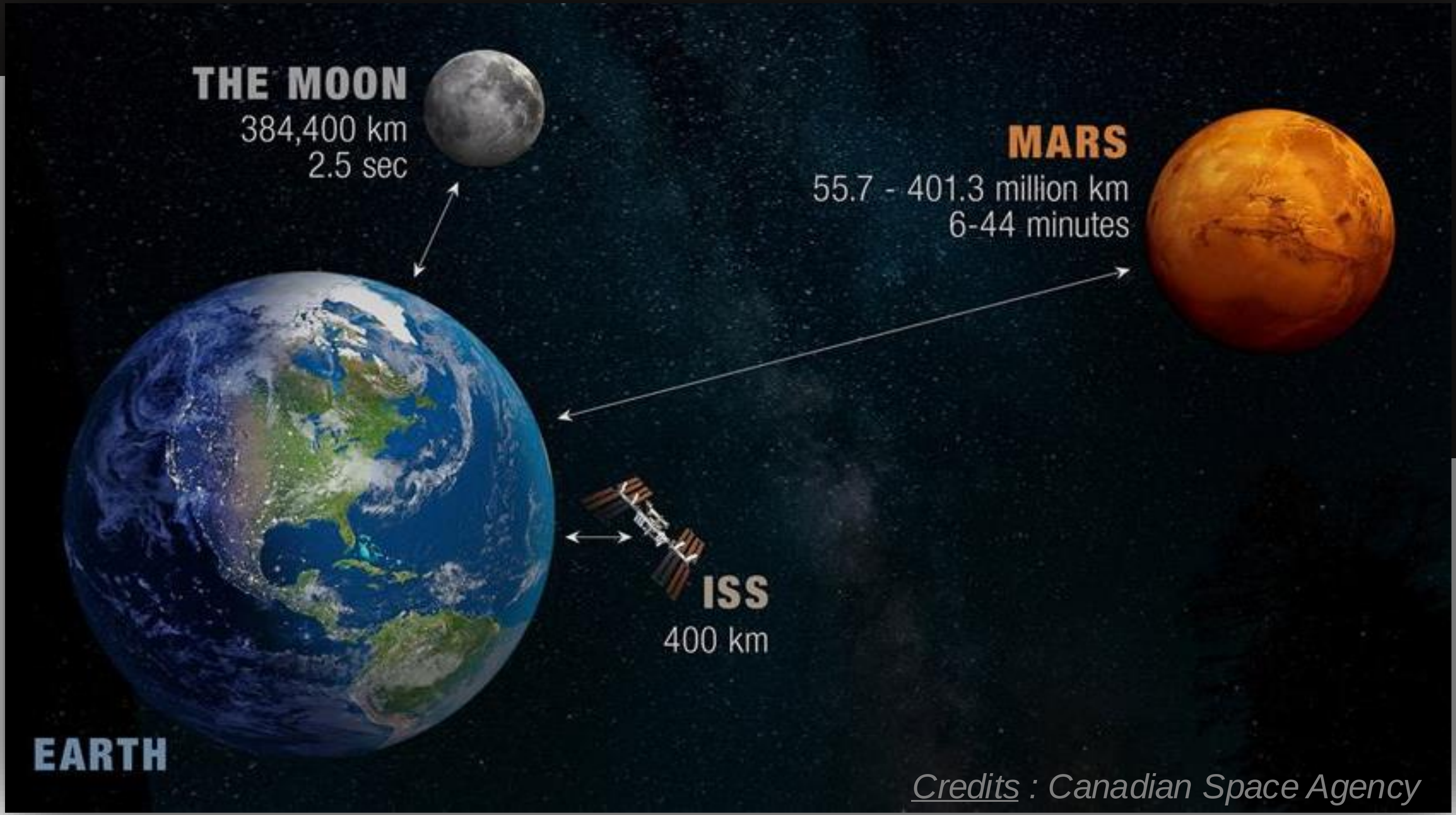
EPFL

Additive Manufacturing in Space



Final report presentation
11.11.2024

Agenda

- Repairs and first steps with ISS (Deborah Dufour)
- 3D Bioprinting (Carolin Hepp)
- Space medicine (Justus Dorsel)
- AM of spacesuits (Alexandre Blaga)
- Additive manufacturing in space using local resources (Mateja Deric)

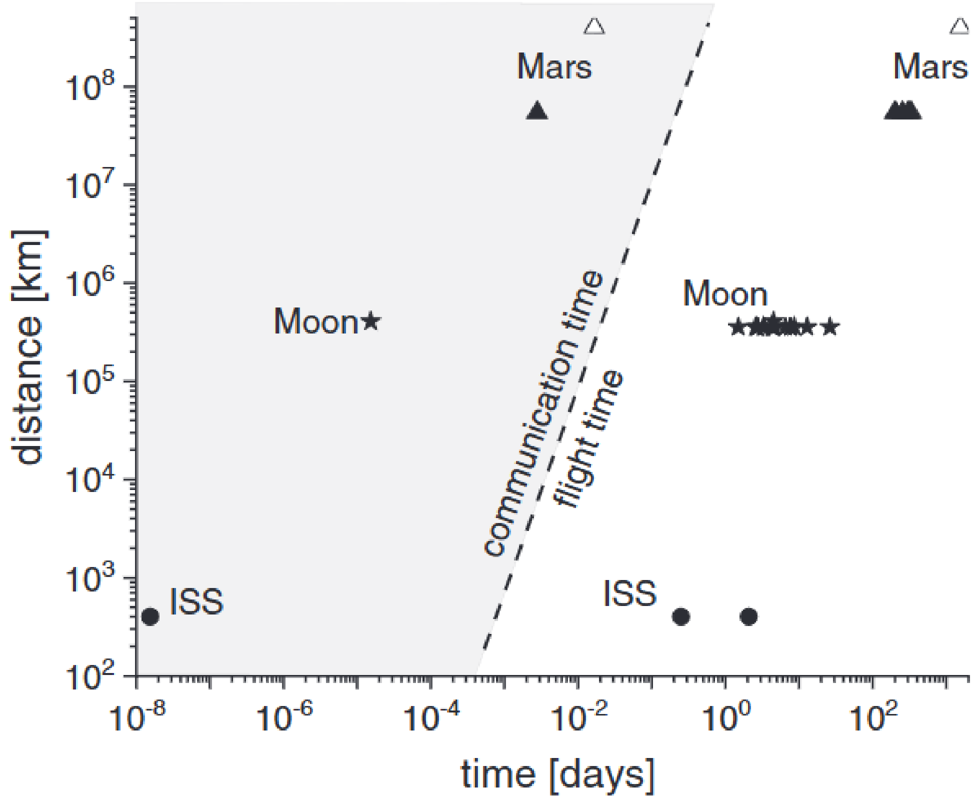
Credits : *NASA*

Repairs and first steps with ISS

- Time efficiency
- Mass and money savings
- Adaptability
- History
- Recycling
- Limitations

Déborah Dufour

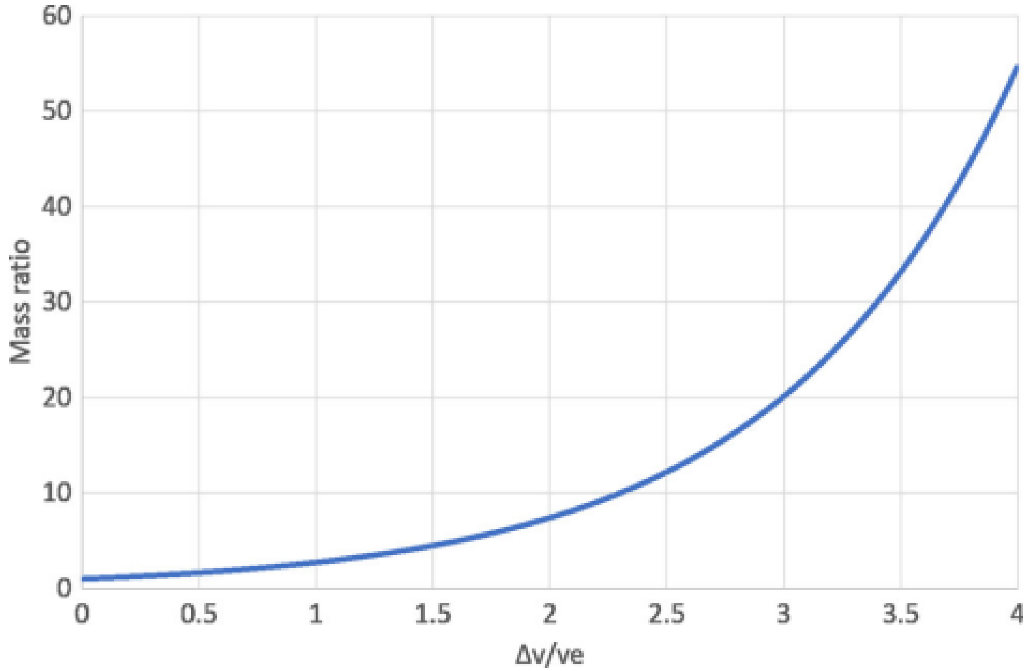
Time efficiency



Credits : Andrea Zocca et al. Enabling the 3D Printing of Metal Components in μ-Gravity

Mass and money savings

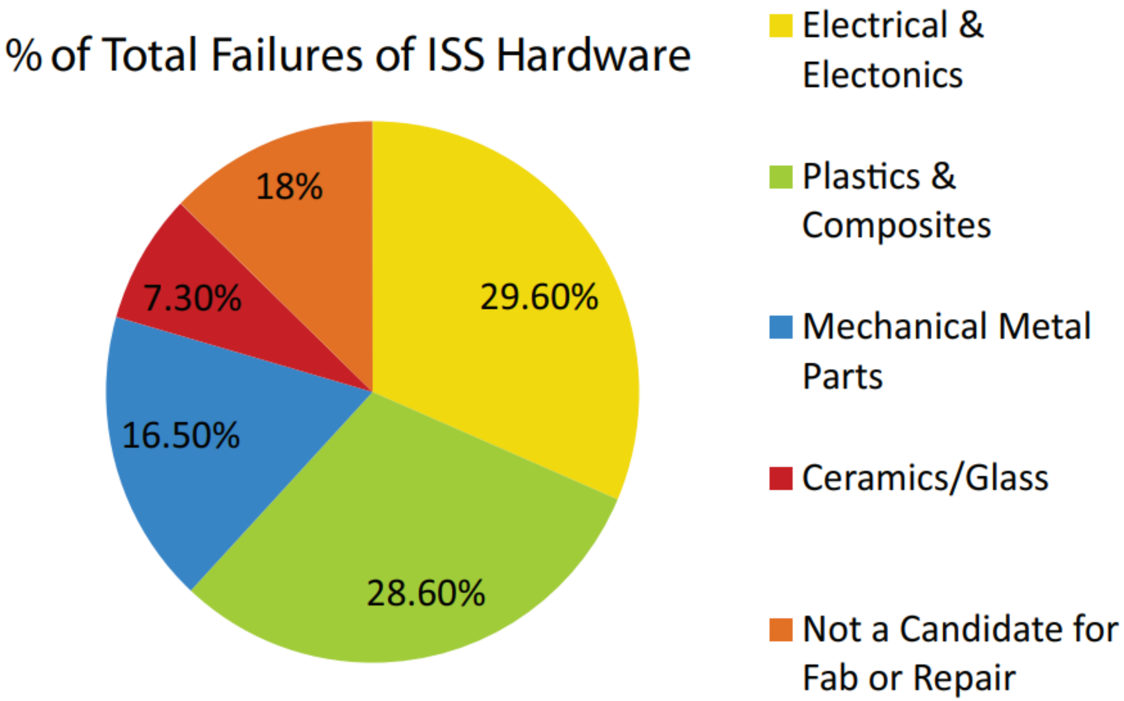
Each part : 3 replacements



Launch vehicle	Mass to LEO	Cost to launch to LEO	Cost per metric tons (MT)	Cost per kg
Space launch system	70	USD 600M	USD 8.57M	USD 8,570
FH	53	USD 158M	USD 2.97M	USD 2,970

Credits : Seung Ki Moon Enea Sacco. Additive manufacturing for space: status and promises

Adaptability : everyday repairs

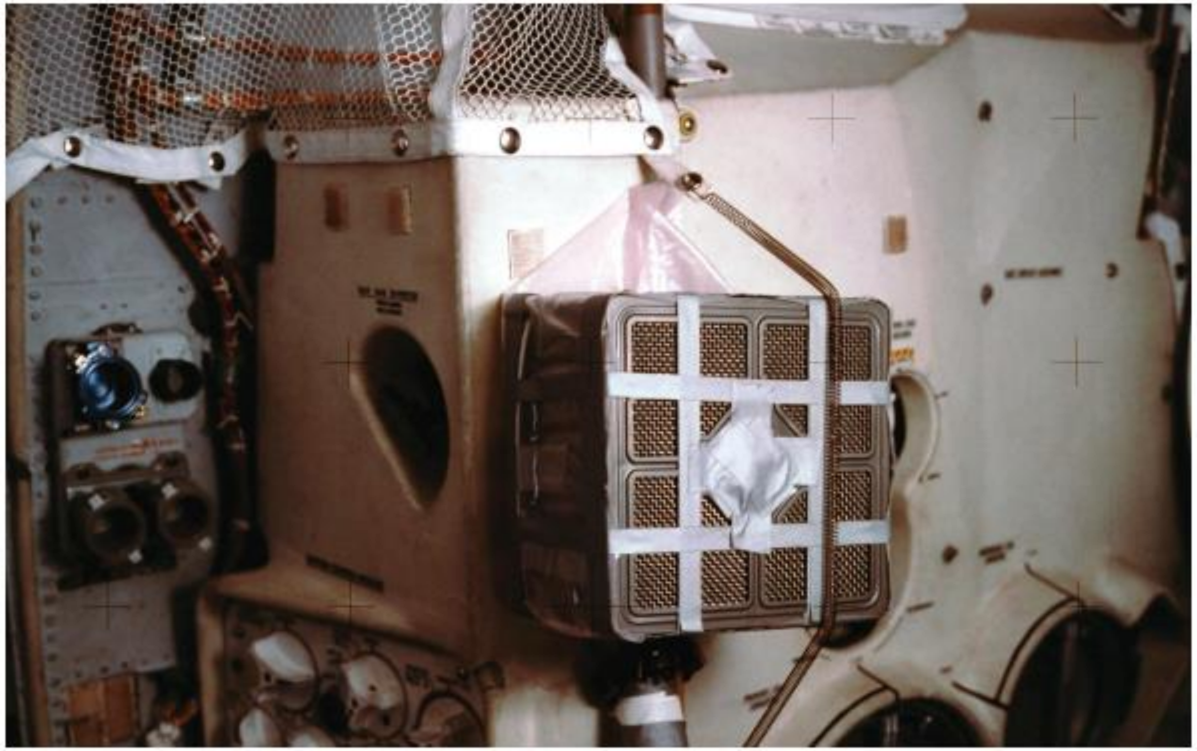


Credits : Made In Space Inc

Credits : NASA

Chapter 1 : Repairs on the ISS

Adaptability: accidents



Credits : NASA

History : On the ISS

3DPrint
P3DP
AMF

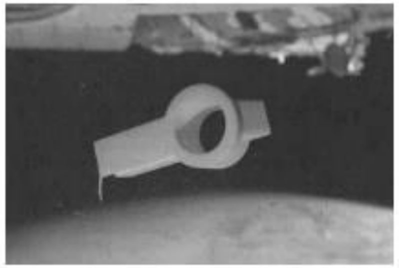
Credits : Moon Seung Ki, Enea Sacco. Additive manufacturing for space: status and promises

AMF on ISS with printed multi-purpose tool floating in front (photos courtesy of MIS)

SPHERES Tow Hitch

Antenna Feed Horn

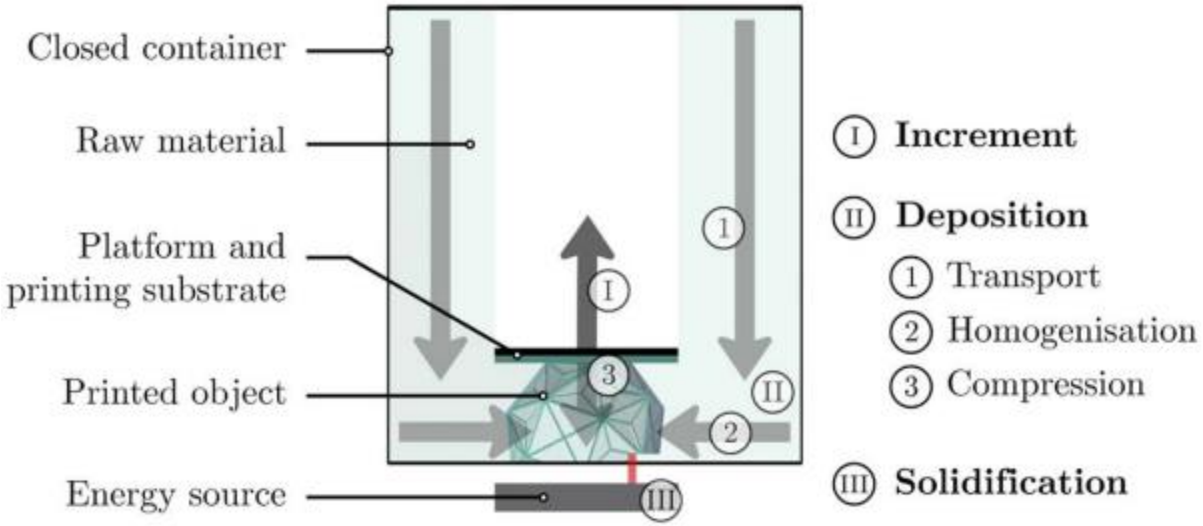
REM Shield Enclosure

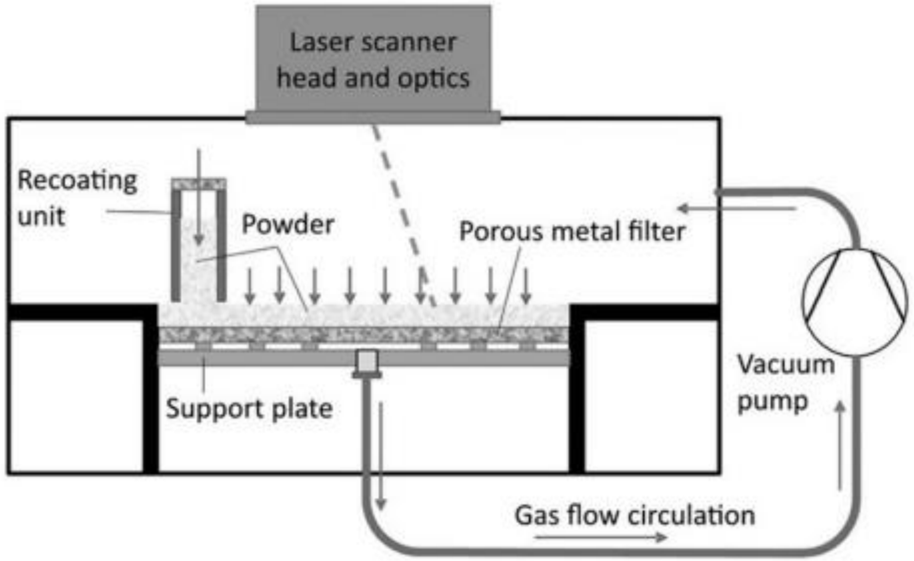


OGS AAA Adapter

Credits : R.G. Clinton Jr. Additive Manufacturing for Human Space Exploration

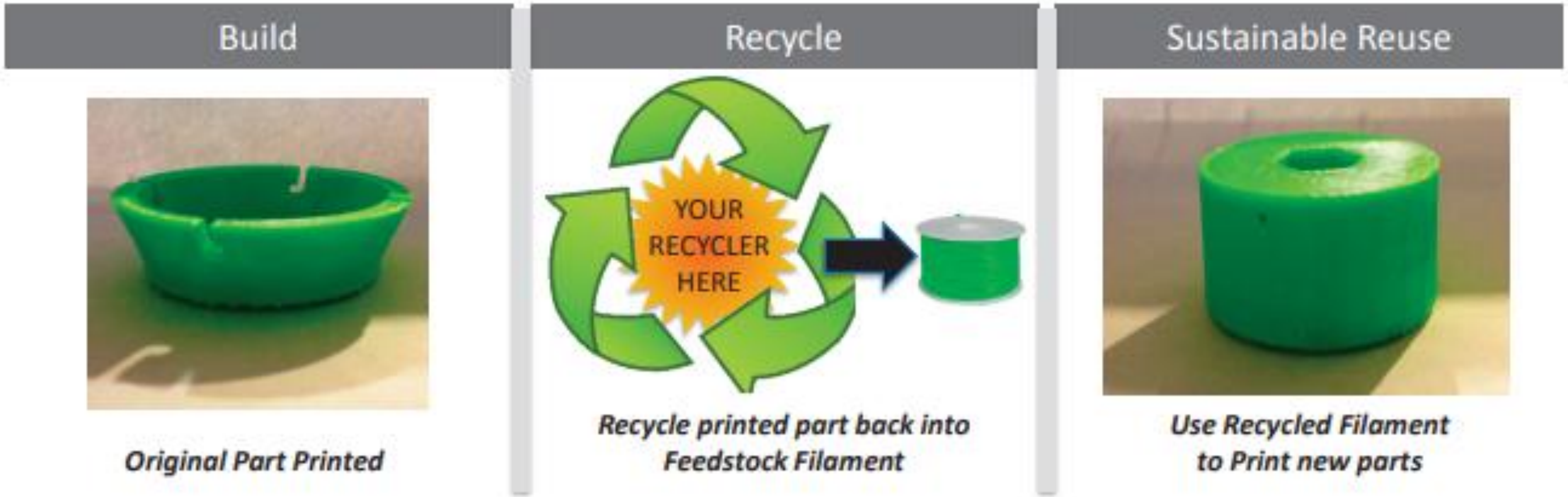
History :
On Earth





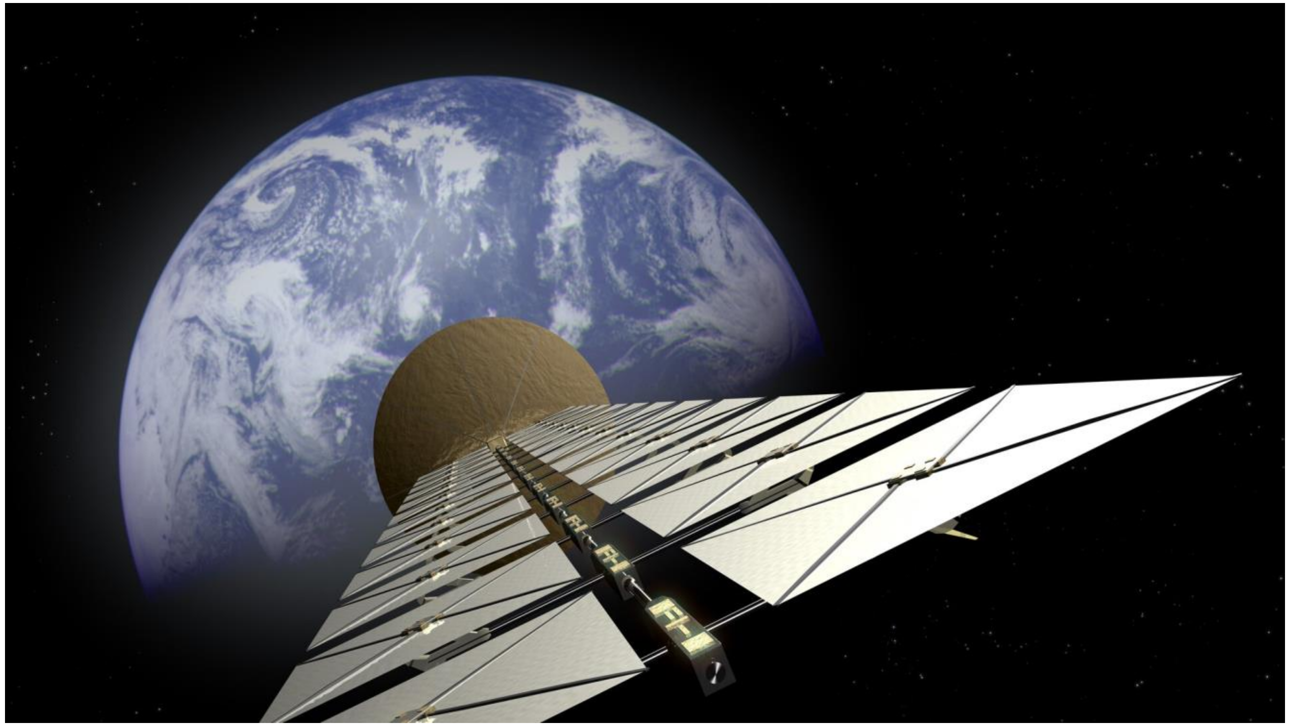
Credits : Alaa Elwany Miguel Hoffmann. In-Space Additive Manufacturing: A Review

Recycling

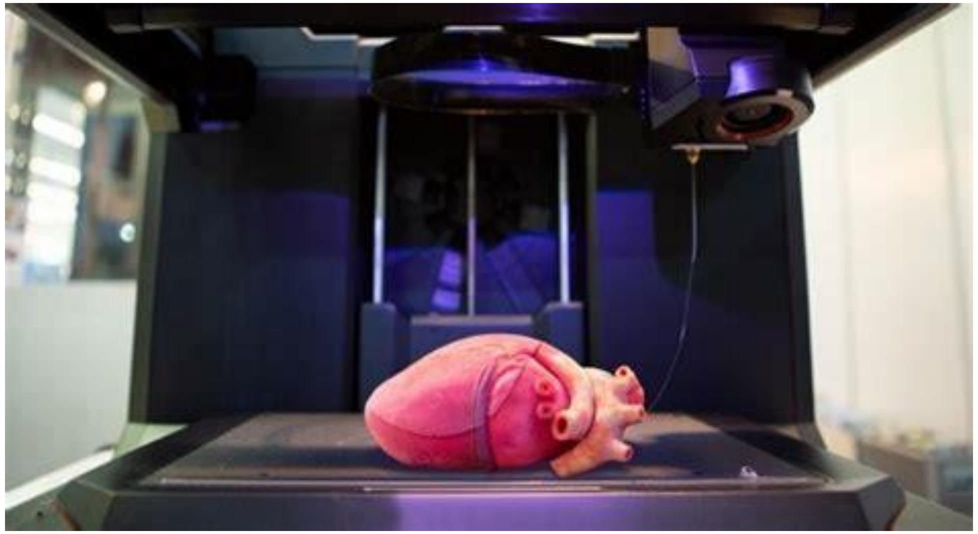


Credits : NASA : The Refabricator

Limitations



Credits : ESA



https://www.technologynetworks.com/cell-science/lists/how-bioprinting-is-advancing-tissue-engineering-350904

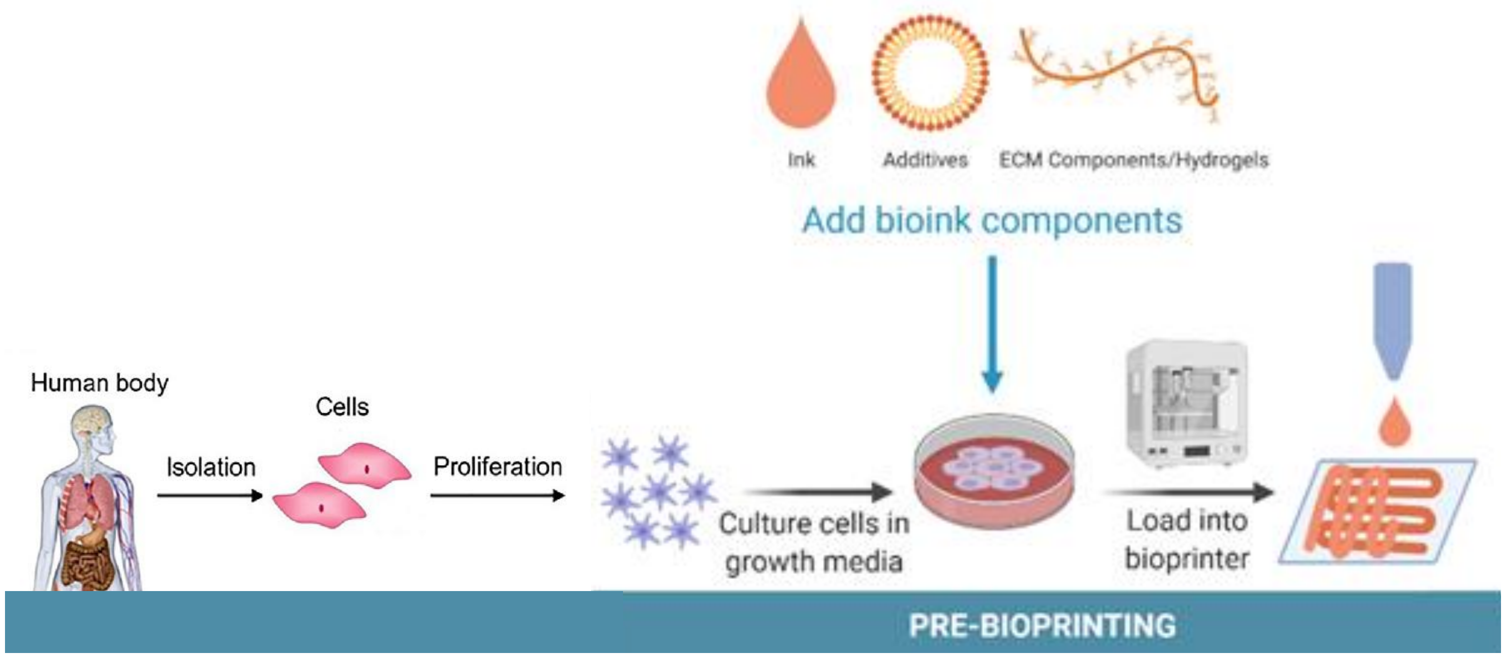
3D Bioprinting

- Introduction
- Bioprinting in Space
- Bioprinting in Microgravity
- Current Research on the ISS

Carolin Hepp

Introduction

- 3D printing with living cells
- Pre-Processing

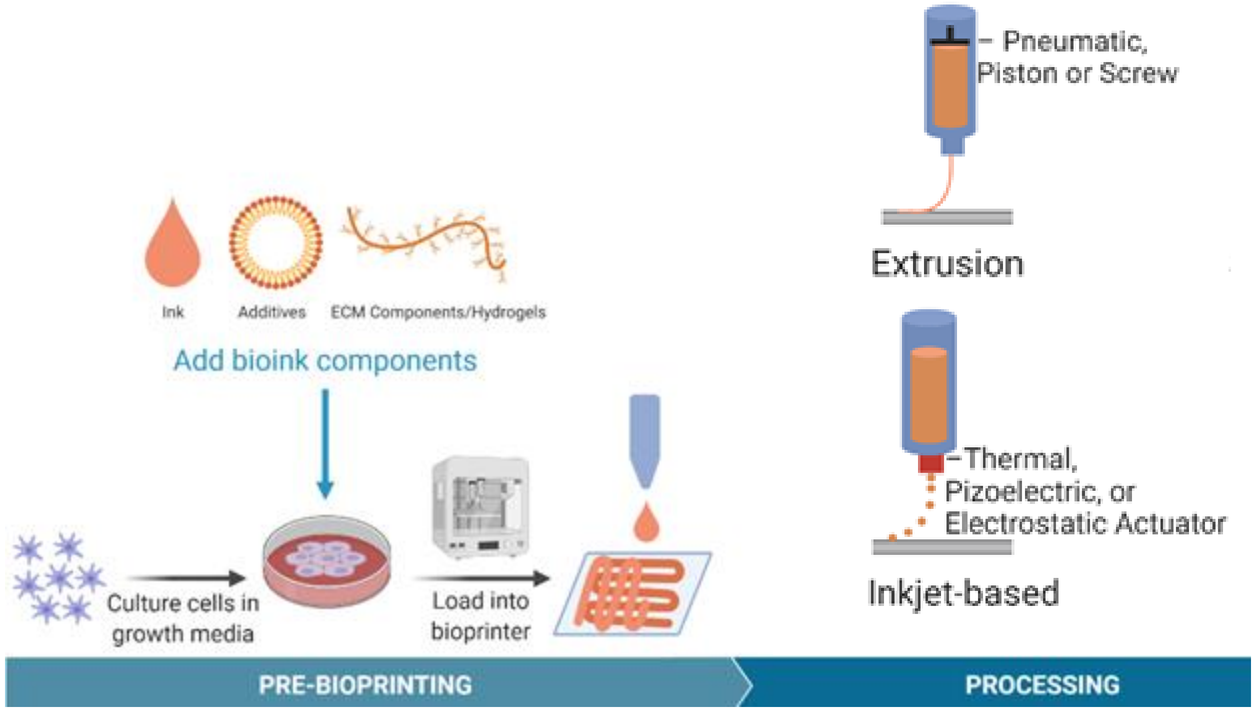


https://meow.wse.jhu.edu/protocols/beginners-guide-to-bioprinting/

Introduction

- 3D printing with living cells

- Processing

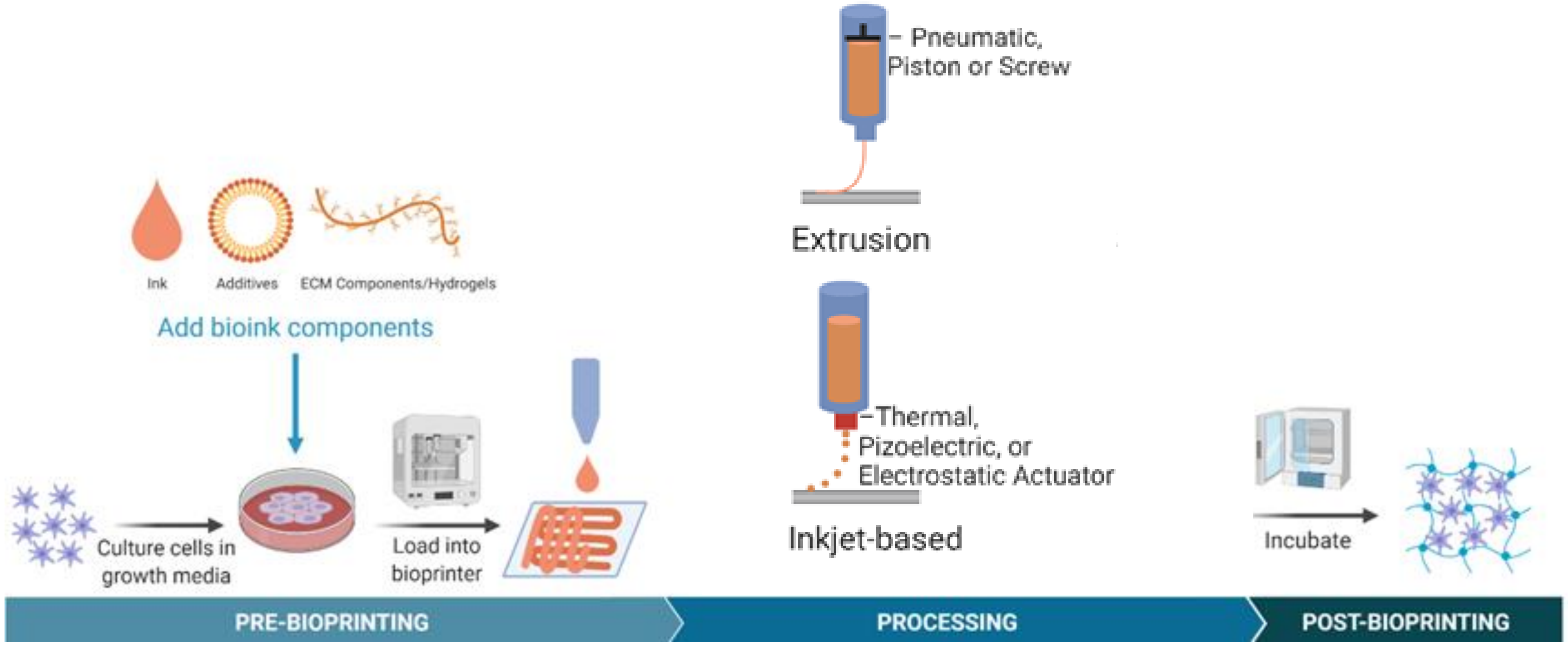


https://meow.wse.jhu.edu/protocols/beginners-guide-to-bioprinting/

Introduction

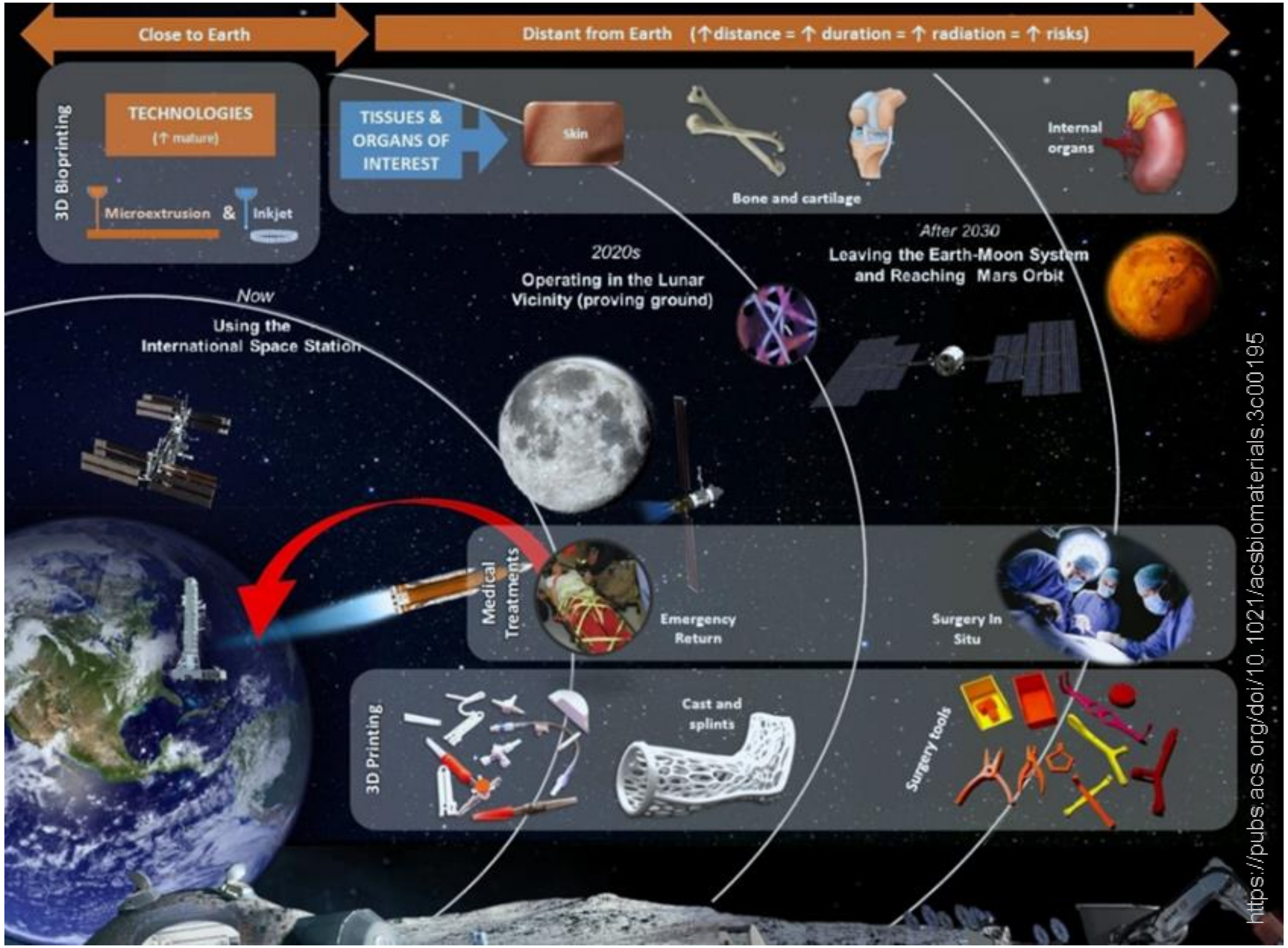
- 3D printing with living cells

- Post-Processing

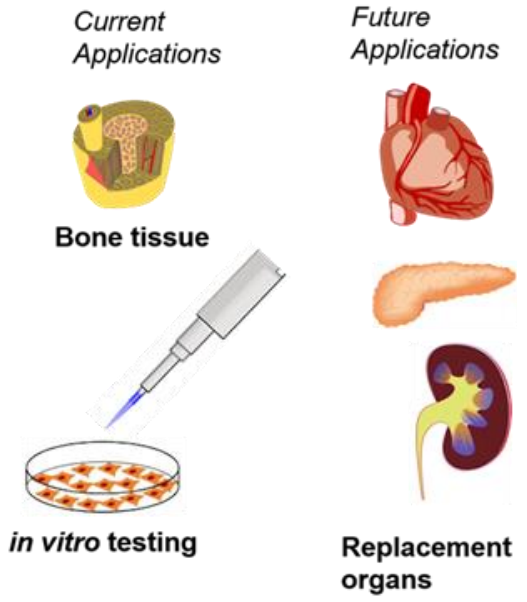


https://meow.wse.jhu.edu/protocols/beginners-guide-to-bioprinting/

Bioprinting in Space



https://pubs.acs.org/doi/10.1021/acsbiomaterials.3c00195

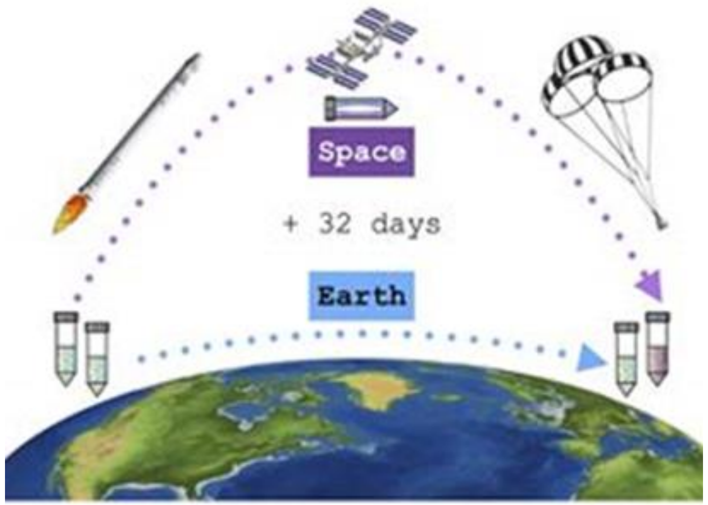


https://se3dedu.blogspot.com/2018/01/3d-bioprinting-is-rapidly-growing-field.html

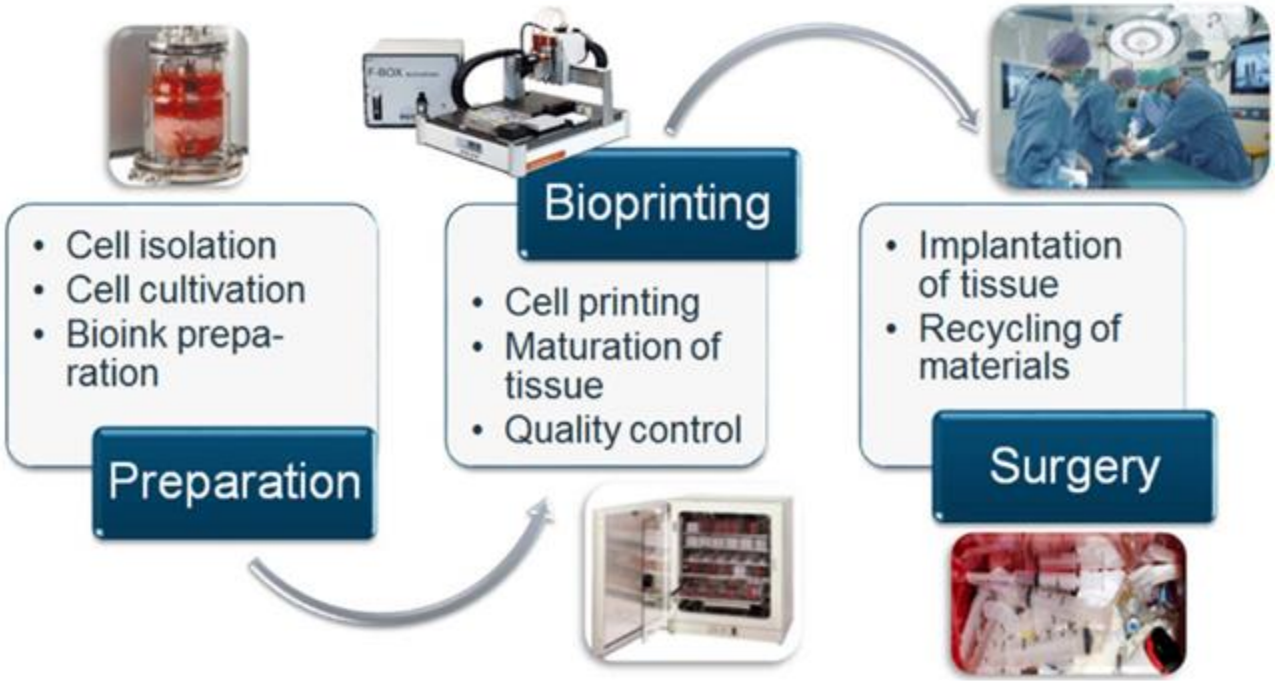
- Medical Infrastructure
- Now: Experimental soft tissue fabrication in microgravity

Bioprinting in Microgravity

- Challenges? -> YES
- Advantages? -> YES



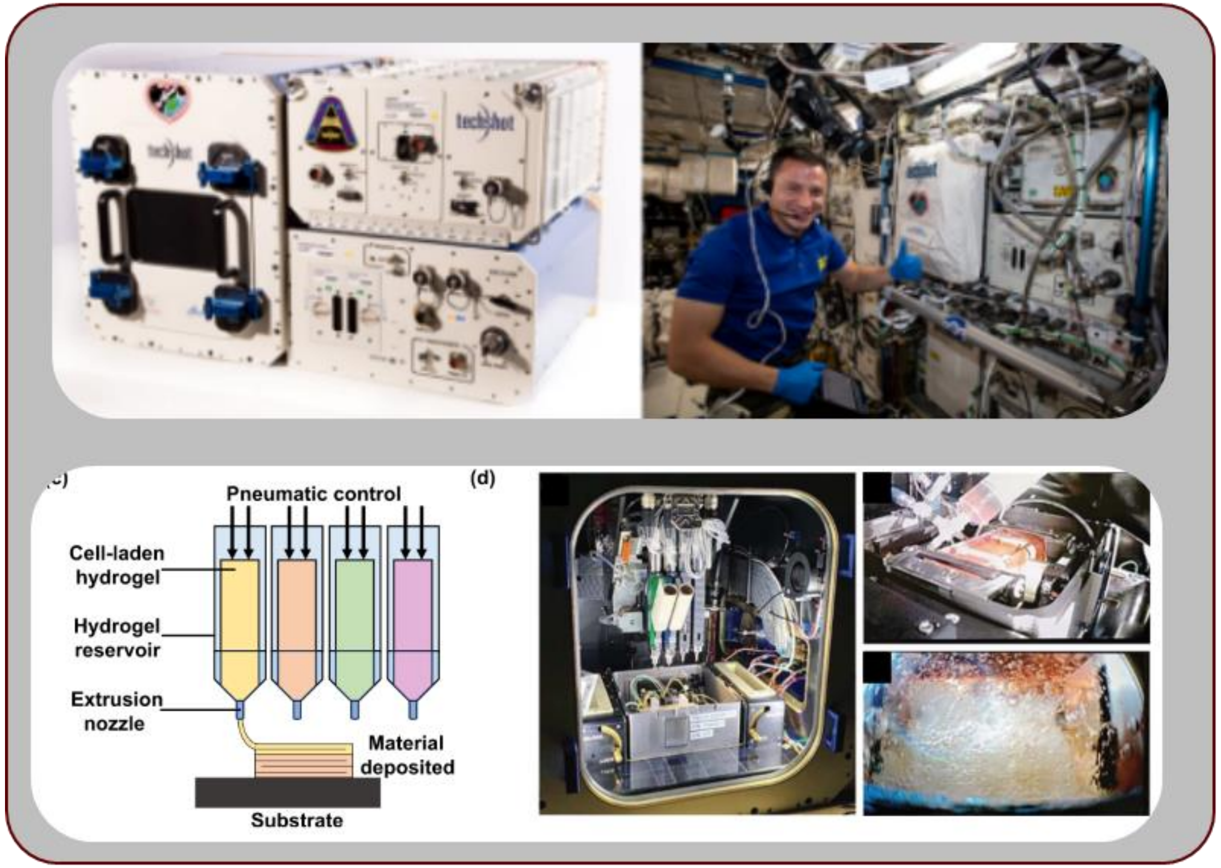
https://www.nasa.gov/missions/station/iss-research/3d-bioprinting/



https://www.researchgate.net/figure/Schematic-showing-the-different-work-steps-for-medical-application-of-bioprinting-in_fig1_344168

Current experiments on the ISS

- BioFabricationFacility (BFF) - since 2019



https://pubs.acs.org/doi/10.1021/acsbiomaterials.3c00195

- Handheld First-Aid Bioprinter

https://www.dlr.de/en/latest/news/2022/01/20220131_3d-printed-bio-plaster

Credits : NASA

Space Medicine

- Need for space medicine
- State of the art
- Risks
- Future

Need for Space Medicine

- Microgravity effects
- Radiation Exposure
- Closed-system health issues
- Future long-duration missions

Credits : NASA

State of the Art

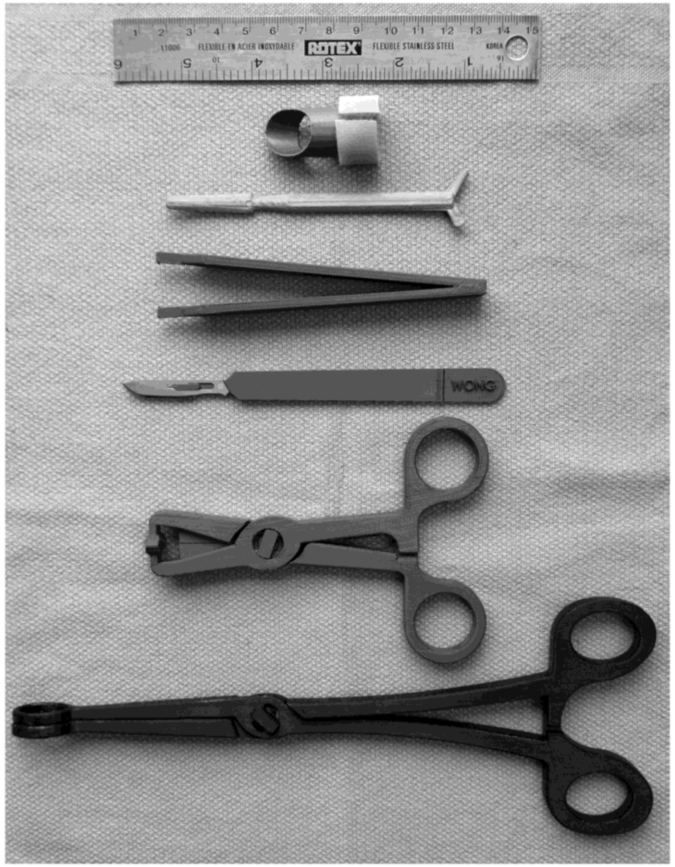
- Astronauts were able to successfully conduct surgery in space
- Robot was remotely controlled from earth to perform surgical tasks on ISS
- Tools are needed:
  - 3D printing allows localized production
  - Production of personalized tools

Credits : World Extreme Medicine

State of the Art

- Hammer splints
- Dental tool
- Forceps
- Scalpel handle
- Towel clamp
- Sponge stick

- Wong used a fused deposition modelling (FDM) printer
- photovoltaic printer
- ABS as material

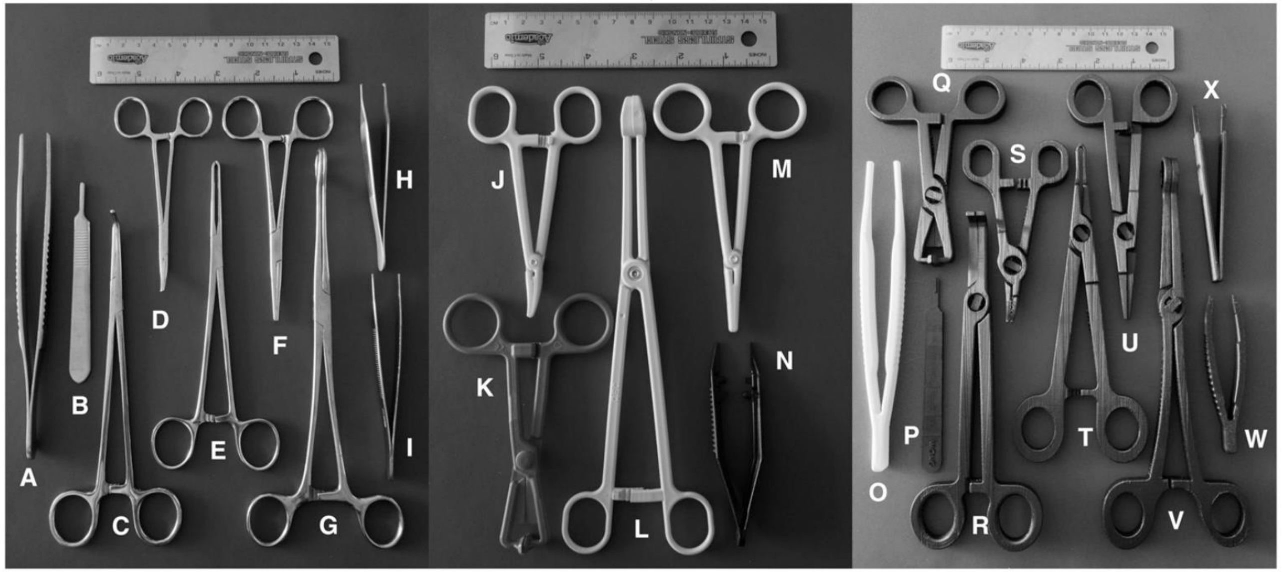


Credits : Wong

State of the Art

- Left: metal tools
- Middle: disposable plastic tools
- Right: 3D-printed tools

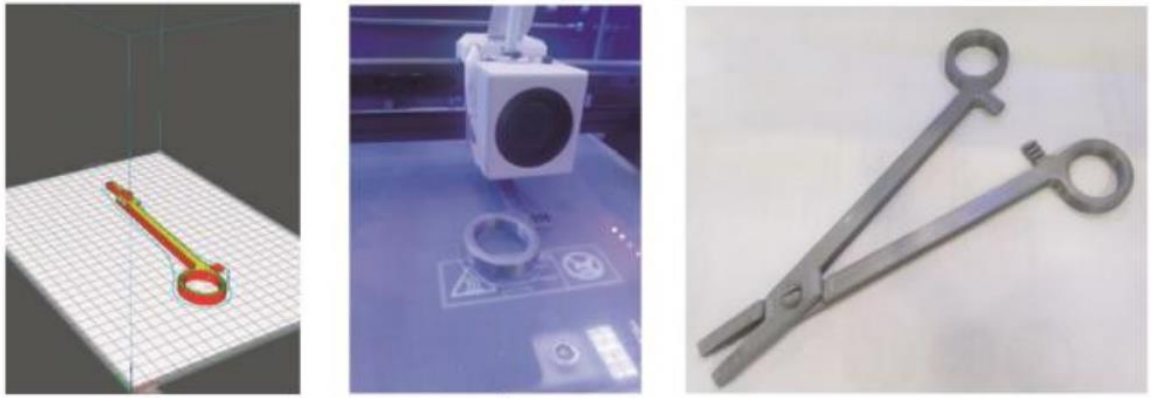
- 3D printer was gravity-independent, single-extruder FDM printer
- ABS thermoplastic
- Size was bigger

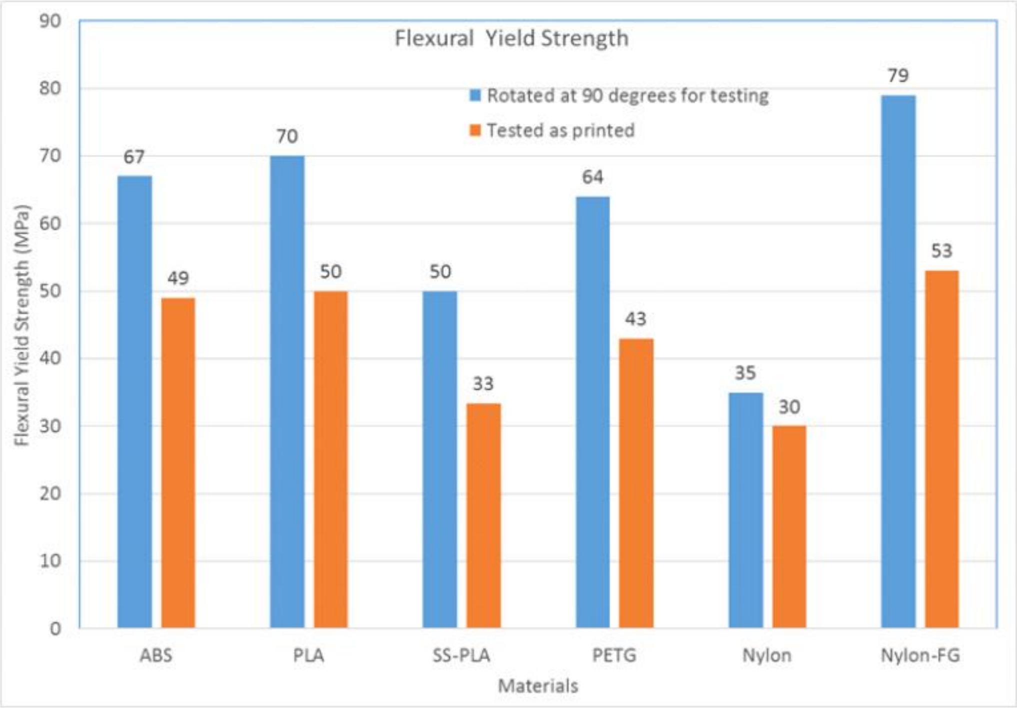


Credits : Wong

State of the Art

- Surgical needle holder
- Tested several materials
  - ABS, PLA, PLA-SS, PETG, Nylon, Nylon-FG

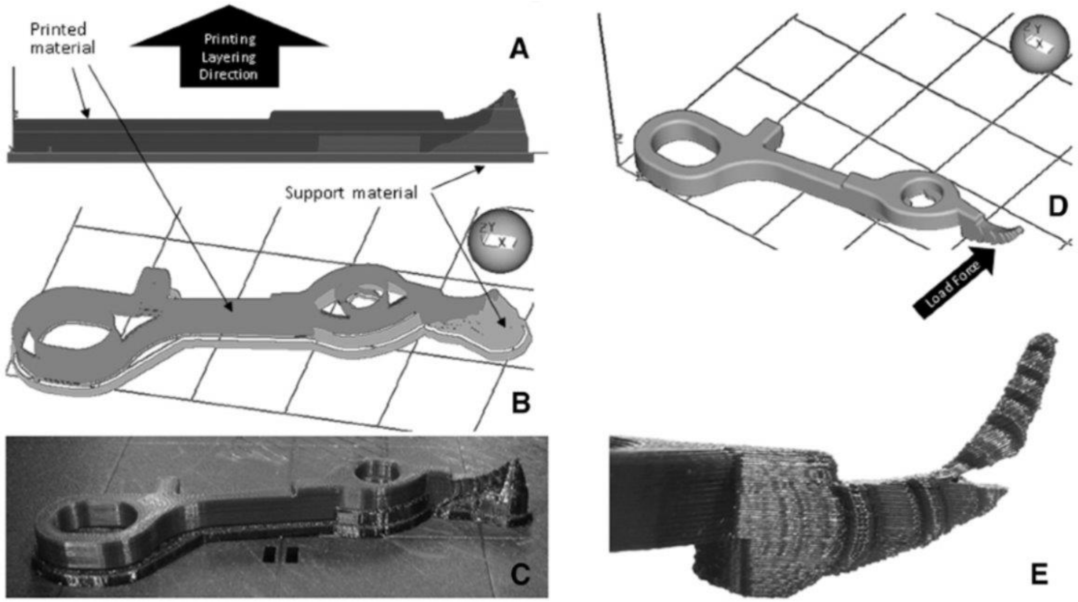




Credits : Efstathiadis

Risks

- Printing time: it can take hours to print
  - No spontaneous surgeries
- Sterility of devices
- Mechanical properties vary
- Material recycling and waste generation



Credits : Efstathiadis

Future of Space Medicine

- Faster 3D printers will increase efficiency
- New printers with wider range of thermoplastic material
  - Variety of medical tools
- Development of equipment to recycle waste helps conserve resources during missions

AM of spacesuits

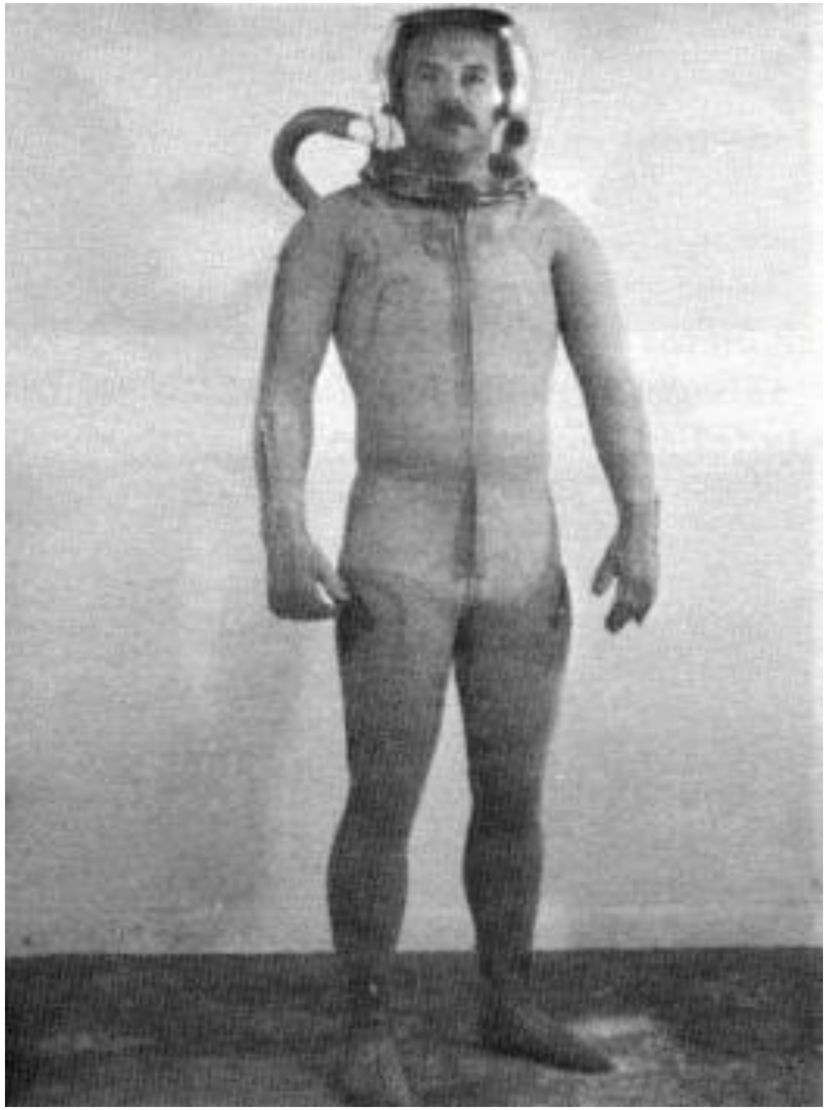
- Direct compression suits
- Indirect compression suits
  - Hybrid suits
  - Hard suits

Credits: Wikimedia Commons

Chapter 5: Spacesuits

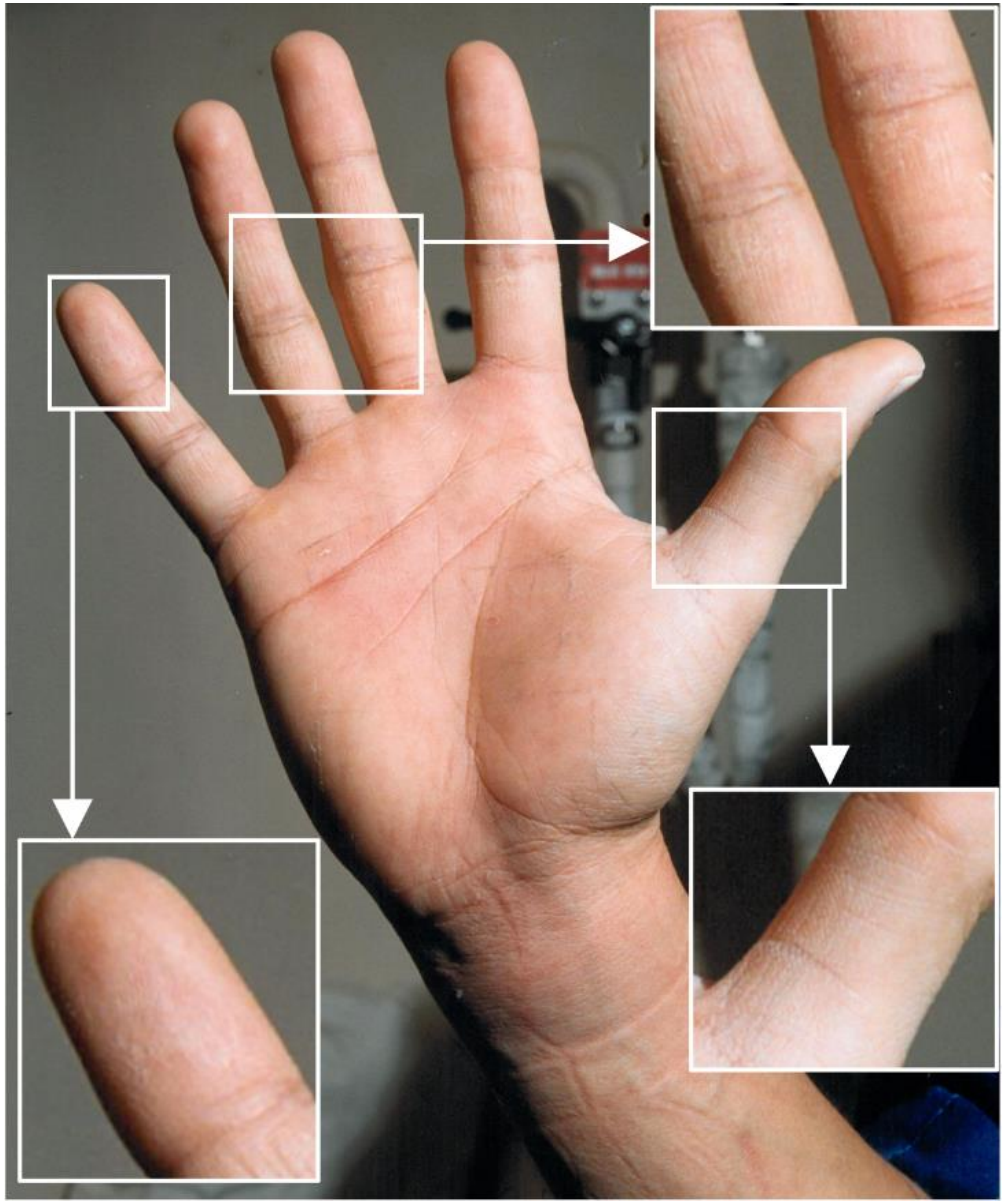
Alex

Direct compression suits



Credits: NASA

Direct compression suits

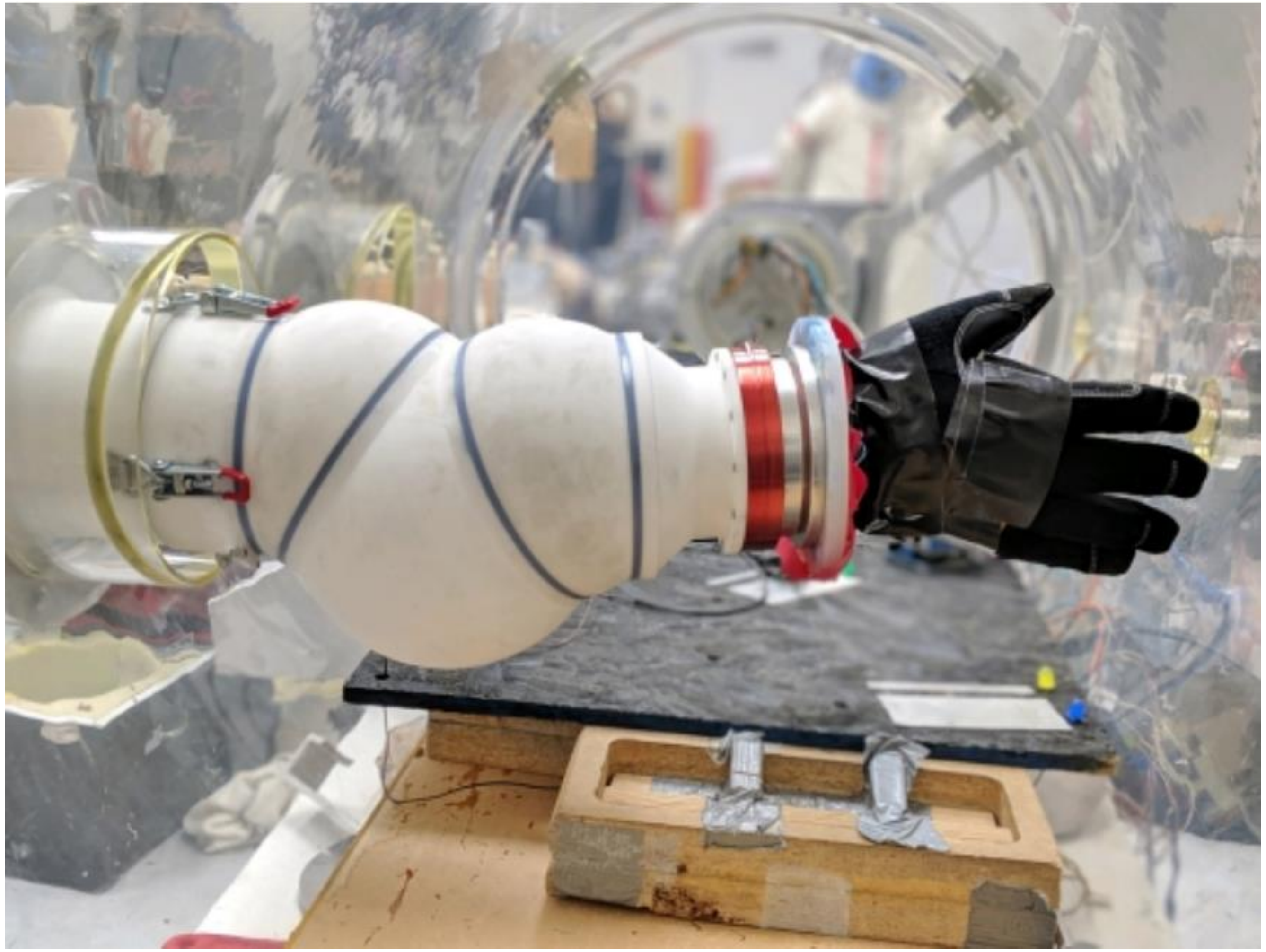


Credits: NASA

Hybrid suits

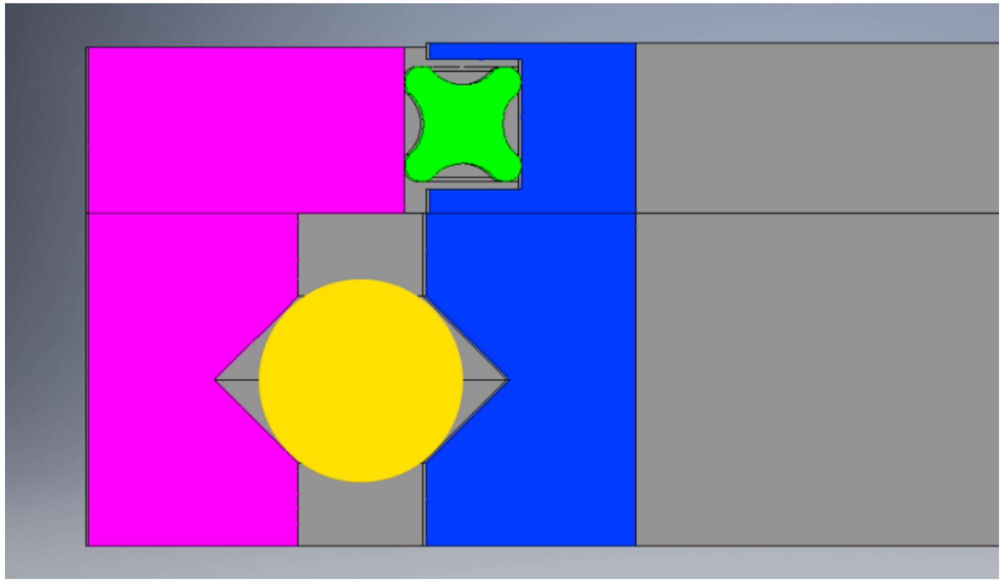
Credits: University of North Dakota

Hard suits



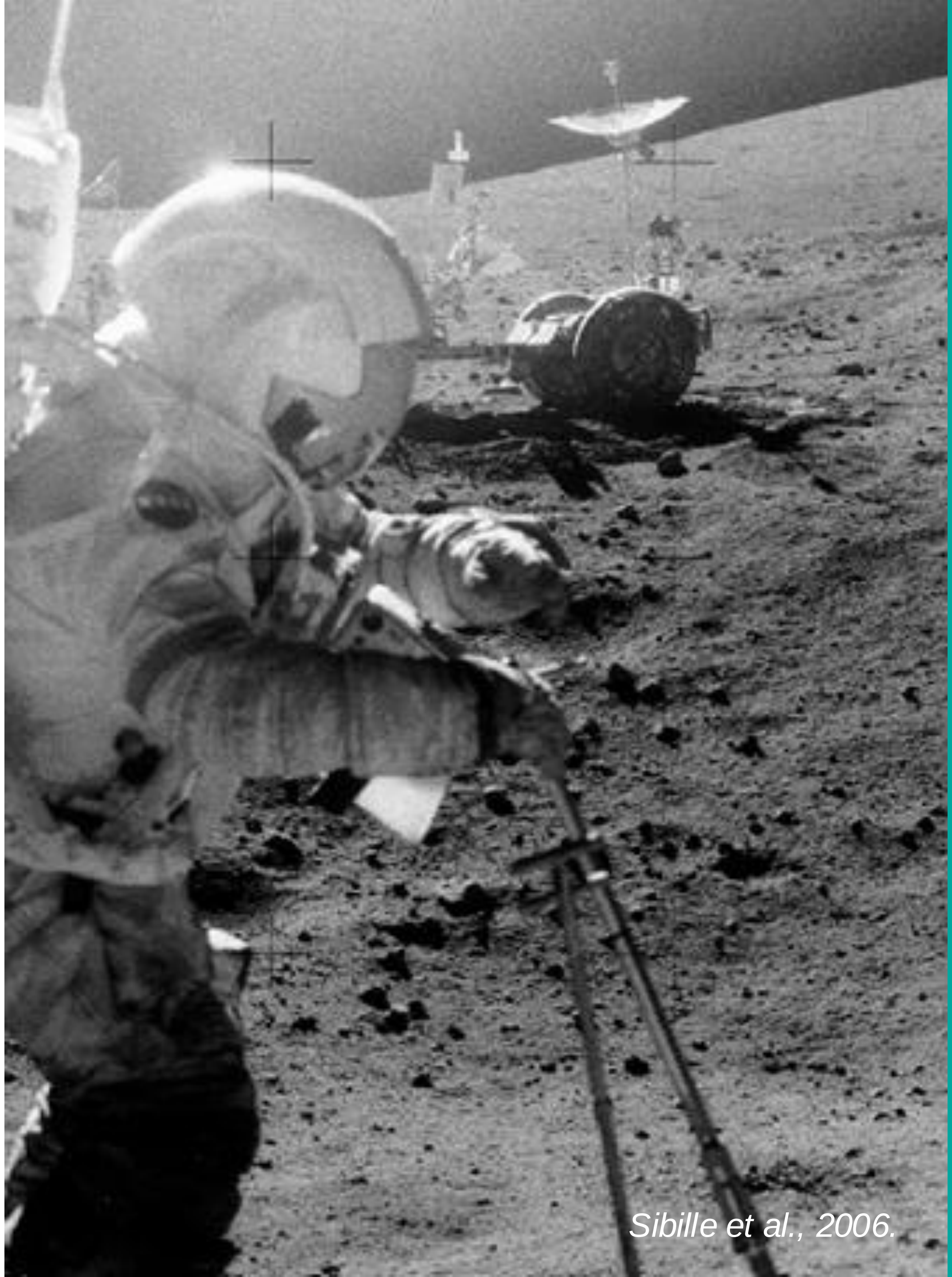
Credits: University of Maryland

Hard suits



Credits: University of Maryland

EPFL


Sibille et al., 2006.

Additive manufacturing in space using local resources

1. Concept of ISRU
2. Regolith and its simulants
3. AM methods suitable for ISRU

Mateja Đerić

Concept of ISRU

- In-situ resource utilization – ISRU
- Local materials
- Reduced reliance on Earth-based supplies

Improve the missions' overall sustainability

Reduce launch mass and volume

Minimize waste

Concept of ISRU

Karl et al., 2022.

Regolith and its simulants

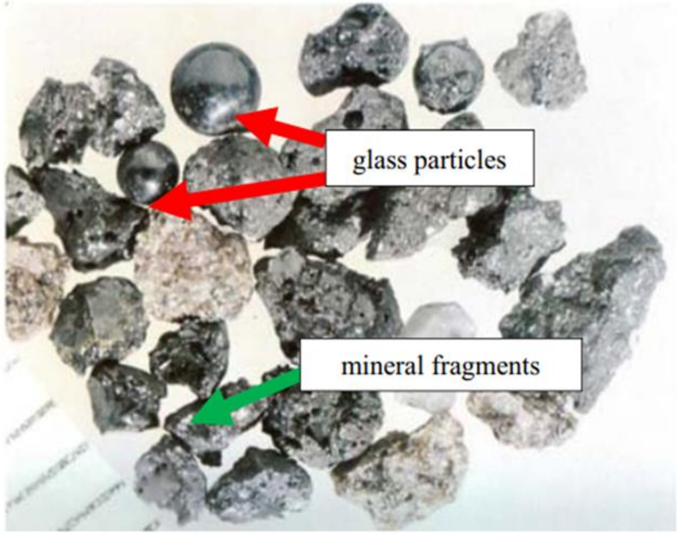


Photo from Wood et al., 1970., Goulas et al., 2021.

Martin and Smith, 2018 Simulating lunar and Martian regolith in laboratory

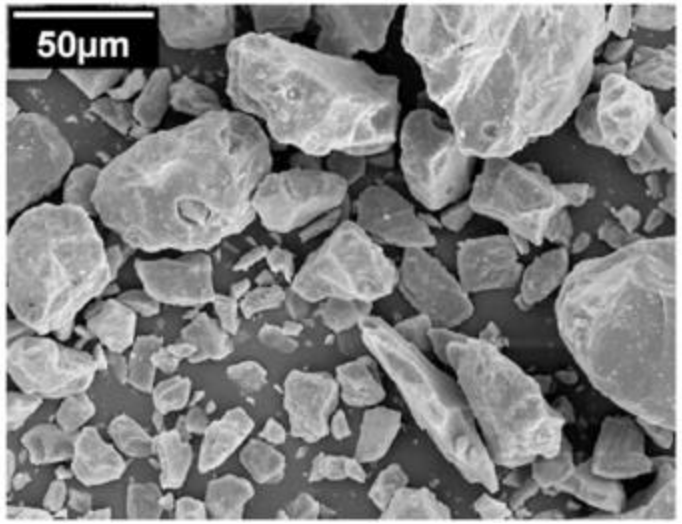
https://www.nasa.gov/

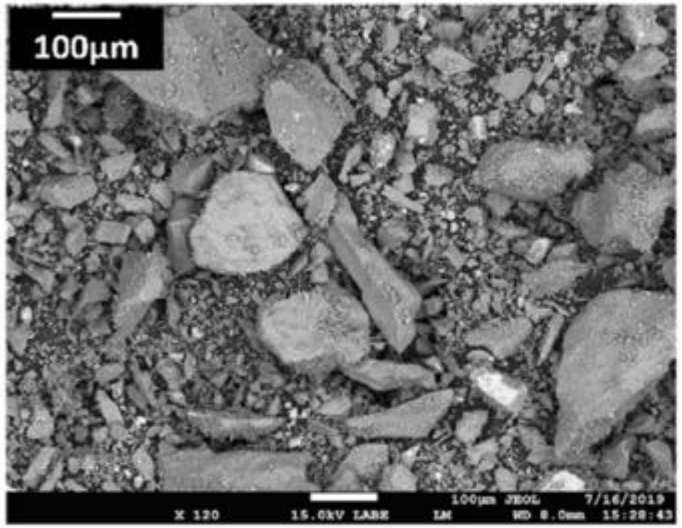
Regolith and its simulants

- Authentic extraterrestrial samples (i.e. regolith samples)

→ Simulant materials

Regolith and its simulants





Isachenkov et al., 2021.

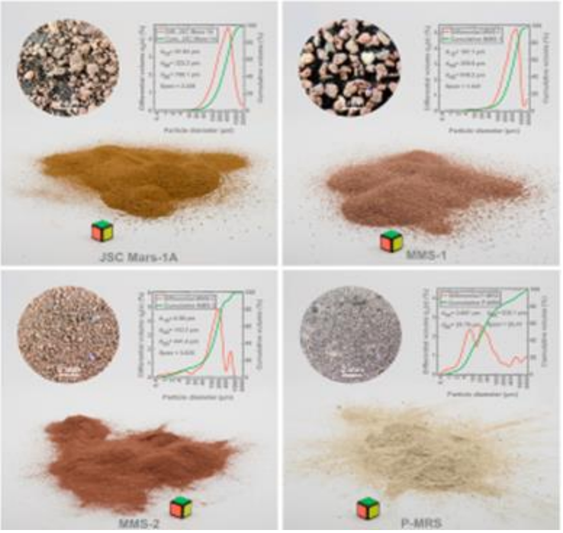
Table 21.1 List of lunar regolith simulants.

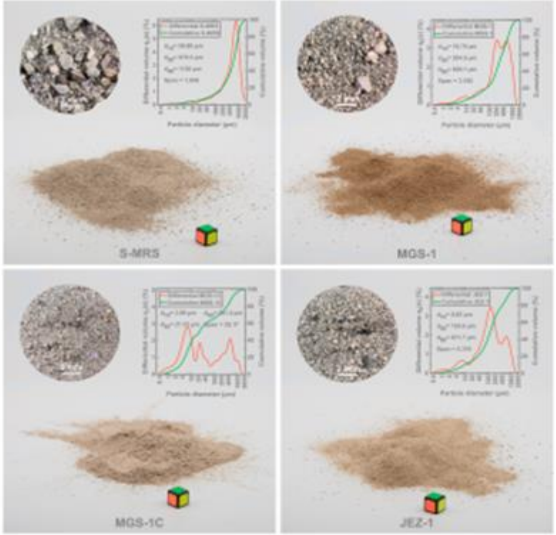
Simulant	Simulant complete name	Detail	Category
MLS-1	MLS-2 Minnesota Lunar Simulant	Highlands	Geotechnical
NAO-1	NAO-1 National Astronomical Observatories	Highlands	General
NU-LHT	NU-LHT-1M	Highlands	General
OB-1	OB-1/CHENOBI Olivine Bytownite	Highlands	General
ALS	ALS Arizona Lunar Simulant	Mare	Geotechnical
ALRS-1	ALRS-1 Australian Lunar Regolith Simulant	Mare	Geotechnical
BP-1	BP-1 Black Point W172158	Mare	Geotechnical
BP-1	BP-1 Black Point W172154	Mare	Geotechnical
CAS-1	CAS-1 Chinese Academy of Sciences	Mare	General
CLRS-1	CLRS-1/2 Chinese Lunar Regolith Simulant	Mare	Unknown
CSM-CL	CSM-CL Colorado School of Mines Colorado Lava	Mare	Geotechnical
CUG-1A	CUG-1A China University of Geosciences	Mare	Geotechnical
DNA-1	DNA-1 De NoArtri	Mare	Geotechnical
FJS-1	FJS-1 Fuji Japanese Simulant	Mare	General
FJS-2	FJS-2 Fuji Japanese Simulant	Mare	General
FJS-3	FJS-3 Fuji Japanese Simulant	Mare	General
GSC-1	GSC-1 Goddard Space Center	Mare	General
JSC-1	JSC-1/1A/1AF/1AC/2A Johnson Space Center	Mare	General
KLS-1	KLS-1 Korea Lunar Simulant	Mare	Geotechnical
KOHLS-1	KOHLS-1/KAUMLS Korean Lunar Simulants	Mare	Geotechnical
	Maryland–Sanders Lunar Simulant	Mare	Geotechnical
MLS-1	MLS-1/1P Minnesota Lunar Simulant	Mare	General
MKS-1	MKS-1 Lunar Simulant	Mare	Unknown
NEU-1	NEU-1 Northeastern University Lunar Simulant	Mare	Unknown
	Oshima Simulant	Mare	General
TJ-1	TJ-1/2 Tongji University	Mare	Geotechnical
CMU-1	CMU-1 Carnegie Mellon University	Other	Spectral
CRC-1	GRC-1/3 Glenn Research Center	Other	Geotechnical
	Kohyama Simulant	Other	General
BLHD20	BHLD20 Lunar Dust Simulant	Dust	General
CLDS-i	CLDS-i Lunar Dust Simulant	Dust	General

Class Exolith Lab; University of Central Florida.

Goulas et al., 2021.

Regolith and its simulants





Karl et al., 2022.

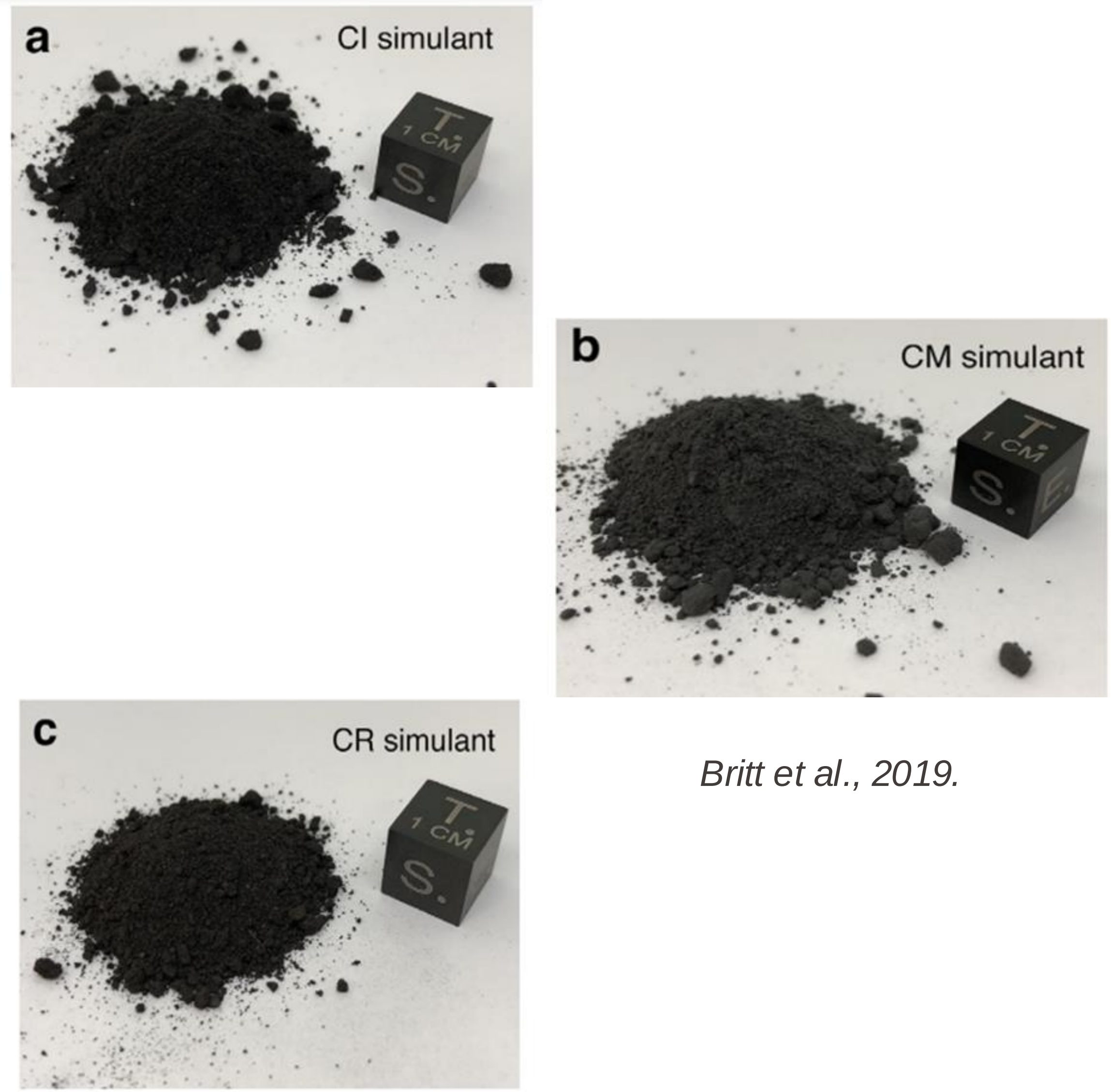
Table 21.2 List of Martian regolith simulants.

Simulant	Simulant complete name	Detail	Category
ES-X	ES-X Mars Simulants		Geotechnical
JMSS-1	JMSS-1 Jining Mars Soil Simulant		Geotechnical
JSC Mars-1/1A	Johnson Space Center	Dust	Spectral
KMS-1	KMS-1 Korean Mars Simulant		Geotechnical
MGS-1	MGS-1 Mars Global		General
MMS	MMS Mojave Mars Simulant		Geotechnical
MMS-1	MMS-1/2 The Martian Garden		General
	MMS Rocknest Augmented MMS		General
	Salten Skov 1	Dust	Magnetic
	UF Acid-Alkaline-Salt Basalt		General
	Analog Soils		
	UC Mars1		Geotechnical

Class Exolith Lab; University of Central Florida.

Goulas et al., 2021.

Regolith and its simulants



Britt et al., 2019.

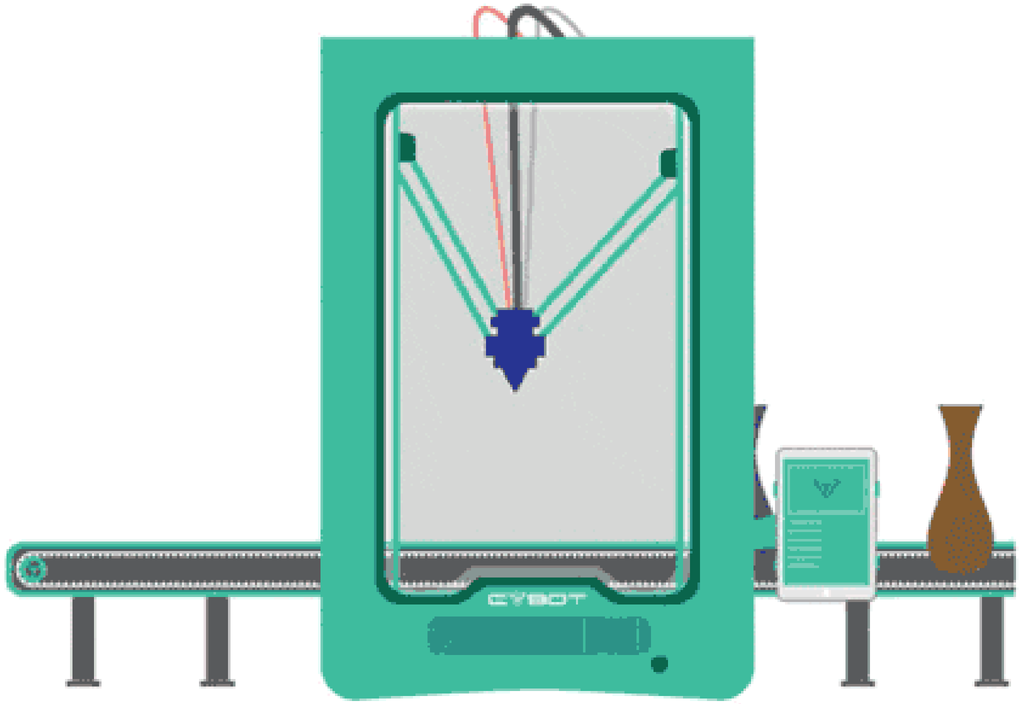
Table 21.3 List of asteroid regolith simulants.

Simulant	Simulant full name	Body	Category
HCCL-1	HCCL-1 Hydrated Carbonaceous Chondrite Lithologies	Asteroid	General
CI	UCF/DSI CI Carbonaceous Chondrite Simulant	Asteroid	General
CR	UCF/DSI CR Carbonaceous Chondrite Simulant	Asteroid	General
C2	UCF/DSI C2 Carbonaceous Chondrite Simulant	Asteroid	General
CM	UCF/DSI CM Carbonaceous Chondrite Simulant	Asteroid	General
	Carbonaceous Chondrite Based Simulant of Phobos	Phobos	General
PCA-1	PCA-1 Phobos Captured Asteroid	Phobos	General
PGI-1	PGI-1 Phobos Giant Impact	Phobos	General
UTPS-TB	UTPS-TB	Phobos	General
UTPS-IB	UTPS-IB	Phobos	General
MPACS	MPACS Mechanical Porous Ambient Comet Simulant	Comet	Geotechnical

Class Exolith Lab; University of Central Florida.

Goulas et al., 2021.

AM methods suitable for ISRU

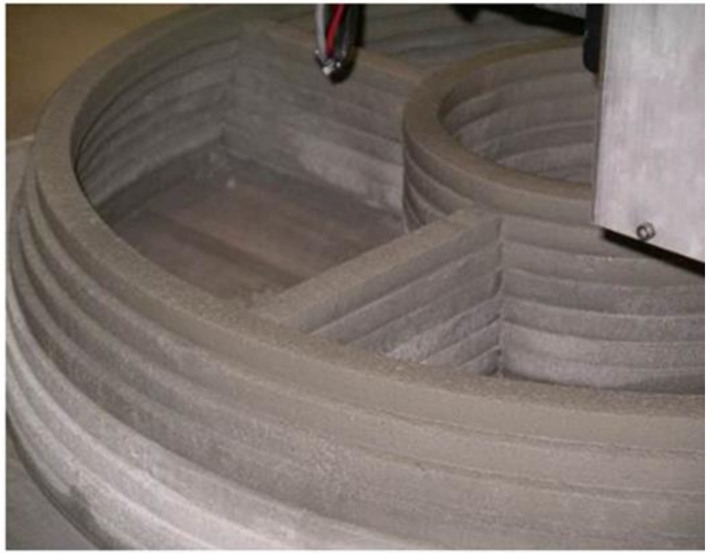


Material extrusion

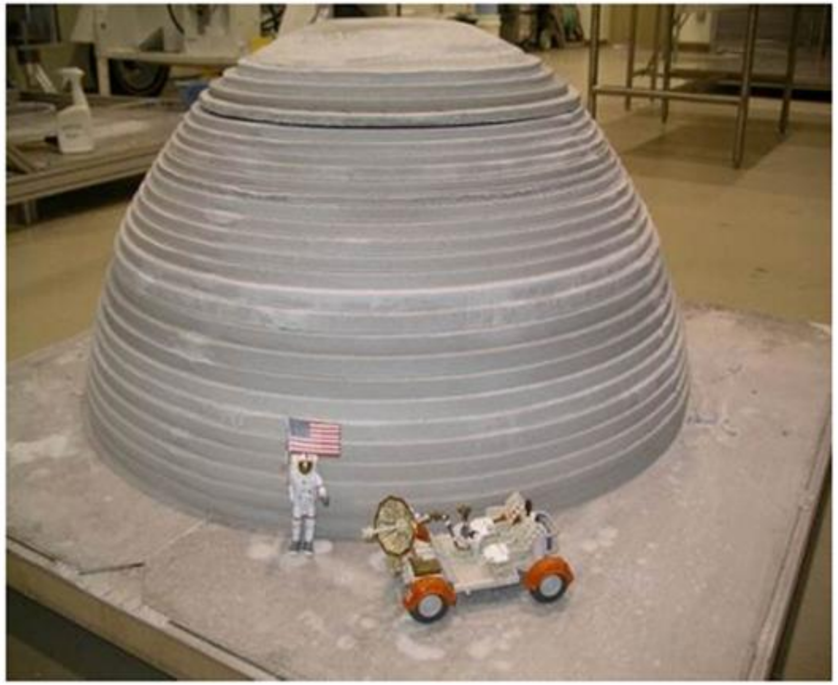
- Filament (metal, polymer or composite)
- Heated nozzle
- Sintering

Karl et al., 2022.

Contour Crafting



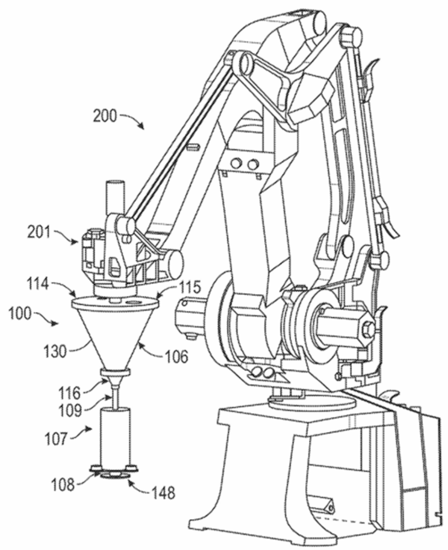
- Extrusion-based technology
- Sulfur-based concrete + JSC-1A
- Technology Readiness Level (TRL) 6



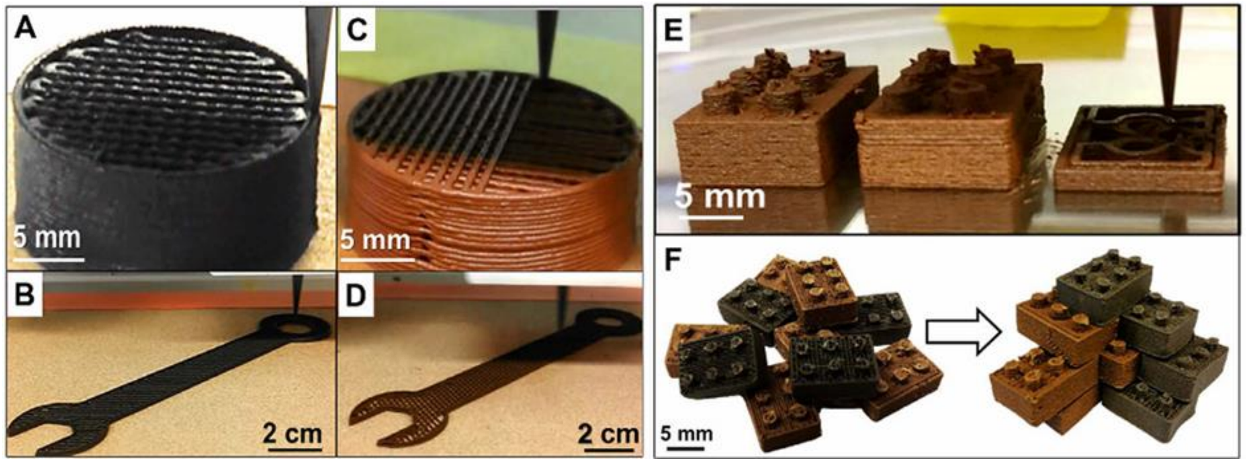
Khoshnevis and Zhang, 2012.

Different aproaches

- Regolith-polymer feedstock
  - Biopolymer (PLGA), filled with JSC-1A and JSC Mars-1A simulants
  - Metakaolin-based geopolymer binder with basalt aggregate
- Protein-based binders



Townsend et al., 2022.



Jakus et al., 2017.

Hojati et al., 2018.

Binder jetting

- Liquid binder agent
- Layer of powder (metal, polymer or ceramic)
- Lowering of build platform

Karl et al., 2022.

D-shape



- Complete building structures or building blocks
- Regolith (DNA-1)-based concrete
- The European Space Agency (ESA)



Cesaretti et al., 2014.

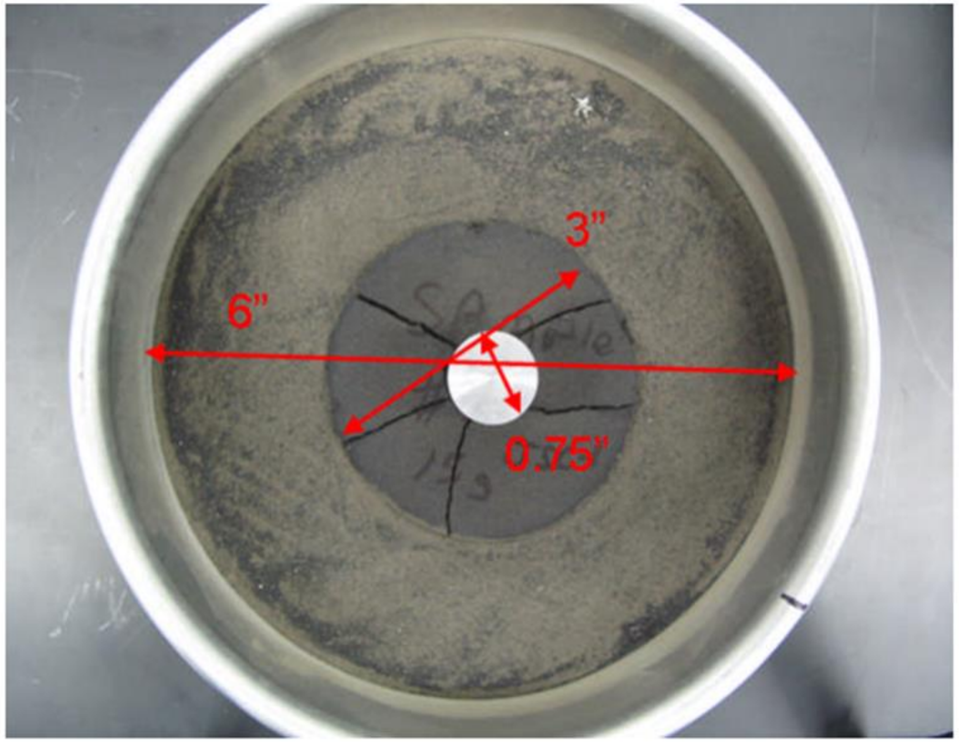
Powder Bed Fusion

Karl et al., 2022.

- Laser or electron beam
- Melt/sinter
- Feedstock (metal, plastic, polymer or ceramic powder)
- Lowering of build platform

Selective Solar Light Sintering (SSLS)

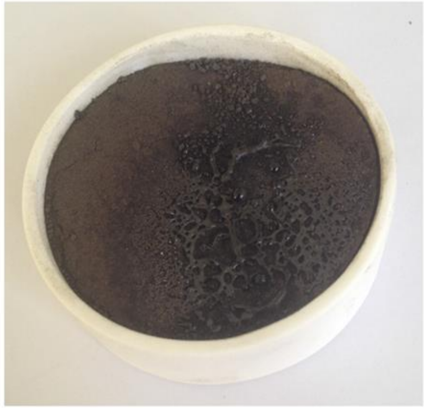
- Ray of concentrated sunlight
- Without any external power source.
- JSC-1 regolith simulant

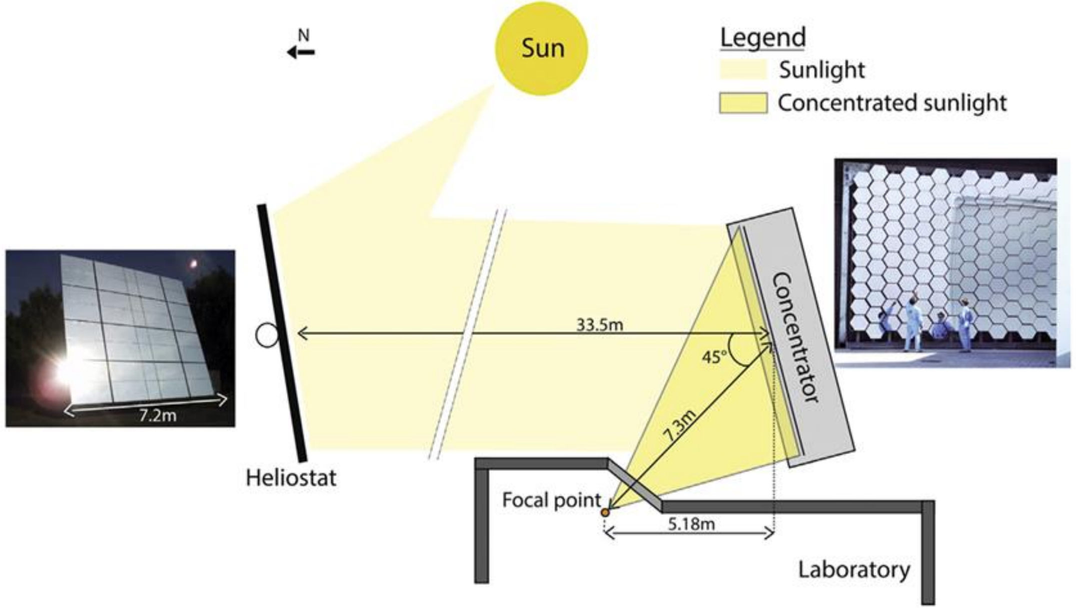


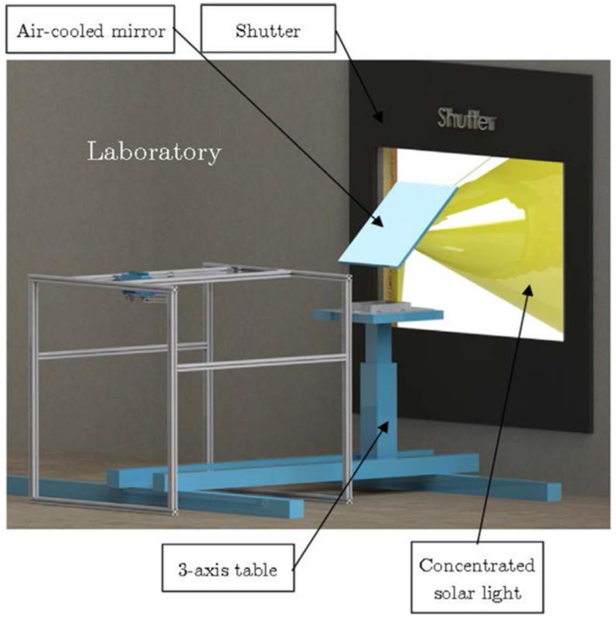
Hintze et al., 2009.

Selective Solar Light Sintering (SSLS)

- JSC-1A and JSC-2A
- Concentrated sunlight



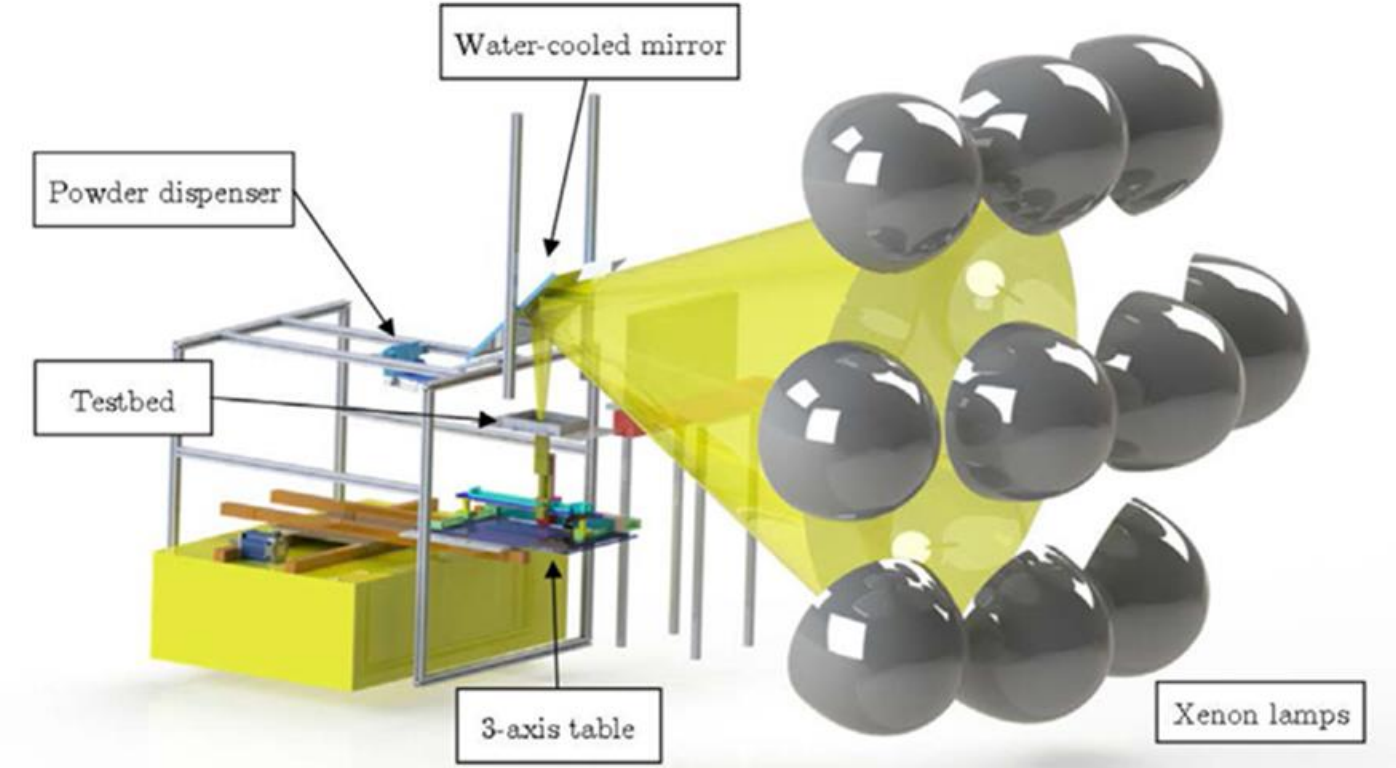





Meurisse et al., 2018.

Selective Solar Light Sintering (SSLS)

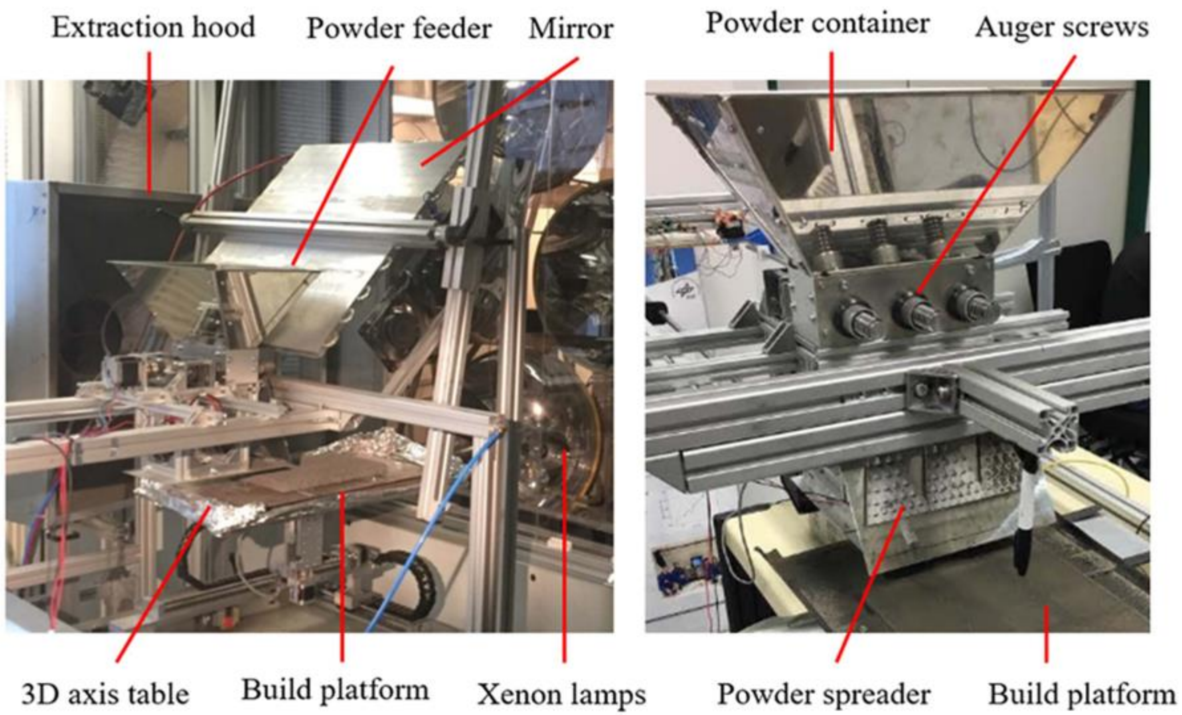
- Focused Xenon light

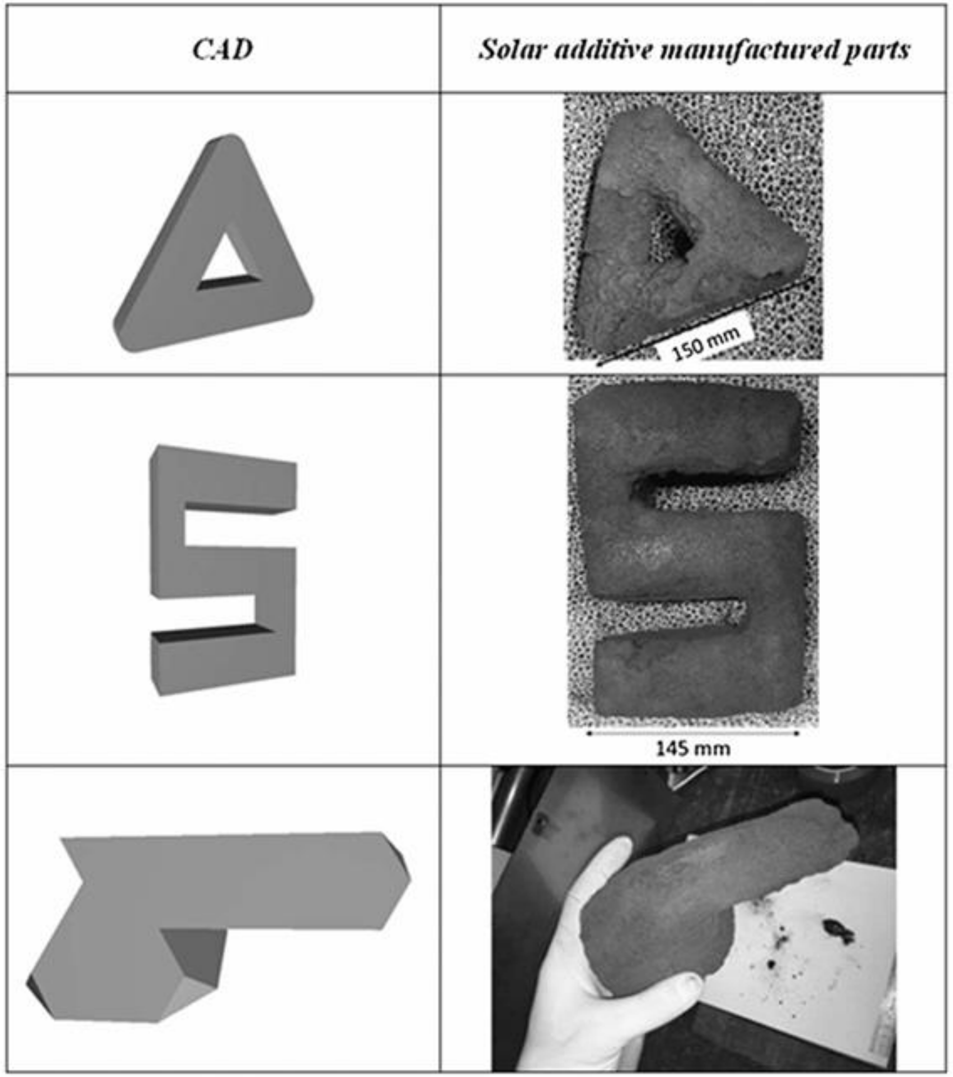


Meurisse et al., 2018.

Selective Solar Light Sintering (SSLS)

- Solar sintering using JSC-1A
- 3D printer designed with xenon lamps

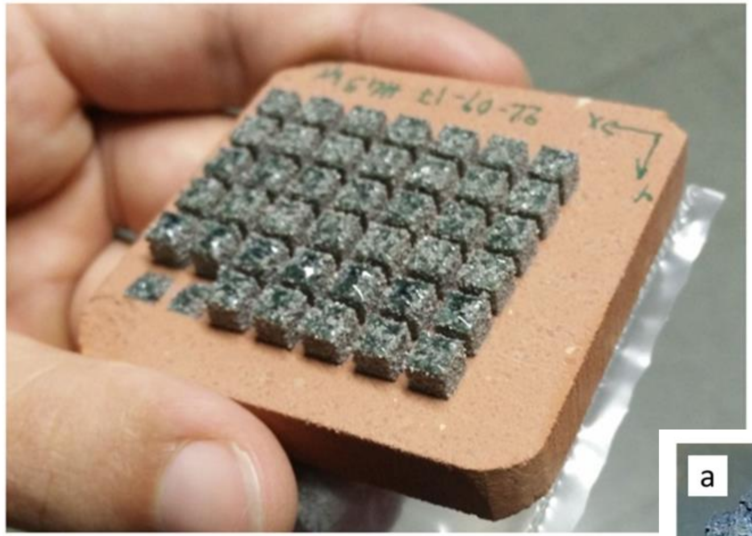




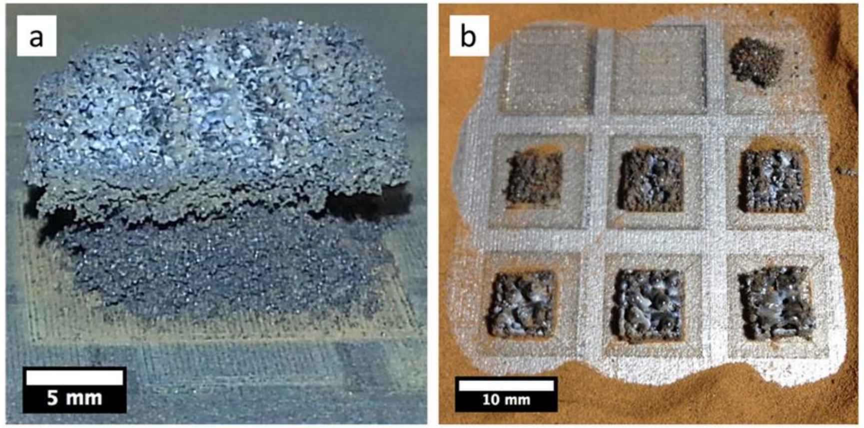
Fateri et al., 2019.

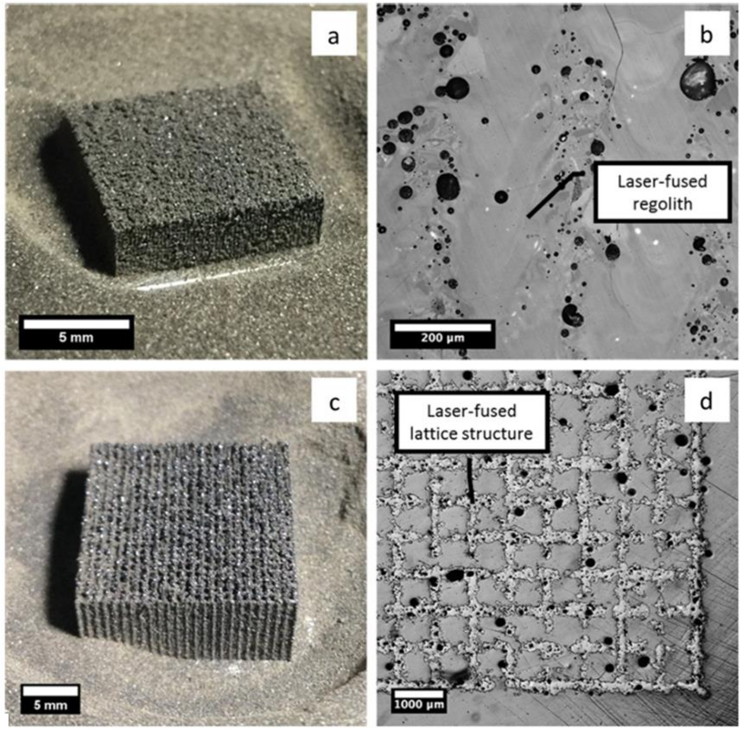
Selective Laser Sintering/Melting (SLS/SLM)

- Laser beam used to sinter/melt the material
- JSC-1A and JSC Mars-1A
- NU-LHT-2M simulant



Sitta and Lavagna, 2018.





Goulas et al. 2017.

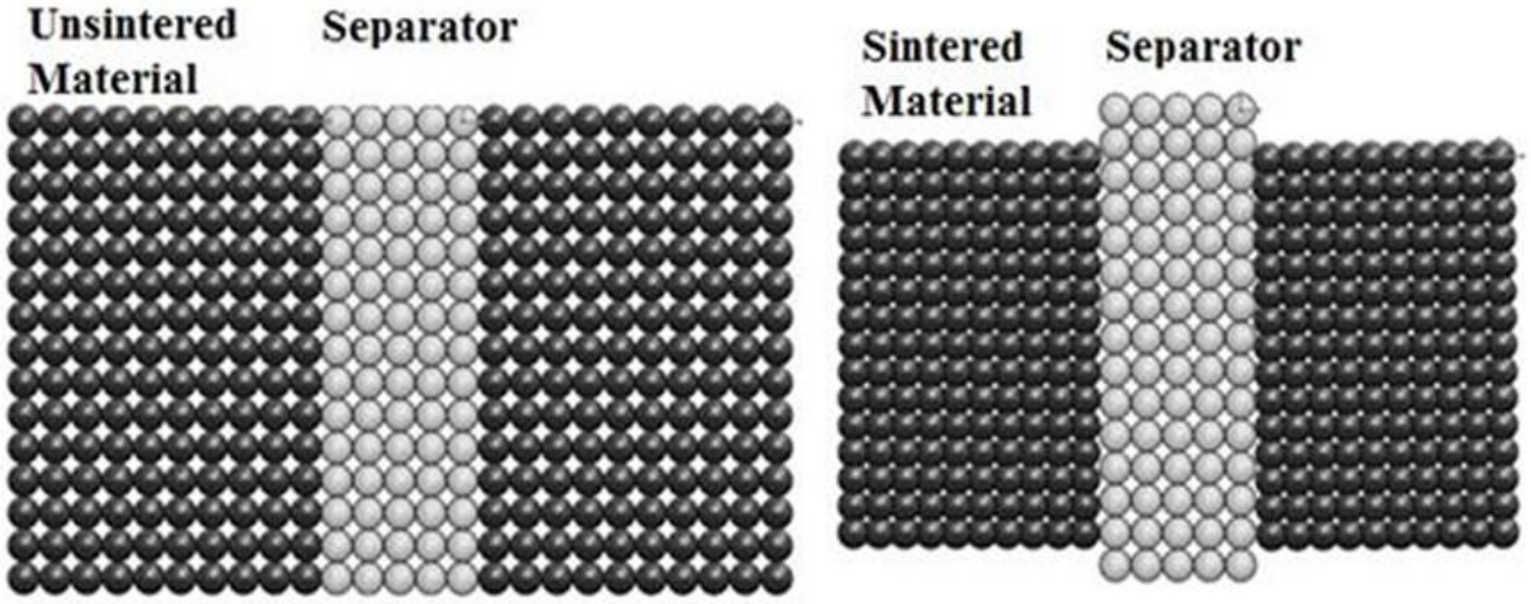
Selective Laser Sintering/Melting (SLS/SLM)

- Basalt powder as a simulant - large-scale outdoor construction
- The Swamp Work lab at NASA's Kennedy Space Center - SLS

A Mueller et al., 2015. B

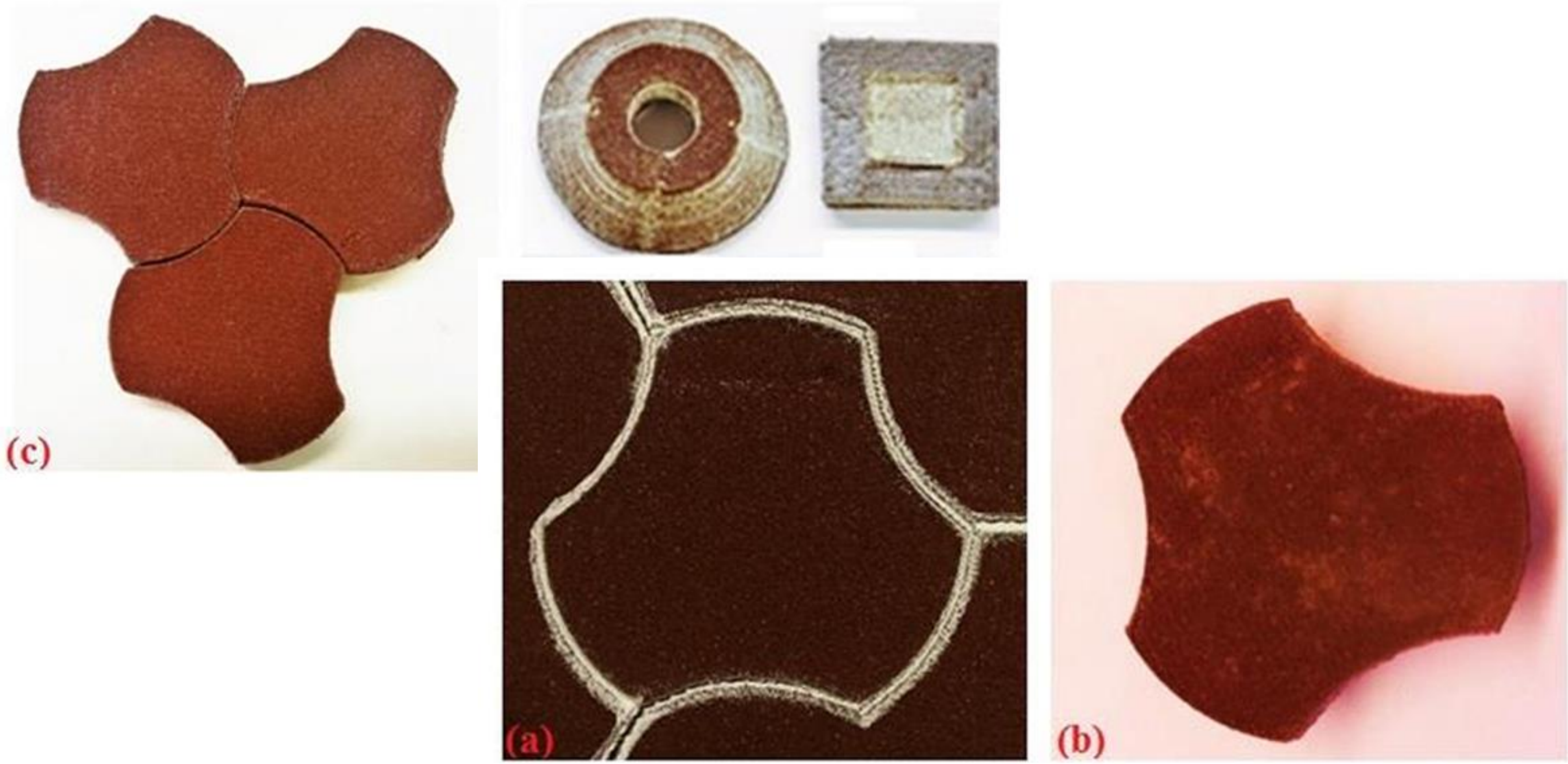
Selective Sparation Sintering (SSS)

- Separating powder - higher sintering temperature
- JSC-1A - base powder
- Alumina - separator powder
- Heated in a furnace



Zhang and Khoshnevis, 2015.

Selective Sparation Sintering (SSS)



Zhang and Khoshnevis, 2015.

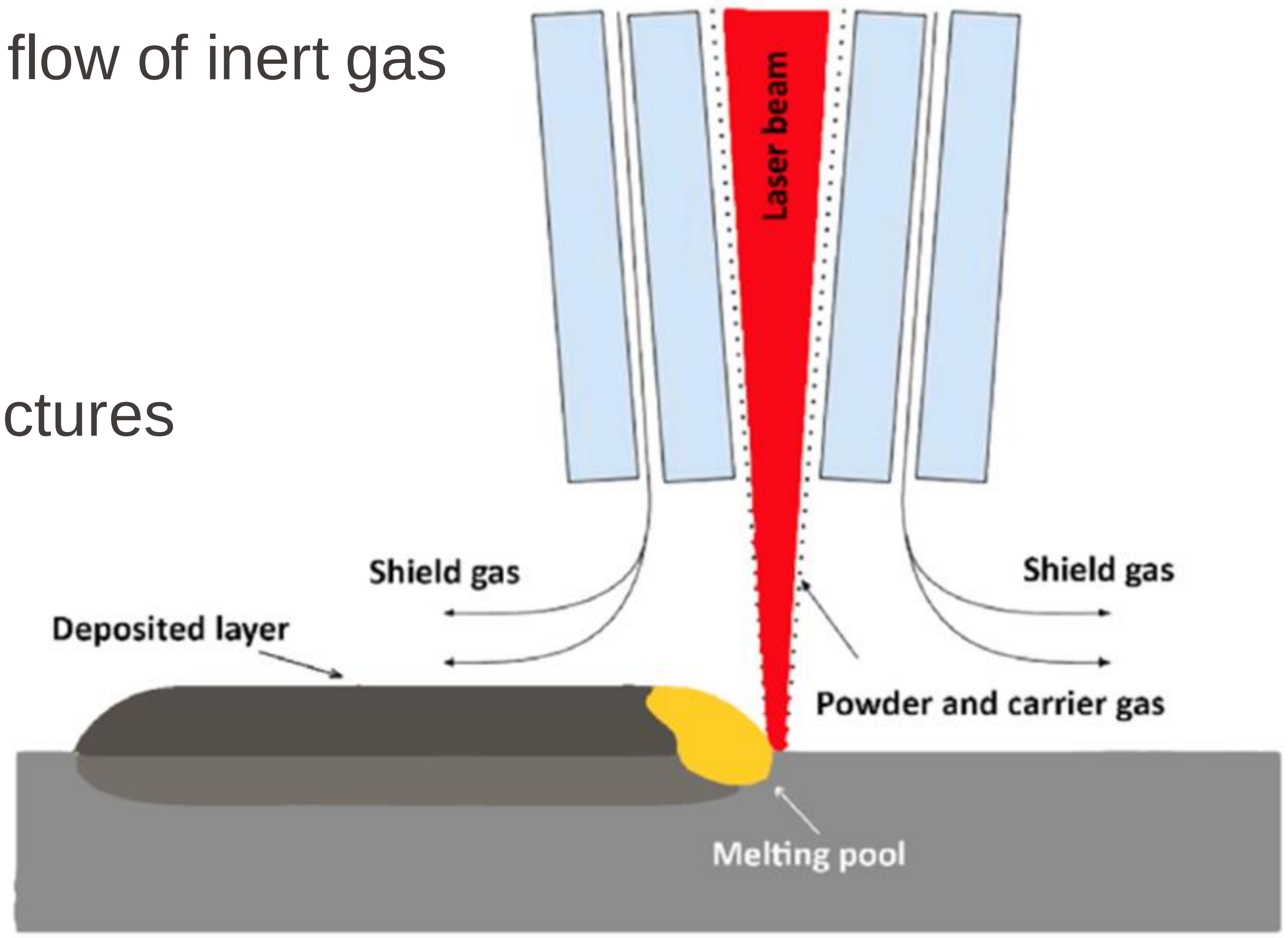
Direct Energy Deposition

- Thermal energy source
- Wires and powders
- Melting the feedstock during deposition

Karl et al., 2022.

Laser Engineered Net Shaping (LENS)

- Powder is conveyed using a flow of inert gas
- Coaxial laser beam
- On-site repair of regolith structures



Isachenkov et al., 2021.

Laser Engineered Net Shaping (LENS)

- JSC-1AC
- Fabricating of solid parts

Balla et al., 2012.

Vat Photopolymerization

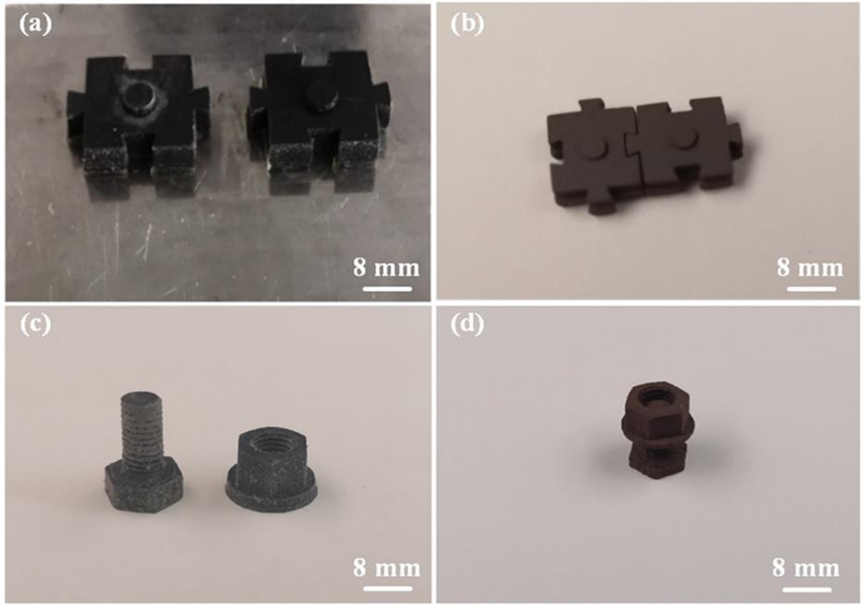
- Liquid polymer resin
- Hardened as a result of curing
- Stereolithography (SLA) - mirrors to reflect a laser
- Digital Light Processing (DLP) - digital light projector

Karl et al., 2022.

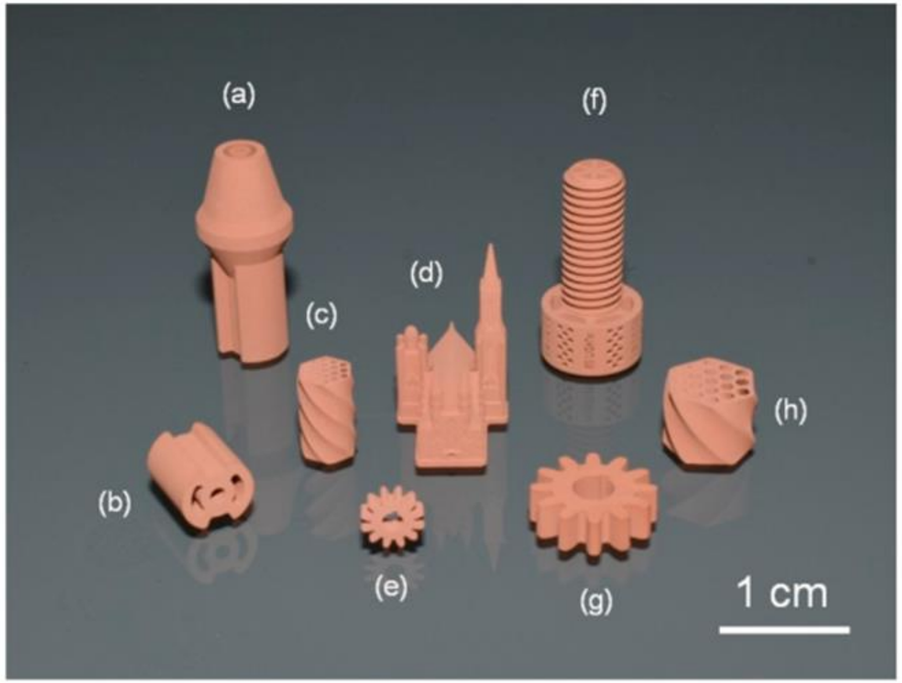
Vat Photopolymerization

- ESA + Austrian company Lithoz - EAC-1A - small ceramic parts

- CLRS-2 – DLP- ceramic parts



Liu et al., 2019.



Altun et al., 2021.

Categories	Technologies	Vacuum/low pressure	Gravity	Temperature	Autonomy	Compressive strength	Flexural strength	Readiness level	Remarks
Material extrusion	*Contour crafting (CC)*	Positive: Lower porosity and better interlayer adhesion Negative: Nozzle clogging	Positive: Microgravity effect on sedimentation and crystallization might strengthen prints	Materials tend to be temperature sensitive	Goal: 3 operators, currently 6	48 MPa	Not reported	1:1 habitat prototype constructed	Judged as the most suited AM technology for direct regolith ISRU
Vat photo-polymerization	*Stereolithography (SLA)*	No effect, process uses enclosed volume	Negative: Requires additional control tech. to maintain a flat liquid interface	Process is temperature sensitive	Not reported	Not reported	Not reported	Few-cm samples of complex shape	Requires large amounts of sensitive polymers. Not feasible for direct regolith ISRU
	Digital light processing (DLP)				Not reported	428 MPa (sintering in air) 55 MPa (sintering in argon)	129 MPa (air) 24 MPa (argon)	Few-cm samples of complex shape	
Powder bed fusion	*Selective solar light sintering (SSLS)*	Positive: Dry environment can increase powder flowability and powder oxidation is hindered	Negative: Powder deposition on Earth is facilitated by gravity; additional tech. needed for powder deposition	Pre-heating and temperature control required	Good	2.5 MPa	0.55 MPa	10–20 cm samples of diff. shape, vac. tested sampl.	PBF produces unfavorable Microstructure for direct regolith ISRU
	Selective laser sintering/ melting (SLS/SLM)				Good	22.7 MPa < 34.1 MPa	Not reported	Few-cm samples of complex shape	
	Selective separation sintering (SSS)				Potentially good	Not reported	Not reported	Few-cm samples sintered	
Binder jetting	*D-Shape*	Positive: Dry environment can increase powder flowability Negative: Liquid droplet ejection might be problematic	Negative: Powder deposition on Earth is facilitated by gravity; additional tech. needed for powder deposition	Binder materials and deposition process can be temperature sensitive	Potentially good	17–20 MPa	1.5–3.5 MPa	1:1 habitat building block (1.3t), vac. tested sampl.	Even though challenging on Moon and Mars, some aspects of the technology could be feasible for building large structures
Direct energy deposition	*Laser engineered net shaping (LENS)*	Positive: Electron beam fusion and laser energy requires/is preferred (in) vacuum	Positive: Microgravity effect on sedimentation and crystallization can have positive effects on prints	Cooling system required to regulate excessive heating	Good	Not reported	Not reported	Few-cm samples of complex shape	Feasible technology for ISRU once refined materials/metals are available

Thank you for your attention!

Any questions?