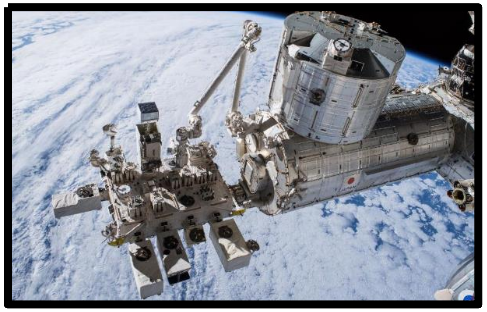
Development Status and Test Results of JAXA's Plant Growth Unit for Advanced Cultivation Experiments.

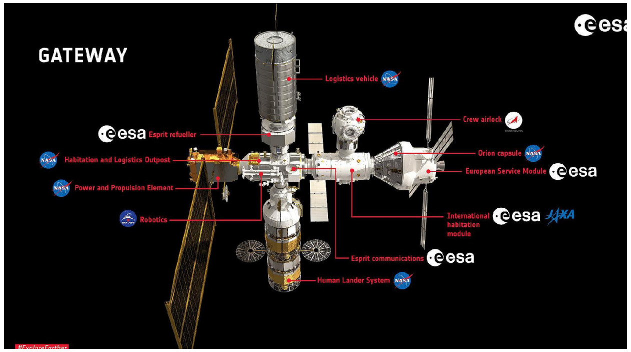
*Dylan Shun Izuma[1)], Yohei Anzai[1)], Satoshi Adachi[1)], Tsuyoshi Ito[1)]

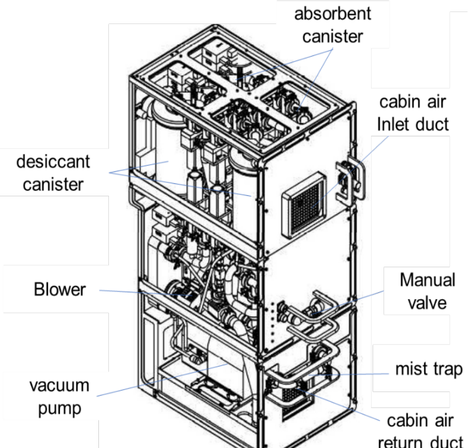
[1] *Japan Aerospace Exploration Agency (JAXA)*

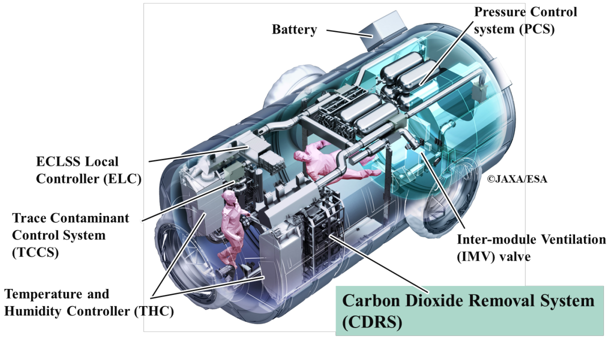
Greeting

- Dylan Shun Izuma
- Japan Aerospace Exploration Agency (JAXA)
- ECLSS R&D team
  - ･Plant cultivation system
  - ･CO_2 removal system
  - ･Temperature and humidity control system



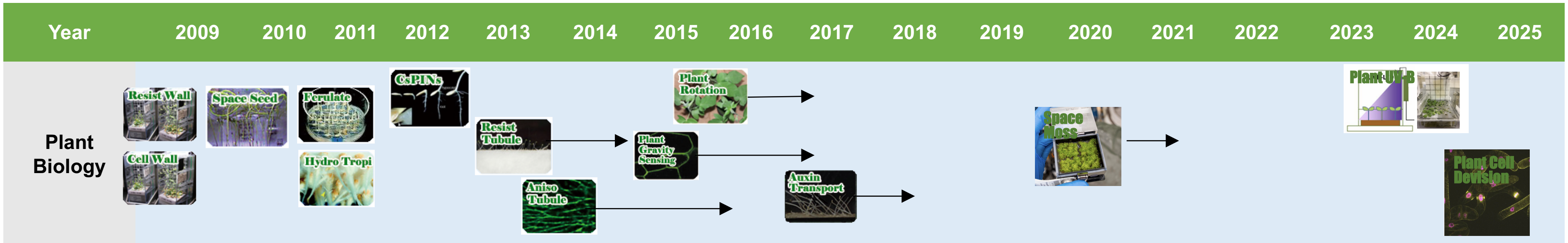






Contents

Plant missions in the past



Space Seed

Life Cycle of Higher Plants under Microgravity Conditions

Arabidopsis thaliana

HydroTropi

Hydrotropism and Auxin-Inducible Gene Expression in Roots Grown under Microgravity Conditions

Cucumber

Space Moss

Environmental response and utilization of mosses in space - Space Moss-

Physcomitella

Ferulate

Regulation by Gravity of Ferulate Formation in Cell Walls of Rice Seedlings

Rice

Resist Tubule

Mechanisms of Gravity Resistance in Plants: From Signal Transformation and Transduction to Response

Arabidopsis thaliana

Plant Gravity Sensing

Molecular mechanisms of differentiation and formation of the gravity sensing system in plant cells

Arabidopsis thaliana

Plant Rotation

Plant circumnutation and its dependence on the gravity response

Rice

Auxin Transport

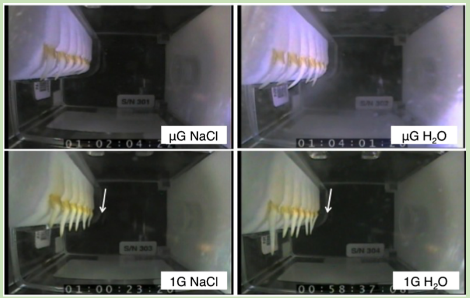
Studies on gravity-controlled growth and development in higher plants using true microgravity.

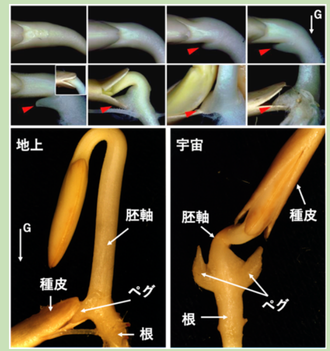
Pisum sativum/Rice

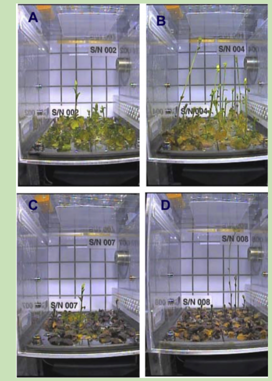
Numerous plant experiments have been conducted in orbit.

Background

What we discovered





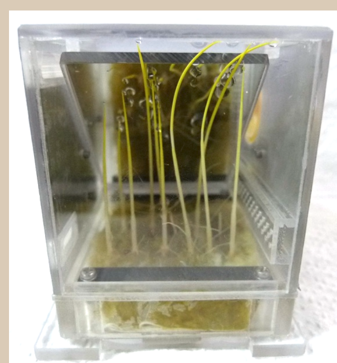


- ✔ Hydrotropic responses in μG*)
- ✔ Morphogenesis in μG**)
- ✔ Seed-to-seed life cycle***)

▼ Fundamental Plant Biology

Issues we had

- ✔ Small cultivation volume
- ✔ Short term experiment
- ✔ Limited species



Plant Experiment Unit (PEU)

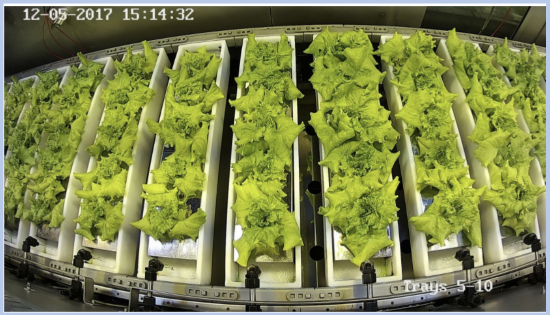
▼ On the other hand

Other nations have been developing advanced plant experiment unit

*) Morohashi *et al*., New Phytologist 2017. **) Takahashi *et al*., Planta 2000. ***) S. Yano *et al*., Advances in Space Research 2013.

Ongoing plant cultivation projects

Examples



MELiSSA (ESA)*)

Advanced plant habit (NASA) **)

Veggie(NASA) ***)

*) https://www.melissafoundation.org/page/melissa-pilot-plant
**) https://images.nasa.gov/details-iss064e006454
***) G. D. Massa, et al., Open Agriculture 2017.

Why ???

Food production

Mental support

Advanced life support system

▼ We recognize

Plant production as a key technology for human space travel
→ Start developing next-generation plant growth chamber

Contents

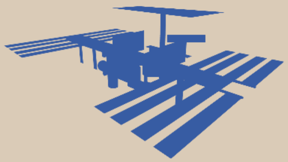
Challenges unique to the microgravity environment

	Grund	μG Unique Challenges	Difficulty
Temperature and Humidity Control	Ventilation with outside air	Control temperature and humidity within a narrow chamber, despite heat from equipment and transpired water from plants, by using dehumidification and ventilation.	Medium
	Air conditioning system	Active air circulation system to homogenize the internal atmosphere in the absence of natural convection	Low
Transpiration Water Recovery	No water recovery	Dehumidification and water recovery, with the reclaimed water returned to the growth medium in accordance with variable transpiration rates.	High
Nutrient solution supply	Circulation of large volumes of nutrient solution, with complete replacement once the solution becomes degraded.	Implementation of a system that integrates nutrient solution, recovered water, and air into the growth medium.	High
		Maintenance of nutrient balance through species-specific formulations of nutrient solutions, optimized for plant-specific absorption characteristics.	High＋
Growth medium materials and encapsulation methods	High flexibility in the selection of construction materials.	Selection of growth media suitable for application in μG environments. Safety control, Water control, etc.	Medium
	Installation and operation are facilitated by the use of gravity.	Encapsulation of the medium using flame-retardant materials to ensure both fire prevention of particle dispersion under microgravity conditions.	Medium
Nutrient solution diffusion into the medium and evaporation reduction	Application of gravity-driven watering and diffusion processes.	Development of techniques to uniformly distribute and retain nutrient solution throughout the entire medium.	Medium
	Simple evaporation-prevention measures such as covering the water surface.	Reduction of the medium's exposure to air to minimize water loss through evaporation and inhibit moss proliferation.	Medium
Seedling cultivation and transplantation	Germination in a dedicated nursery facility, followed by selection of healthy seedlings and transplantation to the cultivation site.	Provision of compact growth media, watering devices, and environmental controls for temperature and humidity during germination.	Medium
		Establishment of procedures for transplanting seedlings after germination and reestablishing them at designated cultivation sites within the apparatus.	Medium

Challenges and requirements in μG

Challenges

- No convection
- Liquid control
- Limited resource



Requirements

- Gravity-independent environmental control
- Anti-mold, algae
- Minimal water usage

Are goals

Develop a device with

Large-volume, long-term cultivation, water recycle

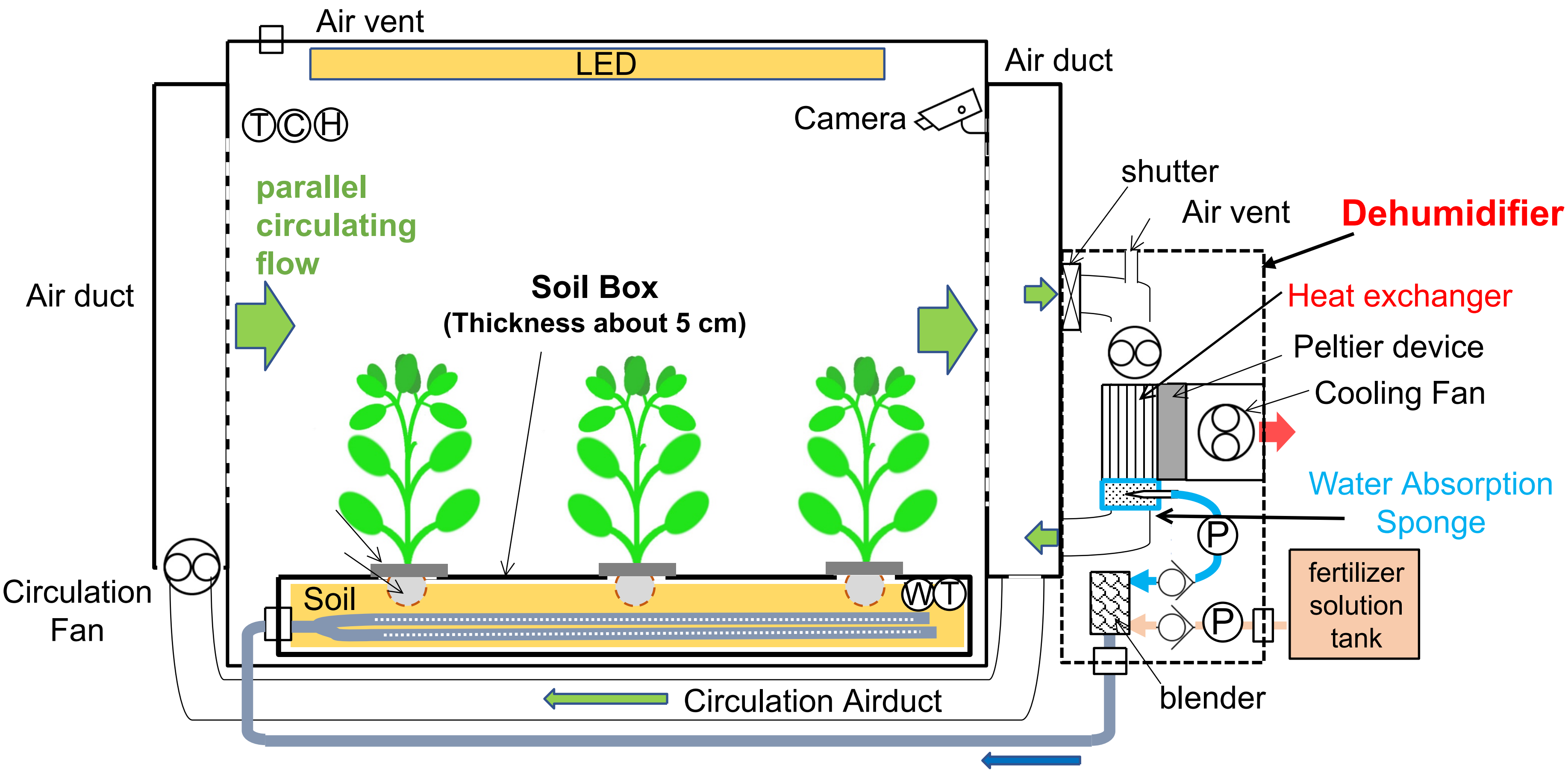
▼ Working on

Water supply, soil, environmental control

〔**Today's talk**〕
Development Status and
Test Results of JAXA's Plant Growth Unit

Contents

Overview of the device



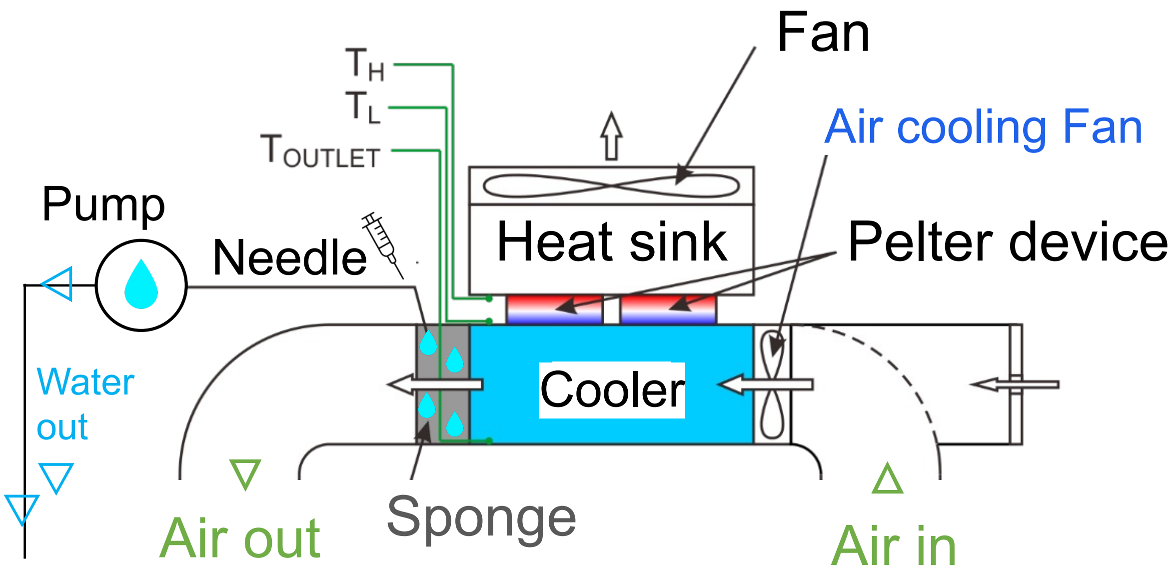
Key points of the device

- **Temperature and Humidity Control:** using the dehumidifier.
- **Ventilation/Circulation:** Parallel circulation flow by an air duct.
- **Recycling Water and Water Supply:** Dehumidified water is returned to the Soil Box.

Contents

Prototype dehumidifier

Grund		μG Unique Challenges	Difficulty
Temperature and Humidity Control	Ventilation with outside air	Temperature and humidity control within a small chamber, despite heat from equipment and transpired water from plants, by using dehumidification and ventilation.	Medium
	Air conditioning system	Active air circulation system to homogenize the internal atmosphere in the absence of natural convection	Low
Transpiration Water Recovery	No water recovery	**Dehumidification and water recovery,** with the reclaimed water returned to the growth medium in accordance with variable transpiration rates.	High



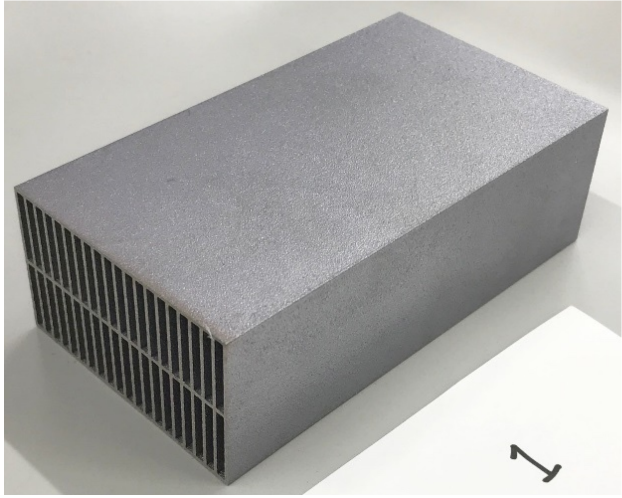


Fig. Aluminum alloy (AlSi10Mg) slit, formed using a 3D printer.

- Transpired water was collected by cooling the Aluminum alloy (AlSi10Mg) slit.
- Water recovery Mechanism that can be used in microgravity.

Prototype dehumidifier

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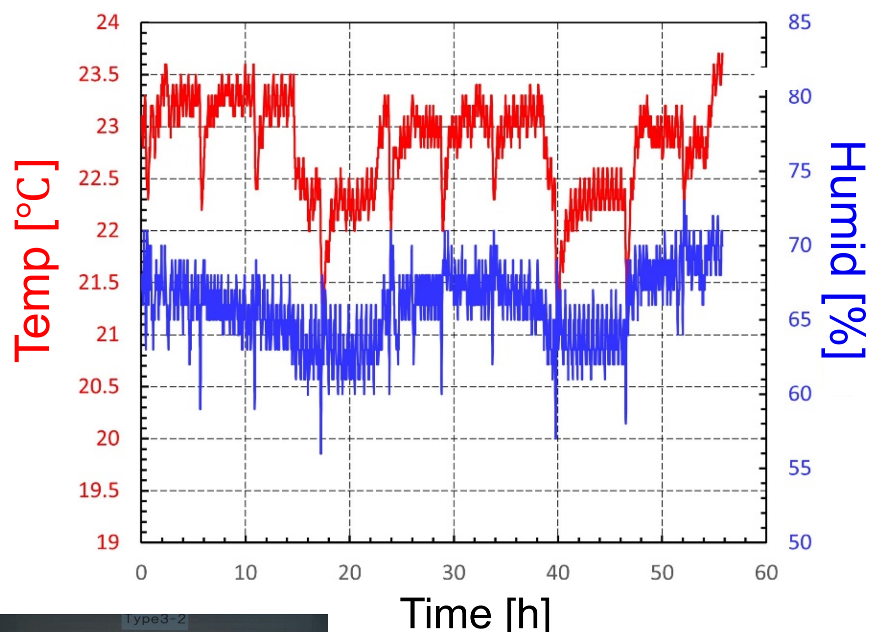

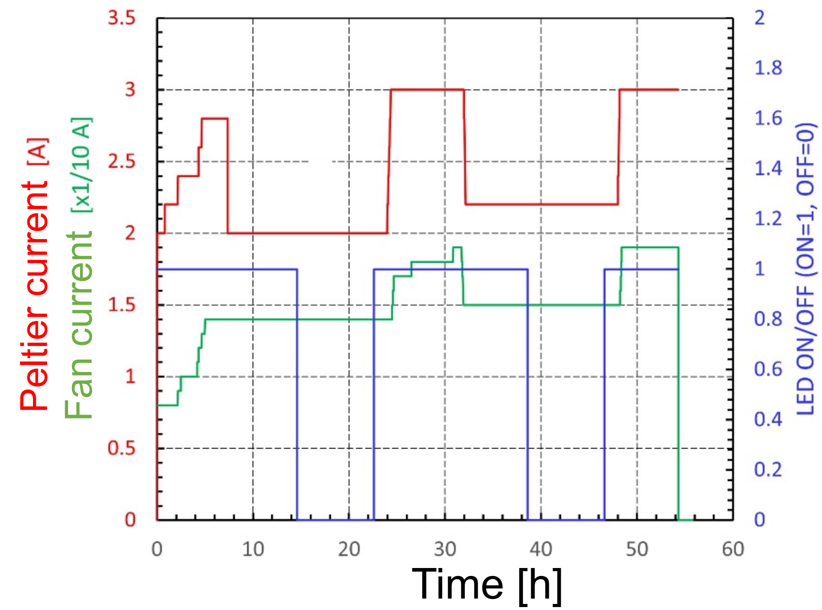

Temperature and humidity controlled by regulating the Peltier current,

▼

Maintaining humidity near the lower limit of the optimal range on the vapor pressure deficit chart (22.5 °C, 65%; 23.0 °C, 66%).

Parallel circulating flow

Grund		μG Unique Challenges	Difficulty
Temperature and Humidity Control	Ventilation with outside air	**Temperature and humidity control within a small chamber**, despite heat from equipment and transpired water from plants, by using dehumidification and ventilation.	Medium
	Air conditioning system	Active **air circulation system to homogenize the internal atmosphere** in the absence of natural convection	Low

Prototype equipped with a flow-straightening plate.

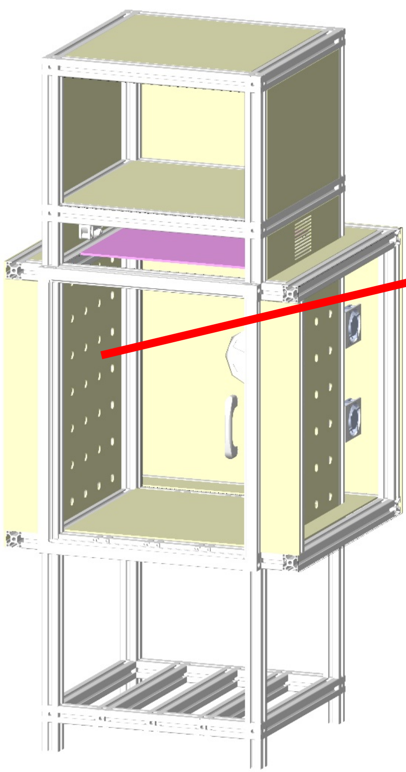

Figure. External view of the prototype.

Numbering

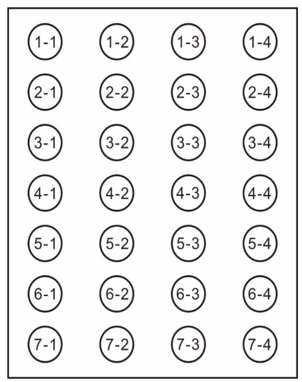

Table. Airflow velocity distribution

Outlet [m/s]	1	2	3	4
1	2	1.9	2	1.9
2	2	1.9	1.9	1.9
3	1.9	1.9	1.9	1.9
4	2	2	1.9	1.9
5	2	1.9	2	2
6	2	2.1	2.1	1.9
7	2	2	2.1	2

✔Successful generation of parallel airflow

✔Reduced the ΔT inside the chamber to Δ0.6 °C.

Parallel circulating flow

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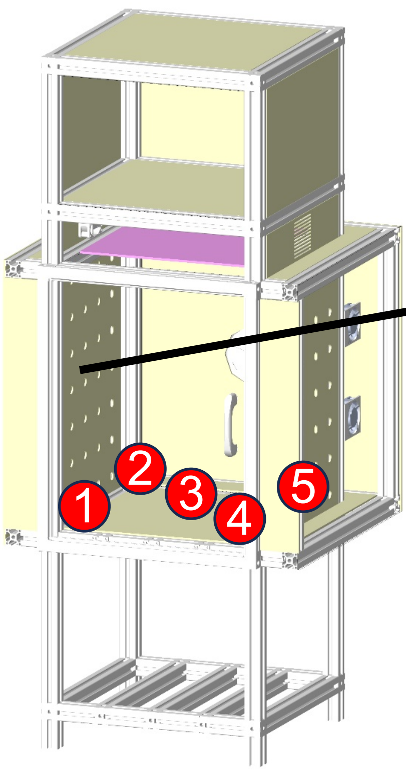

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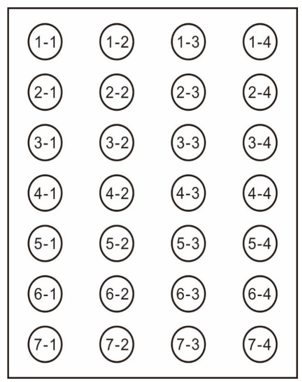

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7	2	2	2.1	2

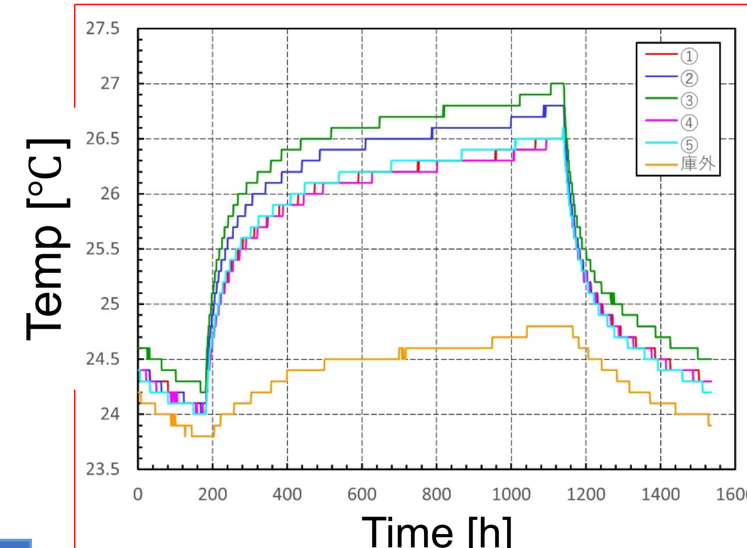


Figure. Temperature log inside the chamber.

✔Successful generation of parallel airflow

✔Reduced the ΔT inside the chamber to Δ0.6 °C.

Nutrient solution supply / Growth soil selection

Grund		μG Unique Challenges	Difficulty
Nutrient solution supply	Circulation of large volumes of nutrient solution, with complete replacement.	Implementation of a system that integrates nutrient solution, recovered water, and air into the growth medium.	High
		Maintenance of nutrient balance through species-specific formulations of nutrient solutions, optimized for plant-specific absorption characteristics.	High＋
Growth medium materials and encapsulation methods	High flexibility in the selection of construction materials.	**Selection of growth media suitable for application in μG** environments. Safety control, Water control, etc.	Medium

Exploration of growth soil suitable for use under microgravity conditions.

Rock wool

Melamine sponge

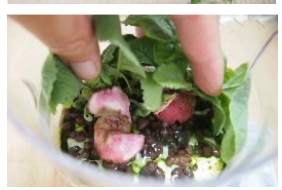
mixture of melamine and urethane sponge

Clay pebbles

Clay pebbles and water-retaining gel

Polyester fibers

After cultivation

	Rock wool	Melamine sponge	Clay pebbles	mixture of melamine and urethane sponge	Polyester fibers	Clay pebbles and water-retaining gel
Mini Cucumber [Day 86]						
Cherry Tomato [Day 86]						
Soybeans [Day 72]						
Watercress [Day 70]						
Radish [Day 25]						

Amount of yielded fruit

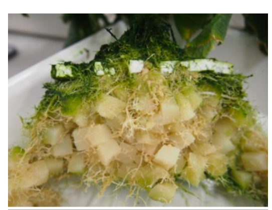
Table1. Amount of yielded fruit

Mini Cucumber		Cherry Tomato		Soybeans		Watercress		Radish	
Substrates	yield fruit [g]	Substrates	yield fruit [g]	Substrates	yield fruit [g]	Substrates	yield fruit [g]	Substrates	yield fruit [g]
MIX	920.2	C&W	143.3	MIX	33.7	C&W	144.2	RW	30.9
RW	863.9	RW	119.4	Polyester fibers	24.5	Polyester fibers	131.8	Polyester fibers	27.7
Polyester fibers	688.2	Polyester fibers	111.0	RW	24.3	MIX	113.3	MIX	26.4
C&W	682.5	Melamine sponge	43.7	Melamine sponge	19.4	Melamine sponge	102.7	Melamine sponge	25.3
Melamine sponge	654.5	MIX	36.8	Clay pebbles	6.9	RW	94.7	C&W	25.1
Clay pebbles	194.5	Clay pebbles	0.0	C&W	6.6	Clay pebbles	69.9	Clay pebbles	11.6

RW = Rock wool, MIX = Mixture of melamine and urethane sponge
C&W = Clay pebbles and water-retaining gel


RW


Melamine


MIX


Clay pebbles

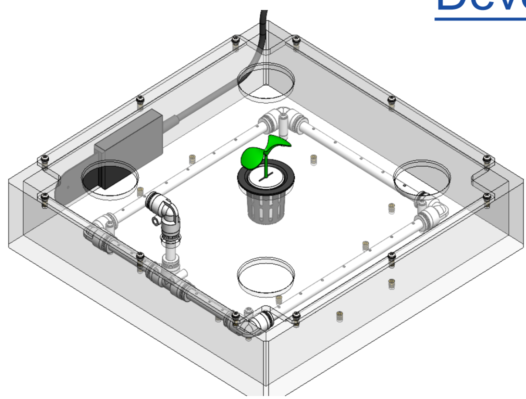

C&W

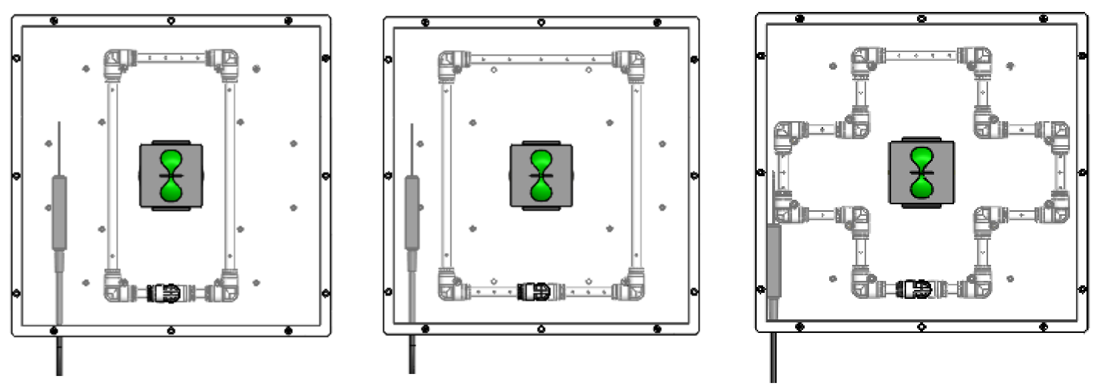

Polyester

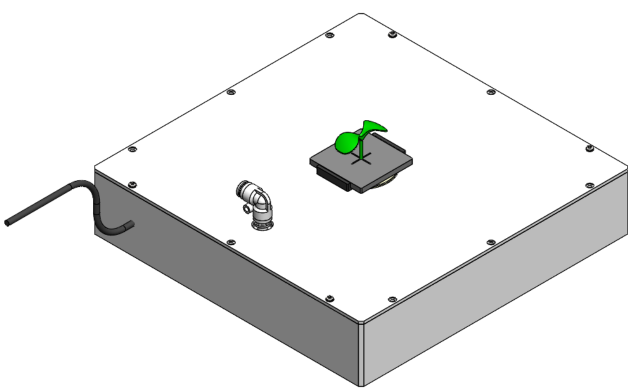
Nutrient solution supply / Growth soil selection

Grund		µG Unique Challenges	Difficulty
Growth medium and encapsulation methods	Installation and operation facilitated by the use of gravity.	Encapsulation of the medium using flame-retardant materials to ensure both fire **prevention of particle dispersion under** microgravity conditions.	Medium
Nutrient solution diffusion and evaporation reduction	Application of gravity-driven watering and diffusion processes.	Development of techniques to uniformly **distribute and retain nutrient solution** throughout the entire medium.	Medium
	Simple evaporation-prevention measures such as covering the water surface.	Reduction of the medium's exposure to air to minimize water loss through evaporation and inhibit moss proliferation.	Medium

Development of the root-zone system





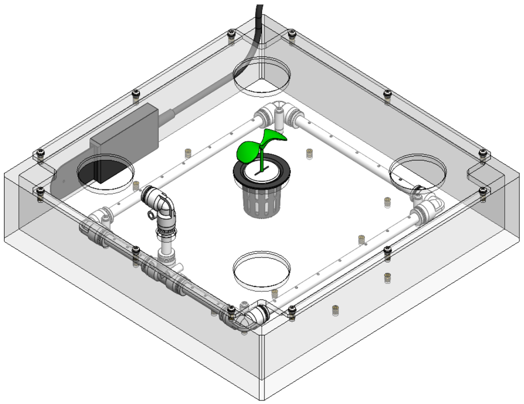


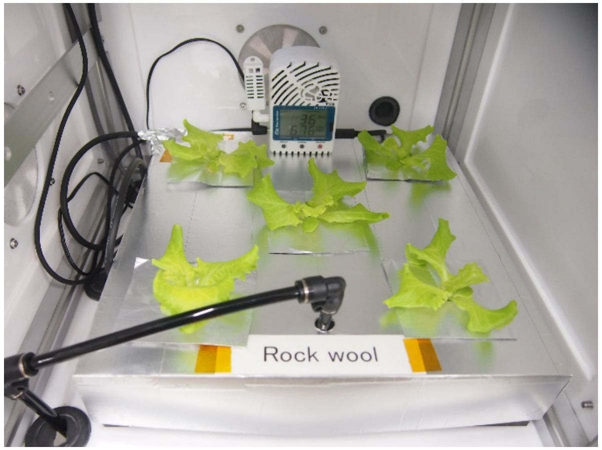
Targets

- No leaking.
- Distribute water evenly.
- Piping can be changed depending on what soil and plant is used.

Nutrient solution supply / Growth soil selection

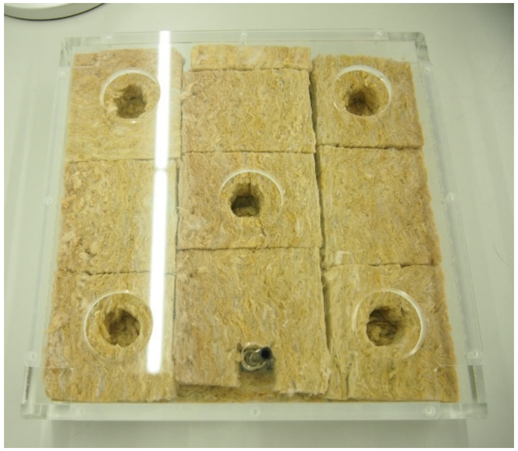
Development of the root-zone system



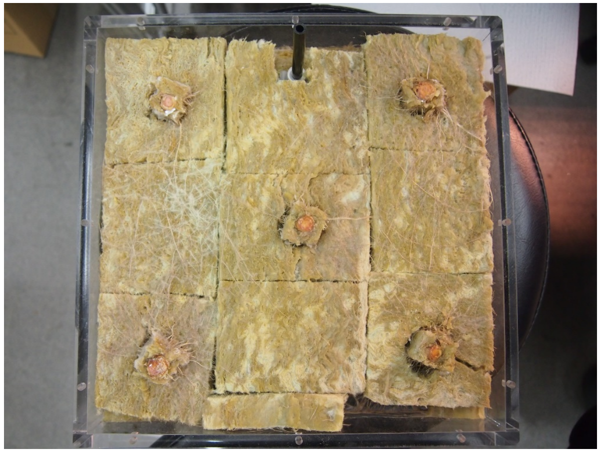


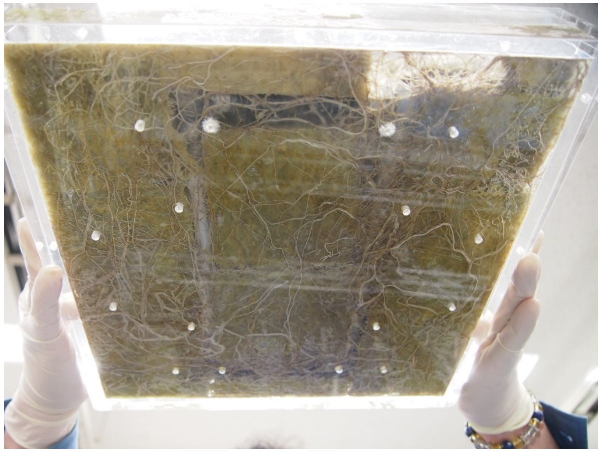
Day 14

Day 35



Before cultivation



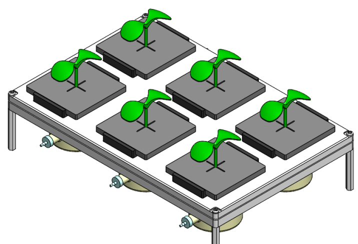


After cultivation

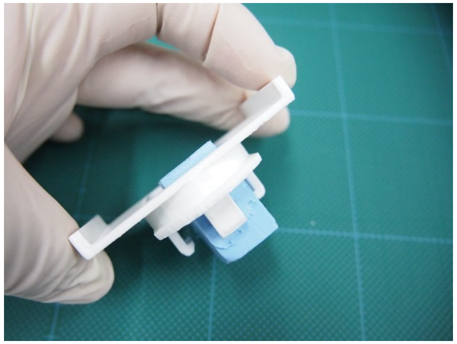
Seedling cultivation and transplantation

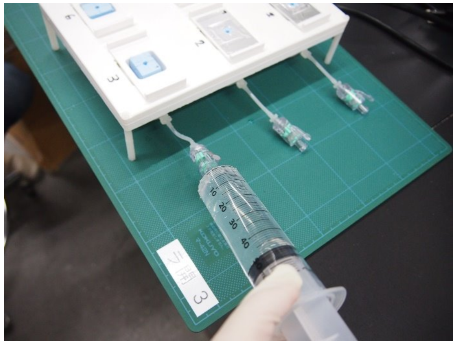
Grund		µG Unique Challenges	Difficulty
Seedling cultivation and transplantation	Germination in a dedicated nursery facility, followed by selection of healthy seedlings and transplantation.	Compact growth media, watering devices, and environmental controls for temperature and humidity during germination.	Medium
		Establishment of procedures for transplanting seedlings after germination and reestablishing them at designated cultivation sites.	Medium

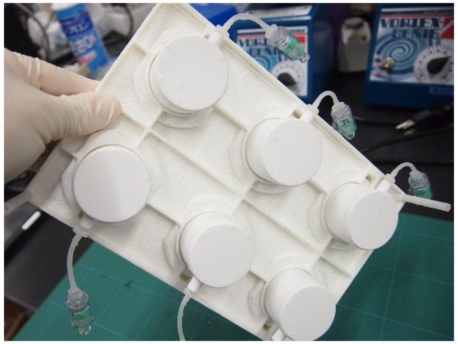
Seedling growth unit suitable for use µG

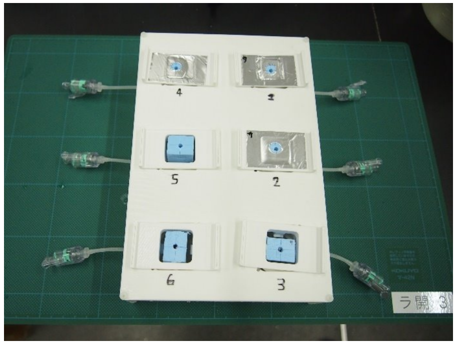


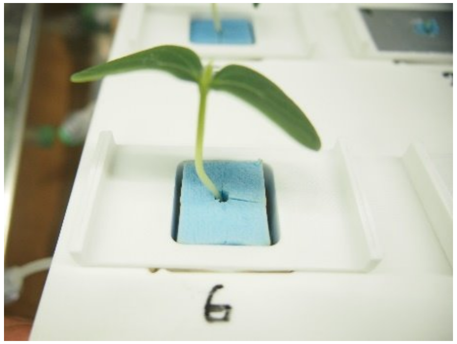
Seeding Box









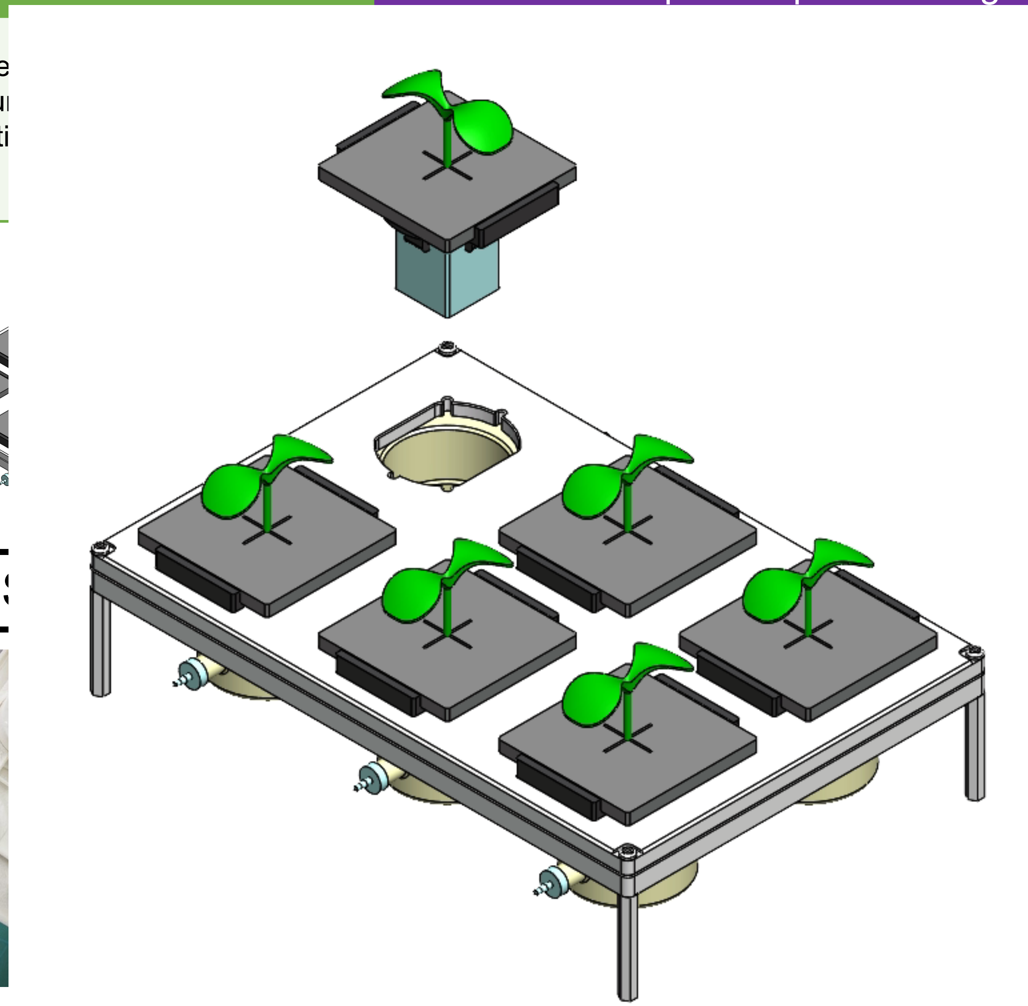


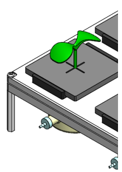
Targets

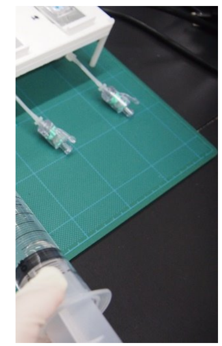
- Seed is packed at the ground
- The seeding is easily moved from the seeding box to the soil box.

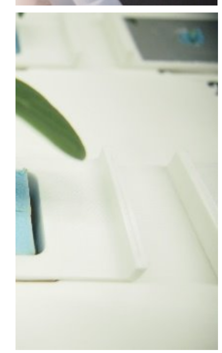
Seedling cultivation and transplantation

Grund		µG Unique Challenges	Difficulty
Seedling cultivation and transplantation	Ge nu selecti	ng devices, and ity during germination.	Medium
		g seedlings after ted cultivation sites	Medium









Targets

- Seed is packed at the ground
- Using quick connect / disconnect
- The seeding is easily moved from the seeding box too the soil box.

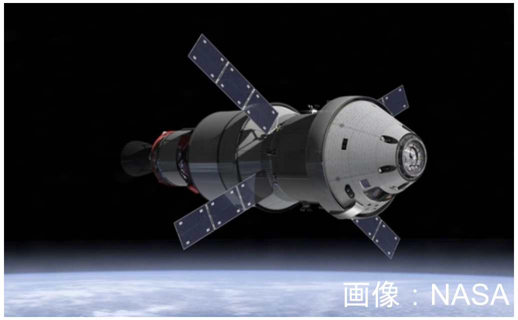
Contents

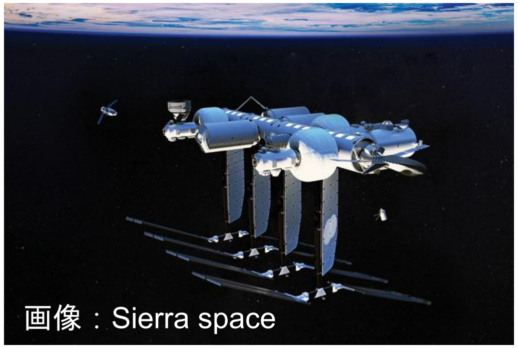
Summary

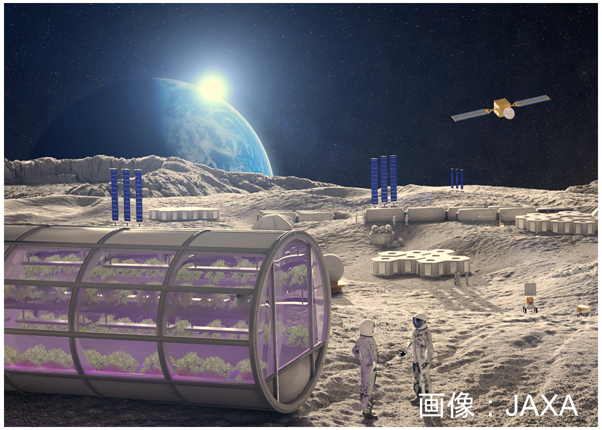
・Japan has been conducting research in fundamental plant science.

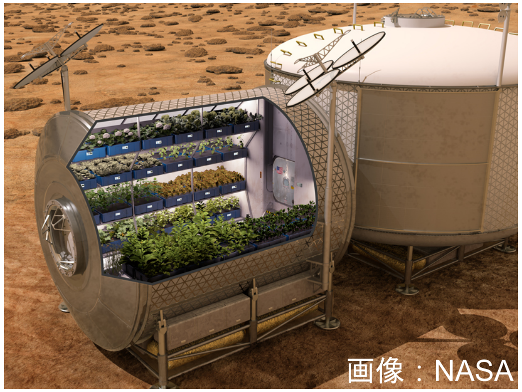
・JAXA is developing a large-scale cultivation system to enable research and development for space exploration.

・The goal is to provide demonstration and experimental environments on the ISS and future commercial space stations.



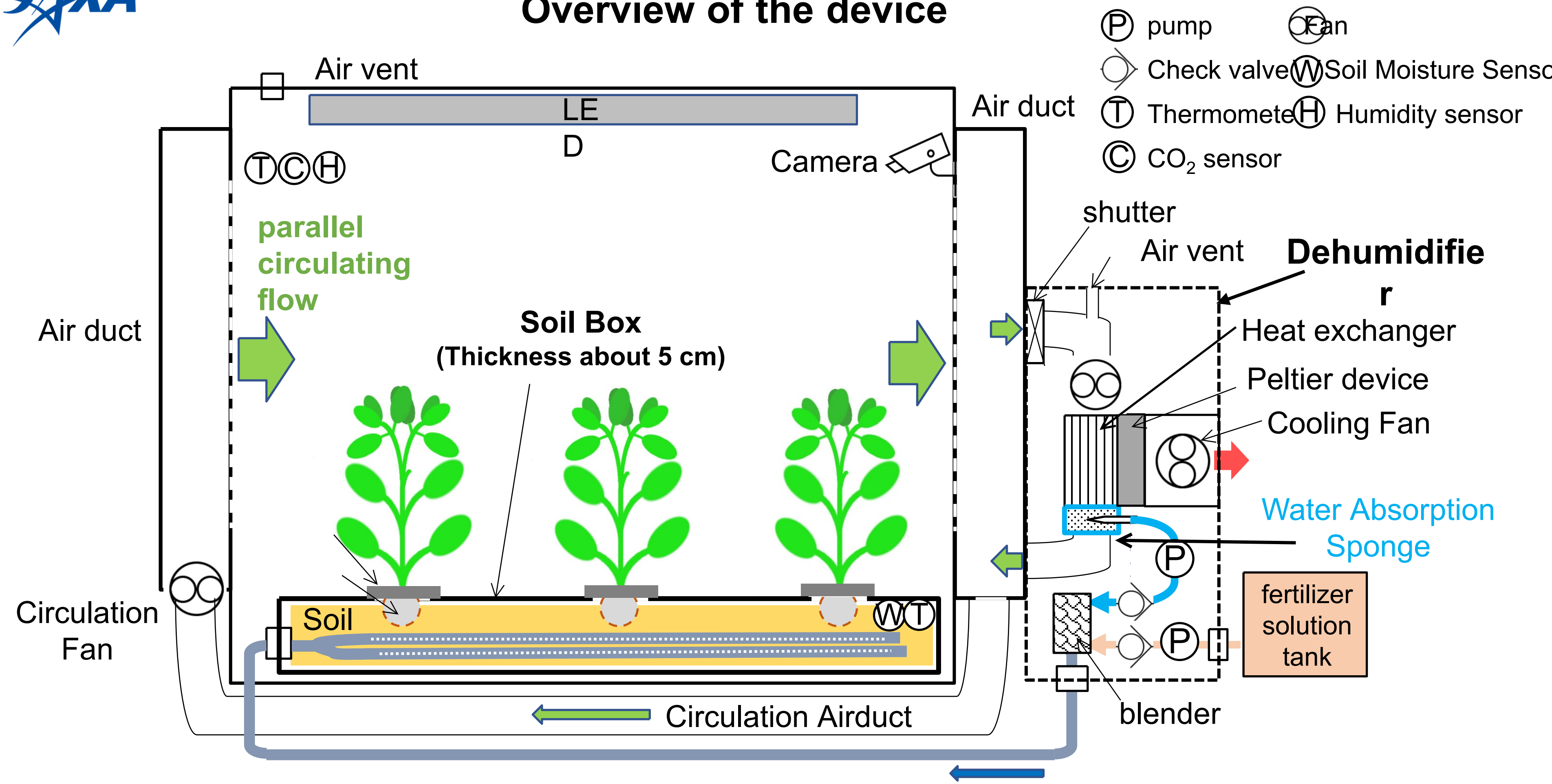






Back up

Overview of the device



Key points of the device

- **Temperature and Humidity Control:** by turning the dehumidifier ON/OFF.
- **Ventilation/Circulation:** Parallel circulation flow by setting up an air duct. Opening and closing the shutters enable/disable internal circulation or ventilation.
- **Dehumidification and Water Supply:** Dehumidified water is temporarily stored in a sponge, then drawn out with a needle, mixed with nutrient solution, and supplied into the Soil Box.

Previous works on the soil selection

Rock wool

Melamine sponge

mixture of melamine and urethane sponge

Clay pebbles

Clay pebbles and water-retaining gel

Polyester fibers

- Watered every day
- No water circulation
- Examined in a round bottle.

Previous works on the soil selection

Table1. Amount of yielded fruit

Mini Cucumber [Day 86]		Cherry Tomato [Day 86]		Soybeans [Day 72]		Watercress [Day 86]		Radish [Day 86]	
Substrates	yield fruit [g]	Substrates	yield fruit [g]	Substrates	yield fruit [g]	Substrates	yield fruit [g]	Substrates	yield fruit [g]
mixture of melamine and urethane sponge	920.2	Clay pebbles and water-retaining gel	143.3	mixture of melamine and urethane sponge	33.7	Clay pebbles and water-retaining gel	144.2	Rock wool	30.9
Rock wool	863.9	Rock wool	119.4	Polyester fibers	24.5	Polyester fibers	131.8	Polyester fibers	27.7
Polyester fibers	688.2	Polyester fibers	111	Rock wool	24.3	mixture of melamine and urethane sponge	113.3	mixture of melamine and urethane sponge	26.4
Clay pebbles and water-retaining gel	682.5	Melamine sponge	43.7	Melamine sponge	19.4	Melamine sponge	102.7	Melamine sponge	25.3
Melamine sponge	654.5	mixture of melamine and urethane sponge	36.8	Clay pebbles	6.9	Rock wool	94.7	Clay pebbles and water-retaining gel	25.1
Clay pebbles	194.5	Clay pebbles	0	Clay pebbles and water-retaining gel	6.6	Clay pebbles	69.9	Clay pebbles	11.6

Table2. Production efficiency by the water use (fruit[g]/water used[1L])

Mini Cucumber		Cherry Tomato		Soybeans		Watercress		Radish	
Substrate	Production Efficiency [g/L]	Substrate	Production Efficiency [g/L]	Substrate	Production Efficiency [g/L]	Substrate	Production Efficiency [g/L]	Substrate	Production Efficiency [g/L]
Clay pebbles and water-retaining gel	74.07	Clay pebbles and water-retaining gel	18.02	Polyester fibers	3.205	Clay pebbles and water-retaining gel	31.78	Clay pebbles and water-retaining gel	59.76
Polyester fibers	66.705	Polyester fibers	17.66	RW	2.91	Melamine sponge	30.23	Melamine sponge	44
Melamine sponge	60.785	RW	16.195	melamine and urethane	2.9	melamine and urethane	26.83	RW	41.06
melamine and urethane sponge	59.65	Melamine sponge	7.71	Melamine sponge	2.64	RW	24.3	melamine and urethane sponge	40.62
RW	59.185	mixture of melamine and urethane	4.76	Clay pebbles and water-retaining gel	1.215	Clay pebbles	22.3	Polyester fibers	37.11
Clay pebbles	44.695	Clay pebbles	0	Clay pebbles	1.21	Polyester fibers	21.73	Clay pebbles	27.78

Dehumidifier

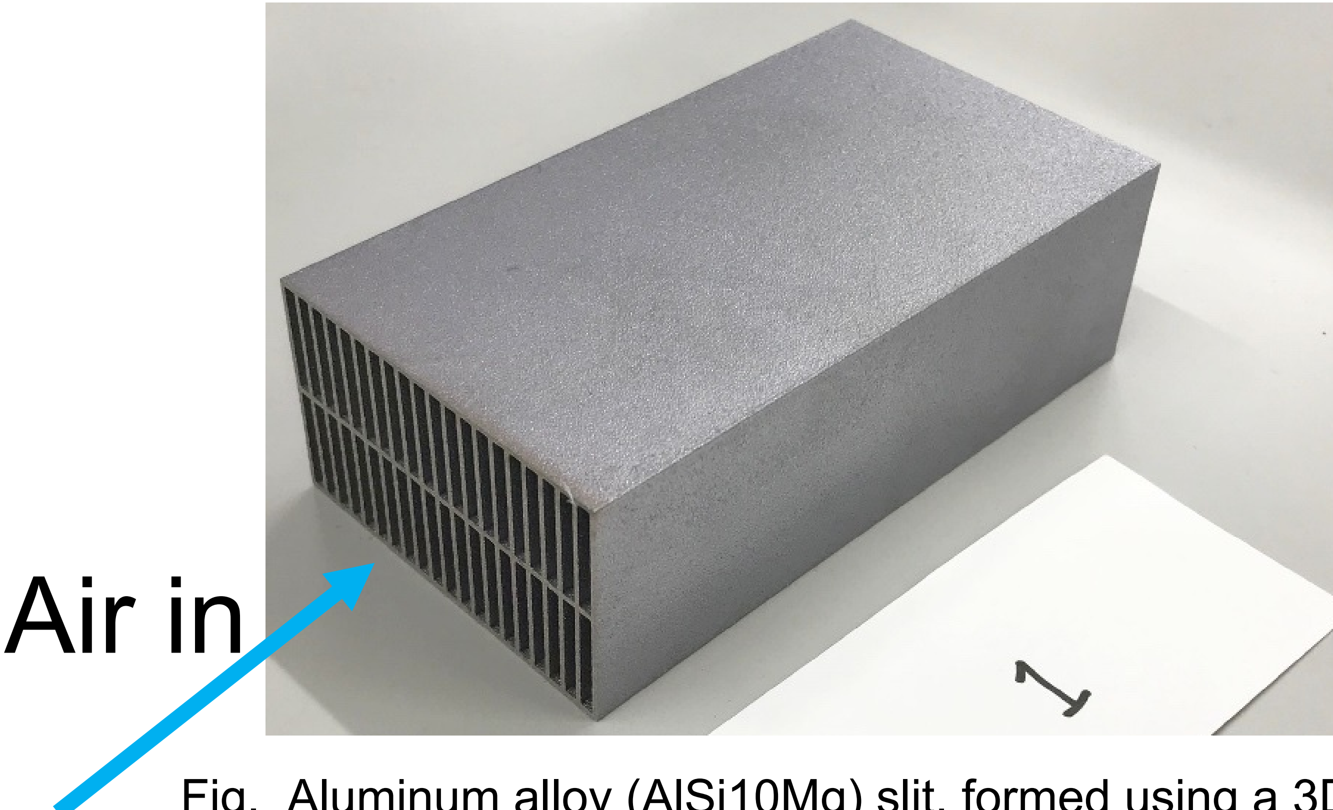
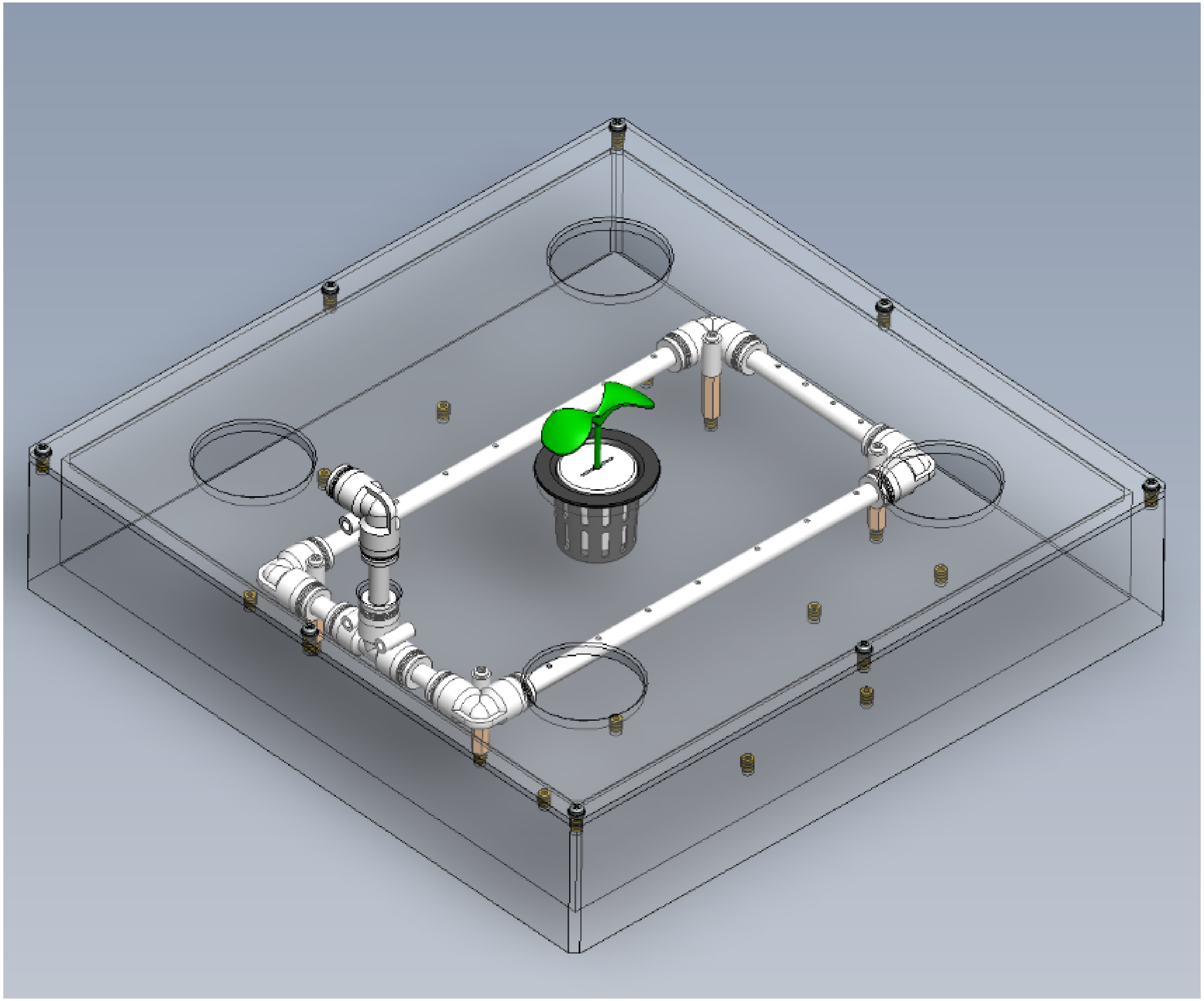


Fig. Aluminum alloy (AlSi10Mg) slit, formed using a 3D printer.

Cooling by Peltier device

Water is blown with the fan ⇒ Sponge

Soil box



Dehumidifier