Recycling end-of-life equipment on the Moon: Towards the design of equipment and strategies

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ESRIC-LIST

European Space Resources Innovation Centre

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24 PEOPLE

14 researchers
2 engineers

2 commercialisation specialists

RESEARCH

Lunar geoscience
Beneficiation
Reduction and electrolysis
Gas purification
Recycling on moon surface
Microwave processing
Dust mitigation

In partnership with ESA

GROUND-BASED SUPPORT

Dusty Thermal Vacuum Chamber
Ground-Based Pilot Plant

TECH DEMONSTRATORS

Oxygen production from lunar regolith

BUSINESS

Start-up Support Programme
Space Resources Accelerator

COMMUNITY

Space Resources Week
ESA & ESRIC Challenge
Resourceful podcast

Human made objects on Moon

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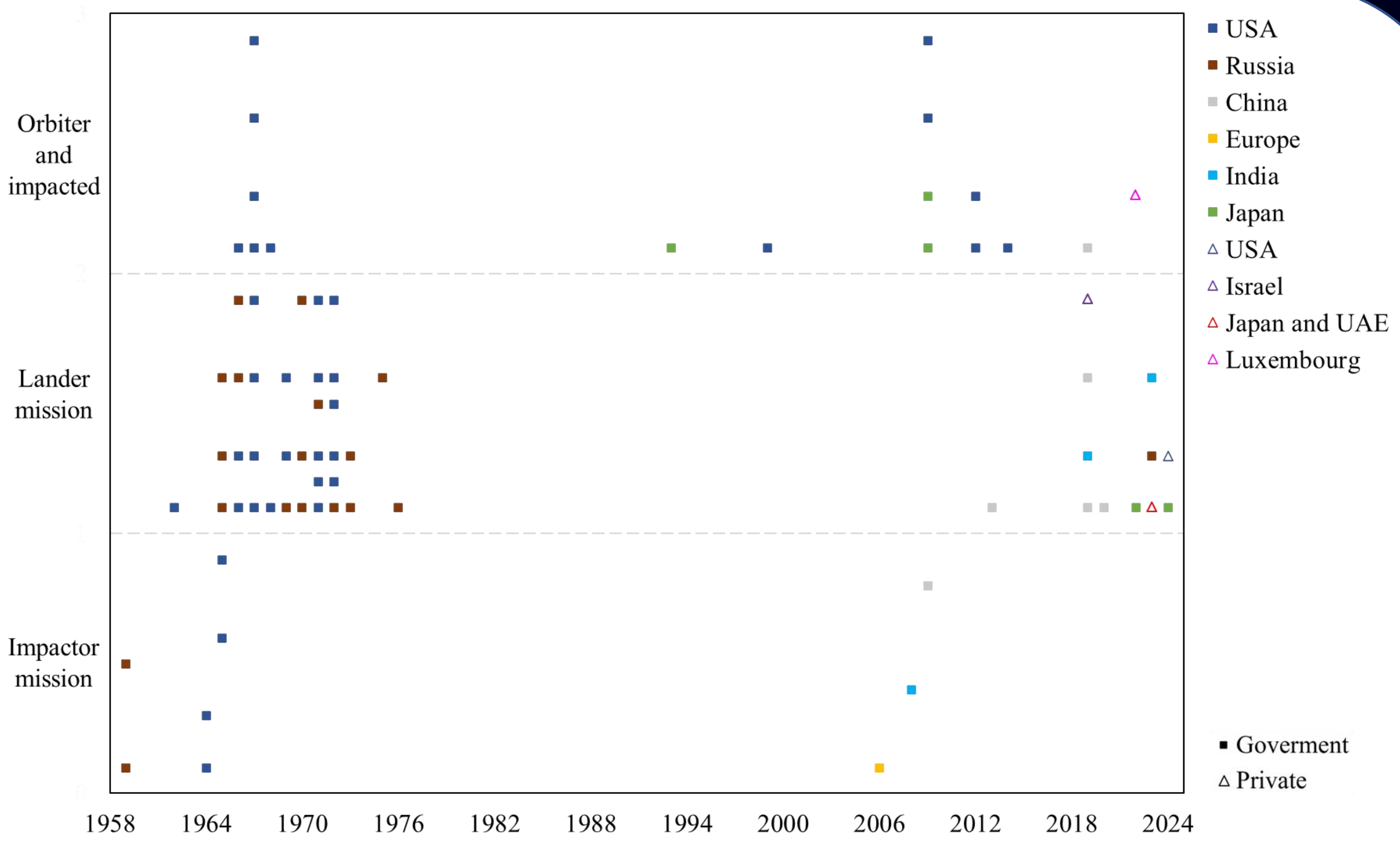
- 73 number of objects have landed, crashed, or intentionally impacted



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Human made objects on Moon

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- In future scenario

226,796 kg

(Available hardware mass on moon)

609,160 kg

(ISRU hardware mass in next decade to produce 200 T/a (tonne/annum) of aluminium–silicon alloys and 680 T/a of oxygen)

2,436,640 kg

(ISRU hardware mass till 2080 to produce 800 T/a of aluminium–silicon alloys and 2721 T/a of oxygen)

(a)Current mass

(b)Next decade

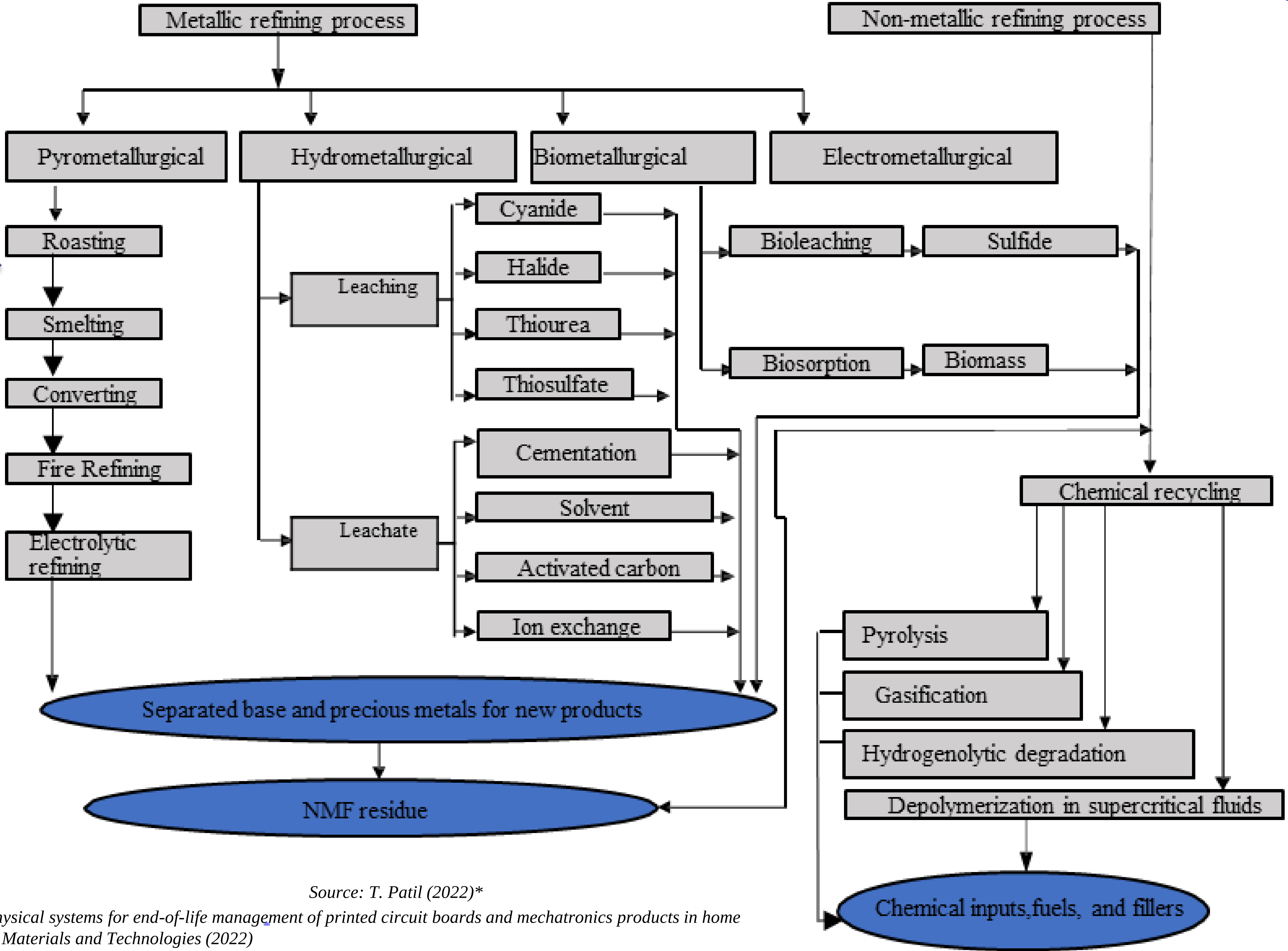
(c)Till 2080

*Data as on 03/May/2024 (Flyby missions are excluded).

Data collected from *F.J. Guerrero-Gonzalez and P. Zabel (2023)**

**F.J. Guerrero-Gonzalez, P. Zabel, System analysis of an ISRU production plant: Extraction of metals and oxygen from lunar regolith, Acta Astronaut 203 (2023)*

- Chemical and thermal recycling process

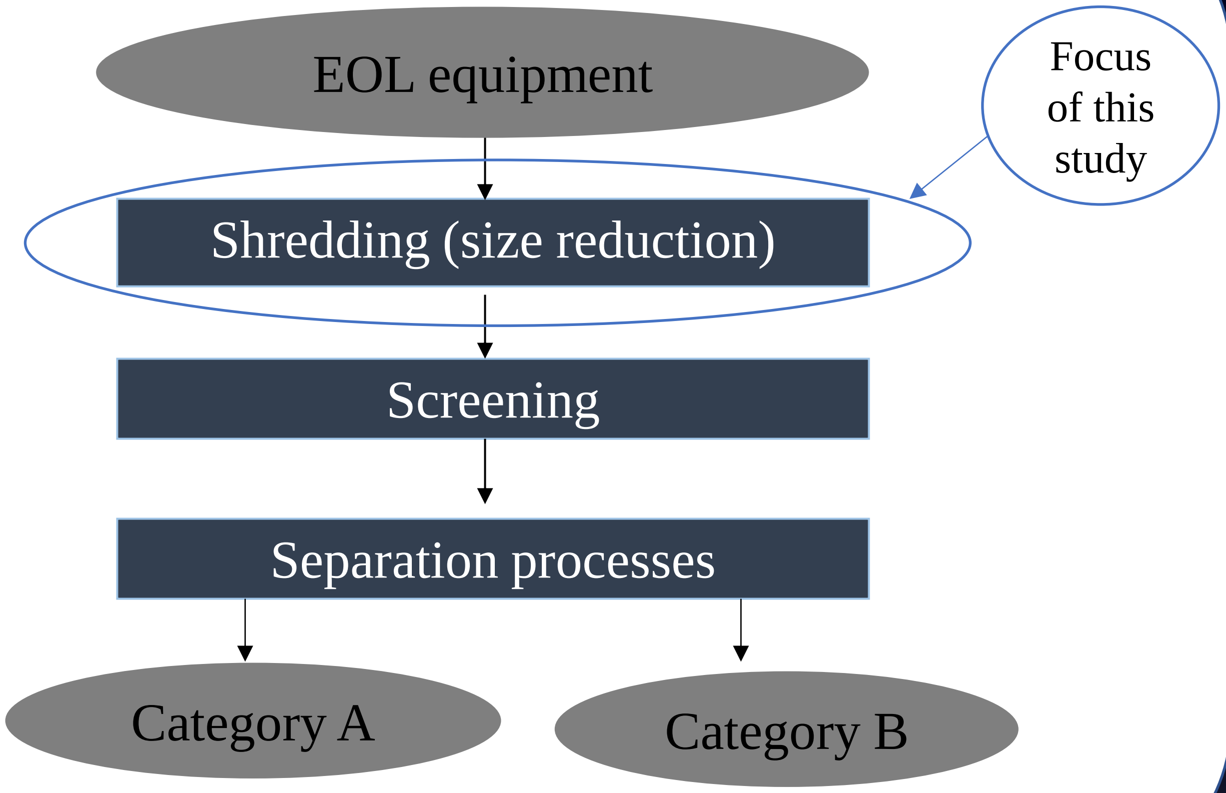


*Source: T. Patil (2022)**

T. Patil et al., Cyber-physical systems for end-of-life management of printed circuit boards and mechatronics products in home automation, Sustainable Materials and Technologies (2022)

Physical recycling method

- ➢ End of life (EOL) equipment ➡
- ➢ Shredding (size reduction) ➡
- ➢ Screening
- ➢ Separation process
- ➢ Category A material ➡
- ➢ Category B material ➡



Recycling of space category cables

- Space category cables are an integral part of every payload
- Material compositions
  - Insulator: Polyimide (Kapton)
  - Conductor: Silver plated copper

Space category cable

(22 AWG)

- Lunar regolith chemical composition

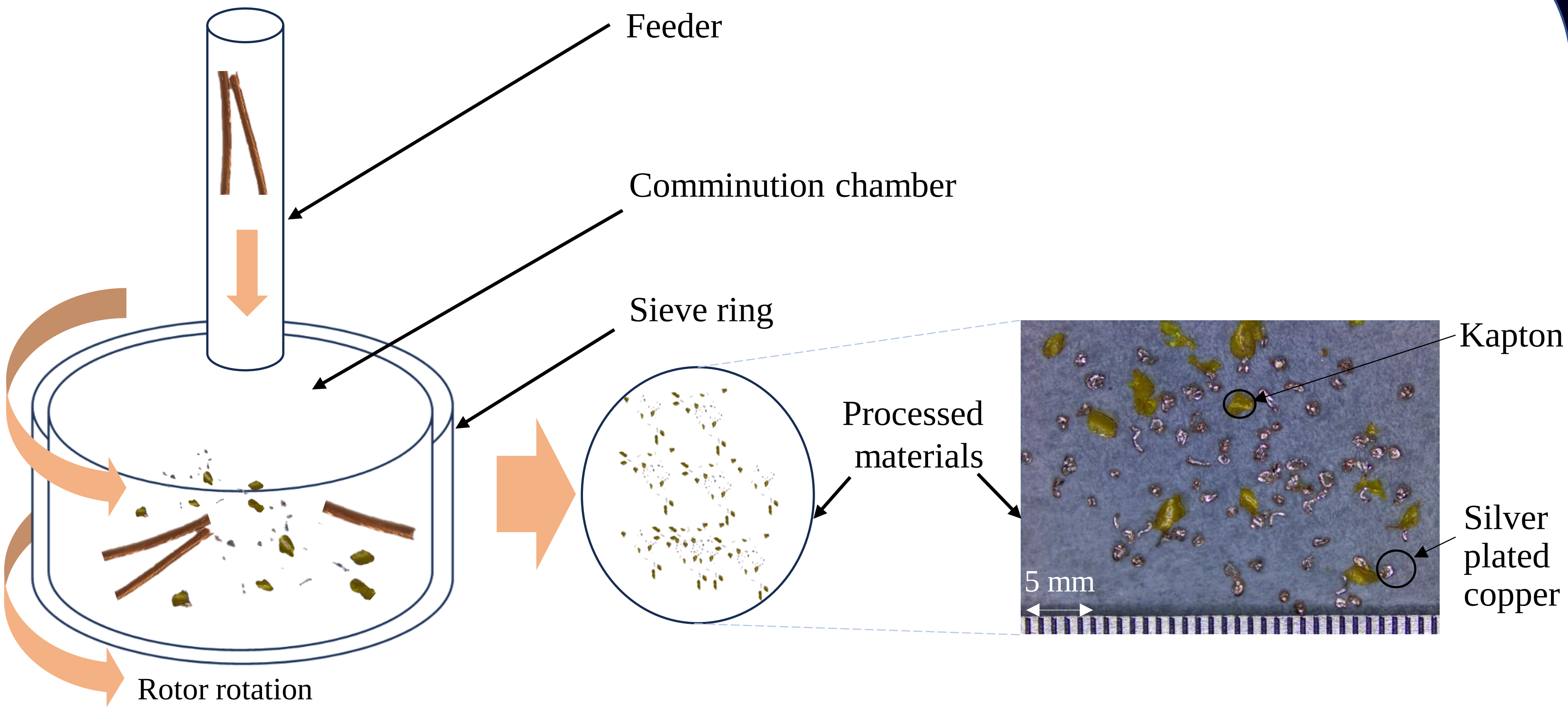
Compound	Concentration*
Silicon dioxide, (silica), SiO_2	42-48%
Aluminium oxide (alumina), Al_2O_3	12-27%
Calcium oxide (lime), CaO	10-17%
Ferrous oxide, FeO	4-18%
Magnesium oxide, MgO	4-11%
Titanium dioxide, TiO_2	1-7%
Sodium oxide, Na_2O	0.4-0.7%
Chromium (III) oxide, Cr_2O_3	0.2-0.4%
Potassium oxide, K_2O	0.1-0.6%
Manganese (II) oxide, MnO	0.1-0.2%

* Concentrations varies according to specific location

Data collected from: H. Fischer (2018) and J.J. Papike, et al.(1982)

Centrifugal mill

- Use of centrifugal force
- Size reduction is due to impact and shearing force between the rotor and the sieve ring
- Particle size, RPM, temperature, hold up mass, and energy consumption



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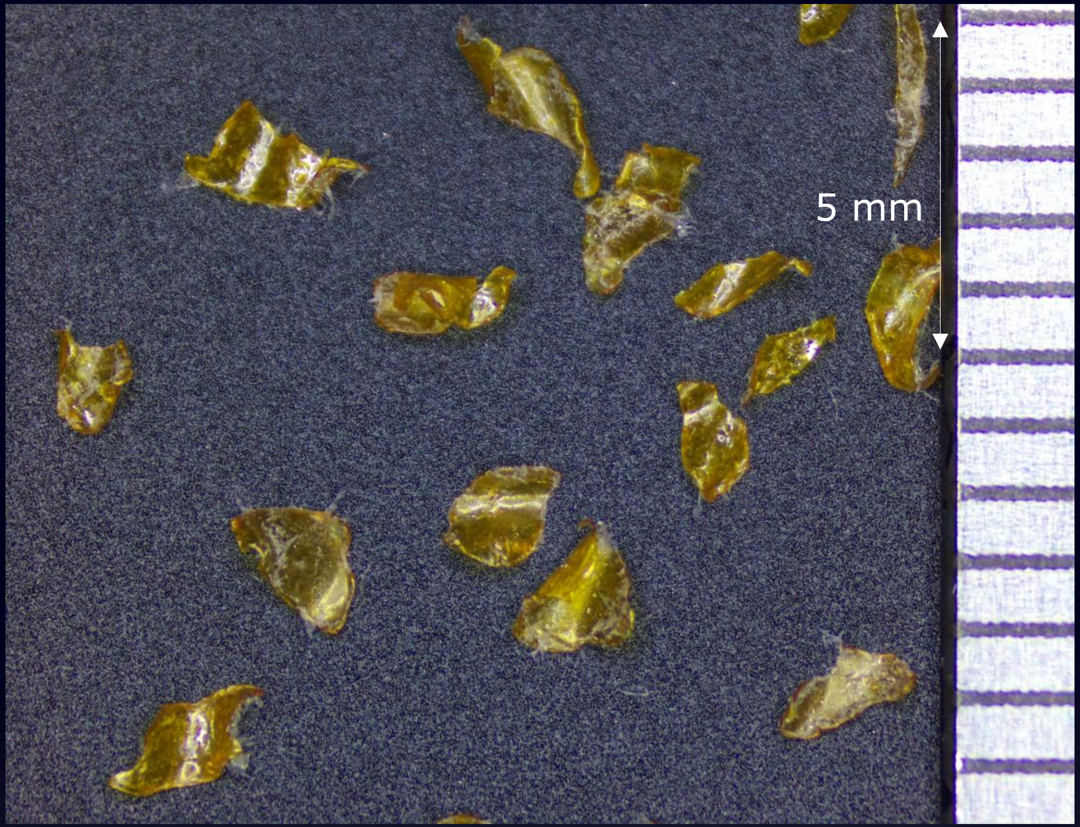
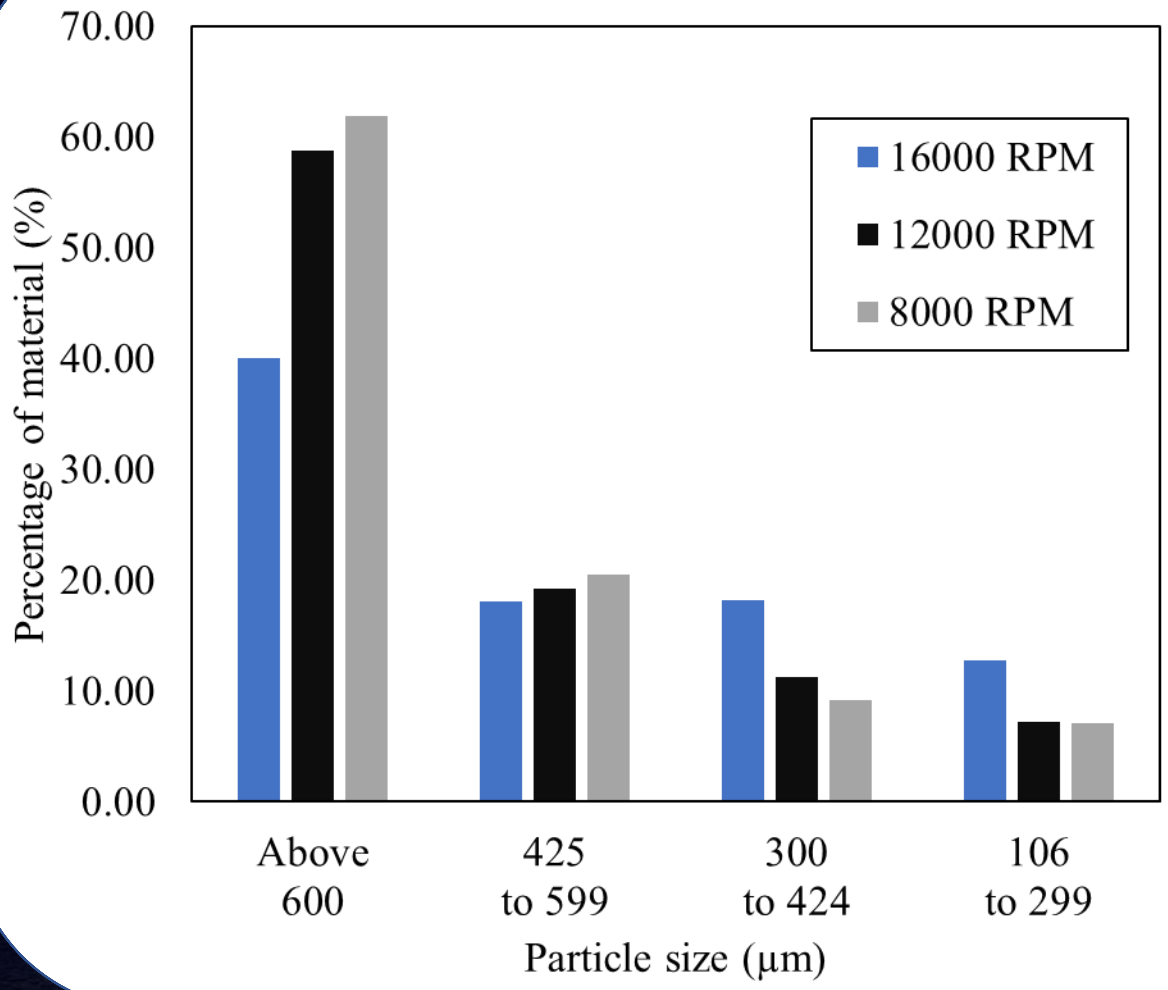
Different size and shape according to material

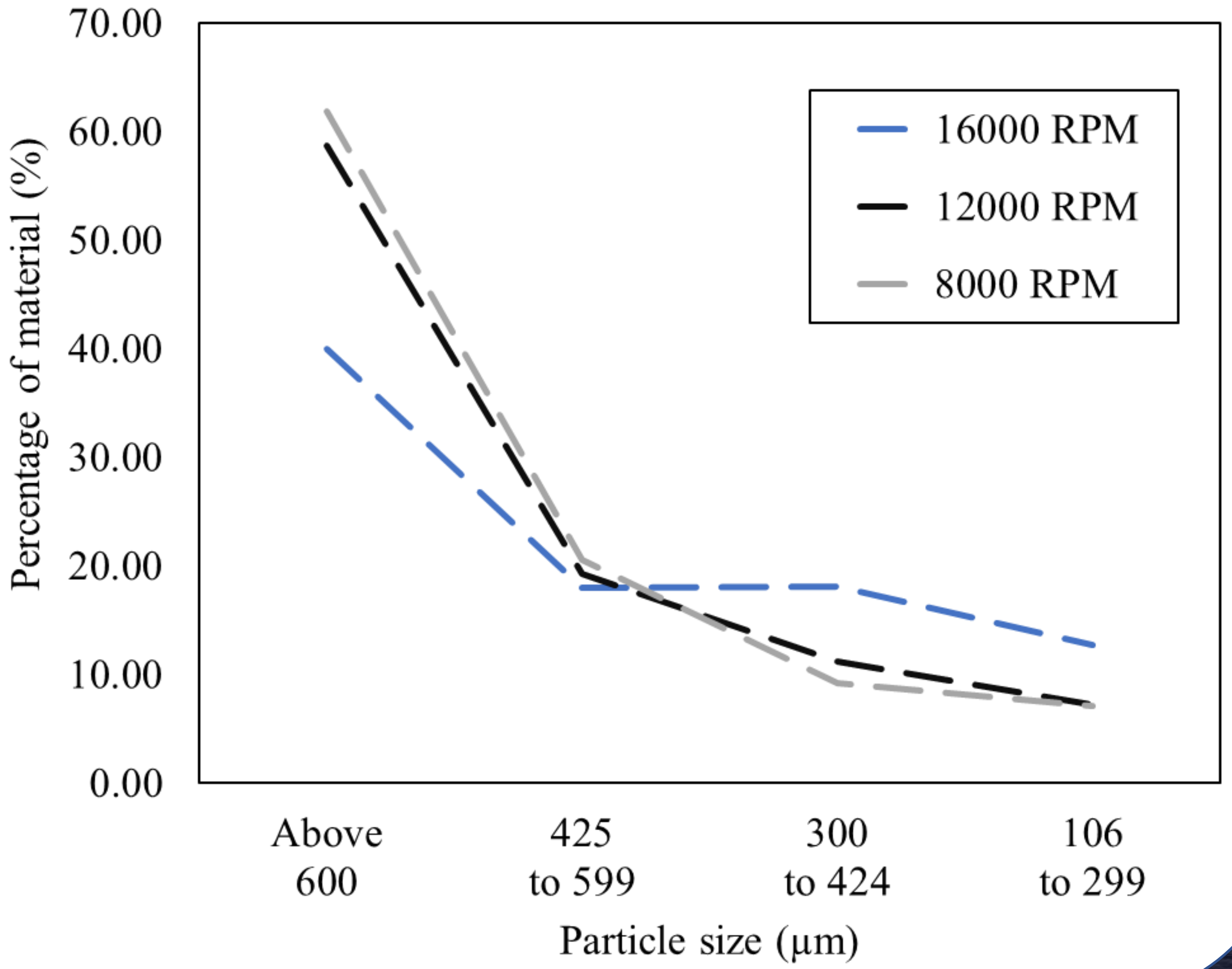
Silver plated copper



Polyimide

Experimental data (Particle size)





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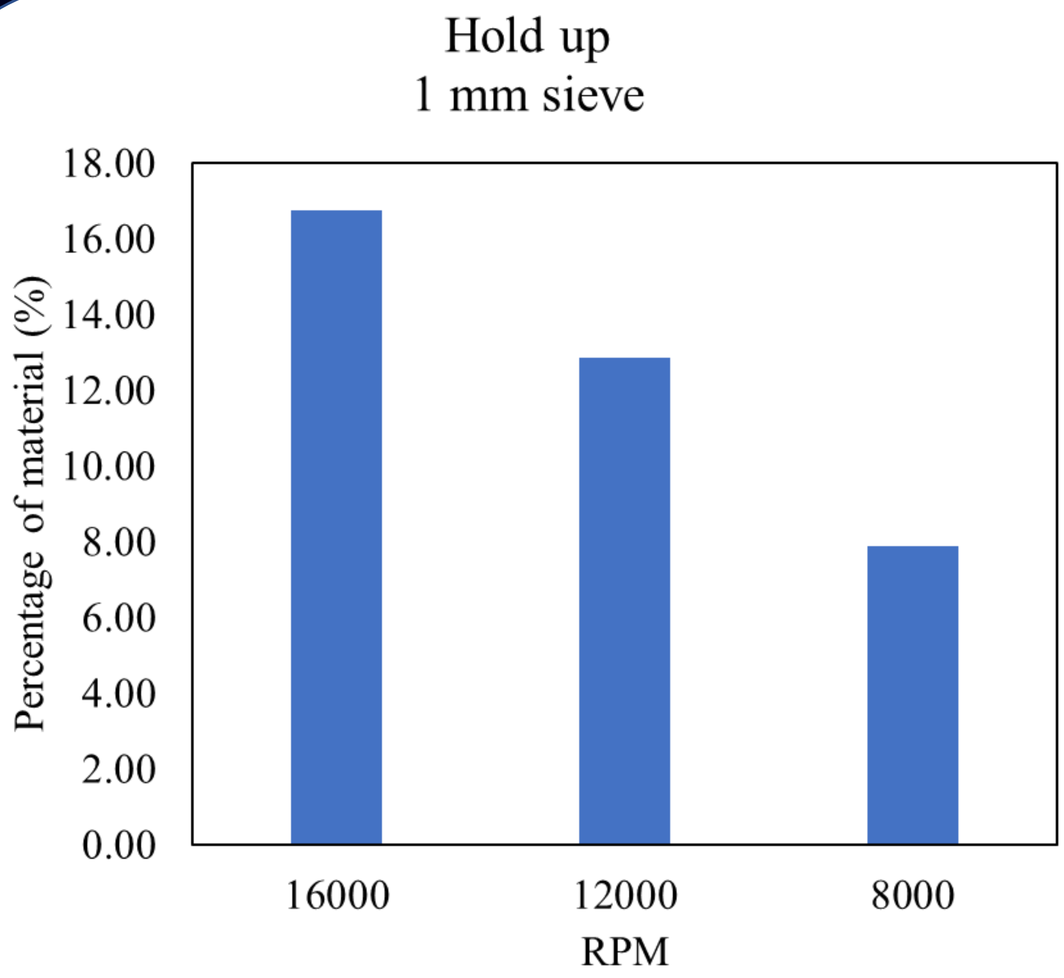
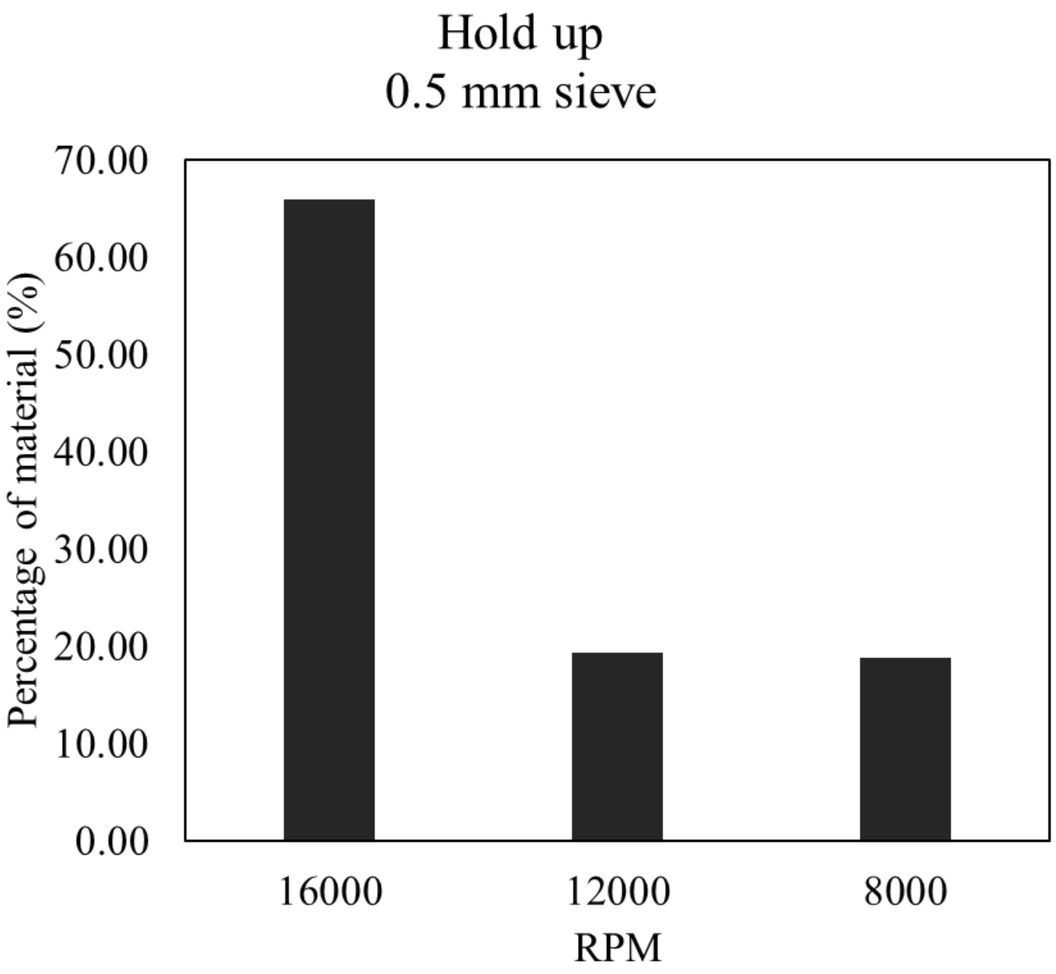
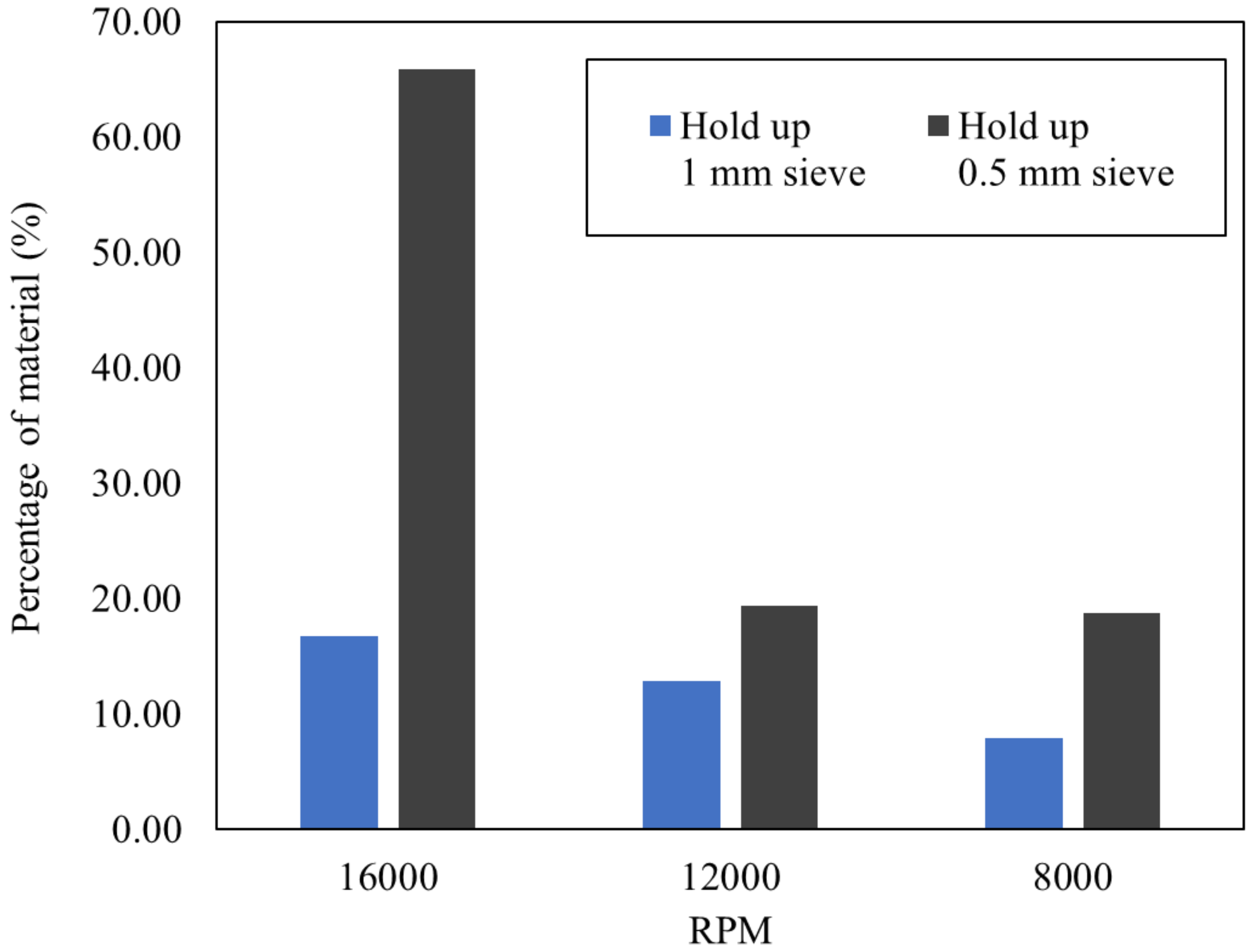
Experimental data (Hold up mass with RPM)





Experimental data (Hold up mass with sieve)



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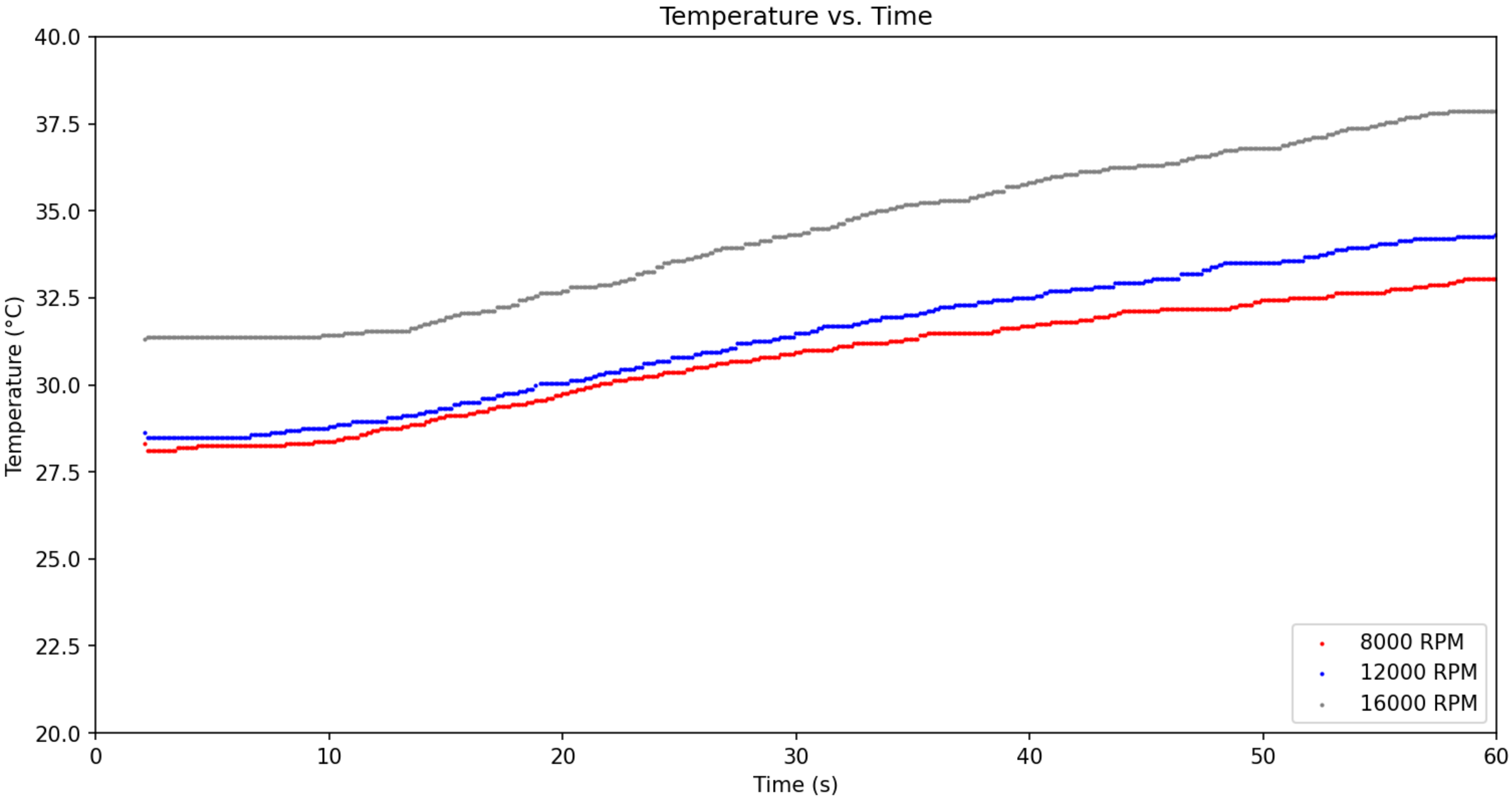
Experimental data (Time vs. Temperature)



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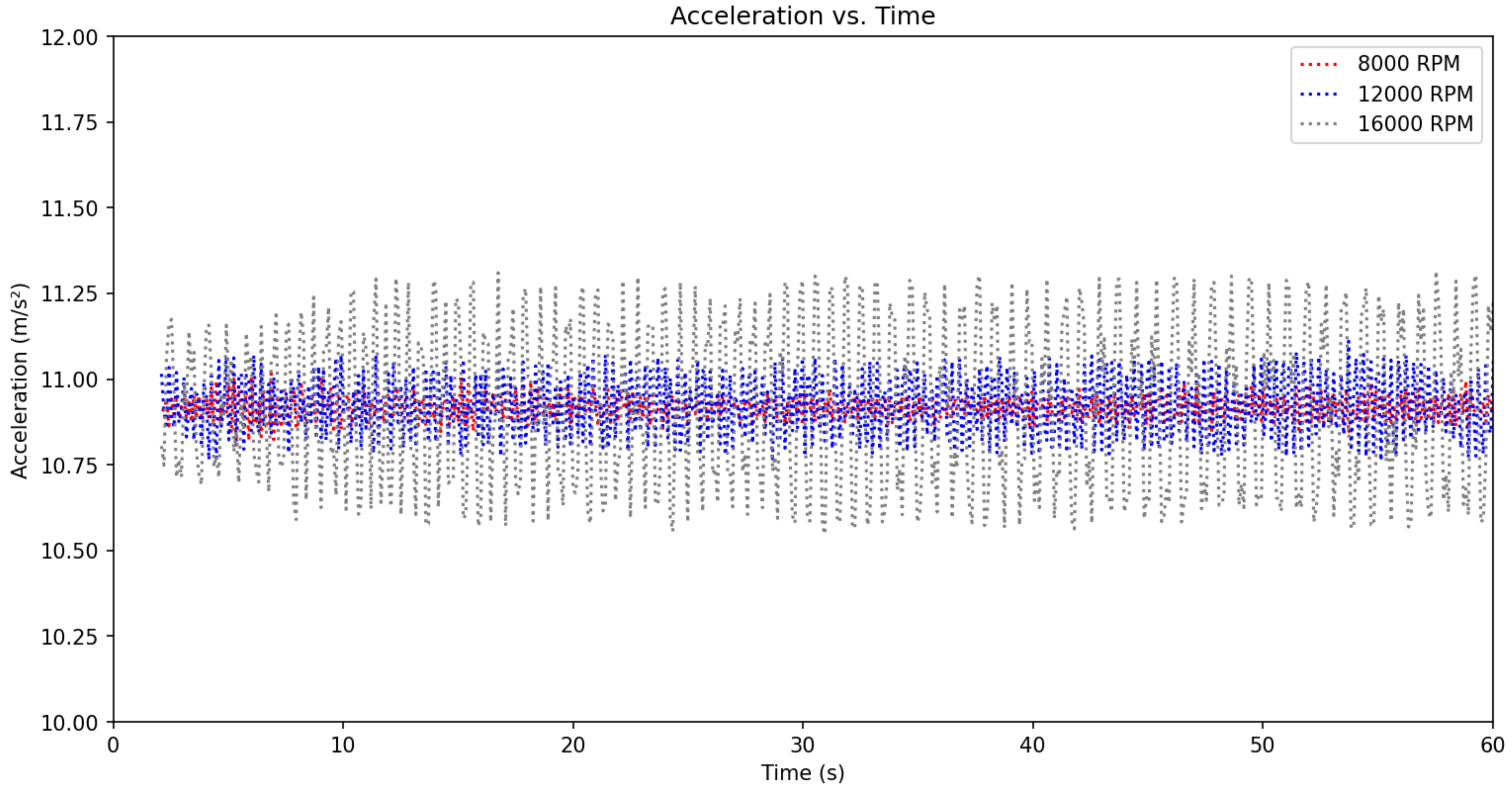
Experimental data (Net acceleration vs. Time)



Energy consumption

- **Energy consumption with inclusion of material properties,**

- $$Power\ (P) = \frac{(Rotational\ kinetic\ energy + Potential\ energy + Energy\ related\ to\ the\ material's\ tensile\ strength + Energy\ related\ to\ the\ material's\ shear\ strength)}{efficiency}$$

- $$Power\ (P) = \frac{(\frac{mr^2w^2}{2} + mgh + \sigma V + SHV)}{\eta}$$

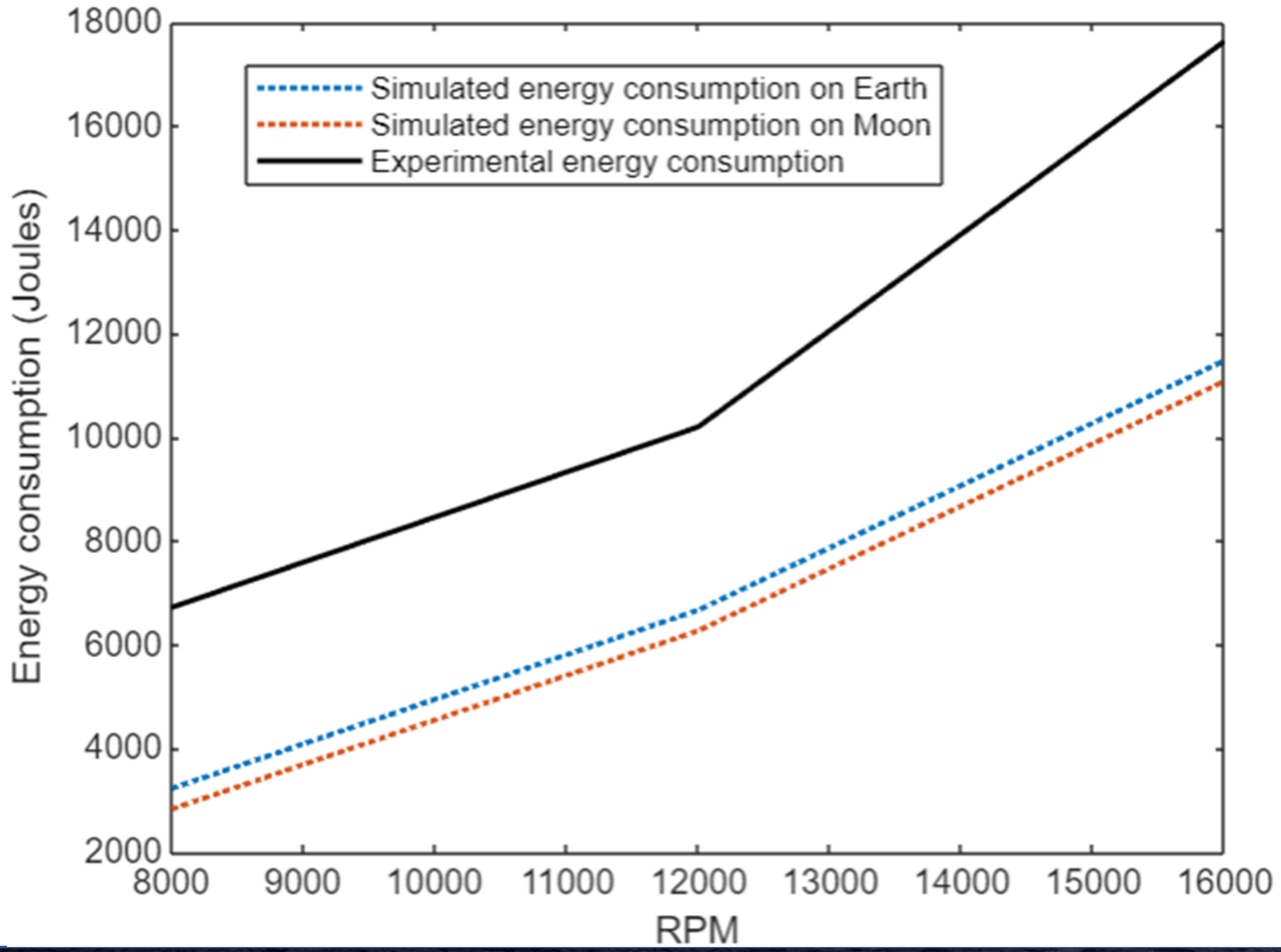
- $Energy\ consumption\ (E) = Power\ \ x\ Time$

- $Energy\ consumption\ (E) = Pt$

Where,

- Material mass (m): the mass of the material being processed.
- Time of operation (t): the duration the mill operates.
- Rotor radius (r): the radius of the rotor.
- Efficiency (η): the efficiency of the centrifugal mill.
- ω: Angular velocity of the rotor (2πN/60)
- Rotor rpm (N): the rotational speed of the rotor.
- g: Acceleration due to gravity.
- h: height of chamber.
- $\sigma \cdot V$: Represents the energy loss due to stress applied to a material with volume V.
- $S \cdot H \cdot V$: Represents energy losses or savings related to material strength (S), hardness (H), and volume V of the material

Energy consumption (η:80)



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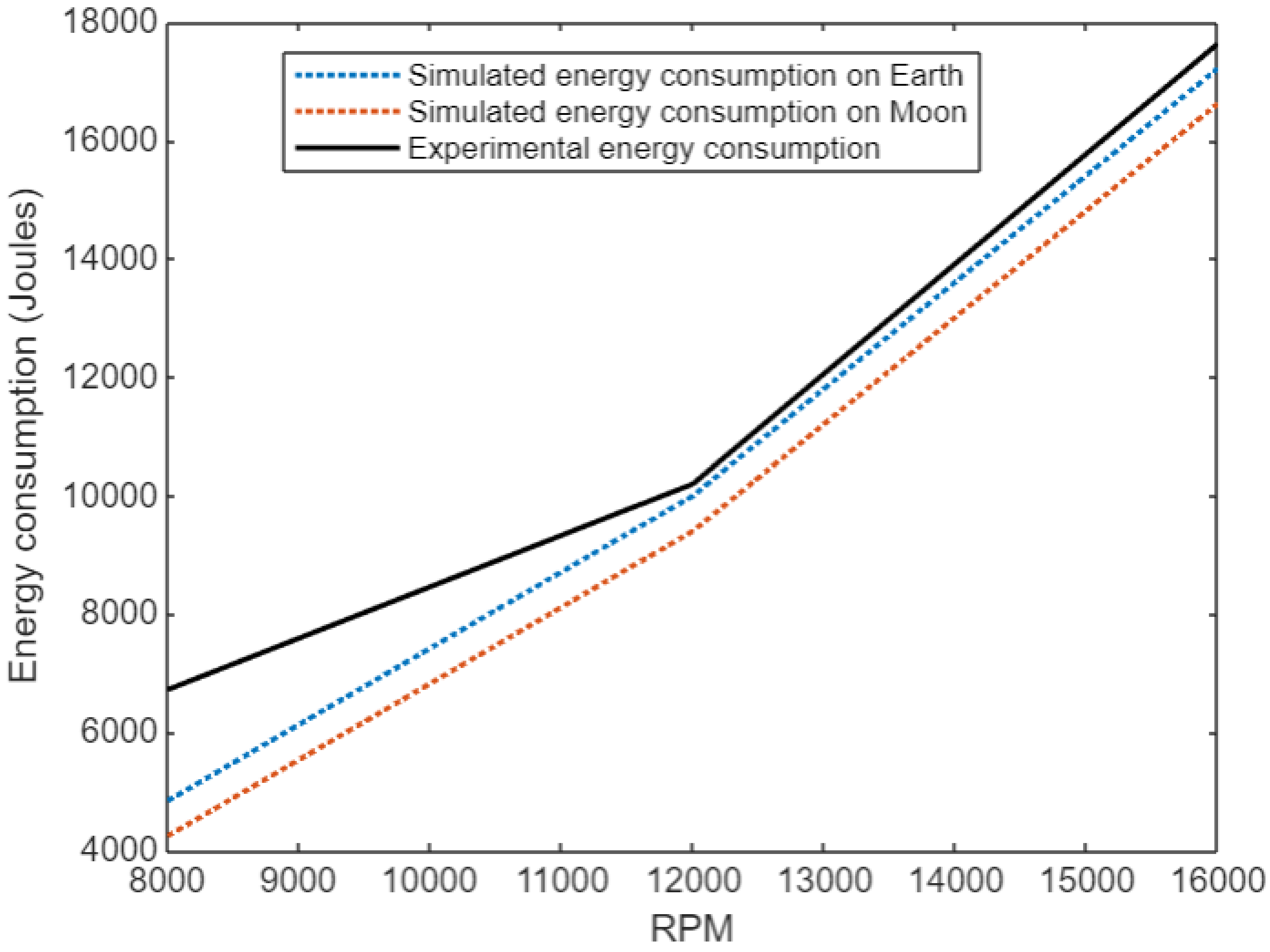
Energy consumption (η:60)



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Comparison with thermal process

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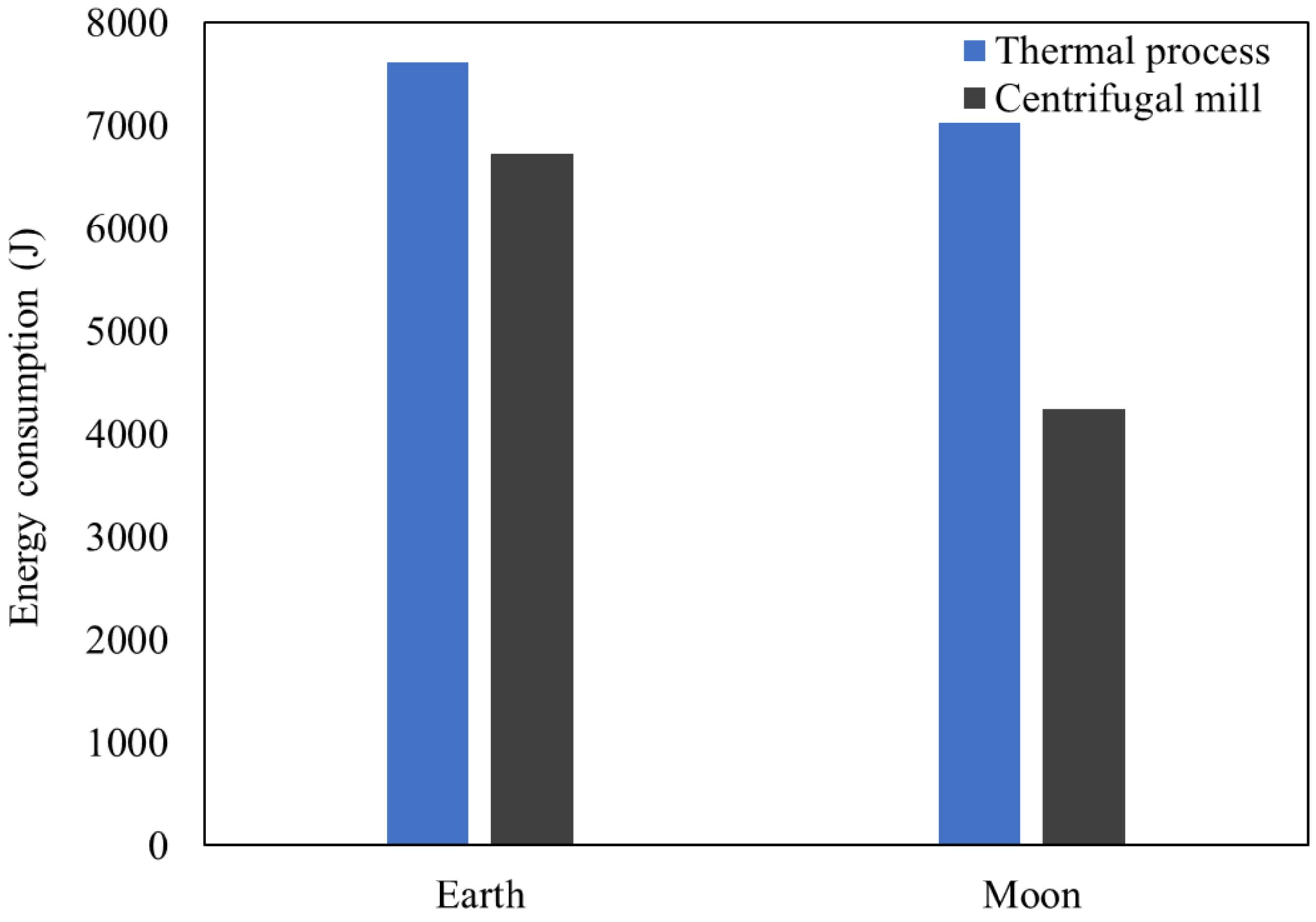

	Thermal process (J)	Centrifugal mill (J)
Earth	7606.432	6720
Moon	7027.84	4244.66

Suggestions for lunar operation

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- ➢ Selection of the lowest possible but optimal RPM
  - ∝ Reduce energy consumption
  - ∝ Reduce temperature in comminution chamber
  - ∝ Reduce vibration to avoid misalignment, wear, and tear issues
- ➢ Selection of right sieve size based on the feedstock structure and compositions
  - Reduce hold up mass in comminution chamber
  - Mitigate the risk of jamming
- ➢ Insulation for equipment for extreme lunar temperature
- ➢ External cooling system for lunar day operation

Conclusions

- Growing need for EOL management of human-made materials on the moon
- Physical recycling methods, particularly centrifugal milling
  - Independent from Earth-based reagents
  - Optimisation of parameters such as RPM, temperature, and energy consumption.
  - Lower energy consumption compared to thermal process
  - Suitable for lunar constraint with minor modifications,
  - Recovery of heterogeneous material possible

Limitations and future work

- **Limitations**:
  - Small quantity of trial,
  - limited experiment conditions,
  - Does not account for the dust interference

- **Future work**:
  - Trial with different feedstock (printed circuit boards)
  - Other parameters such as operation time and feed rate
  - Conduct trials in simulated conditions possibly in dusty thermal vacuum chamber (DTVC)

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Thank you!

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