National Aeronautics and Space Administration

FY23 Strategic Initiatives Research and Technology Development (SRTD)

Venus Aerosol Separator with Mass Spectrometer (VAMS)

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Strategic Focus Area: Technologies for Venus Cloud Environments /Venus In-Situ Aerosol Measurement Technologies | **Strategic Initiative Leader:** James A Cutts

Objectives:

VAMS (Fig 1) is the state-of-the-art aerosol mass spectrometer (AMS) instrument for long-duration planetary aerial missions with a projected mass of 12kg in 12L volume with a nominal power of 59W. Competing commercial AMS from Aerodyne (>100kg and >300W) was deployed on the NASA P3-B, DC-8, and NSF C-130 aircraft [1] but cannot operate under variable outside pressures (0.1-0.8 bar in Venus cloud layer [2]).

The overall objective for VAMS is to perform in the range of harsh environmental conditions expected in the Venus clouds and demonstrate the performance needed to meet the Venus science objectives. Specific FY23 objectives are:

Objective 1) to demonstrate that prototype DPS removes N_2 gas to < 1E-5 Torr inside vacuum chamber;
Objective 2) to interface assembled brass board to Caltech Cloud Chamber and measure N_2/H_2SO_4 enrichment to > 1E6.

Background: The AAI (Fig 1) is the front-end of any mass spectrometer (MS), and its purpose is to extract aerosols from various planetary atmospheres. It has an adaptive high-pressure (60 bar) piezo valve (PV) [3] that enables studies of deep atmospheres of Ice Giants that were prohibitive in the past due to overwhelming amounts of gas to be ingested with aerosol particles [3,4]. AAI maintains the optimal gas flow into MS despite changes in the outside pressure simply by adjusting the PV's gap size. Measuring the composition of aerosols is challenging as they are only a minute fraction of the mass of the atmospheric gases in which they are suspended. We are maturing the AAI to admit atmospheric gas containing sulfuric acid aerosols and then strip away the gas, leaving only the aerosols to enter MS, which analyzes the chemistry of aerosol particles. The AAI uses NanoJet flow cell technology to focus aerosols into narrow beams with mass concentrations as low as ten parts per billion (ppb) at outside pressures varying from 1 mbar to 60 bar.

Approach and Results: This task relied on experimental work and assembly of the TRL4 test bed we used to accomplish the following FY23 milestones:

Milestone 1: Demonstrate QIT-MS sensor is operational after 100 μL load of liquid H_2SO_4 (twice the amount in a 90-day Venus aerobot mission); Figure 1b demonstrates MS sensor that has been exposed to 98% concentrated H_2SO_4 and successfully operated during December 2022 – February 2023.

Milestone 2: Analyze mass spectra of liquid 98% H_2SO_4 injected into the QIT-MS sensor; Figure 2 illustrates mass spectra recorded continuously for 90 days, with evidence of thermal decomposition inside the heated capillary.

Milestone 3: Demonstrate Creare Pumps meet target performance; Figure 3b shows that Creare pumps can provide pressures below 1E-5Torr in the vacuum chamber by scrubbing away the outside air at 760Torr pressure, which meets the requirement of Objective 1 and supports Objective 2 since the reduction of gas phase is better than 7.6E7.

Milestone 4: Demonstrate liquid 95% H_2SO_4 can be atomized and focused within a 2mm splat pattern; Figure 4 shows the TRL4 test bed used in the successful focusing of concentrated H_2SO_4 aerosols

Milestone 5: Design portable QIT-MS and procure components for TRL 4 test bed to be installed at Caltech; Figure 5a shows the assembled portable TRL4 test bed that is relocated in Schlinger Laboratory 115 pending the interfacing to the Venus Cloud Chamber; completion of Objective 2 is de-scoped for FY24 because it depends on completion of Milestone 8.

Milestone 6: Assemble and certify trace gas calibration station; Figure 5b shows the assembled and certified toxic gas calibration station located in 231B laboratory. The station was used to prepare two 1L lecture bottles: one containing the mixture of 6ppb PH_3 and 57ppb H_2S in CO2 ballast and the other with 63ppb PH_3 and 567ppb H_2S in CO2 ballast at 10 psig. These bottles will be used in FY24 to demonstrate that VAMS can measure PH_3 / H_2S at various mixing ratios in the presence of a dominant CO2 atmosphere, as in Venus clouds.

Milestone 7: Provide documents and data sets for TRL 4 and TRL 5 assessment; data sets were provided to the TRL review panel on 04/09/23 and 06/14/23.

Milestone 8: Integrate at IDS Aerosol Focusing (AF) subsystem, MEMS Piezo Valve (PV-5) component, and Differential Pumping (DP) subsystem (using prototype Creare Pumps) into prototype Advanced Aerosol Inlet (AAI) system and deliver to JPL. Figure 3a shows the integrated prototype at IDS, which has not been delivered to JPL due to the recent hardware failure of the bearings of the MTP2 pump. Its replacement was provided to IDS by Creare on September 8, 2023 as an early hardware delivery on Creare's SBIR Phase II award. As of writing this report, IDS was still integrating and vacuum testing this upgraded AAI prototype for delivery to JPL in the first quarter of FY24 to complete the remaining FY23 Objective 2 at Caltech.

Significance/Benefits to JPL and NASA: With the removal of Venus as an NF-5 opportunity, our focus is now on maturing the instrument to TRL-6 in FY24, which will enable later NF and Discovery opportunities. Our immediate focus is a successful MatISSE proposal and completion of FY23 Objective 2 ahead of the MatISSE due dates (Step 1 in April FY24, Step 2 in July FY24). We will continue to explore the potential of this instrument on the probe for the Uranus flagship mission [3], as well as potential demonstrations of troposphere measurements on Earth and the chemical composition of volcanic plumes using drones under the PSTAR program. Finally, we are exploring opportunities for using the instrument as a sensor in JPL's Planetary Cloud and Aerosol Research Facility, which will come online in early FY25.

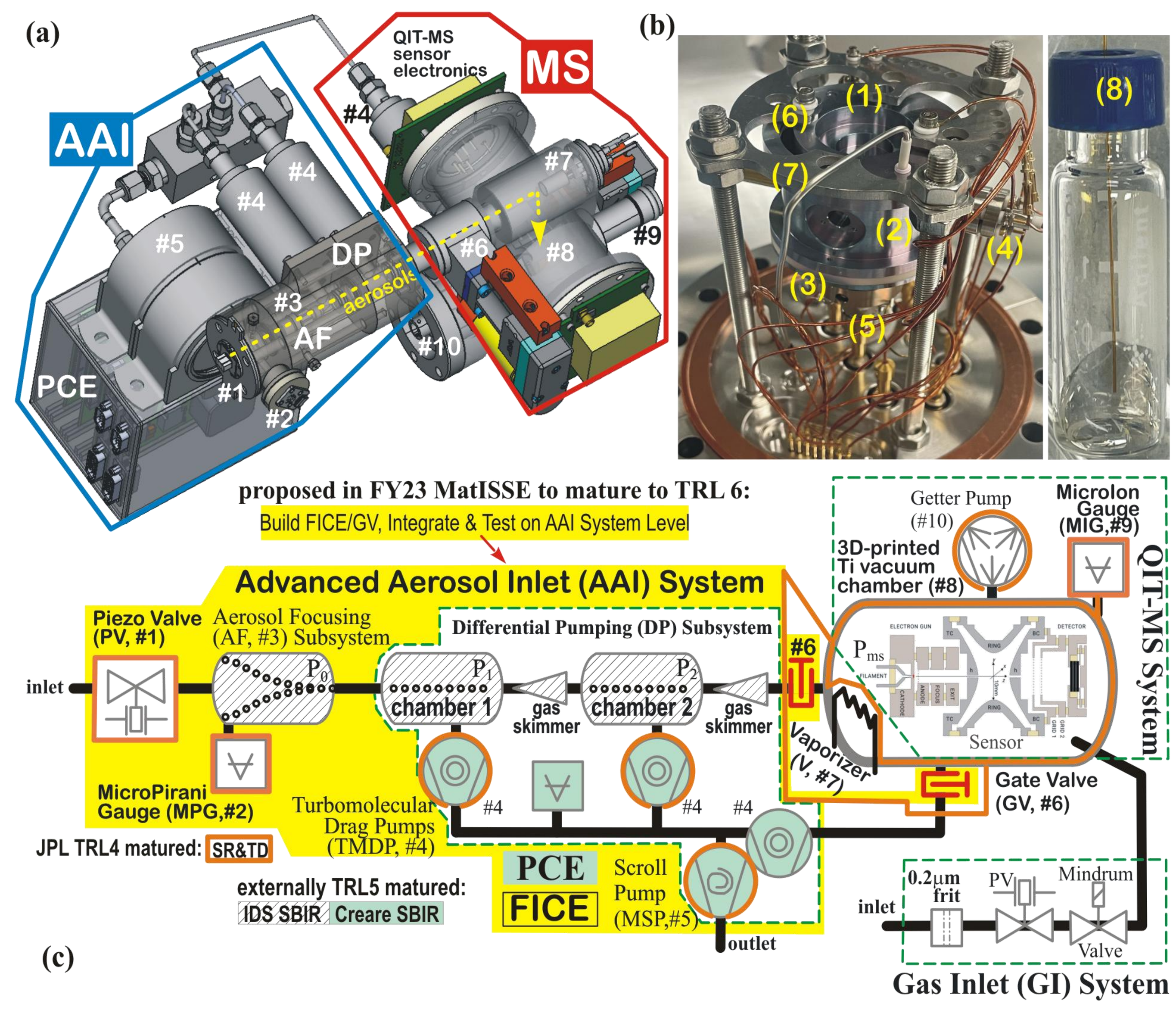

Figure 1. VAMS Instrument. (a) Model of the VAMS instrument with the Advanced Aerosol Inlet (AAI) connected to the Mass Spectrometer (MS). **Milestone 1:** (b) The MS sensor is mounted on a 6" ConFlat flange and was exposed to 100 uL of 98% H2SO4 liquid (8) during 90-day continuous operation; the capillary with acid was inserted into the QIT-MS interior via the stainless steel tube (7); MS sensor has three electrodes: (1) top cap, (2) ring, and (3) bottom cap, an electron gun assembly (4) mounted sideways to the ring electrode, and a Channeltron electron multiplier assembly (5) mounted on the bottom cap. The top cap has a cutout (6) for introducing an aerodynamically collimated beam of aerosols. (c) AAI admits gas with aerosols through the Piezo Valve (PV, #1) using the pressure gradient monitored by the MicroPirani Gauge (MPG, #2). The Aerosol Focusing (AF) accepts and focuses aerosols into the 40-um wide beam, and Differential Pumping (DP) strips away the gas using gas skimmers, two Creare turbo (#4), and a scroll (#5) pump. Pumps are operated by the Pump Control Electronics (PCE) designed to accommodate the Frontend Interface Control Electronics (FICE) breadboard (to be matured in FY24), and the Gate Valve (#6) admits the aerosol beam into the MS vacuum chamber (#8). The vaporizer (V, #7) controls the temperature at which the admitted aerosols are vaporized and analyzed by MS for their composition. Vacuum pressure is monitored by the MicroIon Gauge (MIG, #9) and sustained by the getter (#10) and the third Creare (#4) pump.

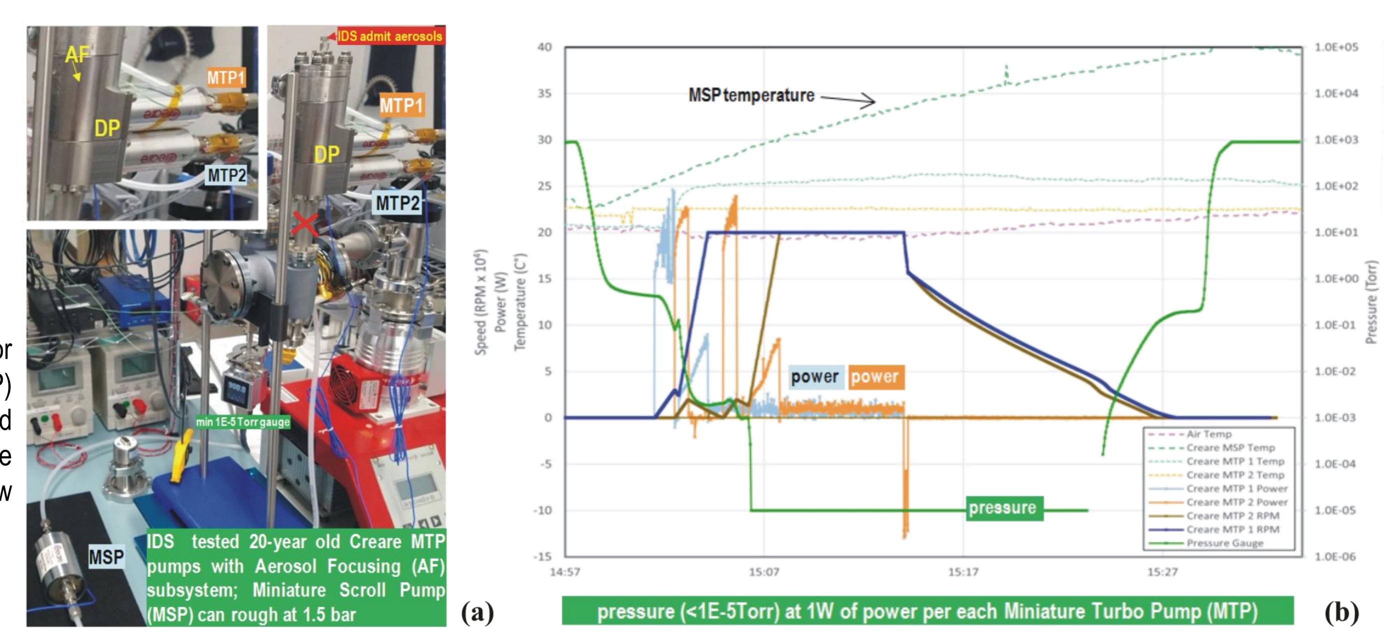

Figure 3. Milestones 3 and 8: (a) Experimental setup for testing the performance of the Differential Pumping (DP) featuring two 20-year-old miniature turbo pumps (MTP) and miniature scroll pump (MSP) from Creare. (b) Performance curves show Creare pumps can provide pressures below 1E-5 Torr at 1W of power consumption.

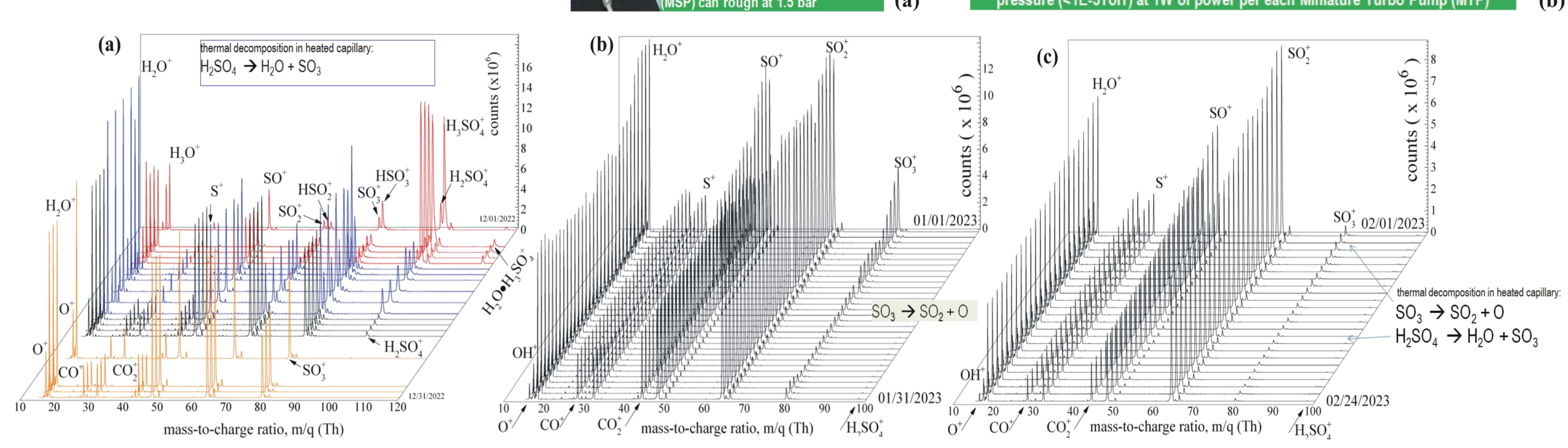

Figure 2. Milestones 1 and 2: (a) Mass spectrum of 98% concentrated liquid H2SO4 eluted through a capillary into the QIT-MS sensor during December 2022 showing major ion fragments: (red) room temperature with (4.9E-8 Torr) and without (1.4E-8 to 1.3E-9 Torr) protonation; when capillary heated to 425K we see initial (black) and full H2SO4 thermal decomposition at 1E-9Torr (orange, with CO2 appearance from capillary coating). During January 2023 (b) and February 2023 (c), the QIT-MS sensor recorded the H2SO4 mass spectrum at low vapor pressures (1.1E-9Torr to 7.1E-10 Torr). Inside the heated capillary occurs the shift of the gas-phase equilibrium toward the thermal decomposition of H2SO4 and SO3.

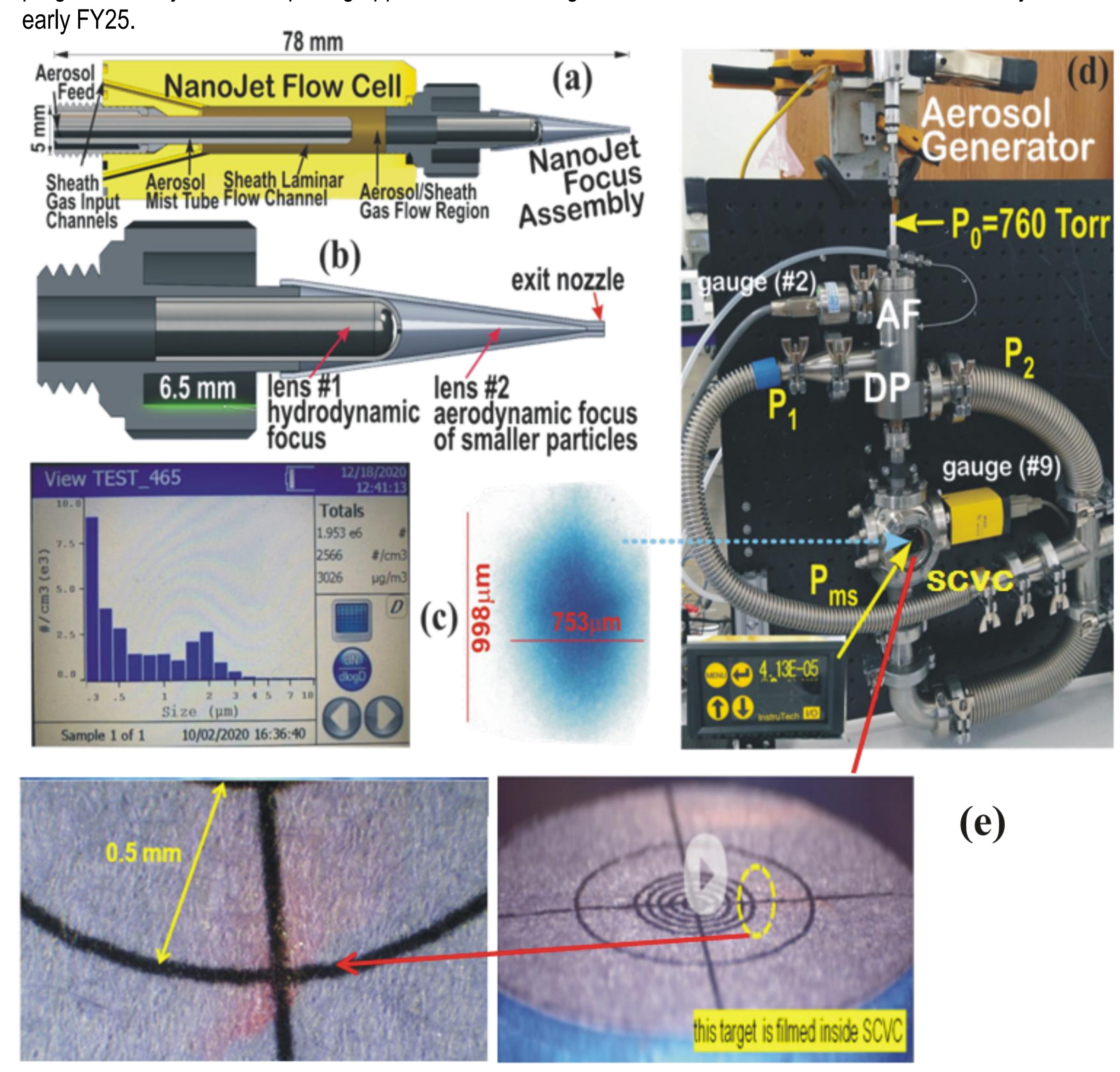

Figure 4. Milestone 4: (a) Cross-sectional view of the NanoJet Flow Cell (NJFC) and the NanoJet Focus Assembly (NJFA) – the two key components of the AF subsystem. (b) Expanded view of the NJFA with two aerodynamic lenses. (c) Divergence of ink aerosols (sizes 0.3um-7 um) 18 cm away from the NJFA exit nozzle gives < 1mm splat patterns on the 8-mm-wide vaporizer (V,#7) inside the spherical cube vacuum chamber (SCVC). The vaporizer consumes 5W at 1200ºC, which is needed to study non-refractory aerosols in Venus clouds. (d) TRL4 test bed of AF/DP subsystems at Po=760 Torr with the ability to maintain a narrow H_2SO_4 aerosol beam over an 18 cm distance. (e) 95% concentrated H_2SO_4 aerosols heated to 80C were focused to < 2mm splats on the litmus target inside SCVC at 22 cm away from the exit nozzle. A high-speed camera records aerosol deposition and splat formation.

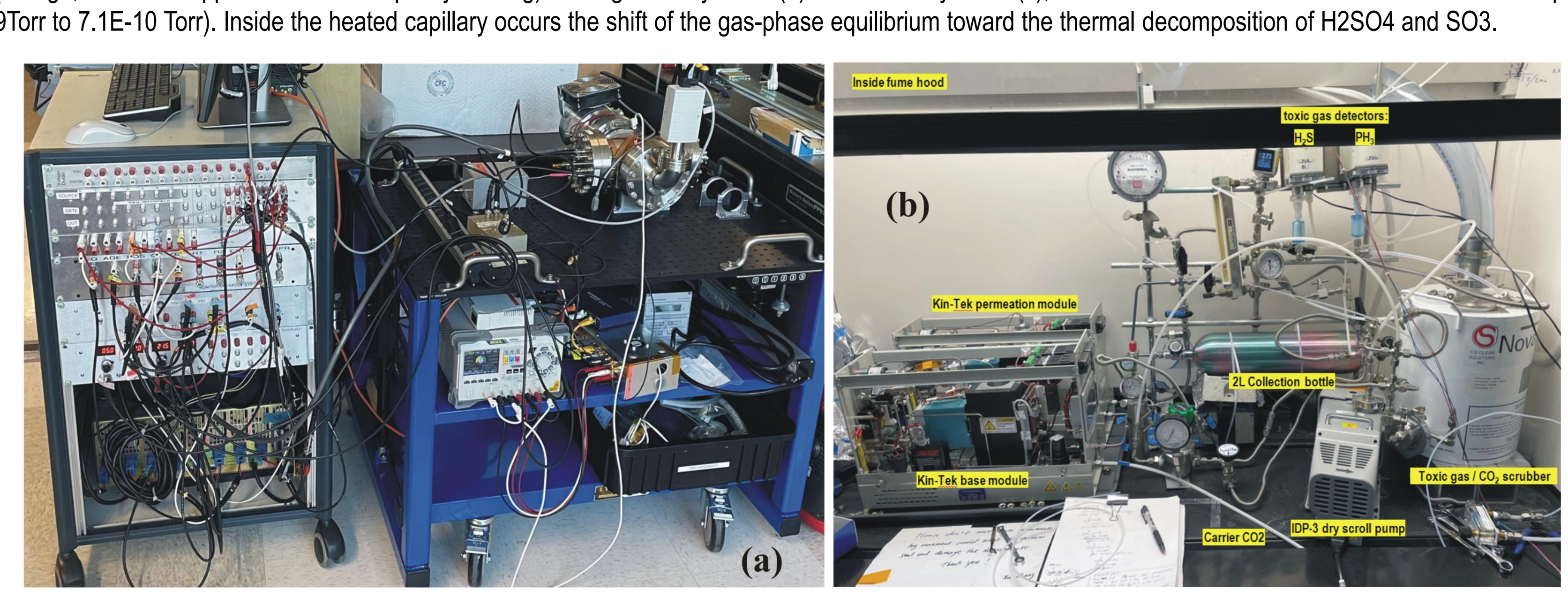

Figure 5. Milestones 5 and 6: (a) Portable TRL4 test bed installed in Schlinger Laboratory 115 at Caltech will be interfaced with Venus Cloud Chamber in the first quarter of FY24 to complete the FY23 Objective 2. (b) We assembled and certified the toxic trace gas calibration station, then used it to prepare two lecture bottles containing PH_3 and H_2S mixtures, otherwise commercially unavailable.

REFERENCES

[1] K. G. Moore II, A. D. Clarke, V. N. Kapustin, et al., "*A comparison of similar aerosol measurements made on the NASA P3-B, DC-8, and NSF C-130 aircraft during TRACE-P and ACE-Asia*", Journal of Geophysical Research 109, D15S15 (2004). doi:10.1029/2003JD003543. **[2]** K.H. Baines, D. Nikolić, J. A. Cutts, et al., "*Investigation of Venus Cloud Aerosol and Gas Composition including Potential Biogenic Materials via an Aerosol-Sampling Instrument Package*", Astrobiology 21(10), 1316-1323 (2021). doi:10.1089/ast.2021.0001 **[3]** J. Simcic, D. Nikolić, A. Belousov, et al.,"*Quadrupole Ion Trap Mass Spectrometer for Ice Giant Atmospheres Exploration*", Space Sci Rev 217, 13 (2021). doi:10.1007/s11214-020-00785-5 **[4]** Y. Chen, L. Xu, T. Humphry, et al., "*Response of the Aerodyne Aerosol Mass Spectrometer to Inorganic Sulfates and Organosulfur Compounds: Applications in Field and Laboratory Measurements*", Environ. Sci. Technol. 53(9), 5176-5186 (2019). doi:10.1021/acs.est.9b00884

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