A BUSINESS CASE FOR SPACE DEBRIS
EXECUTIVE SUMMARY

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SUMMARY

As on Earth, space debris should not only be seen as a threat. Instead, the value of waste as a recycled good should be understood. On Earth, this potential is already fully recognized. The German recycling industry alone generates more revenue than the entire European space industry. Nevertheless, this treasure was never lifted in space. The conducted study by Frank Koch, Orbit Recycling substantiates the thesis, that recycling of space debris is a challenge, but within the framework of Europe`s technical capabilities. The recycling of raw materials for space manufacturing seems to be the initially low-hanging fruit and objects with a high aluminium content the ideal recycling target.

Space agencies around the world expressed their interests in a lunar ground station in the *Global Exploration Roadmap* (GER), which drives the demand for construction material on the Moon. A supply through the recycling of space debris would avoid costly material transports from Earth and could act as an interim solution until lunar *In-Situ-Resource-Utilization* (ISRU) technology becomes available. The estimated price of 150,000 euro per kilogram of recycled aluminium on the Moon should at least be cost-competitive.

The identified use case is shown in Figure 1. By tugging old Ariane upper stages from their current positions in GTO further to the Moon, dozens of tonnes of aluminium could be recovered and recycled. The aluminium could act e.g., as building material, for casting tools and objects or as fuel component.

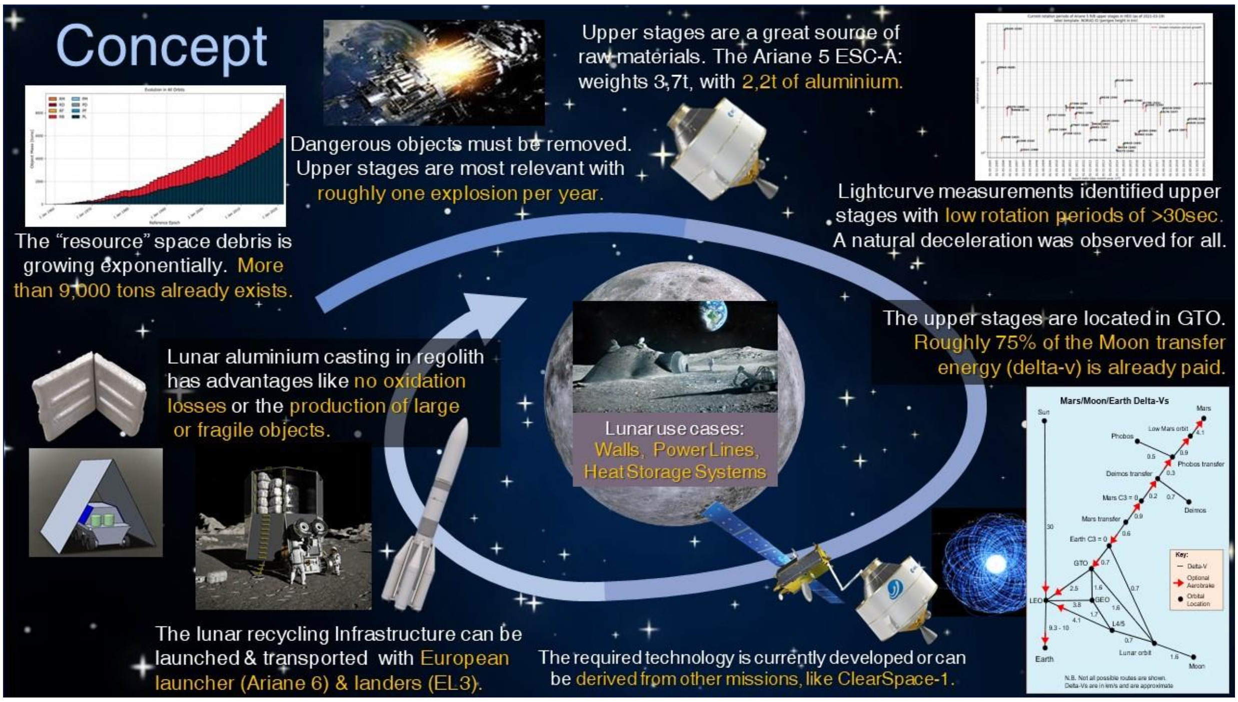

Figure 1: Space Debris Recycling (Orbit Recycling)

In addition, Europe is removing a large part of its entire space debris mass from Earth`s orbit, thereby reducing the overall risk of collision for all other space activities.

Additional research is needed to mature the concept presented and close certain capability gaps. However, since most of the required technology already exists or is currently being developed for other space missions, many synergies could be exploited to reduce the remaining realization budget. The following is a shortened list of relevant activities and identified synergies from the study.

1. To identify the ideal recycling targets, a detailed catalogue of space (debris) objects, including material composition and used components must be created.
    a. European data sets such as DISCOS should be extended by the missing object information. Since this is required for all future space servicing mission, there are no additional costs for space debris recycling.
2. Ground observation of target objects should be carried out to track their trajectories and tumbling behaviour.
    a. Europe has a large amount of data available. However, light curve measurements should be combined with RADAR / LASER observations to generate even better data sets which are analysed via machine learning algorithms to simulate the rotation behaviours. The underlying simulations and rotation models would be beneficial for all types of object movement predictions, especially for complex trajectories of space servicing mission in GTO, where space debris recycling could also benefit.
3. (Contactless) Detumbling technologies must be evaluated and matured for use in space.
    a. The first theoretical foundations exist in Europe, but they need to be improved. Europe must catch up with the US and Japan to develop its own detumbling solution for uncontrolled space objects, if space servicing missions are to be carried out from Europe. Various coil designs and materials should be evaluated for their effectiveness. Space debris recycling could benefit directly from these developments.
4. Gripping technologies must be evaluated and matured for use in space.
    a. Existing tools such as the *European Robotic Arm* and the upcoming *ClearSpace-1* solution should be examined for their general reuse & scaling potential for space servicing missions, where recycling could also benefit from.
5. For material transports from the Earth (orbit) to the Moon, various space tug concepts are required.
    a. Depending on the application, fast but expensive solutions or slow but more cost-effective solutions are used to supply the upcoming Lunar Gateway as well as any lunar ground station. A CDF is proposed to discuss these contradictive requirements. The technology to-be-developed for theses supply tugs could be the basis for space servicing mission as well as for space debris recycling tugs.
        i. Existing development in the field of propulsion technology such as AVUM+, Space Rider, ESM/ATV and others could be shared between the different scenarios of lunar supply, space servicing and space debris recycling.
        ii. The technology developments of the GNC / AOPS components (e.g., *Clerarspace-1*) could be shared between the scenarios of lunar supply, space servicing and recycling.
        iii. Communication infrastructure and ride-share launch technology could be shared between the different scenarios of lunar supply, space servicing and recycling.
        iv. Trajectory calculations for optimized Moon transits (e.g., EL3) could be used for the upcoming lunar supply missions as well as the recycling missions.
6. The European Moon lander (EL3) could be shared between the currently planned lunar supply and research missions as well as for the transport of the recycling infrastructure to the Moon.
    a. EL3`s cargo capabilities should be evaluated against the recycling infrastructure requirements to identify potential limitations in the current design phase of EL3.
    b. Lunar impact simulations should be performed to better understand the effects of a failed EL3 mission. Space Debris recycling could directly benefit from the impact simulation results for its own concept of material transports to the Moon.

7. Planned lunar rover designs (such as PHASR) should be evaluated for their potential for use in collecting debris fragments from the lunar surface and for transporting them to the recycling station.
    a. These include the rover itself, its power supply, any manipulators, cameras, and sensors, as well as the transport capabilities to identify limitations and the necessary (minor) modifications for a dedicated recycling version of the rover.
    b. The transport of the rover to the Moon as well as any necessary communication infrastructure to control the rover should be evaluated for the potential use of the EL3 during the planned recycling missions.
8. Additional studies should be carried out on aluminium casting on the Moon, where Europe could become a world leader in lunar manufacturing. Even if it were not used for the recycling of space debris, it would also allow the production of local large objects derived from (ISRU) aluminium.
    a. Synergies in all areas (rover, furnace, power, communication, etc.) should be identified to minimize development efforts and costs.
    b. The sintering of regolith moulds and aluminium casting capabilities should be aligned with the requirements of the upcoming lunar ground station.
        i. The recycling concept enables various expansion stages of the recycling infrastructure as well as the removal of debris. The casting capacity could be scaled by 2 tonnes to 14 tonnes per year to meet the annual supply demand during the station construction.
        ii. In addition to space debris, EL3 lander modules and rovers could also be recycled.
        iii. By-products of the oxygen production from regolith such as aluminium and other metals should be evaluated for their use as an additional casting material.
    c. In addition to the recycling concept, Fresnel lenses could be the most energy-efficient way to sinter and glaze large surfaces on the Moon. This avoids dust clouds and rover wheel damages at frequently used passages (e.g., between the landing site and habitat). Further tests should be carried out to validate this concept.

In terms of content, the first part of the study begins with a brief overview of the problem of space debris and discusses the identified recycling potential. The second part deals with relevant technology aspects and highlights synergies with existing (research) activities of ESA and its industrial partners. The third part calculates the business case and compares relevant alternatives.

Frank Koch, Orbit Recycling has built up a network of renowned research and industry partners in recent years with the necessary skills and abilities of the above-mentioned areas. These partners are described in the study to emphasise that Europe can carry out a mission to recycle space debris.

All it takes is the political will to "*Turn Waste into Value*".

A BUSINESS CASE FOR SPACE DEBRIS

The following table compares the cost for different landers for 100 tonnes of aluminium to the lunar surface with recycled aluminium from space debris. Commercial lander-offer Moon transports for ca. 1 million euro per kilogram. The *European Large Logistic Lander* (EL3) calculates a total cost of 750 million euro for around 1.5 tonnes, which corresponds to 500,000 euro per kilogram. Although the actual delays of the SLS program have already doubled the SLS launch price, the following comparison uses an "*official*" price of 800 million euro, INCLUDING a yet-to-be-developed lander.

	Small Commercial Lander	EL3 Cargo Mission	SLS 1.0 Mission	Recycling Mission
Payload / Recycling mass	200kg	1,500kg	4,000kg	2,200kg
Number of missions for 100-tonne aluminium	500	67	25	55
Price per tonne to the Moon / per recycling tug	1 billion (1 million per kg)	500 million (750 million per 1.5 tons)	200 million (800 million per 4 tons)	150 million
Avg. launch cost per mission	Incl.	Incl.	Incl. (800 million)	60 million
Mission operation costs	1 million	1 million	1 million	4 million
Total price for 100 tonnes	**100.5 billion**	**50.3 billion**	**20 billion**	**11.77 billion**
Costs for Moon infrastructure				50 million
Replacement costs (= 1 EL3 mission)				750 million
No. of replacements over 10y recycling time				2 (5y) 5 (2y)
Total costs recycling infrastructure over 10y				**1.6 billion (5y) 4 billion (2y)**
Total price per option	**100.5 billion**	**50.3 billion**	**20 billion**	**13.4 billion (5y) 15.8 billion (2y)**
Price per kg Al	1 million	503,000	200,000	134,000 158,000
Max. Savings	**87.1 billion 84.7 billion**	**36.9 billion 34.5 billion**	**6.6 billion 4.2 billion**	/

Table 1: Business Case Calculation

As shown in Table 1, the recycled material on the Moon can be offered at a significantly lower cost than material from Earth. The recycling mission scenario reaches a total price of 13.4 to 15.8 billion euro per 100 tonnes of recycled aluminium or 134,000 to 158,000 euro per kilogram, far below the alternative lander options. More scenarios and detailed description of the various aspects can be found in the study.

SUMMARY THESES AND CONCLUSION PART 1

SUMMARY OF THESES PART 1

T-SD-1	Space debris endangers all space activities due to uncontrollable collision risks.
T-SD-2	The amount of space debris is growing.
T-SD-3	Funding of ADR missions remain challenging.
T-RE-1	Recycling is driven by political decisions or financial benefits.
T-RE-2	Recycling can be separated in life cycle extension, reuse of components or material recycling.
T-RE-3	Terrestrial Recycling works best for certain raw materials like metal.
T-LCE-1	Life Cycle Extension (LCE) is proven in space.
T-LCE-2	Costs for LCE competes with costs for "*space object replacement*" (object successor)
T-RoC-1	Reuse of Components (RoC) is hardly proven in space.
T-RoC-2	Costs for RoC competes with costs for "*space object replacement*" (object successor)
T-RMR-1	Raw Material Recycling (RMR) is commodity on Earth but new to space. Still, RMR seems to be realistic for certain space scenarios like metal (aluminium) recycling, especially on the Moon.
T-RMR-2	Costs for RMR competes with costs from Earth materials or with local material alternatives (ISRU).
T-LA-1	Neither the UN space treaties nor the most recent space law provisions address the space debris problem.

Table 2: Theses Summary Part 1

SUMMARY OF CONCLUSIONS PART 1

C-SD-1	Like on Earth, Active Debris Removal (ADR) is needed to reduce or to stabilize the amount of space debris.	T-SD-1 T-SD-2
C-SD-2	Like on Earth, recycling might be a financing option for waste treatment in space.	T-SD-3
C-SD-3	Like on Earth, a better understanding of the debris composition is needed to allow ADR missions as well as recycling of space debris.	C-SD-1 C-SD-2
C-RE-1	Like on Earth, the right political decisions could boost a sustainable space recycling industry.	T-RE-1
C-RE-2	Like on Earth, due to technical limitations, recycling is not the answer for every kind of debris.	T-RE-2 T-RE-3
C-LCE-1	Life Cycle Extension (LCE) needs to be included already in the design phase.	T-LCE-1
C-LCE-2	Without standardization, LCE is financially not attractive as no scaling effects could be realized.	T-LCE-1 T-LCE-2
C-LCE-3	LCE in space is mostly interesting for objects with high launch costs, like heavier objects or objects in higher orbits (GEO)	T-LCE-1 T-LCE-2
C-RoC-1	Reuse of Components (RoC) needs to be included already in the design phase.	T-RoC-1
C-RoC-2	Without standardization, RoC is financially not attractive as no scaling effects could be realized.	T-RoC-1 T-RoC-2
C-RoC-3	RoC in space might be interesting for components with high launch costs, like large antennas or optics or for higher orbits (GEO). Still, hardly any financially attractive use case could be identified.	T-RoC-1 T-RoC-2
C-RMR-1	Terrestrial Raw Material Recycling (RMR) process technology is mature and proven and could be applied to space with minor adjustments.	T-RMR-1
C-RMR-2	Metal, especially aluminium, seems to be the “sweet spot” for RMR.	T-RMR-1
C-RMR-3	RMR works best for larger objects and objects with a high metal content.	T-RMR-1 T-RMR-2
C-RMR-4	RMR has the highest ROI of all identified recycling use cases.	T-RMR-2
C-RMR-5	The Moon is the financially most attractive recycling spot due to the upcoming metal demand for constructions of the planned Moon station.	T-RMR-2
C-LA-1	A legislation like the law of salvage under maritime law could be a solution to allow active debris removal from another country.	T-LA-1

Table 3: Conclusion Summary Part 1

SUMMARY RECOMMENDED NEXT STEPS PART 1

- Space debris should be officially considered as another (important) space resource, which should be researched at the *European Space Resources Innovation Centre* (ESRIC).
- Compared to Earth, the ownership or authority of a space object, functional or debris, does not terminate. Therefore, any space servicing operation incl. space debris recycling would not be possible without the explicit agreement of the registered owner of such an object. A legal base to handle these activities needs to be developed. ESA should continue its support and funding of the *European Centre for Space Law* (ECSL) and should encourage ECSL to focus further on the topic to provide a solid legal base for future activities from Europe in this area.
- Official space debris data sets like DISCOS should be extended with object material information to support future waste management activities. On Earth, this missing information hinders efficient treatment of old landfills. In space, similar problems will occur when debris will be addressed in the future. Ideally, this is done as part of or as an extension of the currently rebuilt of ESA`s LCA data set.
- Life cycle extension in space is a proven way to address the common "throwaway" mentality of space missions. Low hanging fruits for life cycle extensions could be docking plates or refuelling concepts, while mid-term, replaceable external components like antennas and solar panels should be standardized. Long-term, internal component replacements, of e.g., batteries or *Guidance, Navigation & Control Systems* (GNC) should follow. ESA should support this sustainable development by including it in its own tender for future space missions.
- The recommendations for reusing components in space are like the life cycle extension scenario. But even with the help of future standards, a valid business case for LEO is hard to imagine due to the decreasing satellite and launch costs. In higher orbits, such a business case could be developed over time with the increasing number of standardized satellite interfaces. Being (at least partly) responsible for the large European satellite fleet of the *Copernicus* and *Galileo* service, ESA should request the mentioned capabilities for its own next satellite generations and could act as a best practice for life cycle extension.
- As raw material recycling from space debris is within Europe`s technology capabilities, ESA should consider the usage of recycled material for future space manufacturing activities, especially on the Moon. Even if the material would not come from orbital space debris at the beginning, lunar lander or rover material could be recycled after their missions to reduce or avoid additional material transports from Earth. These end-of-life recycling aspects should be included in future mission profiles.
- Without a clear political commitment, the recycling activities for space debris will remain a challenge, regardless of any potential economic benefit. While *ClearSpace-1* is a first step in the right direction, the funding of following ADR missions remains unclear. With the financial benefits of a space debris recycling concept, a successful *ClearSpace-1* mission might unlock additional public budgets for future ADR missions, if prepared well enough in advance. If ESA sees advantages in such activities, this topic (space debris recycling) should be included on the agenda of ESA`s next Council at Ministerial Level.

SUMMARY RECOMMENDED NEXT STEPS PART 2

- The selection criteria to identify space debris targets for recycling could be further improved through the following activities:
  1. The data regarding space object composition is limited but crucial for future recycling activities. Efforts should be considered to extend the existing debris data sets like DISCOS with detailed material information, ideally provided by the manufacturers. This such be considered for the next update project for DISCOS.
  2. GTO upper stages cross many other object trajectories. Due to their sizes, any fragmentation event through explosions or collisions would generate a large amount of secondary space debris objects, which expose all other space objects to unpredictable risks. Like in the LEO environment, the associated risks for GTO debris objects should be reviewed and modelled in more details as part of a dedicated research study.
- The rotation and tumbling behaviour of upper stages in GTO should be understood in more details, as this would simplify any upcoming recycling mission. For this, a European research activity is suggested as a dedicated follow-up to this study:
  1. The already and ongoing light curve measurements of the CastelGAUSS observatory and its partner network should be combined with the capabilities of the Fraunhofer FHR TIRA instrument. This would allow Europe to generate a unique data pool of different GTO data sources.
  2. The data should be used for object tumbling modelling by institutes like the *Astronomic Institute* of the University Bern (AIUB) around Professor Zimmerwald or the *Institute of Technical Physics* from DLR in Stuttgart. The derived tumbling rates could be further reviewed and improved through illuminated 3D models in an experimental setup.
  3. To validate the derived tumbling and rotation models, a precursor mission in GTO is proposed. A visual inspection of a derelict upper stage should occur, which would help to not only determine the exact tumbling and rotation movements of the upper stage, but to inspect and to observe any space aging effects of the upper stage material. Ideally, such a precursor mission is executed as a (university) research competition. By offering a free slot in one of the planned GTO rideshare launches, ESA could support this precursor mission concept with an affordable investment.
- Contactless detumbling methods are very promising solutions to stabilize any kind of space objects. It is suggested to conduct experiments and studies in Europe, driven by ESA, with different coil designs regarding diameter and conductor material to develop a generic tool to be used for various detumbling scenarios in the future.
- Europe has started its own active debris removal mission *ClearSpace-1* to grab an object in space. It is highly recommended to verify, that the developed solution could be scaled for larger targets like the Ariane 5 upper stages. This could be done as part of a dedicated industry study.
- The recycling space tug concept is still at an early development stage and additional research needs to be done.
  1. ESA should take the presented concepts as a baseline for a CDF engagement to find the optimal balance between the contradicting requirements of quickly approaching the target in GTO and the long Moon transfer.
  2. Synergies with existing activities should be identified, like the Vega-C Venus upper stage or the *Space Rider* propulsion technology, developments in GNC, AOCS or manipulators. Especially the *ClearSpace-1* mission should be followed closely to validate, that the developed technology components could be scaled for the larger recycling targets and tugs. This should be done as part of a dedicated cooperation office within ESA.

- To better understand the crater dependencies on the impact velocity and impact angle, additional studies and impact experiments should be carried out. The MfN in Berlin, Germany around Prof. Wünnemann as well as the Fraunhofer EMI Institute, Freiburg, are both perfectly suited for such activities and could execute such a study in partnership with Orbit Recycling.
- The presented early-stage concept to recover aluminium fragments of an impacted Ariane upper stage on the Moon should be re-examined at a time when more information about the Ariane 6 A64, EL3, and PHASR is available. A CDF is proposed like the space tug situation, where experts from ESA, Orbit Recycling as well as the European space industry should evaluate the synergies with other relevant developments in this area.
- The overall knowledge of aluminium casting in regolith mould is still limited. As part of a shared PHD with the EAC, further studies at TU Berlin and Orbit Recycling will occur over the next 3 years. In addition, aluminium smelting and casting experiments under vacuum conditions should be executed. These experiments should give a better understanding of the achievable cast quality on the Moon.
- The effectiveness of Fresnel-lens-based aluminium melting in regolith should be studied. Additional tests should validate the preliminary results under vacuum conditions, where cooling would only happen through heat radiation. This could be done as part of a shared PHD or a dedicated industry study of Orbit Recycling with the support of EAC or ESTEC laboratories.
- Additional Fresnel lens sintering experiments should occur with different regolith simulants as well as under vacuum conditions to validate the achievable mould quality. This could be executed by Orbit Recycling with technical support of ESTEC laboratories.
- Different Fresnel lens material should be evaluated for its usage under lunar conditions. This could be executed by Orbit Recycling with technical support of ESTEC laboratories.
- Rover with Fresnel lenses should be tested to determine the size of the achievable glazed surface areas per time unit for different lunar applications. This could be executed by Orbit Recycling and its Partner PTS, Berlin, and TU Berlin with technical support of EAC and ESTEC laboratories.
- By mixing aluminium (powder) with regolith, a new material composition (*ALReCo*) could be produced. First experiments show a superior heat conductivity and thermal capacity of this new material compared to pure regolith, which needs to be validated in dedicated experiments. As this material might be even suitable as a heat storage solution to power a lunar ground station, corresponding research should occur to validate these assumptions.
- The presented business case estimations are based on public information and assumptions. These numbers should be validated from Orbit Recycling and experts from various ESA directorates at a dedicated workshop, as a side meeting of an upcoming ESA conference.
- Beside the direct cost savings, space debris recycling has positive effects on the environment and reduces the overall risks through space debris. These positive effects should be validated in a dedicated *Life Cycle Assessment* (LCA).