

Extreme Environment Simulation - Current and New Capabilities to Simulate Venus and other Planetary Bodies

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Abstract—Science, technology, and planetary mission communities have a growing interest in components and systems that are capable of working in extreme (high) temperature and pressure conditions. Terrestrial applications range from scientific research, aerospace, defense, automotive systems, energy storage and power distribution, deep mining and others. As the target environments get increasingly extreme, capabilities to develop and test the sensors and systems designed to operate in such environments will be required. An application of particular importance to the planetary science community is the ability for a robotic lander to survive on the Venus surface where pressures are nearly 100 times that of Earth and temperatures approach 500C. The scientific importance and relevance of Venus missions are stated in the current Planetary Decadal Survey. Further, several missions to Venus were proposed in the most recent Discovery call. Despite this interest, the ability to accurately simulate Venus conditions at a scale that can test and validate instruments and spacecraft systems and accurately simulate the Venus atmosphere has been lacking.

This paper discusses and compares the capabilities that are known to exist within and outside the United States to simulate the extreme environmental conditions found in terrestrial or planetary surfaces including the Venus atmosphere and surface. The paper then focuses on discussing the recent additional capability found in the NASA Glenn Extreme Environment Rig (GEER). The GEER, located at the NASA Glenn Research Center in Cleveland, Ohio, is designed to simulate not only the temperature and pressure extremes described, but can also accurately reproduce the atmospheric compositions of bodies in the solar system including those with acidic and hazardous elements. GEER capabilities and characteristics are described along with operational considerations relevant to potential users. The paper presents initial operating results and concludes with a sampling of investigations or tests that have been requested or expected.

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1. INTRODUCTION

Science, technology, and planetary mission communities have a growing interest in components and systems that are capable of working in extreme (high) temperature and pressure conditions. Terrestrial applications range from scientific research, aerospace, defense, automotive systems, energy storage and power distribution, deep mining and others. As the target environments get increasingly extreme, capabilities to develop and test the sensors and systems designed to operate in such environments will be required. An application of particular importance to the planetary science community is the ability for a robotic lander to survive on the Venus surface where pressures are nearly 100 times as that of Earth and temperatures approach 500C. Refer to Figure 1 for a snapshot of Venus temperature and structure as a function of altitude. Figures 2-5 shows expected temperature and pressure profiles for Venus and temperature profile for Jupiter.

The scientific importance and relevance of Venus missions are stated in the current Planetary Decadal Survey. [1] Further, several missions to Venus were proposed in the most recent Discovery call. Despite this interest, the ability to accurately simulate Venus conditions at a scale that can test and validate instruments and spacecraft systems via accurate simulation of the Venus atmosphere has been lacking.

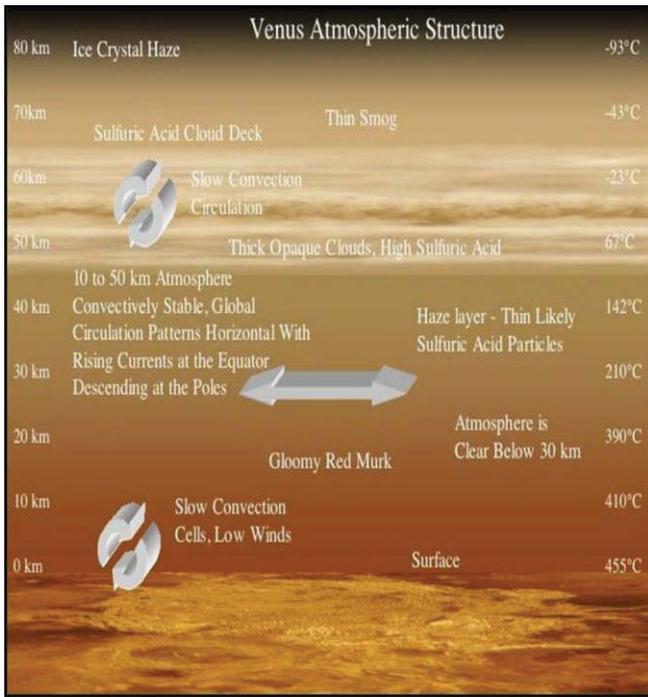


Figure 1 – Venus Structure and Temperature versus Altitude [2].

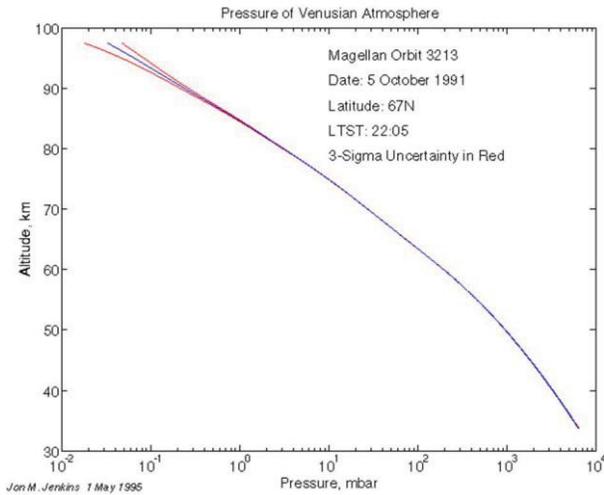


Figure 2 – Pressure Profile of Venus Atmosphere [3]

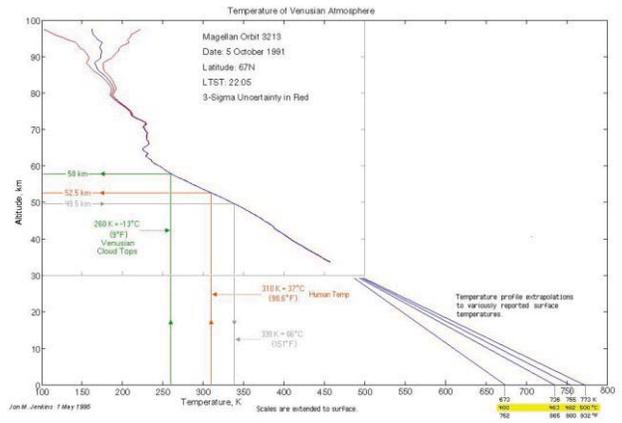


Figure 3 – Temperature Profile of Venus Atmosphere [4]

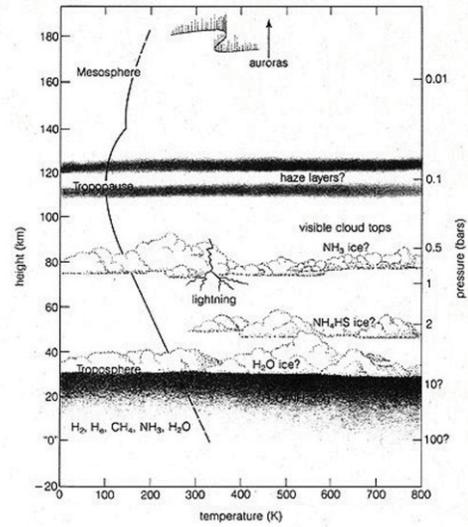


Figure 4 – Temperature Profile and Potential Composition of Jupiter [5]

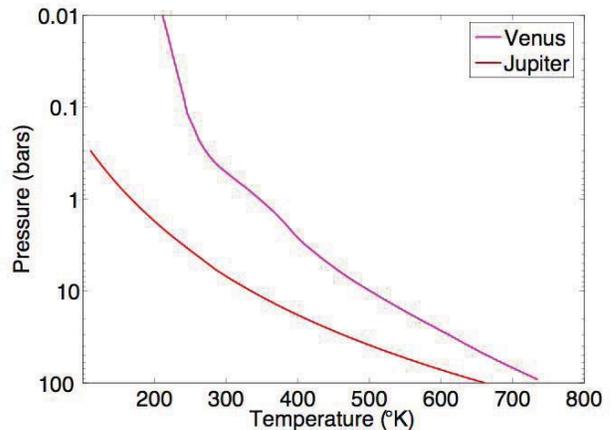


Figure 5 – Expected Temperature versus Pressure Profiles for Venus and Jupiter [6]

This paper discusses and compares the capabilities that are known to exist within and outside the United States to simulate the extreme environmental conditions found in terrestrial or planetary surfaces including the Venus atmosphere and surface. The paper then focuses on discussing the recent additional capability found in the NASA Glenn Extreme Environment Rig (GEER). The GEER, located at the NASA Glenn Research Center in Cleveland, Ohio, is designed to simulate not only the temperature and pressure extremes described but can also accurately reproduce the atmospheric compositions of bodies in the solar system including those with acidic and hazardous elements. GEER capabilities and characteristics are described along with operational considerations relevant to potential users. The paper presents initial operating results and concludes with a sampling of investigations or tests that have been requested or expected.

2. SUMMARY OF CURRENT AND NEAR-TERM CAPABILITIES

Current Capabilities

The ability to simulate the extreme conditions that exist on planetary bodies in our solar system is of interest to the scientists and engineers that study them and develop missions to investigate them. One community in particular, the Venus Exploration Analysis Group (VeXAG), is keenly interested in the capability to simulate the conditions found in the Venus atmosphere and surface. Understanding the composition and processes on that planet is of high scientific value and has significant implications for us here on Earth. Recently the VeXAG, initiated a survey of laboratories and facilities that could currently, or in the near future, simulate both high temperature and high pressure conditions approaches those of the Venus surface with at least the basic compositional elements of the Venus atmosphere, namely Carbon Dioxide (CO₂) and Nitrogen (N₂).

The survey found that there are nine known facilities that can meet some aspects of the chemistry, pressure, and temperatures conditions desired. These are listed by order of size and location in Table 1.

Table 1. Extreme Environment Facilities to Simulate Some Venus-like conditions.

Georgia Institute of Technology	1.05 ft ³ , 100 bar, 343C, CO ₂ , N ₂ Not publically available
Jet Propulsion Laboratory (JPL)	<ul style="list-style-type: none"> • 0.5 ft³, 103 bar, 500C, CO₂, N₂, H₂O, SO₂, CO, He, Ne, Ar – Materials • 0.45 ft³, 103 bar, 500C, CO₂, N₂, H₂O, SO₂, CO, He, Ne, Ar – Optical access • (Requires investment prior to re-start) • 0.0009 ft³, 1000 bar, 1000C, CO₂, N₂, SO₂– Weathering
Massachusetts Institute of Technology (MIT)	<ul style="list-style-type: none"> • 0.001ft³, 200 bar, 700C, CO₂ • 0.03ft³, 200 bar, 700C, CO₂ • Not publically available
NASA Goddard Space Flight Center (GSFC)	0.13 ft ³ , 95.6 bar, 500C, CO ₂ , N ₂ , SO ₂ – Materials
Los Alamos Nat'l Laboratory (LANL)	0.005 ft ³ , 10,000 bar, 150C, CO ₂ Not publically available
University of Wisconsin	0.008 ft ³ , 270 bar, 650C, CO ₂ Not publically available
Other	Other high temperature and pressure simulation capabilities exist, such as combustion chambers, but these are for specialized use and not practical for the purposes discussed in this paper

Figures 6-8 depict some of the facilities in the survey.



Figure 6 – The Georgia Institute of Technology simulation chamber [2].

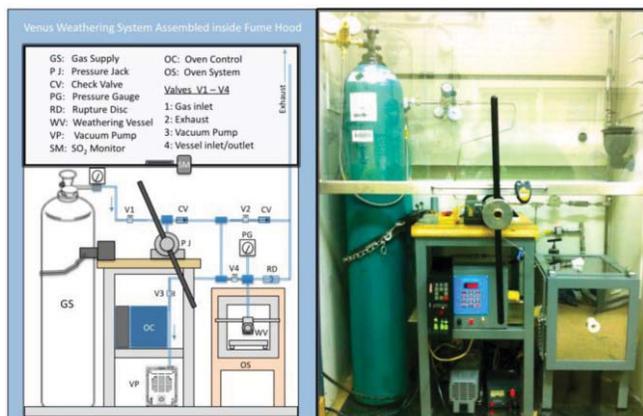
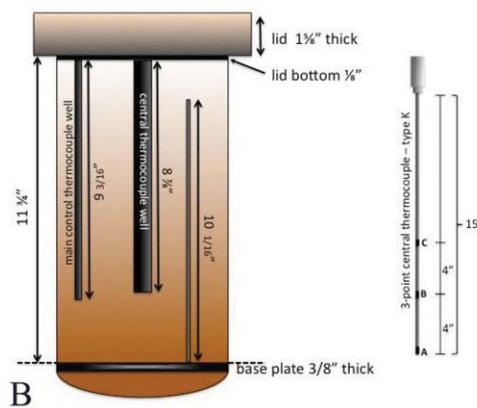


Figure 7 – The three JPL rigs: Venus Materials, Raman and Libs test bed, and Venus weathering, respectively [2].



A



B

Figure 8 – Venus simulation chamber (VICI) at GSFC: (A) Chamber image, (B) Interior schematic.

This chamber is appropriate for smaller volume component testing under Venus conditions. Material studies are also possible. This setup is ideal for shorter duration testing, i.e., a few hours to several days. The chamber can be reconfigured to accommodate real-time monitoring of tested items via a variety of feedthroughs.

A cursory look at the facilities capabilities, as shown in Table 1, results in several important observations:

- (1) Even the largest chamber is just over 1 ft³ in internal volume. In fact, only 4 chambers on the list are larger than 0.1 ft³. While this is ample for some chemistry or

other small scale experiments, it is inadequate for development testing or qualification of most flight like instruments of spacecraft systems. In other words, as of the survey, March 2012, there was no currently operational capability to do full scale tests of most instruments and spacecraft systems that may be sent to explore the Venus surface or perhaps its atmosphere.

- (2) Only seven (7) facilities achieve both Venus surface temperatures and pressures (the largest being 0.5ft³).
- (3) Only the JPL and GSFC (4) facilities can handle more than the basic atmospheric elements of CO₂ and N₂.
- (4) None of the facilities operating as of the survey could handle all the known elements in the Venus atmosphere such as HF, HCl, H₂S, H₂SO₄ and others that may have significant bearing on the current Venus environment.

Near Term Capabilities

The fact that prior capabilities could not address the need for a chamber large enough to accommodate testing of flight like instruments and space craft systems and that none of the prior facilities could accurately simulate the compositional structure of the Venus atmosphere, or that of the other planetary bodies, resulted in an effort to develop the necessary capability at NASA's Glenn Research Center (GRC).

It is expected that new and powerful capabilities will exist to accurately simulate extreme temperature, pressure and chemical conditions, even those found on the Venus surface, by the time this paper is presented. The details of the capability are discussed in the next section.

3. NEW CAPABILITIES WITH GEER

The development of the Glenn Extreme Environment Rig (GEER) at NASA's GRC began with defining requirements. The capability development team contacted science and engineering experts to capture the known or expected conditions, driven mainly by Venus atmosphere and surface conditions, and ascertain the critical factors to enable accurate simulation. Based on the work, led by Dr. Rodger Dyson from NASA's GRC, the following key goals were derived for the desired facility:

- (1) The initial chamber will be large enough to contain a notional probe, which was determined to be on the order of 25 ft³.
- (2) The chamber will be able to achieve both Venus surface temperatures (~500C) and pressures (~100 bar) simultaneously.
- (3) The supporting infrastructure; such as the chemical storage, mixing, pressurization, data acquisition, and other supporting systems will be sized to accommodate multiple chambers or significantly larger ones. The

supporting infrastructure was sized to handle a chamber cylindrical chamber that would be at least 7-ft in diameter.

- (4) The atmospheric composition will be controlled to part-per-billion accuracy.
- (5) The supporting infrastructure will be designed to, as much as practically possible, simulate the changing composition and temperature/pressure growth that may be experienced by a notional probe dropping by parachute.
- (6) Be flexible in design to enable future uses to simulate other extreme environments such as complex composition at cryogenic temperatures.

The basic characteristics/features of the main chamber and supporting infrastructure include an internal volume for the chamber of over 28ft³. The internal dimensions for the test chamber are 3ft diameter, cylindrical, and 4ft long. The chamber wall is made of 2 inch thick 306 stainless steel with end plates of the same material. The bolted end is 9.5 inch thick and the welded end is 6.75 inch thick. The chamber is completely lined with Inconel 625 to minimize the effects of the harsh chemicals that are expected to be used. The plumbing for the gas streams are made of 304 stainless steel except in high temperature regions adjacent to the vessel, where the tubing material changes to Inconel 625 and the fittings change to Monel. Provisions exist for two optical ports (4" in diameter) at opposing ends of the chamber. Four access ports exist in addition to those dedicated for optical viewing and the heater feeds. These are visible in Figure 9 at the 10, 12 and 2 o'clock positions. The Center ports at each end are the ones reserved for the optical windows. Figure 10 shows the inside of the chamber and the internal heaters and insulation. A small portion of the scrubber is visible to the left of the chamber.

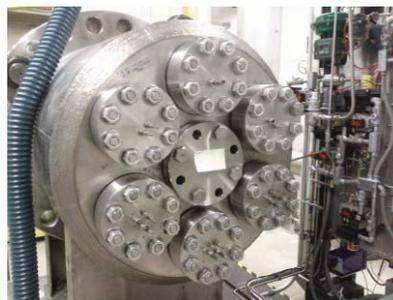


Figure 9 – GRC GEER chamber showing some of the access ports. [2].



Figure 10 – GRC GEER chamber showing heaters and insulation.

The gas mixing system consists of nine (9) separate gas streams that are accurately mixed to desired proportions using thermal mass flow controllers and then pressurized and fed into the chamber. The gases are stored in bottles in monitored and controlled safety cabinets. Each gas bottle can contain pre-mixed set of gases and therefore virtually any planetary atmosphere composition can be simulated within the limits of the containing materials. A Fourier Transform Infrared Spectroscopy (FTIR) spectrometer will measure the chamber chemistry and provide feedback, allowing the chamber composition to be modified as necessary. Figure 11 implies some of the complexities of the Venus atmosphere and the need for an elaborate system to accurately simulate it. Figure 12 depicts the gas analyzer and valve station

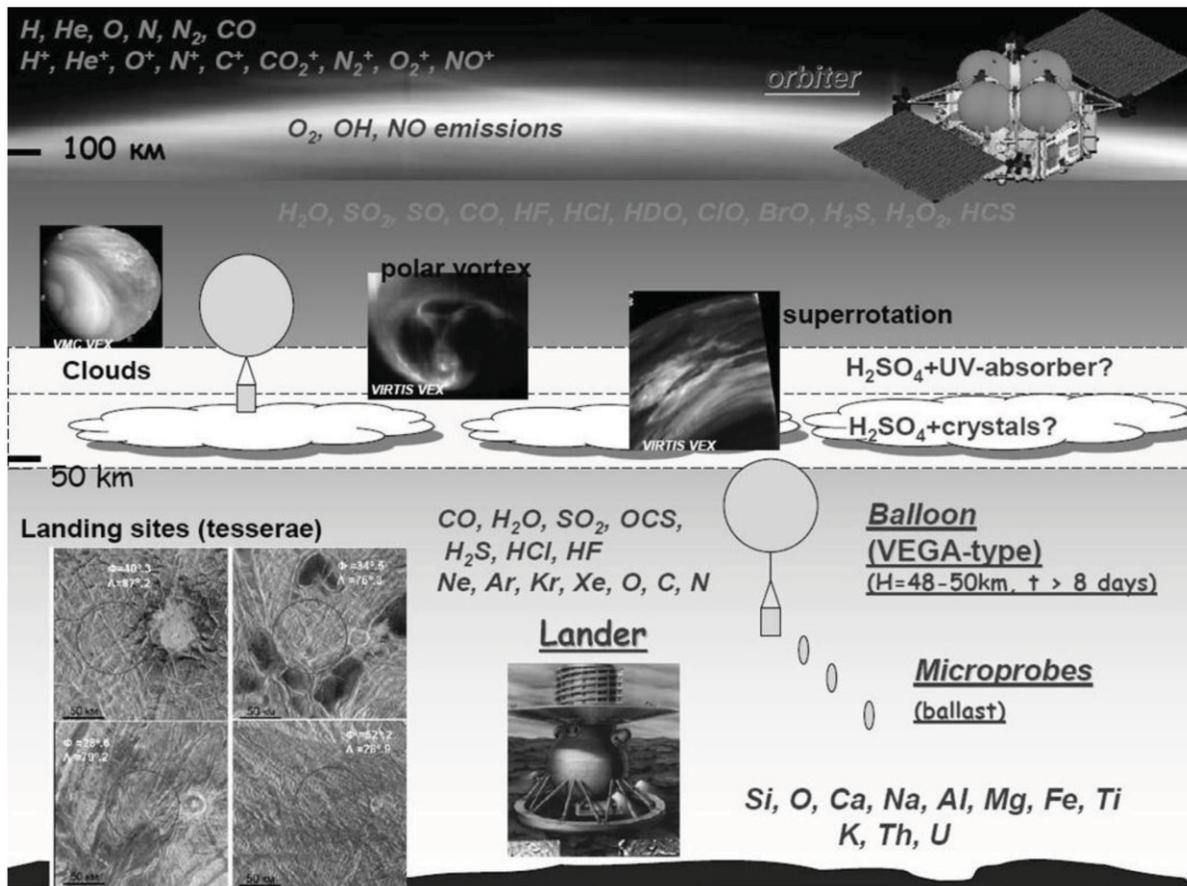


Figure 11 – Complex Venus Atmosphere



Figure 12 – GRC GEER Gas analyzer and a Valve station.

A scrubber system has been designed and installed for future use should it become necessary based on gas compositions and concentrations in order to meet current EPA, OSHA and NASA guidelines.

Operations are conducted from a remote station in another part of the building (Figure 13). All aspects of the operations can be remotely implemented so that it is not necessary for operators to come in contact with the chamber during operations, even though it would be safe to do so. The room with the chamber is designed and built for hazardous operations and is inherently suited to safely handle anomalous events, should they occur.

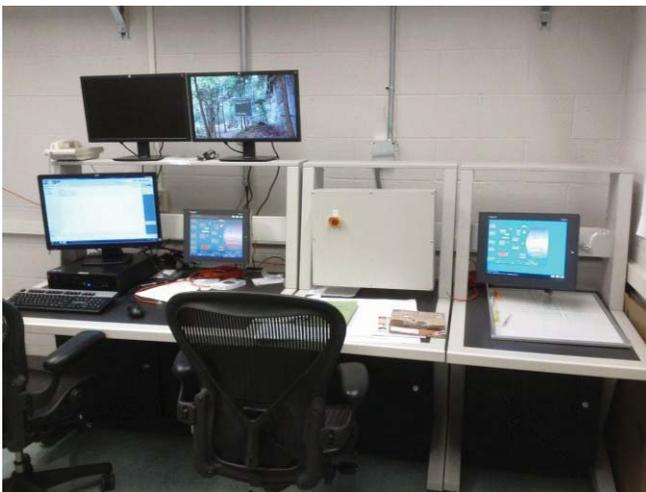


Figure 13 – GRC GEER Control Station.

A simplistic description of the operation is as follows:

- 1) System starts at ambient temperature

- 2) Component gasses are blended using gas mixer
- 3) Test chamber is filled with desired gas mixture up to 500 psi (at ambient temperature) for the desired end state chemistry
- 4) Heat is applied and controlled to bring system to steady-state operating point (1350 psi, 500C)
- 5) After testing chamber and plumbing are vented and purged

Operation Considerations

The operational considerations for potential users are strongly driven by the nature of the testing required. There are several factors that will need to be addressed for every test. Some of these include:

- 1) Test set-up, duration, and tear down
- 2) Access to the site before, during and after the actual test operations
- 3) Requirements for the facility, such as number of test simulations, duration at each operating point, amount and nature of data
- 4) The complexity of the test, For example will there need to be active control of an article in the chamber real time. Will it be just a “cook and look” test?
- 5) The need for direct viewing of the test article or for optical measurements
- 6) Instrumentation and control requirements for the test hardware (e.g. number of data lines, sample rates, or the need to control a mechanism).

Each test will be worked on a case by case basis. It is expected that there will be opportunities for “cost-share” testing. That is; a primary test is planned for the chamber but it will not consume all the volume or other resources of the facility and can tolerate additional hardware within the chamber. This may allow taking advantage of the time at an extreme condition while sharing cost and chamber time.

The facility is currently going through check-out and start-up processes. A battery of tests will be implemented prior to declaring operational readiness and several of them will reach both 100 bar and 500C. These tests are scheduled to run for several months to allow characterization and operating procedures to be refined and mastered. Barring any unexpected anomalies during the test and checkout phase, the facility is expected to be operational in the first quarter of 2014.

The infrastructure and hardware systems have been designed and sized to accomplish the goals listed earlier. However, all these capabilities are not planned to be readily

available the first day of operations. Rather the approach being taken is to gain experience and fully understand the regimes and breadth of capability with the simpler chemistry and gradually roll in more advanced features over time. First operational tests may likely be simulating Venus surface conditions and holding them for some period of time to understand chamber effects and impacts of the materials used in the chamber (liner, heater, etc.) on the control and measurements of the internal gas composition. Additional operating regimes to be characterized will include transitioning from one composition to another to simulate various altitudes in the Venus atmosphere. More experience with the dynamics of this unique capability will lead to automated and dynamic simulation of the atmosphere as seen by a balloon, unmanned aerial vehicle (UAV), or a dropped probe / lander. The priority or order of capability realization will be driven by complexity, resources and demand.

4. INITIAL CHECKOUT TESTING AND PLANS FOR FUTURE OPERATION

The first of a series of commissioning tests began in December 2013 when the GEER chamber was filled with an atmosphere of 97% CO₂ and 3% N₂. The tests began with low pressure (100 psig) heating tests and proceeded to high temperature and pressure tests. In the first series of tests, the chamber achieved 460C at 960 psig. The testing continues and facility components are stressed and upgraded in this process. Recent examples include specialized surfacing of chamber sealing surfaces. Additional tests will slowly build up to the introduction of the specialized gases and operating regimes. The purpose of the commissioning tests is to demonstrate the capability of the system to operate at high temperature (500 C) and high pressure (100 bar) simultaneously including the ability to recharge the chamber at high pressure using the boost pump.

After completion of the commissioning tests, a full-up system test will be performed using a gas mixture which will replicate the Venus atmosphere at surface conditions including temperature, pressure and composition. The system test will use a 96.5% CO₂ and 3.4% N₂ mixture with the addition of SO₂ (130 ppm), HF (5 ppb), HCl (0.5 ppm), NO (5.5 ppb), CO (15 ppm), COS (27 ppm) and H₂O (30 ppm). One important goal of the system test will be to demonstrate the ability to control the gas mixture composition using the FTIR. Once the system test is complete, the facility will be available for research use by Government, academic or commercial organizations.

5. SUMMARY

Simulation of the extreme conditions found on Venus and other planetary bodies is an important capability. Current state of capability supports small scale experiments or very specialized efforts. New capabilities are coming on line at the NASA Glenn Research Center that will enhance

NASA's and the worlds' capability in extreme environment simulations in several key ways. First, it will dramatically increase the size of the hardware and experiments that can be tested. This will allow full scale instruments and spacecraft systems to be tested. Another significant addition that GEER brings is the ability to accurately generate and control the chemical composition. In addition to CO₂, SO₂ and N₂, GEER will be able to handle the acidic and toxic elements that exist in many environments and represent significant species for understanding the system under study. Features of the GEER and the operating modes and methods will evolve and expand with increasing experience.

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BIOGRAPHIES



Tibor Kremic is currently working at NASA Glenn Research Center in the Space Science Project Office where he guides science related initiatives at the GRC. Formally he served on a detail as the assistant Division Director for Planetary Science where he contributed to the management of NASA planetary science program. Prior roles included management of organizations and project or program manager on a variety of NASA efforts, including NASA's In-Space Propulsion Technology Project. He also serves on a number of panels and teams focusing on science or space related technologies. Among the other duties he was the lead for the study discussed in this paper.



Dan Vento is currently working at NASA Glenn Research Center as Extreme Environments Manger for the NASA Glenn Space Science Project Office. He is a thirty-four year veteran of NASA with extensive background in propulsion and related technologies such as propellant handling, cryogenic fluid management, testing and system integration, as well as flight projects. He was a project manager for the X-33/RLV Propellant Densification Project which received the first-ever Low-Cost Access to Space TGIR award. Dan served as lead systems engineer for various Atlas/Centaur and Titan IV missions including Cassini, EOS Terra, and others. He also was an Atlas propulsion system engineer, and participated in or led numerous flight experiments in cryogenic fluid management and microgravity science. He is a skilled project manager for spaceflight hardware systems. Dan holds a Master of Science Mechanical Engineering from the University of Toledo (1987) and a Bachelor of Mechanical Engineering for Cleveland State University (1982).



Nick Lalli is the mechanical engineering technical lead in the Space Power and Propulsion, Communication and Instrumentation Branch at the NASA Glenn Research Center. He currently serves as the GEER project manager for the Testing Division. He has an extensive background in facilities engineering and wind tunnel testing and has led numerous successful facility enhancement projects and test programs at all of the major aerospace test facilities at GRC, including the first ever lightning test in an icing wind tunnel. Nick is also a member of the Process Systems Safety Committee and has led several safety reviews. He graduated from Cleveland State University in 1987 with a Bachelor's degree in Mechanical Engineering and has been at GRC for 24 years.



Tim Palinski is an electrical engineer in the Space Power and Propulsion, Communication and Instrumentation Branch at NASA Glenn Research Center. He graduated from the University of Toledo in 2009 with a Bachelor of Science in Computer Science and Engineering, and is currently pursuing his Master of Science in Electrical Engineering at Cleveland State University. Tim is especially interested in developing instruments and techniques that help enable scientific exploration and discovery. For his thesis research, he is investigating the infrared spectra of carbon dioxide at Venus-like pressures and temperatures, and the ability to predict chemical compositions in this environment.