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VIPER ROVER: FLIGHT BUILD AND ENVIRONMENTAL TEST STATUS

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The NASA Artemis Program plans to return humans to the Moon to stay. Extended human stays on the Moon will require substantial resources to sustain human presence, requiring continuous supplies delivered from the Earth. However, if some of the resources were indigenously available, Earth logistical requirements could be substantially reduced by "living off the land" with in-situ lunar resources. Local volatiles could be processed into propellants and human life-supporting needs, reducing risk of maintaining a permanent human presence on the Moon.

LCROSS[1], LRO and other missions have confirmed the presence of lunar volatiles resources in polar regions, so the next step is to understand the physical distribution of those resources, as well as the scientific basis for how water got there, and why it is *still* there.

The Volatiles Investigating Polar Exploration Resource (VIPER) is a surface mobility scientific platform, designed to spend ~100 days mapping and surveying four different Ice Stability Regions to understand the scientific nature and distribution of water and other volatiles. VIPER will also provide scientific mineralogical context of the lunar regolith, such as the presence of silicon and light metals in lunar regolith, providing a composite picture of resource availability and sustainment.

This paper will discuss VIPER's completion of the flight rover build, as well as current progress in environmental testing, preparedness for mission operations, and overall readying for launch integration with our CLPS partner.

VIPER is managed within NASA's Science Mission Directorate (SMD), utilizing the Commercial Lunar Payload Services (CLPS) lunar delivery model.

I. MISSION OVERVIEW

The VIPER Mission is focused on supporting long-term stays on the Moon, including understanding the nature and concentration of water and other volatiles. VIPER intends to study both the processes that formed/enable volatiles, as well as understanding their distribution. VIPER will inform future missions planning, both state-sponsored and commercial, in moving towards harvesting and processing those resources. These goals will ultimately result in the creation of lunar resource maps, enabling assessments of the ore grade of lunar polar volatiles, as well as the economic suitability of using these resources for human sustainment and fuel. The utility and uses of these resources were discussed in an earlier IAC paper on the VIPER mission[2]. VIPER represents the next step forward for lunar polar missions, beginning with resource identification, then In Situ Resource Utilization (ISRU), and finally mining, bulk production, and storage.

The VIPER team has established four different regions in the lunar polar landscape, each defined by their predicted thermal stability of ice. These regions are called Ice Stability Regions, or ISR's, which range from surface regions, down to 1m below the surface. The VIPER traverse will explore multiple instances of these ISR's to get a solid statistical set of data. These data will enable extrapolations to be made across the entire polar region, enabling broad resource planning to sustain humans on the Moon.

II. VIPER BUILD COMPLETION

The VIPER team completed the build of the flight VIPER rover in 6/4/2024 at 4:30 pm CDT. This section will illustrate some of the key developments in the build of the rover, including some of the issues that were addressed along the way.

VIPER was approved to begin system assembly and test after passing its Key Decision Point-D (KDP-D) review at NASA. However, even earlier, the VIPER team was already doing multiple levels of subsystem assembly and test, as illustrated in an earlier VIPER IAC paper[3]. As those early subsystems are being built and tested, the chassis is the starting point for the build of the flight rover [Fig. 1]. The VIPER chassis represents not only the structural core of the rover, but it will also house VIPER's batteries, support the entire warm box (used to keep critical electronics within an acceptable thermal environment), as well as support each of the four rover wheel active suspension systems.

Fig. 1: Early lower chassis assembly activities

The VIPER team had to wait for several critical components to arrive, given the extraordinary industry supply chain impacts witnessed due to the global pandemic. This forced the integration team to be flexible with the planned order of subsystem installations. Some of these installations were not in the ideal order of assembly, but we needed to press forward to preserve as much schedule as possible. In [Fig. 2] the MSolo instrument is installed in the lower chassis, along with several harness installations and some early MLI work.

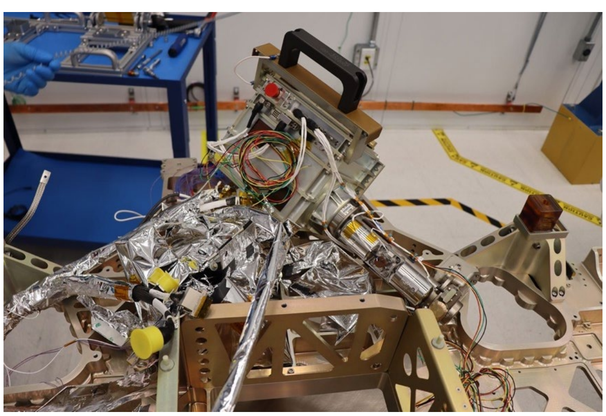

Fig. 2: MSolo instrument into the lower chassis

VIPER continued to make progress by moving onto wheel suspension systems installation, helping viewers to finally see this assembly is indeed a rover [Fig. 3]. With each of these steps more and more cable harnesses are installed as well. Harnesses are the least exciting installation of the system, but one of the most important, as these harnesses carry all signals and power for the rover. The VIPER team pre-tested most all the harnesses and practiced routing them with a harnessing jig, making sure the design intentions match the realities of the as-built rover.

Fig. 3: Wheel suspension system installation

In parallel with the lower chassis build-up described in these first few images, the VIPER team also started working on the Upper Frame assembly. This was another opportunity to keep the assembly of the rover structure moving forward, while waiting from vendors of key subsystem hardware. [Fig. 4] shows the upper frame assembly with the Neutron Spectrometer System (NSS) sensor head mounted on the front of the frame (left side in image), ready to sense neutron count changes during the mission, indicating the likely presence of water ice.

Next was the substantial task of building-up and populating the four sides of the "warm box". Each side of the warm box is a heat spreader, which provides a nominal temperature range for thermally constrained electronics. Populating the heat spreaders was delayed

Fig. 4: VIPER upper frame assembly

due to late arriving hardware, such as the Integrated Avionics Unit (IAU), which was more than 16-mo late. Delaying the heat spreaders means the warm box cannot be assembled, slowing overall integration. [Fig. 5] illustrates one of the four heat spreaders going into the chassis. Considerably more cable harnessing and

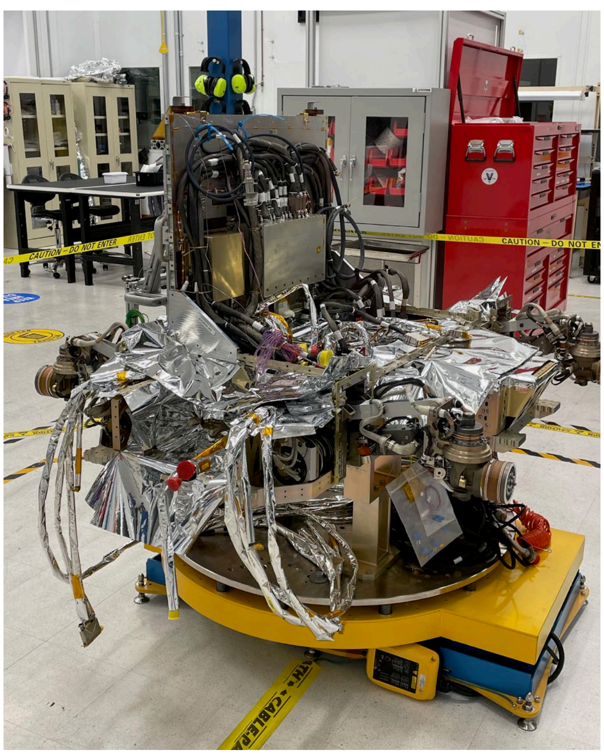

Fig. 5: Lower chassis with one of the four heat spreaders installed

MLI installations are also apparent. The next step is to install these two elements together to create a completed VIPER structure [Fig. 6].

Now that the upper frame structure is installed, the key facets of the thermal management system can be

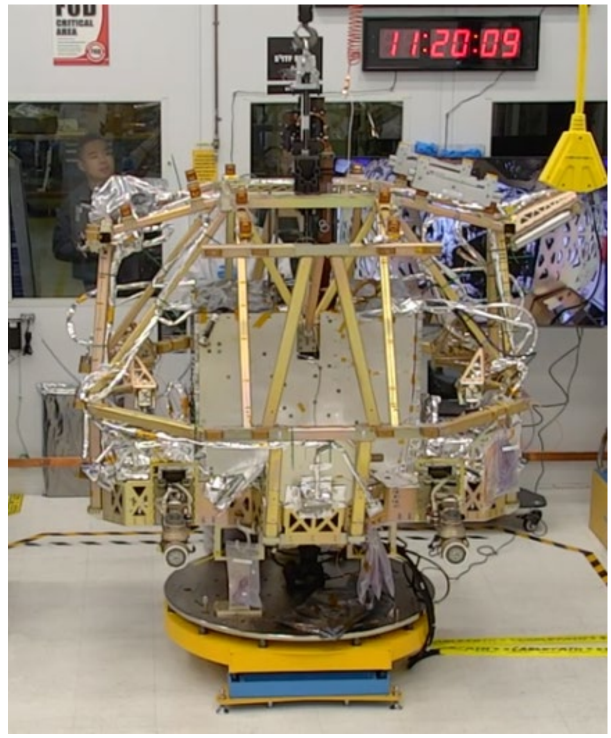

Fig. 6: Upper frame installed on lower chassis, with warm box (heat spreaders) complete.

installed as well as the system's solar array panels. However, the first step is to install the VIPER mast, fully outfitted with the VIPER principal navigation cameras system, the VIPER lighting system "head lights" and the two communications antennae (low gain omni, and high-gain directional) [Fig. 7].

Now that the mast is bolted-on and the heat-rejecting radiators are installed along the top of the rover, the central core of the rover can be wrapped in Multi-Layer Insulation (MLI). MLI is a remarkable material that acts as an effective thermal barrier, keeping heat on one side of the material from passing to the other side, including radiative thermal energy. This is critical for a mission which will experience temperature swings as low as 30 degK, all the way to 300 degK. VIPER at times will be very cold and other time very warm, so VIPER's temperature needs to be highly controlled. Key to that design is to make sure heat stays inside the rover when in a cold environment, but heat is rejected when in a warm environment, and this is where the MLI comes in. MLI is wrapped

Fig. 7: VIPER mast installation

around the entire rover prior to completing the rover build.

Fig. 8: VIPER solar arrays being installed.

The final step in rover assembly is the installation of the three solar arrays which will power the rover [Fig. 8]. These solar arrays can each power the rover on their own, with optimum power occurring when the sun points on rear corners of the rover, lighting two panels at the same time. The solar arrays were tested through extraordinary temperature ranges, given they are not protected by the MLI during the mission. The flight rover was completed the first week of June 2024, [Fig. 9].

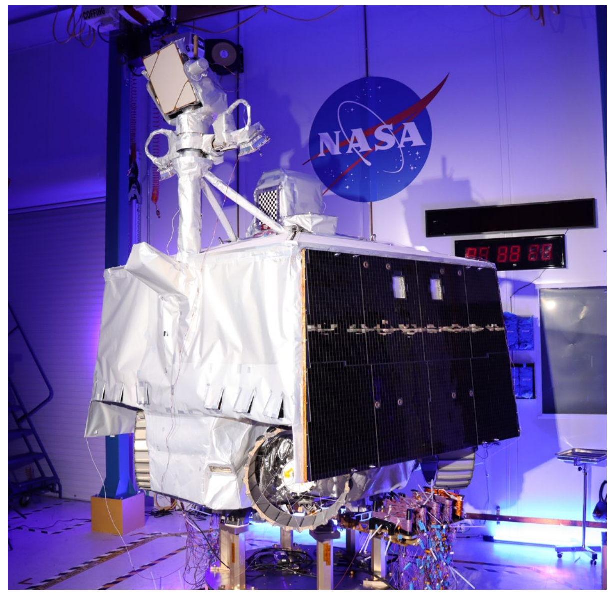

Fig. 9: VIPER build complete.

III. VIPER SYSTEM TEST STATUS

Now that the rover build is complete, there are two types of testing that need to occur, to confirm the rover is ready to conduct its mission:

1. Functional/Comprehensive tests
2. Environmental tests

Functional/comprehensive performance testing assures the design and build process resulted in the intended rover performance. There were several earlier tests (like flatsat testing), which should have confirmed vital subsystems played well with each other, but system-level testing is the first chance for the team to see the whole rover operate at once, as a whole system. Non-conformances to requirements can be adjudicated during these tests, which can include waiving requirements, or attempting to successfully meet the original requirements, if feasible remediations are possible. Schedule remains a strong driver at this phase, so sometimes difficult decisions may have to be made.

On the heels of the comprehensive testing, it is also critical to understand how VIPER will behave when operated in analogous environments, like during lunar transit or when on the Moon. This is where environmental testing comes in. Environmental testing attempts to understand and verify the rover can survive environmental stresses, such as vibration during launch and landing, or operating at extreme cold, while in a very deep vacuum. It is important to understand any issues that would have otherwise appeared later, when addressing them would be much more difficult/costly.

Fig. 10: VIPER undergoing Sine-Vibe testing.

The VIPER team created a waterfall schedule of testing, which first checks the system level performance with a Comprehensive Performance Test (CPT#1), to make sure all is well going into environmental testing. Any discrepancies will be noted and addressed or noted, followed by continuing forward into testing. This initial test is important because it reveals the condition of the rover prior to being put under environmental testing. If something does fail or change during testing, this first CPT will make it much easier/faster to identify what has changed and address it before proceeding further.

Now that the rover's performance is noted/recorded, our first environmental test will be sinusoidal vibration testing, or "sine-vibe" testing, as well as random sine-vibe environmental testing [Fig. 10]. The sine-vibe test focuses on revealing a spacecraft's resonance frequencies, weak points, and how it will perform in a dynamic launch environment. The random vibe environment focuses on verifying the rover design's capability to withstand the launch vibroacoustic environment, and to screen for any workmanship issues. These tests should first and foremost, not result in any rover hardware breaking or falling-off, but more importantly we're looking to see if our modeling of the natural modes and frequencies of the rover match what was built. It is critical to verify this rover can survive the energetic environment of launch and landing. If the modeling does not match what is measured during test, then decisions must be made, trading the difficulty of making changes to the rover, against available schedule.

After the vibe testing, we must confirm that the rover's key functionality is still operational. VIPER does this by executing a Limited Performance Test (LPT), which checks out functions such as: Drill functionality, payload instruments functionality, Wheel and suspension system functionality, Solar array functionality, etc.

Later End-to-End testing goes one step further, checking even broader functionality from the rover back to the Multi-Mission Operations Center (MMOC) at NASA-ARC. All of this is to make sure we have confidence that everything is still operating after that initial application of launch loads.

The next environment the rover will experience is acoustic testing. Acoustic testing can reveal a spacecraft's ability to withstand the acoustic environment of the launch vehicle payload fairing, which will be generating broadband random acoustic high-intensity noise, which could affect the rover's structure or avionics, [Fig. 11].

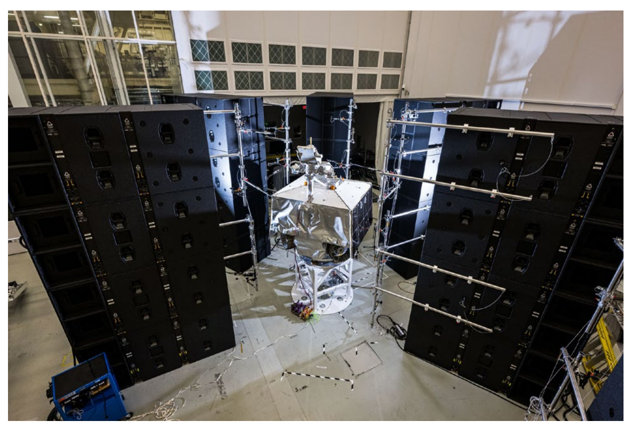

Fig. 11: VIPER undergoing Acoustic testing

Similar to the post-sine-vibe testing, after the acoustic testing we confirm that the rover's key functionality is still operational by executing another Limited Performance Test, which checks out functions such as: Drill functionality, payload instruments functionality, Wheel and suspension system functionality, Solar array functionality, etc.

The final, and arguably most important test is the Thermal Vacuum Chamber "TVAC" test. TVAC testing verifies the rover's ability to withstand the extreme temperatures and low pressures of space. TVAC testing can reveal a lot about a spacecraft, including:

- Temperature regulation: How a spacecraft heats and cools without air to help regulate its temperature.
- Design flaws: Identify design issues and workmanship flaws before the mission.
- Mathematical models: Help evaluate the accuracy of mathematical models by comparing analysis to actual test data.

At the end of this series of environmental tests, VIPER will then have its mass properties measured. Mass properties measurements identify not only the weight of the vehicle, but also its center-of-gravity, essential for assuring the modelling of the vehicle is meeting requirements of the launch provider.

With the environmental tests complete, we conclude with several other tests, such as lander egress-like testing, a subsurface assay test (drill use), and conclude it all with yet another CPT test. CPT #1 and CPT#2 results would ideally by very comparable if nothing has changed with the vehicle as it progresses through testing. If something is different, the team must study the nature of the difference and make a judgement if remediation is needed before launch.

At this point, the vehicle is ready for launch and the mission, awaiting operational readiness for the VIPER team. This operational readiness has been occurring in parallel with the rover assembly and testing, by practicing numerous scenarios for both nominal and off-nominal operational scenarios.

IV. VIPER PREPAREDNESS FOR OPERATIONS

The VIPER operations, science, and surface planning teams have been working rover surface plans since mission inception, and even earlier, building on the pathfinding work of the NASA-ARC Resource Prospector (RP) mission[4] design construct.

As of May 2024, the VIPER operations team had executed numerous mission simulations and developed a series of Ground Data System (GDS) software releases, in support of the mission, [Fig. 12].

GDS Build-9 was just released in May-2024, which is the "features complete" release. This is a critical step in GDS development as it is where all the needed features to execute the mission are now available for

Fig. 12: VIPER Mission Operations Center, NASA-ARC, California

use. Any future releases would only be to address discovered bugs or other issues. Some of those completed features include:

- Lunar Surface Housekeeping
- Rover Rails Driving
- Science Stations
- Lunar Transit Housekeeping
- Lunar Transit Payload Checkouts & Cal's
- Science Station operations
- Rover Safe Haven and Hibernation
- Rover PSR entry/exit

The VIPER team is using their suite of custom Artificial Intelligence (AI) planning tools developed at NASA-Ames Research Center in California[5]. These tools help the team plan visits to multiple ISR's, characterizing their nature. Armed with VIPER's data, broader conclusions can be made, across the entire lunar polar region.

V. PROGRAM STATUS

The VIPER rover flight build completed on June 4, 2024. Since that time, the VIPER rover has completed Sine-vibration and random-vibration testing, followed by confirmational post-test operational performance. Further, the VIPER rover has completed launch-simulating acoustic testing, enduring levels of 138 db energy bombarding the vehicle, similar to what it will experience during launch. Post-test operational performance has also been confirmed, indicating

VIPER is qualified for launch. TVAC is scheduled for Aug-Sep 2024, which will complete VIPER's mission and launch readiness.

The VIPER team has been challenged by *many* late vendors delivering their critical hardware to the VIPER team. The pandemic, and the ensuing global supply chain, has impacted everything from the most complex flight hardware, to the availability of simple solvents. Some VIPER vendors are also under financial stress, requiring some very careful planning and close dialogue with the leadership of these companies.

This supply-chain reality forced VIPER into a continuous state of adaptation, planning and replanning around breaking news about hardware late deliveries. The VIPER team has had to navigate more than half a dozen key rover deliverables being between 12-18 months late, with some hardware still outstanding as of the writing of this paper.

Given the delays to both VIPER's assembly and test, as well as that of the CLPS lunar partner's delays, the Agency has decided to look to fresh partnerships to delivery VIPER to the Moon. The process of seeking and evaluating options for these partnerships is evolving as this paper is being written. Further updates can be provided at the podium presentation at the IAC 2024 conference.

VIII. SUMMARY

Since 1994, several lunar exploration missions have indicated the presence of volatiles, specifically hydrogen, in potentially large quantities in permanently shadowed regions at the lunar poles. Lunar missions from Clementine and Lunar Prospector to LCROSS[1] and LRO have confirmed the presence of volatiles at the lunar poles in permanently shadowed regions (PSRs). Now it is time for a mission to go into these volatiles areas of interest and confirm the makeup and composition of volatiles to inform follow-on missions. Follow-on missions will perform technology demonstrators, performing early-ISRU demonstrations, that will later be scaled for harvesting these important resources in bulk.

The VIPER rover is built, has passed launch campaign qualifications and is (at the time of this writing) imminently going into TVAC testing to complete the mission readiness campaign.

NASA is presently looking to a new partnership to delivery VIPER to the Moon and conduct important lunar science.

All images courtesy of NASA.

[1]Andrews, D. R., "LCROSS – Lunar Impactor: Pioneering Risk–Tolerant Exploration in a Search for Water on the Moon," 7th International Planetary Probe Workshop (IPPW-7), Barcelona, Paper IAC-11-A5.1.4, 2011.

[2]Andrews, D. R., "VIPER: Introduction to the Resource Prospecting Mission" 72nd International Astronautical Congress (IAC-21), Dubai, UAE, Paper IAC-21,A3,2A.4,x63298, October, 2021.

[3]Andrews, D. R., "VIPER: Systems Integration Status" 74th International Astronautical Congress (IAC-23), Baku, Azerbaijan, Paper IAC-23,A3,2A,3,x75804, October, 2023.

[4]Andrews, D. R., "Resource Prospector (RP): Pathfinding In-Situ Resource Utilizations", 14th Reinventing Space Conference, London, UK, Paper BI-RS-2016-31, 2016.

[5]Button, K., "VIPER's AI Assistant", Aerospace America, https://aerospaceamerica.aiaa.org/departments/vipers-ai-assistant/, June 2024.