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The use of plasma generators for the reuse and recycling of spacecraft solar arrays

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Abstract

To begin recycling spacecraft, exploring potential recycling processes and use cases for the materials and defining initial approaches are essential. For that, the different materials used in solar arrays and their layering are characterised and an overview of widely used array materials is presented. The degradation of solar panels due to space weather is explained and existing recycling techniques on Earth are assessed based on their feasibility in space. Candidates for first recycling experiments are identified. Lastly, process suggestions for destroyed rigid-panel solar cells, focusing on recycling the aluminium backsheet, and reusing still-intact cells are presented.

1. Introduction

Sustainability in space refers to the ability to continue space activities until the indistinct future, having equal access to the benefits of exploration and research to meet the needs of present generations while preserving access to the space environment for future generations.[83] To reach this goal, the space community introduced several techniques to assess and counteract space debris.[84] Space sustainability, however, should not be limited to the problem of space debris, but should also consider other challenges, such as increasing the esteem of resources and decreasing the impact on the Earth's atmosphere. To address these problems, the concept of circular economy has to be introduced into the space economy.

The concept of circular economy can be described as economic models aiming to minimise waste and discarded products by keeping them in use as long as possible, through strategies like reusing, remanufacturing and recycling. This approach is expected to reduce the need for extracted raw materials. ESA has presented plans to focus on developing in-orbit servicing missions starting in 2030, aiming to refuel, assemble and recycle in orbit.[61] More actors conducting research in the fields of recycling and manufacturing in space, and recycling strategies for the different spacecraft parts are required.

Solar arrays constitute one of the most common parts of spacecraft. Depending on the array configuration, they are composed of rare materials, increasing the interest and priority for recycling, and they are comparably accessible for dismounting. Thus, they pose good candidates for the first recycling approach, for which a plasma generator was suggested.[15]

Plasma generators are a tool to generate high-enthalpy streams of ionised gases, providing a high heat flux to another body. Since the development of inductively heated plasma generators, the power requirements for the plasma generation are low enough to be provided for by solar arrays in space. They can thus be used as a tool for waste management in space.[40] A plasma generator was investigated for electrical waste treatment on space stations, which produced numerous gases that can be used as fuel.[5] Therefore, the possible applications of a plasma generator for the recycling of solar arrays in space are investigated in this paper.

To develop a recycling approach for solar arrays in space, different recycling strategies have to be explored. For that, the structure of solar arrays and their degradation in the space environment must be understood. As a starting point, the different recycling strategies applied for solar panels on Earth and their applicability in space are explored.

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With this basis, different solar arrays are rated based on their circularity potentials, and the possibilities of recycling and reusing with a plasma generator are explored.

2. Solar array structure

This chapter explains the general array structure and the preferred mounting techniques and configurations used in space. Following this, the space environment and its degrading influence on the arrays are described to assess the physical state of the materials when ready for recycling.

2.1 Array structure

The core of solar modules are the solar cells made of semiconductor material. The most abundantly used solar cells in spaceflight are silicon (Si), gallium arsenide (GaAs) and multi-junction cells based on GaAs. They convert the Sun's light into an electrical current based on the photoelectric effect. Electrodes, mostly made of silver, are sintered onto both sides to extract the photocurrent.[94,12]

Solar modules consist of many cells wired in parallel and series to combine voltage and current as needed.[8] The modules consist of a material laminate, as shown in fig. 1, designed to provide mechanical stability and cell protection.

The coverglass mainly provides mechanical rigidity and protection to the cell and enhances the thermal emittance of the cell. The covers most frequently used in space are made of fused silica and ultra-thin borosilicate glasses.[63,12]

The adhesive layers between the glass and the cell and between the cell and the backsheet serve as an encapsulant for the cells, protecting them from the environment and as a glue. Usually, siloxane encapsulants, especially room-temperature vulcanising (RTV) silicons, are used, due to their high heat resistance, low outgassing behaviour, low-temperature flexibility and high UV stability.[85,86,21]

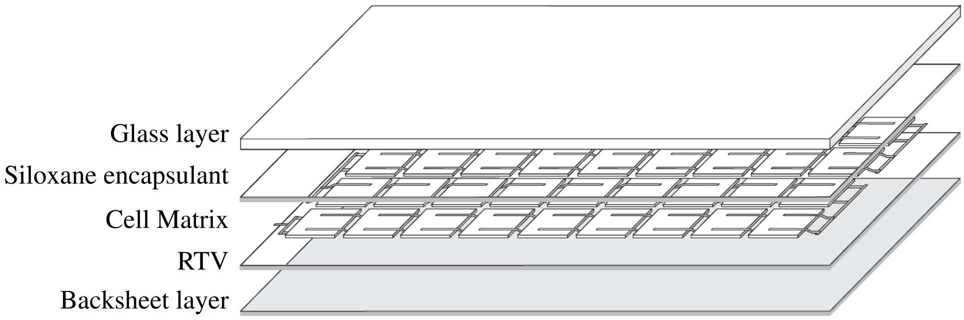

Figure 1: Basic structure of the laminated materials in solar modules. Modified from Tobías et al..[78]

The backsheet structure depends on the array configuration of the spacecraft, which in turn depends on the array's mounting, deployment and storage during launch. The different satellite array solutions can be classified into body-mounted, rigid panel planar, flexible fold-out and flexible roll-out arrays.[63]

Body-mounted arrays are particularly selected for small satellites that don't need that much power. Their backsheets are oftentimes made of fibre-reinforced polymers, as used in printed circuit boards.[10]

Rigid panel planar arrays have been frequently used for the first satellites due to their simple achievement of stability during launch, and are still used when several hundred watts of power are required. The backsheet is usually made of a sandwich structure with honeycombed aluminium between either aluminium or carbonfibre reinforced polymer (CFRP) layers. Between the solar cells and the sandwich structure, a Kapton® layer for thermal and electrical insulation is used.[12,85] These panels are framed in aluminium or CFRP.[10,63]

The flexible fold-out arrays are the preferred choice for several kilowatts of power and high packing efficiency, especially for astronomical or Earth observation satellites. Those flexible backsheets are made of Kapton® or other polyimide substrates with stable aluminium or CFRP frames.[97,63]

The fourth array type, the flexible roll-out array, requires highly flexible thin-film solar cells to be rolled tightly into a cylinder during launch. The backsheets are made of polyimide substrates, without a frame enclosing the material laminate.[10,63]

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To give an overview of often-used materials in spacecraft solar arrays, the arrays of navigation, communication and television satellites have been investigated. The most numerous constellations and satellite bus types are listed in tbl. 1 with their rigid panel planar array material combinations, as far as publicly available.

Table 1: Overview of satellite constellations' and bus types' solar array materials

		cell			**contacts**				**coverglass**				**adhesives**					**backsheet**				**launches**	
		Si	GaAs	triple-junction GaAs	Kover	Silver	Copper	Tin & Lead	fused silica	CMX	CMG	Spec 3.4	RTV 560	GE 566 RTV	DC93500	Elastosil S 690/695	RTV-S 691	Al honeycomb	CFRP	Kapton	Kevlar	from	till
Starlink	Block v0.9[48,77,81,80]	×				×	×	×										×				2019	2019
	Block v1.0[48,77,81,80]	×				×	×	×										×				2019	2021
	Block v1.5[48,77,81,80]	×				×	×	×										×				2021	2023
	Block v2-Mini[48,77,81,80]	×				×	×	×										×				2023	2024
	Block v2-Mini-D2C[48,77,81,80]	×				×	×	×										×				2024	–
GPS	Navstar[48,74,79,52]	×				×			×				×					×	×			1978	1985
	Navstar-2[48,74,79]	×				×			×				×					×	×			1989	1990
	Navstar-2A[48,74,79]	×				×			×				×					×	×			1990	1997
	Navstar-2R[48,79,30,67]	×			×		×		×					×				×		×		1997	2004
	Navstar-2RM[48,79,30,67]	×			×		×		×					×				×		×		2005	2009
	Navstar-2F[48,82]			×														×				2010	2016
	Navstar-3[48,76,73]			×														×	×			2018	–
Galileo	IOV[48,32,2,9,3,25,26,38]			×	×	×				×					×		×	×	×			2011	2012
	FOC[48,32,2,9,3,25,26,19,38]			×	×	×				×					×		×	×	×			2014	–
Communication and television	HS-601[48,49,14]	×			×	×				×					×			×			×	1992	2004
	HS-601HP[a][48,49,14]	×	×	×	×	×					×				×			×			×	1997	2017
	BSS-702HP[48,4]			×	×	×				×										×		2002	2019
	BSS-702MP[48,4,13]			×	×	×				×										×		2012	–
	BSS-702SP[48,4]			×	×	×				×										×		2015	–
	Eurostar 3000[48,24,98,35,73]			×	×	×				×						×	×	×	×	×		2004	2022
	Eurostar 3000EOR[48,24,98,35,73]			×	×	×				×						×	×	×	×	×		2017	2023
	Eurostar 3000S[48,24,98,35,73]			×	×	×				×						×	×	×	×	×		2004	2012

[a] Changed during the years from Si, over GaAs to triple-junction GaAs

2.2 Degradation in space

Spacecraft in orbit must cope with multiple space weather effects. The emptiness of space combined with solar radiation induces substantial temperature variations. This can lead to thermal fatigue in solar arrays, especially in the adhesive layers, solar cell interconnects, and the cells themselves.[63] Furthermore, the charged particle environment in the Earth's orbit charges the spacecraft, which can lead to electrostatic arc discharges. This arcing can happen between solar cells, possibly creating an avalanche effect, spreading the arcing due to increased currents and destroying the entire array through the creation of short circuits and increased leakage current.[41,31] Those arcs occur primarily at the cell adhesive layer and the silver interconnects, leading to delamination effects, melting or vaporising the interconnects and decreasing the neighbouring solar cells' power output.[30]

Ionisation

When high-energy radiation, originating from solar particle events and Galactic Cosmic rays,[58] ionises the semiconductor material, it can lead to an increased leakage current and, therefore, a gradual degradation of the cell.[10] When the semiconductor is ionised by energetic charged particles, as from solar wind, solar particle events and trapped particles in the Van Allen belts, the charged particles might additionally leave ionisation tracks that will cause a current pulse.[58] If cells experience several such impacts in a short time, dangerously high voltages can be generated, which leads to arcing between the cells as described before.

In the coverglass, where most energy is dissipated to shield the cell, colour centres are formed due to ionisation when electrons are trapped by impurity atoms. This leads to a darkening of the glass and, thus, to reduced cover transmittance. Conversely, the absorption of the coverglass and the array operating temperature increase, resulting in a lower cell efficiency.[6,75,63]

Displacement damage

The atomic displacement due to irradiation with energetic charged particles is the dominant cause of degradation in solar cells.[10] An atomic displacement occurs if the incident particle can transfer enough energy to the nucleus of an atom to displace it permanently from its lattice site. The gap that the nucleus leaves behind is called a vacancy. The atom gets stuck in another vacancy, called a replacement collision, or amid other atoms in an off-grid place. This is then called an interstitial.[58] These displaced lattice atoms disrupt the crystal structure, which results in a declining power output and efficiency of the cell.[10]

Displacement damage can be partially reversed by irradiating solar cells with energetic charged particles at high material-dependent temperatures, which leads to an increased reorganisation of defects towards the perfect grid structure. These replacement collisions also occur during normal operating conditions of the array, but the annealing effect is subordinate compared to the damage.[28,75] In case of Si, the required temperature for an improved cell grid is between 200 °C and 400 °C[10,75] and in case of GaAs high annealing degrees were reported at a temperature of 120 °C.[28,10]

Hazardous meteoroids and orbital debris

The interplanetary space and the orbits around Earth are filled with micrometeoroids that can hit the spacecraft in orbit. The ever-increasing number of space debris in the Earth's orbit must also be considered a possible threat to the spacecraft.[44] Due to the comparably large area of solar panels, the probability of being hit is particularly high. The damage a solar array receives from an impact relies heavily on the particle's size, density, velocity and the accumulation of impacts. Small particles with diameters of 1 µm to 100 µm are mostly the cause for optical degradation of the glass cover by micro-cracks, scratches and craters, diminishing its transparency. When the arrays are penetrated by particles of large sizes and high velocities, the cells can also be damaged due to complete penetration and by induced plasma generation. In graveyard orbit, an area of $0.024\,\mathrm{m}^2$ is perforated every year.[22] Furthermore, when particles hit cables, some of the output power of the solar array is lost, and the heat generation of the burning can spread the damage to other nearby cables.[44]

3. Solar panel recycling approaches

3.1 Recycling methods in practice on Earth

There are many practical ways to recycle solar panels on Earth, but all the processes follow a certain scheme, as sketched in fig. 2. First, the panel's aluminium frame and bus bar are removed mechanically. In the next step, the coverglass, the cell and the backsheet are separated using different combinations of mechanical, chemical, and thermal techniques. After this delamination, the different materials are sorted, and the solar cells are leached with chemicals. The valuable materials from the electrodes are extracted via filtration and electrolysis, to be recovered separately from the Si.[88,7,57]

The module delamination aims to remove the adhesive layers that bind the cover, the cell and the backsheet together.[88] Ethylene vinyl acetate (EVA) is the most frequently used binder on Earth. It can be dispersed via different

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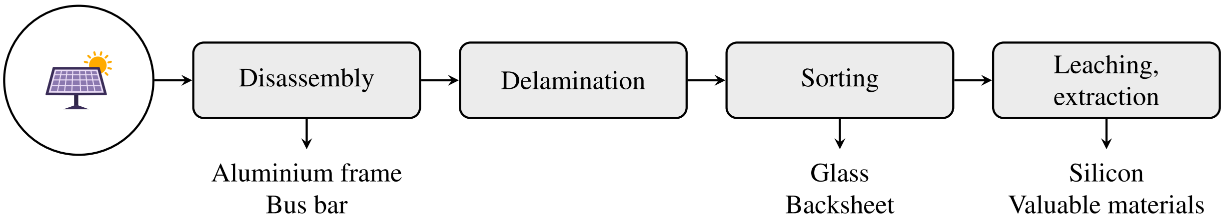

Figure 2: Schematic of solar panel recycling processes on Earth.

organic or inorganic solvents and thus poses a good method to delaminate the materials without breaking the cells.[92] Even though the solubility of the cell adhesive WACKER® RTV-S 691 was shown with success,[15] due to processing and outgassing problems of fluids in space, and due to the general safety issue of chemicals, this technique poses no practical solution for space processes.

Mechanical delamination techniques crush the laminate into small pieces or cut or peel the glass or the backsheet from the remaining material. These methods are used as pre-treatments for chemical or thermal delamination steps.[17]

EVA has a melting temperature of 90 °C, a characteristic that is put to advantage using a thermal delamination approach. An efficient method is the pyrolysis of EVA, which describes the chemical decomposition of the binder in an inert environment. In the case of direct pyrolysis, the module is heated with the backsheet until the polymers are entirely removed. However, this process also produces toxic gases released from the backsheet material.[88] The two-stage pyrolysis addresses the problem of toxic gases by heating the module first to a lower temperature to soften the EVA and facilitate the stripping of the backsheet, followed by a hold at a higher temperature for complete polymer removal.[33,87] Thermal treatment of solar arrays can be implemented in microgravity and is thus the best approach for delamination in space.

3.2 Recycling possibilities

Due to the space weather, the satellites orbit and their time in space, solar arrays will be in different physical states. Consequently, the recycling approach has to be adjusted to the state of the array. The solar cells' efficiency will decrease depending on the incident particle dose and can be partially recovered with annealing. The transmission of the coverglass will be reduced by micrometeoroid and space debris impacts, as well as by ionisation-induced colour centres. Additionally, the entire array could be penetrated. Therefore, depending on the severity of the physical damage, the delaminated array materials can either be used for remanufacturing new solar arrays with annealed solar cells or recycled for other purposes in spaceflight.

Looking at the mass proportions of typical rigid-panel planar arrays, more than half of the panel's weight is comprised of the aluminium honeycomb structure. Since aluminium alloys are often used in spaceflight, their recycling should be aimed for. Possible use cases are spare parts for satellites, space stations' structures and experiments. Since the parts don't have to be qualified for the high forces during launch, the demands for structural stability are generally lower, which permits a less material-consuming design.[50] In the summer of 2024, the first stainless steel parts were printed with a wire-fed Direct Energy Deposition (DED) in microgravity. This technique melts metal with a high-power laser, depositing it layer by layer to create a three-dimensional structure. The metal can be fed as a thin wire or as a fine powder.[27,1] To produce metal wire, metal billets are usually rolled into round bars to be drawn through dies with decreasing diameters.[42] The fine powder is produced via atomisation, where small droplets are broken from molten metal and cooled in an inert atmosphere to solidify.[70,46] However, both processes need to be verified in microgravity first.

When looking at the material values of solar cells, these semiconductor materials are by far the most valuable component of the array. When they're not damaged due to physical impact, keeping the cells intact during recycling would be a favourable approach to anneal them afterwards and reuse them for new solar arrays. When the cells are damaged, the materials should be extracted for further use. The required process for gallium and arsenic extraction is still scarcely researched, and the few proven methods require solvents or are based on vaporisation.[96,95] Broken Si cells can be used as an alloy element for the recovered aluminium. Adding silicon to the widely used Al5056 in space engineering improves the melt fluidity, suppressing the manufactured part's hot cracking.[51,59] The alloy can be produced with electromagnetic levitation, where the material is melted inductively and mixed strongly due to the electromagnetic field, ensuring a very homogeneous material. To cool the metal, an inert gas flow can be used to control the cooling rate and transport the excess heat towards the satellite's thermal control system.[29,65]

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The different adhesives, coatings and composite layers comprise approximately 10 % of the solar array's weight. These materials can be partially transformed into fuel gases. These gases can be used to refuel several satellites to extend their lifespan in orbit, or for orbit transfers and for the approach of disused spacecraft of the recycling satellite itself. Lastly, using the emerging gases to generate power for the recycling system should also be considered.[40]

The coverglass comprises more than 10 % of the panel's mass and can either be remanufactured for new solar panels or be used to manufacture optical lenses for instruments on space stations, if the degree of impurity isn't too high due to the impacts. This glass processing can also be performed via additive manufacturing. To achieve very high accuracies in the glass structure and excellent optical parameters, two-photon polymerisation (TPP), a photopolymer-based process, has been developed.[91,47,89] The shape of the manufactured part is printed by activating the photocurable resin matrix enclosing the glass nanoparticles to form an exoskeleton for the glass part. Afterwards, this body undergoes pyrolysis to remove the resin, followed by the sintering of the glass part. The nanoparticles for TPP can be synthesised by electron beam[11] and plasma synthesis.[68] In both processes, the material is melted and evaporated through the heat transfer from the accelerated charged particles. The vapour condenses due to a cool inert gas or on the cold chamber walls, forming small nanoparticles. The feasibility of these processes also needs to be demonstrated in microgravity first.

To recycle the solar panel materials as described above, it is necessary to separate them first. The thermal degradation of the adhesive layers and the other polymer layers can be achieved with a plasma generator. Since satellite solar arrays are huge, a mechanical process is required to cut the array into smaller pieces for the plasma generator treatment. This step needs to be designed with care so as not to break the solar cells if their reuse is aimed for. The complete recycling process is sketched in fig. 3. After the delamination, the materials must be sorted for further recycling. This is especially difficult if the glasscover and the solar cell are broken due to the potential mixing of these particles. Therefore, assessing the probability of cell and glass breakage in the delamination process is important.

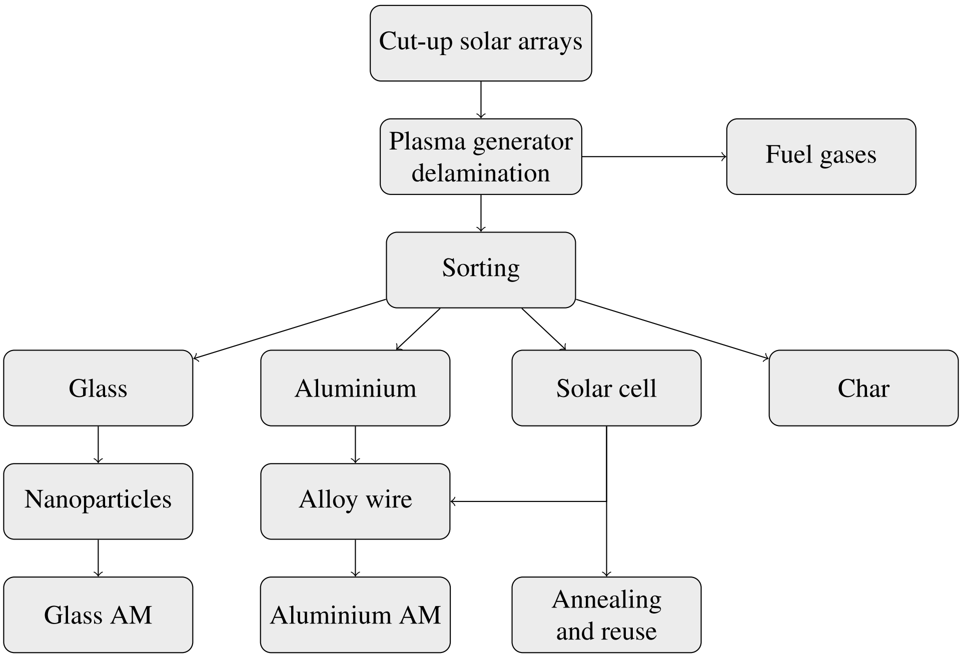

Figure 3: Graphical depiction of the proposed recycling approach

3.3 First recycling targets

Since recycling solar panels in orbit still has to prove viable, the first spacecraft types aimed for recycling should be very similar in their array configuration so that one process can be applied. Furthermore, it is favourable if several satellites with the same structure belong to the same entities, making it easier to gain recycling rights. Another aspect is the complexity of dismounting the solar panels from the spacecraft. Body-mounted arrays are rather difficult to dismount compared to deployed rigid or flexible arrays, pointing away from the main body. Lastly, it is beneficial when the satellites are in similar orbits, so that as little fuel as possible is required for orbit transfers, and if the satellites are in less crowded orbits for higher accessibility.

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Spacecraft that fit these criteria are large satellite constellations for navigation, communication and television as listed in tab. 1. Numerous of these satellites are already out of service due to their age or malfunctioning. These satellites are either still positioned in medium Earth orbit or have been transferred to the graveyard orbit. These satellite types are thus good candidates for first recycling missions.

4. Material parameters for thermal degradation

The first recycling step is the separation of the array materials. Silicon elastomers do not melt, but they degrade at high temperatures. The adhesive layers between the materials have to be decomposed enough so that the materials can be separated without degrading the remaining materials during the process. Thus, the melting temperatures, or in the case of glass, the softening temperature, have to be considered. In tbl. 2 the various decomposition temperatures of frequently used materials are listed. Al 5056 is a frequently used alloy for the aluminium honeycomb structure, and the alloy Al 2024 is usually used for outer sandwich layers.[34]

Table 2: Decomposition temperatures for solar panel materials

Material layer	**Material specification**	**Decomposition temperature (°C)**
Coverglasses	Fused Silica[16]	1585
	Microsheet[72]	720
Adhesives	DC 93-500[66]	>200
	WACKER® RTV-S 691[64]	>200
Solar cells	c-Si[56]	1414
	GaAs[55]	1238
Contacts	Silver[64]	962
	Copper[64]	1080
	Kovar[64]	1450
Backsheet materials	Al 2024[64]	502-638
	Al 5056[64]	571-638
	CFRP[43]	>350
	Kapton®[64]	>600

When looking at the adhesives, coatings, and polyimides of the backsheet, the decomposition temperatures listed are equal to the onset temperatures where the first breakdown reactions occur. The thermal degradation of space-grade CFRP[39] and Kapton®[37,60] has already been investigated and published in reducing and inert environments. Both materials degrade completely in an oxygen-rich atmosphere, while close to half of the mass remains in an inert environment. Kapton starts degrading at temperatures above the melting temperature of aluminium. For complete decomposition, it is consequently necessary to treat this layer separately from the honeycomb layer and therefore after the delamination process.

There are no results of thermal degradation experiments of the adhesives published yet for relevant temperature ranges. Due to the organic nature of the adhesives, the degradation characteristics strongly depend on the exact composition and structure of the molecules, even when based on the same molecule chain.[18,36] It is thus necessary to test the exact used adhesives for the detailed process design.

4.1 Experimental setup

Thermal decomposition characteristics have been determined with a thermogravimetric analysis (TGA). The material of interest is heated up to typically 1000 °C with a constant heating rate in an inert or reducing environment. During the heating, the mass loss of the material is measured. This analysis yields the decomposition onset temperatures and how much char is left after complete decomposition.[54]

The WACKER® RTV-S 691 samples have been analysed according to DIN EN ISO 11358-1[20] with a constant heating rate of $10\,^{\circ}\mathrm{C\,min^{-1}}$ from room temperature up to 1000 °C in both nitrogen and oxygen atmosphere to assess the maximum mass loss upon heating due to pyrolysis and molecular oxygen. Additionally, isothermal holds of three hours were performed at 450 °C, heating up with $20\,^{\circ}\mathrm{C\,min^{-1}}$, to assess the amount and speed of degradation of the adhesive at a temperature below the melting temperature of the aluminium layers.

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4.2 Thermal degradation of WACKER® RTV-S 691

Samples of the cured WACKER® RTV-S 691 have been subjected to thermogravimetric testing described above. The results of the experiments are plotted in fig. 4.

For the constant heating rate experiments, in both the reducing and the inert environment, the sample pieces started to degrade at around 300 °C. In an argon environment, the degradation converged with a residual mass of 63.6 %, whereas in air, a mass of 71.4 % was left. The residues of both samples were cracked and brittle in their structure. The samples degraded in the argon atmosphere turned black, while the samples in air stayed red as the original material.

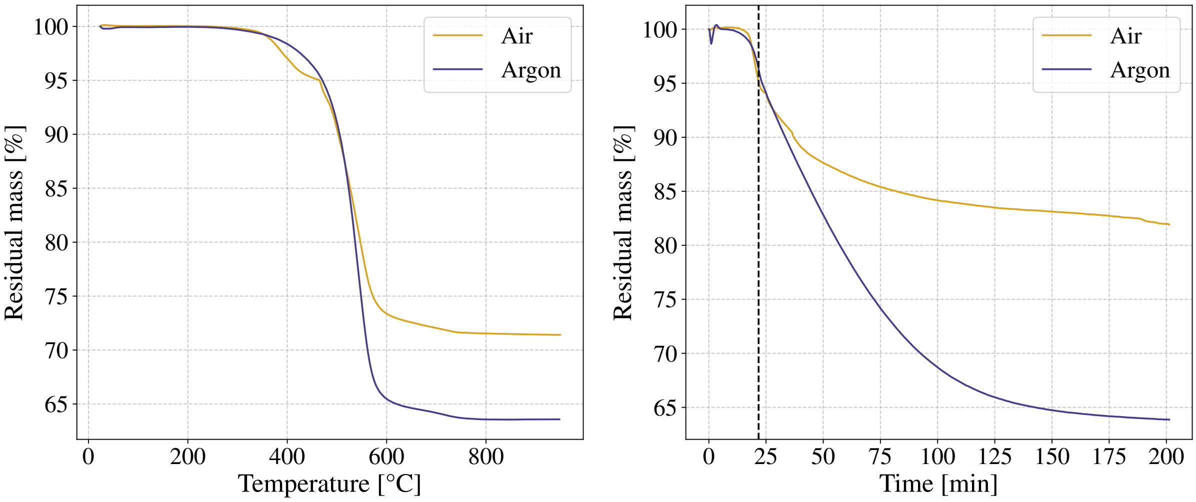

Figure 4: TGA results of WACKER® RTV-S 691 with a constant heating rate of 10 °C/min (left) and an isothermal hold at 450 °C for three hours (right)

For the isothermal holds, the time at which 450 °C was reached is marked with the black dashed vertical line. The samples degraded in argon showed a similar residual mass to the results with the constant heating rate. However, more than 80 % of mass was left for the samples degraded in air. This indicates that the samples degraded in several steps in a reducing environment, which is also visible as the step at around 480 °C for the constant heating rate. This second degradation step thus needs a higher activation energy and happens at a much lower rate at 450 °C. Nevertheless, both residues were as brittle as those from the constant heating rate experiments and showed the same colour.

5. Material separation with a plasma generator

A plasma generator is a good tool for quickly heating material to high temperatures. However, this also leads to the consequence that planning the exact required process parameters is indispensable if some materials are not meant to be destroyed. It is thus necessary to find the fitting heating rate and treatment time to reach the decomposition temperature for the adhesive layers without exceeding the temperature limits of the other materials.

The simulation was performed on a rigid solar array with an aluminium honeycomb backsheet. The model has a base area size of 21.3 mm x 33.15 mm. The modelled materials are from top to bottom: Fused Silica 7980, DC 93-500, c-Si cell, WACKER® RTV-S 691, Kapton®, CFRP, Al 5056 Honeycomb and CFRP. The height of the modelled material layers and their material parameters are listed in tab. 4. The wall thickness of the honeycomb structure is 0.2 mm. For these first simulations, mostly constant parameters were used. For the exact planning of the recycling process, temperature-dependent material parameters are required.

For the simulation, the model's symmetry was used so that only a quarter of the model had to be meshed. The materials had, at a minimum, two layers above their thickness, and the element size at the contact areas to the honeycomb structure was matched. As quality criteria, a maximum aspect ratio below 10, a minimum element quality of 0.2 and a maximum skewness of 0.8 were aimed for.[71] Linear and quadratic element orders were chosen for the thermal and structural analysis, respectively. The mesh independence for the results was proven with a maximum change of temperature by less than 1 %.

As obtained by TGA, for degrading the adhesive layers, a temperature above 400 °C must be held for several hours. To achieve this value without degrading the glasscover or the aluminium, a heat flux of 200 kW m^{-2} with an

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Table 3: Material parameters used in the simulations

Material	**Density** $[\frac{kg}{m^3}]$	**Young's modulus** [GPa]	**Poisson's ratio** [-]	**Shear modulus** [GPa]	**Specific heat capacity** $[\frac{J}{kgK}]$	**Thermal conductivity** $[\frac{W}{mK}]$	**Thermal expansion coefficient** $[10^{-6}\frac{1}{°C}]$	**Layer height** [mm]
Fused silica[16]	2200	73	0.16	31	770	1.38	0.57	0.5
DC 93-500[48]	1030	2.5e-3	0.48	8.4e-4	867	0.146	300	0.05
c-Si cell[45,93]	2330	170	0.28	66.4	677	148	2.6	0.2
WACKER® RTV-S 691[48]	1420	2.5e-3	0.47	8.5e-4	701	0.39	200	0.1
Kapton®[23]	1420	2.76	0.34	1.03	1090	0.2	34	0.25
CFRP[69]	1550	2	0.3	0.77	1000	2.5	10	0.3
Al 5056[53]	2640	75	0.33	28.2	900	115	24.1	20

impingement time of 12 s was found. This results in an equilibrium temperature of the laminate of 490 °C, which is even higher than the temperature investigated in the isothermal TGA experiments. The resulting brittleness enables the physical separation of the material laminate layers. Additionally, the adhesive residues are likely detached from the other materials, making further surface treatment unnecessary. However, it has to be tested whether residues react with the material surfaces when exposed to these conditions, bonding them to the surface.

As described earlier, heating the material laminate will result in thermal stresses, which could lead to the breakage of the coverglass and the cell. The resulting maximum normal stresses perpendicular and shear stresses parallel to the material planes are listed in tab. 4, together with the material strengths at room temperature. The strain point of fused silica is at 893 °C. Above this temperature, the material parameters begin to change, and the strength will decrease.[16] For crystalline silicon, the decrease in material strength will start slowly around 600 °C.[62] It must be kept in mind that the coverglass very likely has some scratches and impact points on the surface, leading to decreased material strength. Cutting the solar array for the plasma generator treatment could also lead to increased material stresses. However, the induced stresses are considerably lower than the material strengths. Therefore, the risk of breakage of the coverglass and the solar cell due to thermal stress can be assumed to be small.

Table 4: Material strengths and maximum induced stresses

Material	Tensile Strength [MPa]	Max. normal stress [MPa]	Shear Strength [MPa]	Max. shear stress [MPa]
Fused silica[16]	54	0.540	-	0.300
DC 93-500[48]	6.7	0.870	3.2	56.7e-3
c-Si cell[45,93]	150	1.07	-	0.542
WACKER® RTV-S 691[48,90]	4.5	0.935	2.5	16.8e-3

The cracked TGA WACKER® RTV-S 691 sample residues introduce another cracking source for these materials. This risk is even higher with high heating rates, as are present with plasma generators, since even more energy will be released. This behaviour first needs to be investigated thoroughly with the exact material combinations on hand, but the risk is high. Consequently, recycling the aluminium honeycomb backsheets is the most promising part and should be focused on first.

6. Conclusion

For the first recycling approaches, rigid planar solar arrays of satellite constellations were recommended based on their accessibility in construction and orbit and the higher number of identical array configurations. An overview of the constellations' solar array materials was presented, as far as publicly available.

Based on the structure of rigid planar solar arrays and the degradation mechanisms, in-space recycling strategies for solar array materials were identified. The materials must be separated to use the solar array materials to remanufacture new solar arrays or recycle them into other parts for spaceflight. This separation can be achieved through thermal

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degradation of the adhesive layers with a plasma generator due to its high heat flux densities and good control of the plasma parameters. The process requires careful cutting of solar arrays between cells into smaller pieces to fit into the vacuum chamber and enable better handling without damaging the coverglass or solar cells. The thermal degradation will generate fuel gases that can power the recycling process and orbital manoeuvres of the recycling spacecraft or other spacecraft. High-quality recovered glass can be used to manufacture new coverglasses or other optical elements through additive manufacturing. The aluminium backsheet can be reused or recycled for other metal parts with wire-based DED. If physically intact, the solar cells can be annealed and reused for new solar arrays. Damaged Si solar cells can be used to improve the material properties for aluminium additive manufacturing.

To design an effective thermal degradation process for the adhesive layers, precise knowledge of their thermal behaviour is essential. The thermal behaviour of WACKER® RTV-S 691, selected as a representative cell adhesive, was investigated using two different types of TGAs with a constant heating rate of 10 °C/min and isothermal holds of three hours at 450 °C in a reducing and an inert environment. In both environments and testing conditions, the residual mass of the adhesive sample remained high. Still, the residues became brittle due to crystalline silicon oxide structures, indicating that the array materials can be separated after thermal degradation. The adhesive residues likely detach from connected materials, though further investigation is needed.

To achieve the degradation temperature with a plasma generator without melting the remaining materials, a transient thermal analysis was performed for a typical rigid solar array material laminate. A heat flux of $200\,\mathrm{kW\,m^{-2}}$ with an impingement time of 12 s was found to produce the required temperature. A transient structural analysis of this thermal degradation process was used to assess the risk of cracking in the coverglass and solar cells. The induced thermal stresses were determined to be low enough to consider the risk minimal despite the model's simplicity. However, the TGA samples of WACKER® RTV-S 691 cracked during all experiments, indicating an additional risk of damaging the coverglass and solar cell that needs further testing.

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