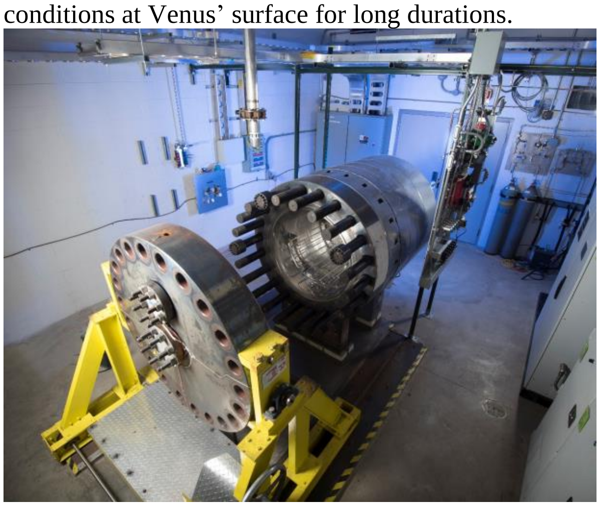
VENUS ATMOSPHERE EXPERIMENTAL SIMULATION PERFORMANCE OF THE GLENN EXTREME ENVIRONMENT RIG. J. A. Balcerski[1], T. Kremic[2], and I. S. Chi[2], [1]Ohio Aerospace Institute (22800 Cedar Point Rd., Brook Park, OH 44142. jeffreybalcerski@oai.org), [2]NASA Glenn Research Center (21000 Brookpark Rd., Cleveland, OH 44135).

Introduction: The rejuvenated exploration of Venus remains a high priority within NASA, as evidenced by the selection of two Discovery class missions (DAVINCI and VERITAS) to be launched within the decade, and the support of the European Space Agency's EnVision mission. All three missions represent a transformative advancement in the understanding of Earth's enigmatic neighbor. In order to maximize the science return from these missions, and to facilitate the infusion of new technologies into potential future missions, NASA's Glenn Research Center operates a unique facility, the Glenn Extreme Environment Rig (GEER), to simulate ambient conditions at Venus' surface for long durations.



The GEER facility consists of a large-volume pressure vessel, fed by 8 independently-controlled gas streams, with precision control of temperature and pressure. The primary pressure vessel, an 800 L stainless steel tank with 7-10 cm thick bulkheads, is outfitted with internal heaters, multiple feedthrough ports, and a roll-away end cap that allows access for large test articles (or to an array of smaller test articles placed on a removable support structure). The opposing ends of the cylindrical vessel contain multiple flanges (3" and 4" diameter), each of which provide internal access via six ½" and one ¾" feedthrough port, or through removal of the flange. Reactive gases (currently, CO_2, N_2, SO_2, CO, OCS, H_2S, H_2O, HF, and HCl) are injected into the vessel through a programmable, remote user interface, and are controlled to the parts-per-billion level through a combination of calibrated mass flow meters, software-assisted mix planning, and analytic verification. An array of internal and external sensors continuously monitor the vessel and perform feedback control that maintains the interior conditions to within a standard deviation of 4.0 mbar and 0.30° C. A combination of automated temperature control and operator-controlled gas boosting/rebalancing allows for operation of the facility and maintenance of test conditions for up to an indefinite amount of time (the longest to date being 80 days continuously.) Minimum experiment durations are generally limited to 10 days, due to a heating rate of 7° /hr (and a slightly lower cooling rate).

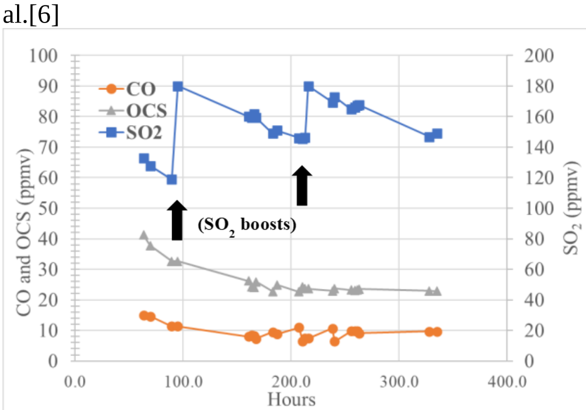
Experimental Usage: GEER's large internal volume, controlled test conditions, and adaptable configurations have enabled a range of scientific and technologic research. Lebonnois et al.[1] studied the phenomena of molecular diffusion between CO_2 and N_2 at Venus surface conditions. In order to complete this investigation, experiments were conducted within a specially built cylindrical test vessel designed by the GEER technical support staff at GRC to sit vertically within the pressure vessel and utilize its gas injection system. Radoman-Shaw et al.[2] performed experiments researching rock and mineral weathering under Venus surface conditions. Geochemical reaction rates relevant for the Venus surface tend to be slow at 460 C, thus these types of investigations benefit from GEER's ability to continuously maintain relevant conditions for long periods of time. Recent experiments, also for at least 60 days in Venus surface conditions, have expanded the range of geologic materials exposed to the highly reactive environment, with the goal of understanding the contemporary and historic composition and petrologic state of the Venusian solid surface.

GEER has also been used to test the resilience of materials and electronic components under simulated Venus conditions and to help mature instruments and spacecraft subsystems for future missions. For example, Neudeck et al.[3] developed and tested two 175-transistor 4H-SiC junction field effect transistor (JFET) semiconductor integrated circuits (IC) under simulated Venus lowland conditions (460 ± 1 °C and 9.3 ± 0.1 MPa) in GEER. The ICs were attached to in-house custom made electrical feedthrough probes which allowed the ICs to be operating and monitored by a digitizing oscilloscope that was located outside of the GEER. In addition, each test provides an opportunity to understand the interactions of a wide variety of materials with the Venus atmosphere (i.e., those that might be used for long-duration surface exploration platforms)[4-5].

Performance Characterization and Verification: Although the stainless 304 of the GEER pressure vessel is extremely robust to the Venus environment, it is nonetheless a consequence of high temperature chemistry that most Fe-Ni-Cr alloys have some reactivity to oxygen and sulfur-bearing species. Evidence for this behavior in GEER includes a decrease in measured SO_2 concentration over the duration of tests (Figure 2). The rate of decrease is variable, depending on contents of the vessel during test. Recent characterization of the empty vessel shows a background consumption of SO2 at ~ 6 ppm/day (Figure 2). And long-duration tests with a high mass and surface area of test articles reflect an SO_2 consumption of approximately 8-10 ppm/day. The fidelity of the test environment is demonstrated in Figure 2 (above) and enabled by unique monitoring and boosting capabilities. (Note that CO and OCS can also be boosted, but were not boosted in this case due to the focus of the test being specifically to address SO_2 consumption rate.) Moreover, we can compare the oxygen fugacity (fO_2) to values predicted for the natural Venus environment by using the following equation from Fegley et al.[6]:

$$log_{10} fO_2 = 2log_{10}\left(X_{CO_2}/X_{CO}\right) + 9.170 - 29607.34/T$$

where X_y is the molar fraction and T is the temperature (in K). Applying the varying CO, and a constant 98.5% CO_2, to this equation results in a log(fO_2) of -21.6 to -20.9, which is within the range predicted by Fegley et al.[6]



Expanded Capabilities and Potential Enhancements: Although GEER has traditionally been used for experiments involving the Venus atmosphere, it has demonstrated utility for other atmospheres as well. A notable recent example is the use of the facility to obtain baseline measurements of the microwave opacity of hot water vapor, which were used to support data from the Juno Microwave Radiometer[7]. Simulation of additional atmospheres is possible, and requests for such experiments are evaluated by the GEER engineering and science staff on a case-by-case basis. The facility has also been used for low-vacuum investigations (at ~ 1 psi), and requests for lower pressure, active cooling, or more rapid control of both temperature and pressure, could be accommodated through additional facility investment.

References:

[1] Lebonnois, S. et al. (2020) *Icarus, 338,* 113550. [2] Radoman-Shaw, B. G. et al. (2022) *Meteoritics & Planet. Sci., 57,* 1796-1819. [3] Neudeck, P. G. et al. (2016) *AIP Adv.*, 6, 125119. [4] Lukco D. et al. (2020) *J. Spacecr. Rockets*, *57*, *1118–1128*. [5] Costa, G. C. et al. (2023) *Corrosion Sci.*, *211*, 110882. [6] Fegley, B. F. et al. (1997) *Icarus*, *125*, 416-439. [7] Steffes, P. G. et al. (2023) *Icarus*, *404*, 115679.

Summary of Capabilities:

Conditions	Values
Temperature Range	Ambient-500 ºC
Pressure Range	< 0.1 - 94 bars
Common Gases	CO_2, N_2, SO_2, CO, OCS, H_2S, HCl, HF, H_2O
Test Durations	Per customer need and technically indefinite. Tests have lasted in excess of 80 days to date.
Inner Dimensions	0.9 m diameter x 1.2 m length; 800 L volume
Access	.9 m with head flange removed. 7 flanges with 3" orifice, 2 opposing flanges with 4" orifice
Feedthrough Capabilities	Multiple feedthroughs using the flanges. Current feedthroughs range from ¼" to ¾"
Data Products	Vessel temperature and pressure monitoring ~1 Hz; gas composition via in-line gas chromatograph

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