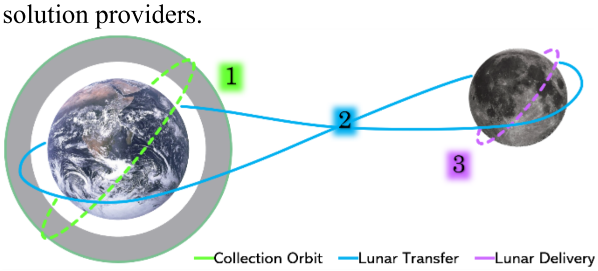
IDENTIFYING 50 RECYCLABLE OBJECTS IN UPPER EARTH ORBIT. R.B. Palmer[1] and E.G. Lightsey[2], [1,2]Georgia Institute of Technology, Space Systems Design Lab, 620 Cherry St. NW, Atlanta, GA 30332. (Contact: bec.palmer@gatech.edu)

Introduction: Recycling derelict objects above low-Earth orbit can bolster in-space assembly and lunar surface manufacturing with a supply of raw materials that do not need to be launched from Earth, reducing the upmass needed for a Cislunar economy. As an alternative to deorbit missions, which increase launch frequency and deposit metal particulates into Earth's atmosphere, recyclable debris is raised to a collection orbit above the geostationary ring (GEO) for transport to the lunar surface, where it will be recycled in-situ. The planned recycling facility will also accept used aluminum from regolith mining or discarded surface vehicles.

International collaboration is key to sustainable innovation and policy, so this analysis has been expanded to include all objects launched by or for signatories of the Artemis Accords. Earlier work focused only on the United States, but after adding Artemis Accords members, the economic advantage and operations efficiency of many allied countries working together is undeniable.

Concept of Recycling Operations: This early concept of operations has three phases, seen in the Figure below. Phase 1 uses ADR vehicles to capture single pieces of debris from high-Earth orbit and transport them to a graveyard collection orbit 300 km above GEO. During Phase 2, a lunar transfer vehicle (LTV) is assumed to cycle between this graveyard and low lunar orbit (LLO) about once each year on a low-thrust ballistic trajectory, the LTV having a 10,000 kg payload capacity to fill with recyclables. Phase 3 delivers the recyclables to the lunar surface for processing into new aluminum filament for use by in-space manufacturing. The dynamics and geometry of this conops are simplified to allow high-level analysis of new revenue opportunities for ADR servicers, LTV operators, and surface delivery solution providers.

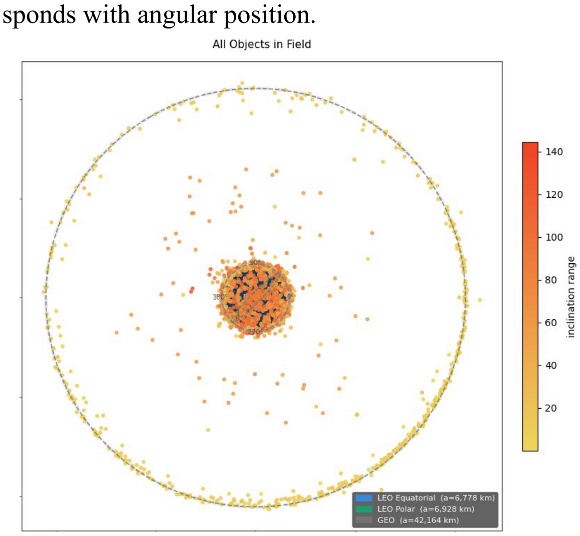


Mission Vehicles. Seven ADR vehicles were modeled for this work; here, the data from just two representative states are analyzed. First, a model imitating current-state capability of a Northrop Grumman MEP or MEV (NG-Type). Second, a theoretical vehicle extrapolated to max payload (TEMP) based on NASA expected performance of the Gateway PPE if it were modified for orbital maneuvers while maintaining a payload capacity for even the largest object in this debris field (6,000 kg). [1,2]

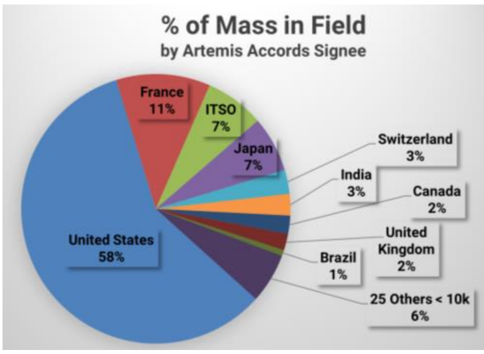
Detailed Survey of Recycling Candidates: Objects were pulled as candidates under the following criteria:

1. Launched before 01-Jan-2006,
2. Large or Medium RCS,
3. Assigned to a member of the Artemis Accords,
4. Semi-major axis greater than 6,800 km.

This final cutoff (~ ISS altitude or higher) was chosen to ensure significant items with higher elliptical orbit would not be excluded, and to enable future work with increased fidelity of the dry-mass database. A detailed investigation into the dry mass of each object was performed, with a goal of publishing the lowest mass according to the best confidence level of data available. A starting point is DISCOS data, which provides the only API source of mass estimates, but usually represents wet or launch mass (LM). In some cases, beginning-of-life (BOL) mass can be calculated from published sources. DISCOS sometimes provides on-orbit fuel use estimates (DF) after BOL. Research at NASA Archives and Libraries in addition to other online archives has provided true dry mass of some orbiting payloads (DM). The database built for this research prioritizes recording mass data from, effectively, lowest kg to least accurate: DM < DF < BOL < LM. This effort is ongoing; about 40% of the current field in this work is considered to be DM values. The figure below is a 2D display of the entire recycling candidate field, viewing on Earth-centered equatorial plane; each object's orbit is not propagated, but inclination range is provided with heatmap color indicator, and argument of perigee corresponds with angular position.



Most objects near the GEO belt range from 0-25° inclination, and as expected these are the objects first selected by the optimization tool as they have lowest cost of delivery to the graveyard belt. The pie chart below briefly summarizes the percent of on-orbit dry mass for each of the Artemis Accords signatories; Parties with less than 10,000 kg mass on orbit are combined into one slice for this abstract.

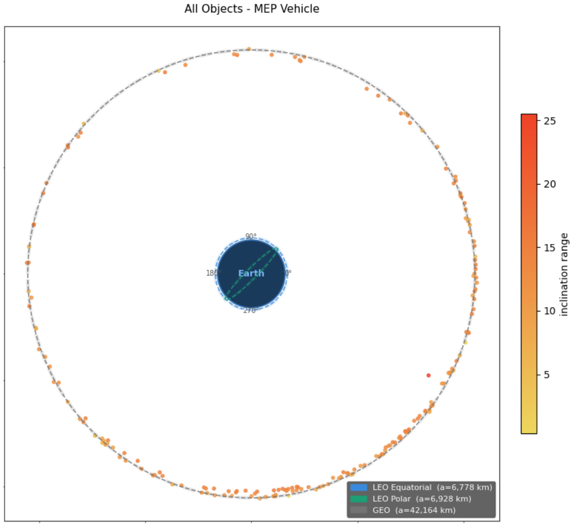


Refueling Costs and Recyclable Value. In the nominal case, a fully-reusable refueling architecture [3] is assumed to cost $300/kg propellant. Near- and far-term pricing was also examined (about $3,000/kg and $30/kg). Orbital debris in this field is assumed to be 38% aluminum by mass, with a pessimistic collection value of $2,002.50 USD / kg aluminum. This is based on 5-year IMF global price of aluminum plus recovered launch costs to LEO.

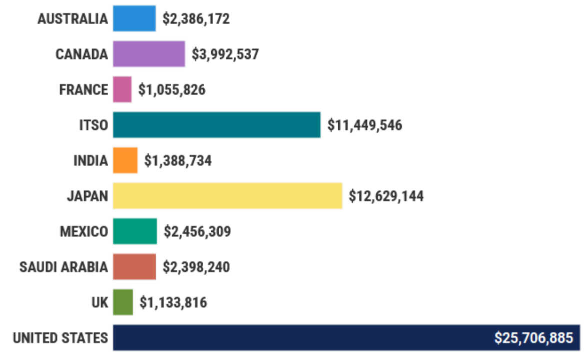
Cost of Delivery Analysis. Cost (ΔV) of debris object collection is done a-priori using the Alfano method for non-coplanar low-thrust transfers [4] and a closed-form analytical method [5]. Debris selection optimization is performed with a knapsack I/O algorithm constrained by LTV duration and capacity.

Results: The NG-type ADR was able to collect less mass over the lifetime of the model than the TEMP ADR, resulting in less potential value for recycling.

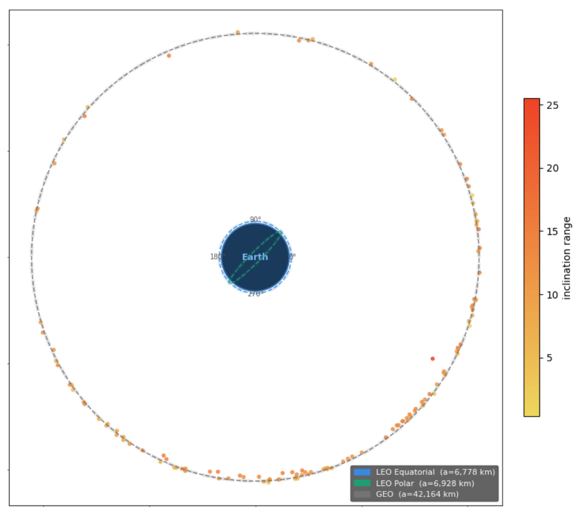
All Objects - MEP Vehicle

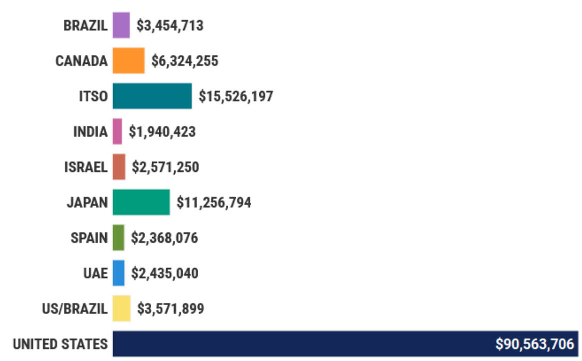


The resulting maps of all objects collected can be seen below in a familiar 2D orbit field. Bar charts showing the value of just the top 50 items collected under each ADR model further emphasizes the importance of international collaboration, not just for ADR technology but also to maximize the potential for cheaper ISRU materials from recycling.



All Objects - TEMP Vehicle





References: [1] Cassady J. et al. (2022) *Space Propulsion Conf.* [2] McGuire M. et al. (2024) *38th Intl Elect Propul. Conf.* [3] Tiffin D. and Friz P. D. (2021) ASCEND AIAA-2021-4066. [4] Vallado D. A. (2022) *Fund. of Astrodyn. and Appl.* [5] Di Carlo M. and Vasile M. (2021) *Celest Mech Dyn Astr 133,* 33.