WHITE PAPER TO THE NRC DECADAL SURVEY INNER PLANETS SUB–PANEL ON

TECHNOLOGIES FOR FUTURE VENUS EXPLORATION

by

Tibor Balint[1] & James Cutts[1]
(818) 354-1105 & (818) 354-4120
tibor.balint@jpl.nasa.gov & james.a.cutts@jpl.nasa.gov

and

Mark Bullock[2], James Garvin[3], Stephen Gorevan[4], Jeffery Hall[1],
Peter Hughes[3], Gary Hunter[4], Satish Khanna[1], Elizabeth Kolawa[1],
Viktor Kerzhanovich[1], Ethiraj Venkatapathy[5]

[1]Jet Propulsion Laboratory, California Institute of Technology;
[2]Southwest Research Institute; [3]NASA–Goddard Space Flight Center;
[3]Honeybee Robotics; [4]NASA–Glenn Research Center; [5]NASA–Ames Research Center

ABSTRACT

The purpose of this white paper is to provide an overview to the NRC Decadal Survey Inner Planets Sub–Panel on key technologies required for future Venus exploration missions. It covers both heritage technologies and identifies new technologies to enable future missions in all three mission classes. The technologies will focus on mission enabling and enhancing capabilities for in situ missions, because most orbiter related sub–systems are considered heritage technologies. This white paper draws heavily on the recently completed Venus Flagship Mission study that identified key technologies required to implement its Design Reference Mission and other important mission options. The highest priority technologies and capabilities for the Venus Flagship Design Reference mission consist of: surface sample acquisition and handling; mechanical implementation of a rotating pressure vessel; a rugged–terrain landing system; and a large scale environmental test chamber to test these technologies under relevant Venus–like conditions. Other longer–term Venus Flagship Mission options will require additional new capabilities, namely a Venus–specific Radioisotope Power System; active refrigeration, high temperature electronics and advanced thermal insulation. The white paper will also argue for a technology development program, since without it future Venus missions might not be achievable.

The primary purpose of this white paper is to provide relevant information to the NRC Decadal Survey Inner Planets Sub–Panel on Venus exploration related technologies. More detailed information is provided in the attachment, and in other reports including the Venus Flagship Mission study report [Hall et al., 2009]; the Extreme Environments Technologies for Solar System Exploration report [Kolawa et al., 2007]; the VEXAG Community white paper [VEXAG, 2007]; the Chapman Monograph chapter on Venus technologies [Cutts et al., 2007]; and the ESA Cosmic Vision EVE proposal [Chassefière et al., 2008].

Technologies discussed here are either based on existing capabilities, heritage technologies, or new technologies that can enable or enhance future missions. However, it should be noted that currently NASA does not have a dedicated technology development program to mature these capabilities. Sparse development activities at a number of NASA centers, targeting narrow research fields, using limited internal funding, is not sufficient and cannot form a coherent and coordinated program to address these issues. Furthermore, developments within industry are demand driven, where the requirements do not generally match the needs of the space industry. For example, demand for high temperature electronics that can operate on the surface of Venus is beyond the scope or development targets of any industry. Therefore, technology developments for exploring extreme environments — such as Venus — should be lead by NASA under a focused technology development program, in close collaboration with industry and academia to leverage their experiences in these fields. Furthermore, to enable a flagship class Venus mission by the second decade, a technology program to address key areas should start in the near future, since these developments are expected to have relatively long life cycles. Residuals from a well–crafted program could also benefit potential prior Discovery and New Frontiers mission, while cross cutting technologies (e.g., on high temperature mitigation) could be used on other planetary missions as well.

The chosen mission architectures and their mission elements are primary drivers for Venus technologies. These architectures can define large Flagship, medium New Frontiers and small Discovery class missions, with single elements or multiple elements. The recently completed Venus Flagship Mission study recommended a multi–element mission architecture for its Design Reference Mission (DRM), which is based on three science–driven platforms, namely on an orbiter, two cloud–level balloons, and two short–lived landers.

Since all of these platforms have been successfully used in the past for Venus exploration missions, this resulted in a very conservative approach to accomplish the mission's science goals. Consequently, the Venus Flagship DRM benefited from heritage technologies and, in turn, minimized the number of new technologies required for the implementation of this mission. This multi–element architecture also allows designers one to draw conclusions for technology needs for smaller (New Frontiers or Discovery class) missions, which would use similar mission elements. NASA's SSE Roadmap [NASA, 2006] and the VEXAG white paper on science [VEXAG, 2007] identified additional architectures, from the near surface Venus Mobile Explorer, to a Seismic Network, smaller New Frontiers class VISE [NRC, 2003] and Discovery class balloon missions [Balint & Baines, 2009], ultimately leading to a Venus Surface Sample Return mission.

Discovery and New Frontiers missions are not expected to include significant amount of new technologies and could be designed without them, although, if made available as part of a technology development program for a future flagship mission, they could benefit from it. For a flagship class mission, the Venus Flagship Mission study identified such broad–use key technologies that would require extensive development. For example, a sample acquisition and processing system for multiple samples that could operate under Venus surface conditions. The high temperature motors and actuators developed for sample acquisition system can be also used for the Venus Flagship Mission's pressure vessel rotation mechanism. The rugged terrain landing system needs to be developed in order to reliably access Tessera and other rugged areas on Venus. The pressure vessel, passive thermal control, and insulation for the short–lived lander (to be designed for 5 hrs) as well as technologies for mid–altitude balloons are considered to be mature. The capability to test and validate scientific measurements and to assess the survivability of all exposed sensors/instruments and lander components in Venus–like environment is critical to the mission success. This testing capability is mostly not available and needs to be developed.

Beside the Venus Flagship Mission architecture, other mission concepts were also assessed over the past few years. These included aerial mobility platforms capable of operating at distinct altitudes (e.g., near surface, mid–altitude and cloud level); long–lived landers; descent probes and drop sondes for atmospheric research; as well as a multi–element architecture in the form of a long–lived seismic network. Therefore, technologies developed to enable the Venus Flagship Mission could provide programmatic flexibility and enable these concepts if the flagship mission architecture is changed or if these concepts are flown later on.

The near–surface aerial mobility platforms will require the development and testing of materials for the lightweight pressure vessel as well as for a high temperature balloon system, likely in the form of metallic bellows. A suitable, low mass refrigeration system is critical for this mission concept. High and medium temperature electronics could provide significant benefits by reducing the temperature lift requirements on the refrigeration system.

Long–lived landers require similar critical technologies as low altitude balloons, but include also design solutions for safe landing. Long life (months or longer) will require new designs for pressure vessel potentially using new materials (e.g., beryllium or honeycomb structure based light weight designs). These static landers would also require a long–lived power source, such as a Venus–specific RPS coupled with an active refrigeration system. In addition, landers will require mechanical systems for robotic arms with an integrated high temperature sample acquisition system in order to acquire samples at different locations around the lander. Development of high, or even medium, temperature electronics and instruments is also crucial for reducing the refrigeration requirements.

An alternate form of long–lived lander is a seismic and meteorological station. A number of such stations can be envisioned to form a integrated network. Such stations may operate in Venus environment for extended periods of time with or without refrigeration depending on the availability of 460°C sensors and avionics. Although detailed performance requirements for these components will depend on the details of the selected architectures as well as on the science data acquisition scenarios, the general list of high temperature technologies will include high temperature sensors, power generation and storage, electronics for data acquisition and storage, power distribution and telecom. Maturing these technologies to the level where they can be used for Venus missions will require detailed planning and a significant long–term investment in technology development.

The summary table below lists the technologies that enable or enhance future Venus exploration mission. High priority technologies for the Venus Flagship Mission are highlighted in bold in a grayed cell, while new capabilities and enhancements to the VDRM are italicized in a lighter gray cell. Further information can be found in the references, and in the Appendix, which is posted with this white paper on the VEXAG website (**http://www.lpi.usra.edu/vexag/**)

Capability	Current State of the Art (TRL level)	Technology development needs to enable Venus missions	Benefits to future Venus missions
Pressure control	TRL 4–9 Titanium pressure vessel is space qualified; New lightweight materials need development.	Advanced materials (e.g., beryllium, honeycomb structures) could reduce structural mass.	Mass saving translates to higher payload mass fraction for the same entry mass.
Thermal control (passive)	TRL 4–9 Aerogels, MLI, PCM are space qualified, but not for high g–load entries and high temperatures.	High performance thermal insulation for Venus environment is required for mission lifetimes beyond Venera demonstrated lifetimes.	Improvements in passive thermal control could extend mission lifetime from ~2 hours to 5 hours or maybe more. (Beyond that active refrigeration and a power source is required.)
Surface sample acquisition and handling (VDRM)	TRL 2–3 Heritage Soviet–derived systems are not available off the shelf, but they demonstrate a feasible approach.	Surface sample acquisition system at high temperature and pressure conditions; Vacuum–driven sample transfer is demonstrated on Venera, but requires development for NASA.	Drilling, sample collection and sample handling are enabling for the Venus Flagship Mission.
Rotating pressure vessel (VDRM)	TRL 2 Rotating pressure vessel concept is powerful but technologically immature.	Full scale design and testing of a rotating pressure vessel with a driver motor and mounted sampling system.	It minimizes the external components, such as drill arms, actuators, motors, sampling systems; and the heat leakage from the outside through the number of windows required for panoramic imaging.
Rugged terrain landing (VDRM)	TRL 2 Russian landers provide proof of concept, however, these landed at benign surfaces and used a drag plate instead of parachutes.	Design and test a landing system that can account for a large variety of unknown landing hazards using parachutes.	Tessera and other rugged areas on Venus cannot be reliably accessed unless a properly engineered rugged terrain landing system is developed and tested.
Power storage	TRL 4 Demonstrated LiAl–FeS2, Na–S, and Na–metal chloride secondary batteries with specific energy in the 100–200 Wh/kg range; Short lived missions could use high TRL primary batteries.	Adapt high temperature cell and battery designs for space applications; Address stability of seals and terminals; Minimize the corrosion of current collectors at high temperatures; Optimize the electrolyte composition to improve performance and reliability.	High temperature batteries operating at Venus surface temperatures would make it possible to keep the power storage outside of the pressure vessel, thus reducing volume and thermal requirements for the pressure vessel.
Instruments (in situ) for the Venus Flagship Mission	TRL 2–9 Descent probe instrument heritage from Pioneer–Venus; New in situ contact instrument need development.	Several Venus Flagship Mission instruments, e.g., heat flux plate, XRD/XRF are at medium TRL; High–T seismometry and high–T meteorology are at low TRL; G–load tolerance during atmospheric entry should also be addressed.	In situ instruments are key drivers for Venus missions and are required for mission success.

Capability	Current State of the Art (TRL level)	Technology development needs to enable Venus missions	Benefits to future Venus missions
Power generation (new capabilities)	TRL 4 Demonstrated single Stirling convertor operation for 300 hours with a 850°C hot–side temperature and 90°C cold–side, 38% efficiency and 88 W power output with heat input equivalent to 1 GPHS module.	Cold side temperature must be raised from 90°C to 480°C with high conversion efficiency preserved (e.g., maintaining ΔT through increased hot end temperature, which would required materials or design development); Material testing, system development and validation for reliable operation in Venus surface environment.	Required for long life operation; Venus specific RPS with active cooling could enable long lived missions, operating for months; Low mass version could power near surface aerial mobility systems; It could power long lived seismometers and meteorology stations on the surface (117 days minimum).
Active refrigeration (new capabilities)	TRL 4 Cryocoolers are space qualified, but high temperature operation is not demonstrated at the system level.	Adopt Stirling conversion based coolers for Venus surface conditions; High efficiency duplex Stirling system must be produced that integrates the heat engine and refrigerator functions into a high efficiency and high reliability device; Refrigeration system should be coupled with the power source; Low mass and low vibration is desirable.	Almost every long–duration (~25 hrs+) in situ platform will require some amount of refrigeration to survive; Focus should be on radioisotope–based duplex systems that produce both refrigeration and electrical power; Low mass version would allow for near surface aerial mobility (metallic bellows); Low vibration version would enable a seismic network (on multiple landers) (117 days minimum); Extended mission life allows humans in the loop.
Advanced passive thermal control (enhancement to VDRM)	TRL 3–9 Venera and PV era insulation and phase change materials are mostly available.	Alternate insulation and phase change material technologies are needed to increase lander lifetimes beyond 2–5 hour operation.	Achievement of 12 to 24 hour lander lifetimes would enable humans–in–the–loop operation by ground controllers; Improved thermal insulation will decrease refrigeration requirements for truly long–term lander missions.
Testing facility (VDRM)	TRL 2-6 Two small Venus environment test chambers are operational at JPL; A small Venus test chamber setup is underway at GSFC; Proof of concept from Russian test chamber (decommissioned).	Large test chamber doesn't exist; Develop large Venus test chamber for full scale in situ elements (probe/lander) testing; Simulate transient atmospheric conditions; composition.	The 12.5 km anomaly on the Pioneer–Venus mission demonstrates the critical need for an environmental chamber using relevant atmospheric composition and conditions; It can test spacecraft components; validate and calibrate science instruments; test operating scenarios under realistic conditions.

Capability	Current State of the Art (TRL level)	Technology development needs to enable Venus missions	Benefits to future Venus missions
High–T and Medium–T components, sensors, and electronics (new capabilities)	TRL 2–4 Geophones could operate up to 260°C; High-temperature pressure, temperature, anemometers used on Venera/VEGA and Pioneer–Venus; Silicon based high–T components are designed for up to 350°C for the automotive and oil drilling industry; Limited number of components and integrated circuit capability demonstrated for SiC at 500°C; Limited electronics packaging at 500°C; Data storage, ADC, power converters, and other needed components never demonstrated.	High–temperature MEMS technology for seismometers could operate at surface temperatures; SiC and GaN high temperature sensors and electronics require development to operate at surface temperatures; Development of data acquisition, processing and storage capability, and packaging; Development of high–T power management; Demonstration of reliability and long life.	Long life on the surface is desirable (especially, for meteorology, seismometry); Sensors, actuators, instruments directly interfacing with the environment cannot be sufficiently protected, and therefore, high temperature components can enable operations and science measurements (e.g., long lived meteorology, seismometry) that otherwise cannot be achieved; High temperature data processing and storage, and power electronics results in a drastic reduction in refrigeration requirements, even at moderately high temperatures (>250°C); Low power dissipation at 300°C and long life reduces environmental tolerance requirements for components.
Upper atmosphere Balloons	TRL 5–7 Russian VEGA balloons successfully operated for 48 hrs over 20 year ago; Large super–pressure balloon have been built and tested at JPL and at CNES; Development for a mid–altitude balloon is underway at JAXA.	Cloud level balloons are considered mature, but further development, testing, verification and validation are required to address lifetime and reliability issues for a 30–day mission; Materials must tolerate high temperatures, corrosive environment (sulfuric acid droplets in clouds).	The Venus Flagship Mission balloons are designed for 30–days operation; An ASRG powered balloon mission could operate for months, circumnavigating the planet and continuously measure dynamics and atmospheric composition.
Near surface balloons	TRL 2–3 Metallic bellows proof–of–concept was built at JPL and tested at high temperatures.	Development is needed to build and test a metallic bellows system and test it under Venus surface pressure and temperature conditions; Near surface operation must address altitude change and surface access.	A near surface mobile platform could traverse hundreds of kilometers over a 90–day mission, image the surface at high resolution and periodically access the surface for sampling.
Descent probes and sondes	TRL 2–9 Pioneer–Venus probe heritage for large probes Microprobes have been designed but not yet tested.	Develop small drop sondes that could be released from a balloon platform (also work as ballast).	Drop sondes can enhance science by providing vertical slice measurements to complement balloon constant altitude measurements of the atmosphere.

Capability	Current State of the Art (TRL level)	Technology development needs to enable Venus missions	Benefits to future Venus missions
High–T Telecom	TRL 2 Demonstrated 2 GHz operation at 275°C using SiC; SiC and vacuum tube based oscillator demonstrated at ~500°C.	Development efforts should address SiC based RF components for transmitters; Miniaturized vacuum tube technology for power amplifiers; SiC based RF components for transmitters.	High temperature telecom on the surface would drastically reduce cooling requirements; It would enable long lifetime (117 days minimum); High data rate (~4.5 kbps) would support seismic operations; However, high temperature data storage at Venus surface temperature may represent a significant technology challenge.
Orbiter instruments and telecom	TRL 3–9 Magellan, Venus Express, Pioneer–Venus heritage; Venus Flagship Mission InSAR needs development.	Development is required for InSAR; passive infrared and millimeter spectroscopic techniques; and cloud LIDAR	InSAR is a key instruments on the Venus Flagship Mission; Ultra–fine resolution radar mapping and cloud LIDAR could provide high resolution science data on the surface and clouds, and highly desirable by science.
Atmospheric entry	TRL 5-9 Carbon-Phenolic (CP) used on Pioneer–Venus and Galileo probe; Provides heritage for use in steep entry flight path angle (EFPA) missions; Special rayon needed to make heritage CP; This rayon is out of production; Current arc jet capabilities are limited; Mars and Titan TPS, lower density, could be useful for lower EFPA.	1. Re-establish test capabilities; 2. Periodic verification of Industry capability to remanufacture heritage CP; 3. Establish alternate to heritage CP TPS, since heritage rayon is not made anywhere, anymore and current supply in hand is limited; 4. Assessment of lower density TPS be performed for shallow EFPA missions.	TPS is essential and enabler; High entry flight path angle (EFPA) entries result in high heat flux, pressure and g-loads; Limited supply of heritage CP enables unrestricted access to the planet; Lower density TPS can provide significant mass savings, but constrain the EFPA and thus the mission architecture.
Autonomy	TRL 4–6 Autonomous operation have been tested in previous missions (e.g., Pioneer–Venus probes), but at a lower complexity than required for a Venus Flagship Mission.	Develop and test reliable autonomous operation for a Venus surface mission, including control of the rotating pressure vessel; drill site selection; sample acquisition; instrument operations; reliable telecom.	Short lived missions (up to 5 hours) does not support humans in the loop; Autonomous operation is required for all science measurements and subsystem control.
Cross cutting technologies	See above	TPS; pressure vessel materials; passive thermal control (insulation; phase change materials).	These technologies can benefit a number of planetary missions, e.g., probes to Venus and deep probes to the Giant Planets.

Based on the information presented above, VEXAG recommends investments in key technologies to enable future Venus missions, including the development of a sample acquisition and handling system; a rotating pressure vessel; and a rugged terrain landing system. Building a test facility that could simulate Venus conditions between the surface and the cloud level is also recommended as

a high priority technology development item. Such a test chamber would be instrumental in the development and testing of new instruments and subsystems to be used on future Venus missions. A Venus Flagship Mission could be further enhanced by longer operating lifetimes on the surface. For this, development of a Venus specific Radioisotope Power System, coupled with active cooling, would be necessary. Development of high temperature tolerant components (e.g., sensors, actuators, and electronics) should be also considered, since these could provide new capabilities for proposed future Venus missions.

REFERENCES

Balint, T.S., Baines, K.H., 2009. "Mission Architecture Trades for an ASRG–Enabled Discovery–Class Balloon Mission", Poster: P8.01, ESLAB, International Conference on Comparative Planetology: Venus–Earth–Mars, ESA/ESTEC, Noordwijk, The Netherlands, May 11–15

Chassefière, E., Korablev, O., Imamura, T., Baines, K. H., Wilson, C.F., Titov, D.V., Aplin, K.L., Balint, T., Blamont, J.E., Cochrane, C.G., Ferencz, Cs., Ferri, F., Gerasimov, M., Leitner, J.J., Lopez–Moreno, J., Marty, B., Martynov, M., Pogrebenko, S., Rodin, A., Whiteway, J.A., Zasova, L.V., Michaud, J., Bertrand, R., Charbonnier, J.–M., Carbonne, D., Raizonville, P., and the EVE team, 2008. "European Venus Explorer (EVE): an in–situ mission to Venus", Experimental Astronomy, ESA Cosmic Vision – CV07 special issue, Springer Netherlands, ISSN 0922–6435 (Print) 1572–9508 (Online); DOI 10.1007/s10686–008–9093–x

Cutts, J.A., Balint, T.S., Chassefiere, E., Kolawa, E.A., 2007. "Chapter 13: Technology Perspectives in the Future Exploration of Venus", Chapman Monograph – Exploring Venus as a Terrestrial Planet, Publisher: AGU, Editors: L.W. Esposito, E.R. Stofan, R.E. Cravens, ISBN 978–0–87590–441–2

Hall, J.L., Bullock, M., Senske, D.A., Cutts, J.A., Grammie, R., 2009. "Venus Flagship Mission Study: Report of the Venus Science and Technology Definition Team", National Aeronautics and Space Administration, Jet Propulsion Laboratory, California Institute of Technology, Task Order NM0710851, April 17

Kolawa, E., Balint, T.S., Birur, G. Brandon, E., Del Castillo, L., Hall, J., Johnson, M., Kirschman, R., Manvi, R., Mojarradi, M., Moussessian, A., Patel, J., Pauken, M., Peterson, C., Whitacre, J., Martinez, E., Venkapathy, E., Newdeck, P., Okojie R., 2007. "Extreme Environment Technologies for Future Space Science Missions", Technical Report JPL D–32832, National Aeronautical and Space Administration, Washington, D.C., Sept. 19

NRC (National Research Council), 2003. "New frontiers in the solar system: An integrated exploration strategy." The National Academy Press, Washington, DC. (2003).

NASA SMD PSD – SSE Roadmap Team, 2006. "Solar System Exploration – Solar System Exploration Roadmap for NASA's Science Mission Directorate", NASA Science Missions Directorate, Planetary Science Division, Report Number: JPL–D–35618, Downloadable from: solarsystem.nasa.gov, September 15

VEXAG (Ed.) 2007. "Venus scientific goals, objectives, investigations, and priorities", Venus Exploration Analysis Group, Website: http://www.lpi.usra.edu/vexag/