.

The sample is irradiated with high energy X-rays from a controlled X-ray tube (XRF analyser). When an atom in the sample is struck with an X-ray of enough energy (greater than the atom's K or L shell binding energy), an electron from one of the atom's inner orbital shells is dislodged. Then the atom regains stability, filling the vacancy left in the inner orbital shell with an electron from one of the atom's higher energy orbital shells. The electron drops to the lower energy state by releasing a fluorescent X-ray. The energy of this X-ray is equal to the specific difference in energy between two quantum states of the electron. Finally, the measurement of this energy is the basis of XRF analysis.

In total 11 different pieces were analysed (i.e. passenger window panels). Of these 11, 2 were not measurable due to their black colour and only 5 of them contained bromine in a range between 1 to 1262 ppm. Moreover, the main polymer is PC, found in 6 of the 11 measured pieces.

6 CONCLUSIONS

After the literature review and the measurements that have been carried out in the A320 at ICL facilities, it can be determined that there is a very low (negligible) content of brominated flame retardants in aircraft components. Therefore, it can be concluded that the aircraft thermoplastic waste streams do not need to be purified from bromine containing flame retardants but should be directed to mechanical recycling. This opens up a reuse opportunity for these materials which is not currently exploited.

7 REFERENCES

- [1]. D. Forsberg, Aircraft Retirement and Storage Trends-Economic Life Analysis Reprised and Expanded Report; Avolon: Dublin, Ireland, 2015.
- [2]. A. Elsayed (Egypt), T. Roetger (IATA) and A. Bann (ICCAIA), "Best Practices and Standards in Aircraft End-of-Life and Recycling", pp 279-284, 2019: https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg279-284.pdf
- [3]. E. Suomalainen¹, A. Celikel¹ and Pierre Vénuat², (ENVISA¹, Bartin Recycling Group²) ,"Aircraft metals recycling: process, challenges and opportunities",2014 : https://www.researchgate.net/publication/328290346_AIRCRAFT_METALS_RECYCLING_PROCESS_CHALLENGES_AND_OPPORTUNITIES
- [4]. Airbus, S.A.S. Process for Advanced Management of End-of-Life of Aircraft (PAMELA); Airbus Academy: Champniers, France, 2008
- [5]. Xiaojia Zhao; Wim J.C. Verhagen and R. Curran, "Disposal and Recycle Economic Assessment for Aircraft and Engine End of Life Solution Evaluation", *Appl. Sci.*,vol.10(2), pp 522, January 2020 : <https://doi.org/10.3390/app10020522>
- [6]. Aircraft characteristics, airport and maintenance planning, Airbus, Rev. December 2020: <https://www.airbus.com/aircraft/support-services/airport-operations-and-technical-data/aircraft-characteristics.html>
- [7]. Mouritz A.P (2012).Aerospace materials: past, present and future. (pp15-pp38) *Introduction to aerospace materials*. Cambridge, UK: Woodhead Publishing Limited
- [8]. <https://www.airbus.com/aircraft/previous-generation-aircraft/a340-family/a340-600.html>
- [9]. <https://www.azom.com/article.aspx?ArticleID=10298>
- [10]. <https://insights.globalspec.com/article/12596/thermoplastic-composites-for-aerospace-applications#:~:text=Thermoplastic%20composites%20for%20aerospace%20applications%20use%20high%2Dperformance%20thermoplastic%20resins,polyaryletherketone%2C%20polyetherimide%20and%20polyphenylene%20sulfide.>
- [11]. <https://rescoll.fr/wp-content/uploads/Fire-Flammability-Test-List-1.pdf>
- [12]. National Air Transportation Centre of Excellence for Research in the Intermodal Transport Environment (RITE) , "Exposure to Flame Retardants in Commercial Aircraft", 2012: https://www.faa.gov/data_research/research/med_humanfacs/cer/media/FlameRetardantsExposure.pdf
- [13]. Flame Retardants for Aerospace Plastics Market Size, Share & Trend Analysis Report By Product (Aluminium Hydroxide, Phosphorous), By Application (Polyolefins, Epoxy Resin, UPE, PVC) By End-Use Industry And Segment Forecast, 2015 – 2022: <https://www.grandviewresearch.com/industry-analysis/flame-retardants-aerospace-plastics-market>

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