Commercial Low-Earth Orbit Destination (CLD)
Capabilities of Interest and Resource Needs

Background

The Commercial Low Earth Orbit (LEO) Development Program team has been working with NASA and the International Space Station (ISS) National Lab (NL) stakeholders to identify capabilities of interest to both conduct research/technology demonstrations and estimate the resources that will be needed from Commercial LEO Destinations (CLDs). Through a series of one-on-one and working group meetings with users/stakeholders, hardware items of interest to the user community were identified and converted into capabilities (e.g., centrifugation, microscope, pressure chamber, etc.). In parallel, resources needed to operate the research equipment (e.g., crew time, number of experiments, volume, etc.) were estimated in order for the CLD providers to better understand NASA's potential future service requirements.

The capabilities and the resources included in this White Paper do not represent NASA requirements. Instead, they constitute a preliminary set of potential capability and resource needs collated to guide CLD providers in appropriately sizing and outfitting their CLD designs. NASA is requesting feedback from industry on how these capabilities and resources align with their own needs as well as those of their non-NASA customers. Information on how the capabilities/resources impact the CLD designs is also requested. After assessing industry's feedback to this white paper, NASA plans to issue a preliminary set of requirements for review.

The NASA groups that participated in the generation, discussions and vetting of the capabilities/resources presented in this paper are listed below. They represent the group of NASA users that lead scientific investigations and/or technology demonstrations that may be conducted on CLDs. Each group created their list based on historical ISS usage or a set of individual goals and priorities that are planned to be performed on CLDs.

- Exploration System Development Mission Directorate (ESDMD)
- Space Operation Mission Directorate (SOMD)
- Space Technology Mission Directorate (STMD)
- Science Mission Directorate (SMD)
  - Biological and Physical Science (BPS) Division
  - Earth Science Division (ESD)
  - Heliophysics Division (HPD)
- Human Research Program/Human Health and Performance (HRP/HHP)

Capability/resource information was also collected from the ISS National Lab (ISSNL) and is included in this White Paper. While NASA envisions a national lab function after transition from ISS to CLD's, the government has not yet determined how current and future ISSNL users will be incorporated into NASA's plans for CLDs. These policy and strategy questions are expected to be clarified in calendar year 2023.

Capability/resource needs from NASA's Office of STEM Engagement (OSTEM), the U.S. Department of Defense, and non-U.S. government space agencies are not included or discussed in this paper.

Some additional user information and references can be found in the white paper released October 26, 2019, "Forecasting Future NASA Demand in Low-Earth Orbit". However, the information contained in this White Paper reflects more up-to-date data from the user community.

NASA Stakeholders and Assessment of Future Needs

Capability and resource information in this White Paper are organized into six major groups shown in Table 1. This table also summarizes the basis each group used to develop the capability and resource information. Some groups have long-range plans guided by, for example, known risk reduction priorities. Groups in the NASA Science Mission Directorate have plans that are guided by the National Academy Committee (NAC) Decadal Surveys. For Biological and Physical Sciences, the NAC decadal survey is expected to be released in 2023; for Earth Sciences, the 2017 decadal survey can found at https://www.nationalacademies.org/our-work/decadal-survey-for-earth-science-and-applications-from-space with the next one expected in 2027, and for Heliophysics in 2024.

Table 1. User Groups and Basis of Estimate

User Group	Basis of Estimate
Technology Demonstrations (Tech Demos)	An agency-led process to fund technology capability gaps in order to meet NASA's needs for exploration (updated annually); therefore, this represents a predictive set of future needs. It includes input from ESDMD, SOMD, and STMD.
HRP/HHP	A risk-driven program consisting of an integrated research plan; therefore, this represents a predictive set of future needs (updated annually and/or periodically as needed).
SMD/BPS	Based on historical ISS usage with an increase of at least 20% to better match actual government requirements. SMD expects their requirements to noticeably increase after the release of the Decadal Survey on Biological and Physical Sciences Research in Space 2023-2032. Consider also technical advances and state of the art innovations realized
SMD/ESD	Based on historical ISS usage of capabilities and resources that were leveraged by ESD and could potentially be of interest on CLDs, depending on the results of National Academy Committee Decadal Surveys.
SMD/HPD	Based on historical ISS usage of capabilities and resources that were leveraged by HPD and could potentially be of interest on CLDs, depending on the results of National Academy Committee Decadal Surveys.
ISSNL	Based on historical ISS usage of capabilities that were leveraged by ISSNL customers.

Capabilities List

NASA is requesting industry feedback on the capabilities listed in Table 2 to determine if 1) there is interest in providing these capabilities to support NASA's needs and 2) whether there are commonalities with potential non-NASA users. Dialog between NASA and industry will help inform how and which of these capabilities will be implemented on the CLD platforms. The capabilities could be provided by the CLD providers, by NASA, or by some combination through partnering. It is also possible that, after further refinement, some of the capabilities listed will not be required.

The capabilities shown are agnostic to CLD design. Potential stakeholder hardware items were converted into capabilities of interest (from "how" to "what") to maximize the opportunities for CLD partners to innovate and implement the use of state-of-the-art capabilities.

There are several capabilities of interest that are assumed to be unique to NASA's beyond-LEO exploration needs and research and are expected to be met by the agency; for example: the Exploration Exercise Device along with a Vibration Isolation System and exploration food systems/food systems hardware. These capabilities are still being assessed by NASA and are not included in this White Paper.

Table 2. NASA User Capabilities of Interest

Capability	Interested User Groups
Integrated data architecture to collect, store, and analyze research data including comm, imagery, and video (up/down).	HRP/HHP, BPS, Tech Demo, ESD, HPD, NL
External payload capabilities (see Appendix 1 for a detailed list of capabilities and interfaces)	BPS, Tech Demo, ESD, HPD, NL
Small Satellite (SmallSat) deployment	BPS, Tech Demo, ESD, HPD, NL
Airlock - as needed to perform external payload manipulation/installation and SmallSat launches	BPS, Tech Demo, ESD, HPD, NL
External Robotics - as needed to perform external payload manipulation/installation and SmallSat deployment	BPS, Tech Demo, ESD, HPD, NL
EXPRESS rack equivalent single, double, and quad sized experiment/payload accommodations with a work area/bench	HRP/HHP, BPS, Tech Demo, NL
Secured privatized transmission pathway of critical research data including comm, imagery, and video (up/down)	HRP/HHP, BPS, Tech Demo, NL
Conditioned stowage – frozen, refrigerated, controlled ambient and elevated temperatures with	HRP/HHP, BPS, Tech Demo, NL

snap-freeze capability (launch/on-orbit/return) (+37C to -160C)	
Gloveboxes for containment and research sample manipulation (MSG and LSG equivalent)	HRP/HHP, BPS, Tech Demo, NL
Laboratory centrifugation for samples	HRP/HHP, BPS, Tech Demo, NL
Consumable supplies & Personal Protective Equipment appropriate for research needs	HRP/HHP, BPS, Tech Demo, NL
Incubators(s) with environmental controls	HRP/HHP, BPS, Tech Demo, NL
Multi-purpose light microscopes (optical and fluorescence equivalent)	HRP/HHP, BPS, Tech Demo, NL
Atmospheric constituent and radiation environment monitoring	HRP/HHP, BPS, Tech Demo, NL
Potable, conditioned (e.g., deionized, ultrapure) and hot water supply	HRP/HHP, BPS, Tech Demo, NL
Mass measurement capability (multiple sizes for research samples; small mass with high precision may be required)	HRP/HHP, BPS, Tech Demo, NL
Agitators, mixers, vortexes, including precision homogenization capability (for test tubes, well plates, flasks, etc.)	HRP/HHP, BPS, NL
Wet laboratories and In-situ analysis and sample preparation capabilities to enable rapid and iterative scientific investigations: • Fixation • Fluid handling tools • RNA/DNA sequencing • Polymerase chain reaction • Spectrophotometer • Protein analysis • Microplate reader • Fluorescence activated cell sorting • Cell counter • Tensile and compression testing • High Performance Liquid Chromatography • Gas Chromatography • Spectroscopy: UV Vis, Fourier Transform Infrared, Raman, static, dynamic and light scattering • Nuclear magnetic resonance • Conductivity and pH meters • Centrifuges • Ovens • Heaters • Glass stirred reactor with a chilled condenser	HRP/HHP, BPS, NL

• Containment for organic chemicals (including flammables) • Evaporator • Distillation column • Sieves/filters • Laminar flow bench	
3D printing capability for biological and materials sciences	BPS, Tech Demo, NL
Sealed variable pressure chamber (0 to 3 Atm)	BPS, NL
Laboratory-grade ultrasound	HRP/HHP
Wearable biometric tracking devices (e.g., Fitbit)	HRP/HHP
Equipment to support plant research, including facility and plant growth container/hardware	BPS, NL
Equipment to support animal and small organism research, (e.g., rodent transportation & housing, sample dissection & collection, bone density scanner, and fruit fly hardware)	BPS, NL
Facility to perform cell and tissue research including automation of environmental controls and monitoring of samples	BPS, NL
Cryogenic fluid transfer	BPS, NL
Cold Atom Laboratory equivalent	BPS, NL
Ring Shear Droplet	BPS, NL
Shear Rheometer	BPS, NL
Furnaces: • Gradient heating • Low and high-temperature furnace • Furnace with x-ray capabilities • Mid-and low-temperature Bridgman • High-temp with quench capability • 1250° C operable in glovebox. Capable of sample translation, heated zones, sample diameter at least 16mm. • Levitation furnace (preferably electrostatic with high vacuum and pressurized capabilities, and a high-speed camera)	BPS, NL
Materials Science Research Rack equivalent	BPS, NL
Fluids Integration Rack equivalent • boiling heat transfer • multiphase flow	BPS, NL

• liquid vapor interface control • liquid and vapor evaporation and condensation • two-phase flow boiling/condensation	
Combustion Integration Rack equivalent • High-pressure combustion	BPS, NL
Lyophilizer for water freeze casting	BPS, NL
High-speed visible IR imagers	BPS, NL
Desiccant chamber	BPS, NL
Vacuum oven	BPS, NL
Compressed gases including combustible	BPS, NL

Resource Estimates

Resource categories and the methodology used by NASA to develop the estimates are shown in Table 3. Tables 4-9 show resources estimated to be needed to conduct research and technology demonstrations for each of the NASA user groups towards the end of this decade. The numbers were calculated using current ISS data, future mission priorities projections and expected needs.

Table 10 contains the estimated resources needs for a possible future National Laboratory (NL) effort. The numbers in this table reflect adjusted values of current resource needs minus estimated commercially funded project resources that are expected to transition from NASA/ISS National Laboratory sponsorship to a fully commercial business-to-business relationship supported.

Table 11 contains the summation of all users resources (all NASA plus NL).

NASA is requesting feedback from industry on the ability of the CLDs to provide the listed resources and potential impacts to CLD designs. Information about plans to accommodate 2 NASA crew members is also requested.

Table 3. Resource Categories and Methodology

Resource Category	Methodology Used to Estimate the Resources
CREW TIME* (Average and Max)	Calculated using Average & Maximum Crew Time Hours from historical ISS increments (HRP/HHP, BPS, Tech Demo STMD) and expected future crew time (Tech Demo SOMD and ESDMD) *Expected to be provided primarily by 2 NASA crew members, but open to some activities being provided by private crew.
EXPERIMENTS (Average and Max)	Calculated using Average & Maximum number of experiments from historical ISS increments (HRP/HHP, BPS, Tech Demo STMD), and expected future experiments (Tech Demo SOMD and ESDMD)
DATA* (IT Assets, Digital Storage, Transmit Rate)	Best estimate from the science POCs based upon historical ISS usage and expected future research needs * General-purpose information technology (IT) assets are computers able to conduct data processing and data storage, and with adequate processing capability to conduct real-time autonomous on-orbit research analysis with minimum ground involvement.
COMMUNICATION (Audio/video channels)	Based on ISS operational history
STORAGE & SPACE (ISPRs, Gloveboxes, Conditioned)	HRP/HHP's numbers are based on historical ISS usage; best estimate for BPS and Tech Demos based upon expected future research needs. NOTE: NASA does not expect 100% continuous occupation of these volumes, and has not yet performed a traffic model to determine average occupancy
TRANSPORT (Up-mass and down-mass)	HRP/HHP's numbers are based on historical ISS usage, best estimate for BPS and Tech Demos based upon expected future research needs
RESOURCES	Resources information calculated using power draw plus: • Supply Pantry (yes/no) (e.g. PPE, gloves, syringes) • Potable Water (yes/no) • Thermal MTL/LTL (yes/no) • Vacuum Vent (yes/no)

Table 4. Summary of Estimated Biological and Physical Sciences (BPS) Resources

Resource Category	Amount
CREW TIME	Estimated crew time needed annually: 375-575 hrs
EXPERIMENTS	Estimated average number of experiments annually: 35 | Max: 45
DATA	- General-purpose IT assets: 2 - On-board digital storage capacity: 500 TB - Data transmit rate: >150 Mbps
COMMUNICATION	- 4 audio channels - 6 video downlink channels
STORAGE & SPACE	- 8 m^3 = 40 singles = 20 doubles = 5 ISPRs | LSG, MSG, CIR, FIR, MSRR* - Avg conditioned volume: 1 m^3
TRANSPORT	Estimated annual mass & volume: - Avg up: ~600 kg and 1 m^3 - Avg down: ~300 kg and 0.5m^3
RESOURCES	- 21 kW of power for 5 ISPRs, LSG, MSG, CIR, FIR, & MSRR - Access to potable water, vacuum vent, MTL/LTL thermal, and supply pantry

* LSG, MSG, CIR, FIR, and MSRR power resources accounted for in BPS Resource Requests

Table 5. Summary of Estimated Human Research Program/Human Health & Performance (HRP/HHP) Resources

Resource Category	Amount
CREW TIME	Estimated crew time needed annually: 430-750 hrs
EXPERIMENTS	Estimated average number of experiments annually: 10 | Max: 25
DATA	General-purpose IT assets: - On-board digital storage capacity: 1 TB - Data transmit rate: >150 Mbps
COMMUNICATION	- 4 audio channels - 6 video downlink channels
STORAGE & SPACE	- 2 m^3 = 8 singles = 4 doubles = 1 ISPRs - Avg conditioned volume: 0.1 m^3
TRANSPORT	Estimated annual mass & volume: - Avg up: 100 kg 0.6m^3 - Avg down: 50 kg and 0.2m^3
RESOURCES	- 2 kW of power for 1 ISPR - Access to potable water, vacuum vent, MTL/LTL thermal, and supply pantry

Table 6. Summary of Estimated Earth Science Division (ESD) and Heliophysics Division (HPD) Resources

Resource Category	Amount
CREW TIME	Estimated crew time needed annually: 0 hrs
EXPERIMENTS	Estimated average number of experiments annually: 5 | Max: 21
DATA	- General-purpose IT assets: 0 - On-board digital storage capacity: 0 TB - Data transmit rate: >150 Mbps
COMMUNICATION	- 4 audio channels - 6 video downlink channels
STORAGE & SPACE	5 to 8 external viewing sites
TRANSPORT	Estimated annual mass: - Avg up: 1,000 kg - Avg down: 1,000 kg Estimated annual volume is not predicted at this time
RESOURCES	5 to 8 kW of power for 5 to 8 external sites

Table 7. Summary of Estimated Exploration Space Development Mission Directorate (ESDMD) Technology Demonstration (Tech Demo) Resources

Resource Category	Amount
CREW TIME	Estimated crew time needed annually: ~1,000 hrs
EXPERIMENTS	Estimated average number of experiments annually: ~10
DATA	- General-purpose IT assets: 1 - On-board digital storage capacity: 1 TB - Data transmit rate: >150 Mbps
COMMUNICATION	- 4 audio channels - 6 video downlink channels
STORAGE & SPACE	~3 m^3 = 16 singles = 8 doubles = 2 ISPRs - Avg conditioned volume: 0 m^3
TRANSPORT	Estimated annual mass & volume: - Avg up: ~1,000 kg 4 m^3 - Avg down: ~300 kg and 2 m^3
RESOURCES	- 4 kW of power for 2 ISPRs - Access to potable water, vacuum vent, MTL/LTL thermal, and supply pantry

Table 8. Summary of Estimated Space Technology Mission Directorate (STMD) Technology Demonstration (Tech Demo) Resources

Resource Category	Amount
CREW TIME	Estimated crew time needed annually: 12-22 hrs
EXPERIMENTS	Estimated average number of experiments annually: ~10 to ~30
DATA	- General-purpose IT assets: 1 - On-board digital storage capacity: 2 TB - Data transmit rate: >150 Mbps
COMMUNICATION	- 4 audio channels - 6 video downlink channels
STORAGE & SPACE	- ~1 m^3 = 4 singles = 2 doubles = 0.5 ISPRs - Avg conditioned volume: 0 m^3
TRANSPORT	- Estimated annual mass & volume: - Avg up: No estimate available - Avg down: No estimate available
RESOURCES	- 1 kW of power for 0.5 ISPR - Access to potable water, vacuum vent, MTL/LTL thermal, and supply pantry

Table 9. Summary of Estimated Space Operations Mission Directorate (SOMD) Technology Demonstration (Tech Demo) Resources

Resource Category	Amount
CREW TIME	Estimated crew time needed annually: 400 hrs
EXPERIMENTS	Estimated average number of experiments annually: ~4
DATA	- General-purpose IT assets: 1 - On-board digital storage capacity: 1 TB - Data transmit rate: >150 Mbps
COMMUNICATION	- 4 audio channels - 6 video downlink channels
STORAGE & SPACE	- ~5 m^3 = 24 singles = 12 doubles = 3 ISPRs - Avg conditioned volume: 0.0 m^3
TRANSPORT	Estimated annual mass & volume: - Avg up: 500 kg 2 m^3 - Avg down: 20 kg and 0.1m^3
RESOURCES	- 1 kW of power for 0.5 ISPR - Access to potable water, vacuum vent, MTL/LTL thermal, and supply pantry

Table 10. Summary of Estimated National Laboratory (NL) Resources

Resource Category	Amount
CREW TIME	Crew time average annually: 870 hrs | Max: 1,270 hours
EXPERIMENTS	Avg # of experiments annually: 60 | Max: 90
DATA	- General-purpose IT assets: 2 - On-board digital storage capacity: 15 TB
COMMUNICATION	- 1 privatized S/G channel - 2 video downlinks
STORAGE & SPACE	- ~6 m^3 = 32 singles = 16 doubles = 4 ISPRs | LSG & MSG | CIR & FIR | MSRR* - Avg conditioned volume: 0.25 m^3
TRANSPORT	Estimated annual mass & volume: - Avg Up: ~2,000 kg & 4 m^3 - Avg Down: ~1,000 kg & 3 m^3
RESOURCES	- Up to 8 kW of power - Access to potable water and vacuum vent and MTL/LTL thermal and supply pantry

* LSG, MSG, CIR, FIR, and MSRR power resources accounted for in BPS Resource Requests

Table 11. Summary of All User Resources (All NASA and NL)

NOTE: The following summary of all user resources represents roughly half of the current NASA and ISSNL utilization of the ISS in terms of crew time, number of experiments, volume, and external sites, and roughly consistent with NASA's previous 2019 white paper estimates.

Resource Category	Amount
CREW TIME	Crew time annually: ~3,000 to ~4,000 hrs
EXPERIMENTS	Estimated average number of experiments annually: ~130 to ~230
DATA	- General-purpose IT assets: 9 - On-board digital storage capacity: ~500 TB - Data Transmit Rate: >150 Mbps
COMMUNICATION	- 4 audio channels - 6 video downlink channels
STORAGE & SPACE	- ~24 m^3 = 124 singles = 62 doubles = 15.5 ISPRs | LSG, MSG, CIR, FIR, MSRR - Avg conditioned volume*: 1 m^3 - 5 to 8 external viewing sites * The volume number represents the total of all the individual user groups. It is not expected that this amount of volume would be needed by NASA at the same time, at any given time, since experiments will be added and removed throughout the year.
TRANSPORT	Estimated annual mass & volume - Up: 5,000 kg and 12 m^3

	- Down: 2,000 kg and 5 m^3
RESOURCES	- 42 kW of power for 15 ISPRs, LSG, MSG, CIR, FIR, & MSRR* - 5 to 8 kW of power for 5 to 8 external viewing sites - Access to potable water and vacuum vent and MTL/LTL thermal and supply pantry

* LSG, MSG, CIR, FIR, and MSRR power resources accounted for in BPS Resource Requests

List of Acronyms

BPS	Biological and Physical Sciences
CIR	Combustion Integrated Rack
CLD	Commercial LEO Destination
ELC	EXpedite the PRocessing of Experiments to Space Station (EXPRESS) Logistics Carrier
ESD	Earth Science Division
ESDMD	Exploration Systems Development Mission Directorate
ExPA	Express Pallet Adapter
FIR	Fluid Integrated Rack
FOV	Field of View
HHP	Human Health and Performance
HPD	Heliophysics Division
HRP	Human Research Program
IR	Infrared
ISPRs	ISS Standard Payload Rack
ISS	International Space Station
IT	Information Technology
JEM EF	Japanese Experiment Module Exposed Facility
kW	Kilowatt
LEO	Low Earth Orbit
LSG	Life Sciences Glovebox
LTL	Low Temperature Loop
Mbps	Megabits Per Second
MSG	Microgravity Science Glovebox
MSRR	Materials Science Research Rack
MTL	Moderate Temperate Loop
NL	National Lab
OSTEM	Office of Science, Technology, Engineering, and Mathematics
PPE	Personal Protective Equipment
S/G channel	Space to Ground communication channel
SMD	Science Mission Directorate
SOMD	Space Operations Mission Directorate
SSCs	Station Support Computers
STMD	Space Technology Mission Directorate

TB	Terabyte or 10^12 bytes
Tech Demo	Technology Demonstration
V	Volts
W	Watts

Appendix 1. Detailed List of Capabilities and Interfaces for External Payload Capabilities

- Communication, power, data and physical volume equivalent to or exceeding capabilities provided by the current ISS
- External payload attachment sites
  - Mass volume capabilities equal or better than JEM-EF
  - Common physical and data interfaces on the platform
- Dual power channels
  - Redundant switched power: 28V regulated power supply with voltage and current monitor per bus @ 100Hz
  - ESD: Desired peak and average power per external slot for CLD is 1,000W each and the survival power (in a visiting vehicle or attached to a robotic arm) is 300W
  - NOTE: ISS today: ELC 2 X 3kW feeds, each are limited to using one a primary and the secondary as backup, they can use both at the same time if the isolation requirements are met. ExPA with two 120V heater power buses one 120 V max 750W operational power bus and one operational 28V power bus.
- Communication capabilities
  - Ethernet, ethernet (WiFi)
  - Data volume/data rate: 100 Mbps downlink, no limit on daily downlink volume, 1 Mbps uplink and no limit on daily uplink volume; data latency < 1 hour
- Structural constraints (mounting arm can survive inertial of station pivoting 90 degrees)
- Launch vehicle survival power
  - Greater or equal to current values which may be launch vehicle dependent
- Robotic arm for installation survival
  - Survival power on the arm
  - Payloads should be able to survive for 6 hours without electrical and thermal accommodations
- Unobstructed Field of View (FOV) in the earth-facing (nadir), space-facing (zenith), and other directions as specified and state of health information for FOV
- Vehicle pointing stability and accuracy
- Ability to provide warning instrumentation for contamination and mitigation
- Service Level Agreement standards – availability of power, field of view, communications etc. for example 90% or 95%
- Operational planning and coordination for station-keeping operations
- Ability to provide minimum and maximum guaranteed thermal interface conditions
- Ability to provide an electromagnetic environment monitor
- Ability to provide radiation and cleanliness monitoring
- Ability to provide time-synced housekeeping packet of monitored data (e.g., voltage, current, radiation, cleanliness, electromagnetic, pointing)
- Guaranteed minimum number of operational days with an option for extension