# WATERFOWL ARCHITECTURE
# For Transfer of Fluids Between Lunar Surface Assets

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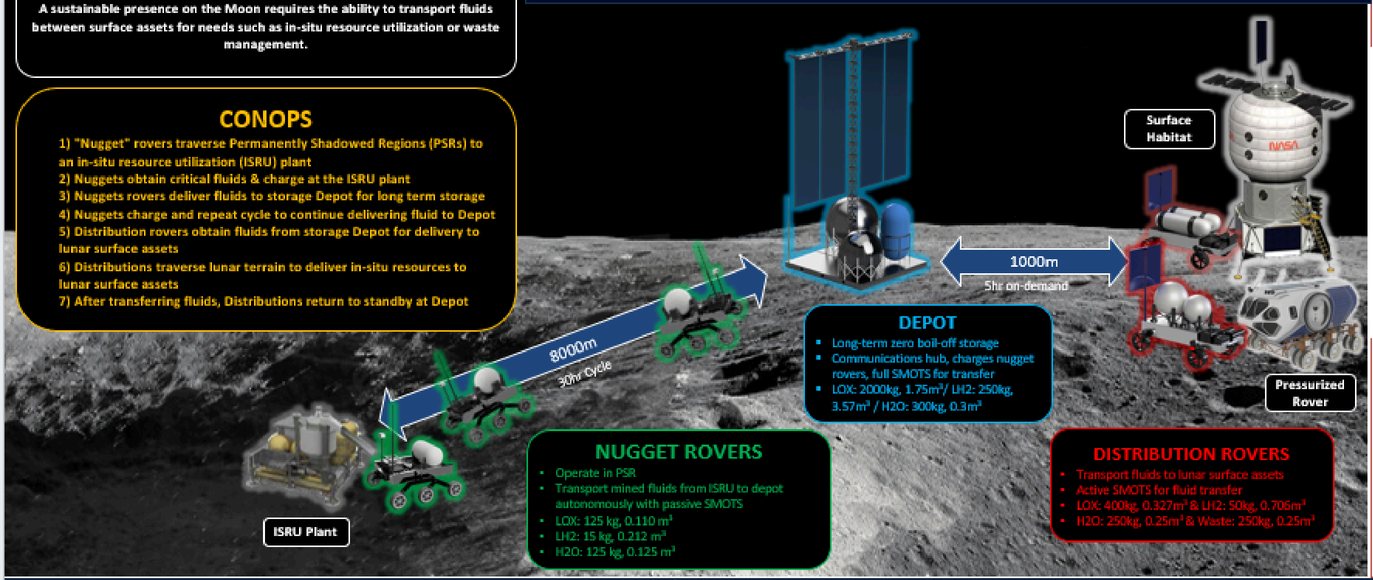
## PROBLEM DEFINITION

**A sustainable presence on the Moon requires the ability to transport fluids between surface assets for needs such as in-situ resource utilization or waste management.**

## CONOPS

1) "Nugget" rovers traverse Permanently Shadowed Regions (PSRs) to an in-situ resource utilization (ISRU) plant
2) Nuggets obtain critical fluids & charge at the ISRU plant
3) Nuggets rovers deliver fluids to storage Depot for long term storage
4) Nuggets charge and repeat cycle to continue delivering fluid to Depot
5) Distribution rovers obtain fluids from storage Depot for delivery to lunar surface assets
6) Distributions traverse lunar terrain to deliver in-situ resources to lunar surface assets
7) After transferring fluids, Distributions return to standby at Depot

## FINAL DESIGN



### DEPOT

- Long-term zero boil-off storage
- Communications hub, charges nugget rovers, full SMOTS for transfer
- LOX: 2000kg, 1.75m³/ LH2: 250kg, 3.57m³ / H2O: 300kg, 0.3m³

### NUGGET ROVERS

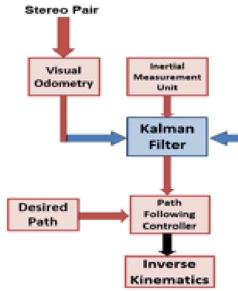
- Operate in PSR
- Transport mined fluids from ISRU to depot autonomously with passive SMOTS
- LOX: 125 kg, 0.110 m³
- LH2: 15 kg, 0.212 m³
- H2O: 125 kg, 0.125 m³

### DISTRIBUTION ROVERS

- Transport fluids to lunar surface assets
- Active SMOTS for fluid transfer
- LOX: 400kg, 0.327m³ & LH2: 50kg, 0.706m³
- H2O: 250kg, 0.25m³ & Waste: 250kg, 0.25m³

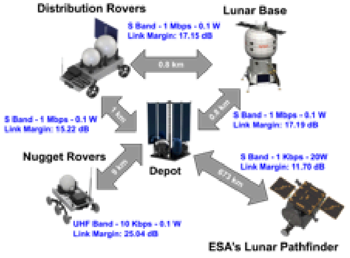
## SYSTEMS

### NAVIGATION



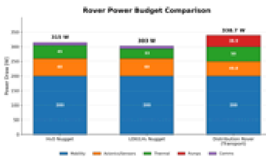
- LiDAR
- FlashPose Algothim
- ICP

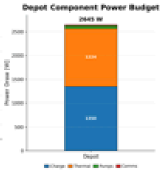
### COMMUNICATIONS



### POWER SYSTEM

| Asset | Power Source | Battery | Solar Area | Key Reason |
|---|---|---|---|---|
| Nugget Rover | Battery only | 4 kWh | 0 m² | PSR operation, no solar |
| Distribution Rover | Solar + battery | 4 kWh | 1.78 m² | Independent charging |
| Depot | Solar array + buffer | 88.4 kWh | 19.3 m² | Charging + transfer support |

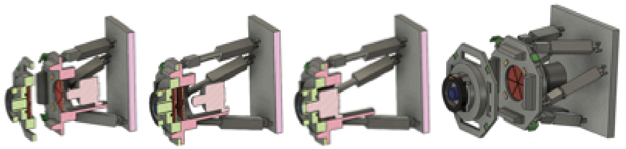




## FLUID TRANSFER

### Self-aligning Modular Off-World Transfer System (SMOTS)

- Stewart-platform based manipulator capable of autonomously aligning and connecting fluid transfer couplings
- Composed of two halves for rigid connection: passive (green) and active (red)
- Essential Steps
  - Use LiDAR to identify the position of passive half, then active half initiates control algorithm for connection
  - Rigidly connect both halves with a latching mechanism, then open the iris to allow coupling
  - Linear stage mates the couplings to enable fluid transfer
  - Linear stage retracts, iris closes, latches disengage, and position resets

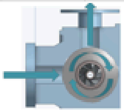


### Flow Logic & Pumping

| Fluid | Mass Flow | Fill Time (Payload) | Peak Power |
|---|---|---|---|
| Water (In) | 0.35 kg/s | 6.0 min (125 kg) | 2.5 W |
| Water (Out) | 2.2 kg/s | 1.9 min (250 kg) | 16 W |
| LOX (In) | 0.40 kg/s | 5.3 min (125 kg) | 4.3 W |
| LOX (Out) | 2.4 kg/s | 2.8 min (400 kg) | 26 W |
| LH2 (In) | 0.025 kg/s | 10 min (15 kg) | 0.27 W |
| LOX (Out) | 0.23 kg/s | 3.7 min (50 kg) | 2.4 W |

- Depot utilizes a dual-Line flow architecture to achieve 97.5% reliability
- SS316 piping with MLI and micron-mesh minimizes cryogenic boil-off during transfer
- Optimized with Pump and Nozzle configuration to throttle flow and maintain safe velocity levels
- Isolation/Check Valves and Sensors are placed to monitor transfer inbound (storage loading) and outbound (rover distribution)

- Low net-positive suction head and seamless design in lunar operations ensure no cavitation risk due to low gravity (1.62 m/s²)
- The regenerative turbine can generate up to 10 times the pressure of standard pumps while maintaining a weight of only 40 kg.
- Efficient low power draw of ~893 W for LOX, ~782 W for $H_2O$, and ~56 W for LH and complete transfers of 400 kg LOX, 50 kg $LH_2$, and 250 kg $H_2O$ in about 2.6 hours.



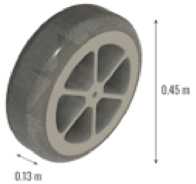
## DESIGN

### Suspension System:

- The Nugget rovers are designed to operate on slopes up to 30 degrees while maintaining stability and traction.
- To account for the slope limit, the rocker-bogie suspension system allows the rovers to climb obstacles twice the wheel diameter while keeping the wheels in contact with the ground.

### Wheel & Chassis Design:

- Scaled off of the Baseline SFR 1.7 configuration, which was utilized in early NASA testing, the material of the wheel was chosen to be NiTi-SMA (Nickel Titanium - Shape Memory Alloy) for its elasticity and capability to withstand excessive deformation.
- From terramechanics analysis, the minimum drawbar pull was found to be 100.6 N, which was averaged for all Nugget Rovers, including both gross and dry mass.
- 6061-T6 Aluminum was chosen as the material for the chassis due to its high strength-to-weight ratio and corrosion resistance.



### Tank Design:

| Parameter | Shell Material | | Multi-Layer Insulation (MLI) | |
|---|---|---|---|---|
| Description / Tank Type | High strength-to-weight ratio, low density | | Reflector: Double-Aluminized Mylar<br>Spacer: Fiberglass paper | |
| Cryogenic | Aluminum Alloy 2219 | $\sigma_{ys}$: 400 MPa | 50 Layers | 2 Layers per 0.854 mm |
| Non-Cryogenic | Aluminum Alloy 6061 | $\sigma_{ys}$: 278 MPa | 20 Layers | |

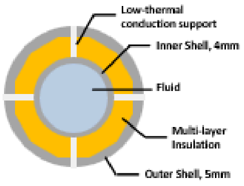
### Pressurization:

A small portion of the liquid is vaporized through a heat exchange cycle and feedback into the ullage to maintain design pressure

| Fluid | Mass Flow Rate | Total Gaseous Mass | Temperature Rise |
|---|---|---|---|
| LOX | 0.156 kg/s | 22.5 kg | 90k – 150k |
| $LH_2$ | 3.38 x $10^{-3}$ kg/s | 2.26 kg | 20k – 50k |

### Passive Thermal Insulation

- NASA cryogenic fluid management architectures emphasize zero-boil-off for long-duration propellant storage, making boil-off minimization a critical design driver for lunar ISRU logistics.
- Waterfowl adopted a <1% boil-off per sortie rover level requirement as a practical storage threshold.
- Insulated support struts and multi-layer insulation were used to reduce radiative heat transfer.
- LOX: 50-layer MLI achieved 0.17% boil-off for LOX and 0.81%
- $LH_2$: 50-layer MLI required to reduce boil-off below threshold to 0.81%



### Active Thermal Management

- Rover electronics are exposed temperatures below 40 K, requiring active thermal protection.
- Batteries and avionics were maintained within an operational range of approximately 0°C to 40°C using an insulated warm electronics box with heating requirements ranging between 26W and 33W respectively
- Radiator sized using the Stefan-Boltzmann law rejects excess heat during operation.

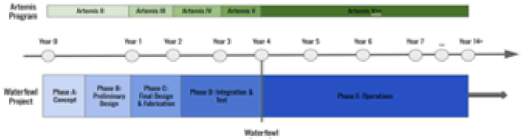
## FUTURE DEVELOPMENT

**Tanks:**

- Design structural support for the tanks
- Include pressure-release valves into tank design
- Design the feedback loop for the autogenous pressurization
- Add tank baffles to control sloshing

**Proposed Testing:**

- Develop and test prototypes of all major subsystems, including nugget rovers, depot interfaces, and distribution systems
- Validate the fluid transfer process under cryogenic conditions to ensure reliable, leak-free operation
- Perform integrated testing of the full system (nugget–depot–distribution) to evaluate coordination and performance
- Conduct environmental testing in lunar-like conditions, including vacuum, extreme temperatures, and dust exposure
- Refine communication and autonomy to improve reliability during long-duration, low-visibility operations
- Evaluate scalability of the architecture for larger lunar infrastructure and sustained missions



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