CLOUD PARTICLE CAPTURE MODELING AND VALIDATION TESTING FOR A VENUS DESCENT PROBE

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Background: Clouds, hazes, and dusts (collectively, *aerosols*) are key drivers of phenomena from short-term weather and climate to long-term planetary evolution. Venus diverged dramatically from Earth in its planetary history in part through the formation of its dense, persistent cloud layers, which – though primarily sulfuric acid – hold much of Venus's remaining available water. The many unknowns of Venus's clouds, including their detailed composition and potential role in habitability, have led to a raft of planned missions for the next decade[1], including DAVINCI, VERITAS, EnVision, Rocket Lab's Morningstar, and Venera-D.

However, aerosols are highly dynamic in space and time, and difficult to study remotely. Large flagship missions with sondes or other platforms capable of aerosol sampling, such as the past Pioneer Venus, Venera, and VeGa missions, are not frequent enough to capture such rapid dynamics; upcoming descent probe concepts such as DAVINCI target overall atmospheric measurements but do not separate out particles directly. The ability to fit aerosol sampling and analysis in a small spacecraft mission envelope would complement these upcoming missions by enabling the data coverage needed to characterize these planetary dynamics for the first time.

Nephele and AERACEPT: Nephele is a SIMPLEx-style small mission concept to measure the composition of the Venus cloud particles. It is designed to operate during the roughly four minutes of a passive descent trajectory through the Venus cloud layers (63 km to 39 km), which is all subsonic (Fig. 1). During this interval, the probe will ingest a stream of aerosols and separate them from the gas stream. The captured aerosols can then be assessed by optical spectroscopy or other similar rapid-analysis techniques to achieve a transect.

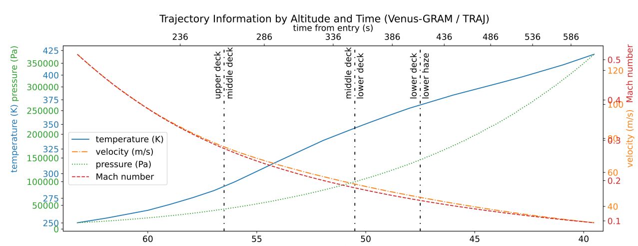

Figure 1. Properties of a notional passive descent trajectory for the Nephele probe at Venus, with the approximate cloud deck boundaries marked for reference.

Nephele implements the AERACEPT (AErosol Rapid Analysis Combined Entry Probe/sonde Technology) design[2]. AERACEPT allows a single self-contained aeroshell to act as a combined entry vehicle, descent probe, and instrumented aerosol sonde. A controlled inlet port embedded directly in the thermal protection material (TPM) at the nose uses the velocity of descent to drive aerosol ingestion, and the internal velocity and pressure ratio to separate the particles from the gas stream via inertia (Fig. 2). This inertial separation leads the particles to form a gradient based on mass (and effective diameter) across the collector, which creates the possibility of discrete analyses for different size classes of aerosol. The former technique is similar to that used in some instrumented thermal material tests, and the latter has extensive heritage in Earth-based airborne science.

To validate AERACEPT for use with Nephele mission, it must be shown that enough sample can be captured for analysis; the sample can be analyzed and data returned within the short operational window; the thermal protection function of the TPM is not compromised; and the residual heat from the hot aeroshell and the kinetic heating associated with aerosol ingestion will not alter the captured sample beyond the limits of the mission science goals. This abstract presents the modeling and first test results for the computational flow dynamics (CFD) and particle tracking modeling and wind tunnel validation test campaign. Thermal modeling and preliminary validation have already been presented[3], and cadence testing with aerosol analog materials is underway[4].

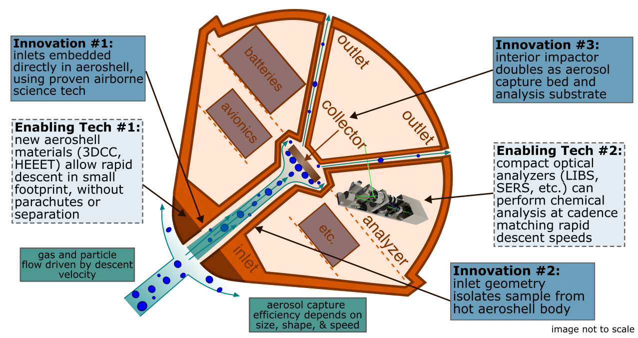

Figure 2. Concept diagram of AERACEPT as implemented in a Pioneer Venus-style aeroshell, with key features marked.

Flow and particle capture modeling: Because of the interdependence between the Nephele probe's thermal and flow behaviors in the hypersonic phase of entry and its ability to achieve its science goals in the subsonic science portion of the descent – as well as the specifics of its internal flow geometry – a pipeline of custom links between normally independent modeling tools was required. The TPM response was modeled using TRAJ → DPLR → BLAYER → PATO, with the wall and kinetic heating in OpenFOAM. A compressible flow solver (rhoPimpleFoam) and a particle tracking solver (denseParticleFoam) were linked to allow prediction of particle capture efficiency binned by size. Lastly, the thermal model conditions were used to predict the alteration experienced by the captured particles. This pipeline is further detailed in [3].

The current model results predict an accumulated sample volume of 24 µL. The equivalent capture efficiency is reasonable for particle diameters >0.5 µm; however, the sample volume is dominated by the sparser large particles (99 % >5 µm). The separation gradient on the collector surface spans 3 cm. As this modeling used a proof-of-concept (non-optimized) AERACEPT inlet geometry, improvement is expected in future design iterations.

Validation testing: A test campaign was designed using NASA Ames Research Center's Fluid Mechanics Laboratory

Table 1. Conditions for each validation test: size of test section, conditions of Venus descent to match, scale (relative to flight) and diameter of test article, test section blockage, and applied vacuum pressure.

	Venus conditions			external flow			internal flow
test section (inch^2)	altitude (km)	Mach (-)	$\frac{P_{\text{in}}}{P_{\text{out}}}$ (-)	scale (-)	model (mm)	blockage (%)	P_{diff} (kPa)
17 × 11	57.4	0.305	0.913	59	118	8.7	8.718
48 × 32	47.0	0.148	0.979	166	332	8.7	1.993

(FML), matching the Mach, Reynolds, and (internal) Stokes numbers of two points along the Nephele Venus descent trajectory. The test article consists of a cylindrical section of the aeroshell nose around the inlet, including the internal flow pathway up to the collector. In addition to the flow generated by the wind tunnel, a vacuum is drawn behind the test article.

Capture substrates installed in the test article collector are removed and imaged after each run using an optical microscope and scanning electron microscope. The images are passed through an automated particle-counting tool to generate size-binned particle counts for five radial distances on the collector, focusing on particles 0.2 µm to 10 µm. These results can then be compared to the model predictions given the wind tunnel measurements, test article geometry, and ambient particle (dust) counts for the intake air.

Test conditions are shown in Table 1. Due to the relatively large difference in conditions between the altitude points, the maximum size limit of the test article scale that could be cost-effectively manufactured, and the blockage limit for each wind tunnel test section, each test point was run in a different tunnel at the same FML facility. The final altitude points (57.4 km and 47 km scale) were chosen to keep the blockage percentage constant between each test.

Both the 59 % and 166 % scale test articles were 3D-printed from nylon and vapor-polished for smoothness. The collector assembly for the smaller article (Fig. 3) consists of: a transparent 40 mm diameter, 0.17 mm thick optical glass substrate; a semiflexible seat (yellow) allowing easy removal and replacement of the glass; and a rigid aluminum backing mount. The larger article collector uses four tiled rectangular substrates instead of a single round piece. The glass substrates are the surface on which the particles are deposited. The substrates are swapped out for each test run and can be imaged after removal without further treatment.

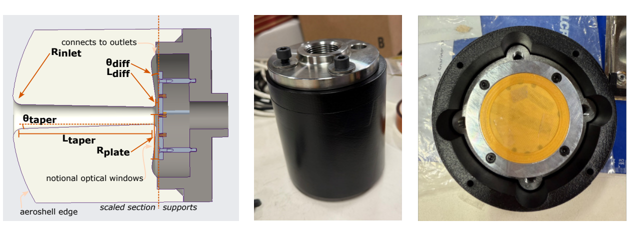

Figure 3. (l) Cutaway schematic of the test article; (c) small-scale test article, inlet facing down; (r) back portion of test article (inlet removed) exposing the collector assembly.

Preliminary results: The test campaign is (as of Febrary 2025) currently under way. Pilot tests showed that coating the substrate with a silicone oil substantially improved retention of particles on the substrate, so to reduce the run time for the full tests, coated substrates were used.

Fig. 4 shows particles captured onto substrates from runs with the smaller article. The left photo shows visible particle deposition on a substrate from a pilot run at a lower flow rate than the test conditions (800 L min^{-1}) for a much longer period of time (45 min). This successfully demonstrates the basic function of the system.

The right two micrographs are from a substrate taken from one of the smaller-scale test runs of 4 min duration. At a relatively coarse 100× magnification, it is apparent that larger-size particles are concentrated towards the center of the plate (middle image compared to right image). This successfully demonstrates basic functionality and at least partial size separation under intended flow conditions.

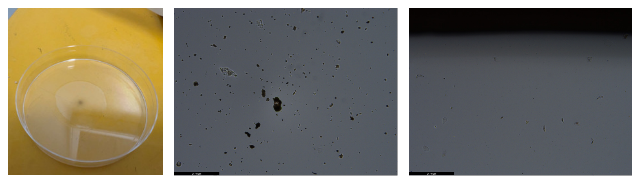

Figure 4. (l) Glass substrate (in a larger plastic petri dish) with visible particle deposition. (c) 100× magnification of particles on the center of a substrate from a small-scale test run. (r) As (c) but at the edge of the substrate.

Future work: The remainder of the test campaign will conclude by March 2025. A series of post-test CFD simulations will be run based on the flow conditions as measured by the facility instrumentation and and ambient aerosol loading as measured with a commercial particle sizer. These simulations will yield predictions of Stokes number vs. capture efficiency for a range of different particles sizes. Those predictions, in turn, will be used to compute the expected particle count per size bin at different radial locations on the capture substrate. Lastly, these predictions will be compared to the actual particle count histograms generated from the image analysis of the test substrates. The expected success criteria are accuracy within 50 % for the particles <2 µm and 10 % for particles ≥2 µm across all flow conditions.

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