Progress Towards the Development of a Long-Lived Venus Lander Duplex System

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NASA has begun the development of a combined Stirling cycle power and cooling system (duplex) to enable the long-lived surface exploration of Venus and other harsh environments in the solar system. The duplex system will operate from the heat provided by decaying radioisotope plutonium-238 or its substitute. Since the surface of Venus has a thick, hot, and corrosive atmosphere, it is a challenging proposition to maintain sensitive lander electronics under survivable conditions. This development effort requires the integration of: a radioisotope or fission heat source; heat pipes; high-temperature, corrosion-resistant material; multistage cooling; a novel free-displacer Stirling convertor for the lander; and a minimal vibration thermoacoustic Stirling convertor for the seismometer. The first year effort includes conceptual system design and control studies, materials development, and prototype hardware testing. A summary of these findings and test results is presented in this report.

Nomenclature

APL = Applied Physics Laboratory
ASD = Advanced Stirling Duplex
ASRG = Advanced Stirling Radioisotope Generator
DOE = Deparment of Energy
FSP = Fission Surface Power
GPHS = General Purpose Heat Source
JPL = Jet Propulsion Laboratory
PIDDIP = Planetary Instrument Definition and Development Program
Po-210 = Polonium 210
Pu-238 = Plutonium 238
REP = Radioisotope Electric Propulsion
RPS = Radioisotope Power System
TRL = Technology Readiness Level
VEXAG = Venus Exploration Analysis Group
VISM = Venus Interior Structure Mission

I. Introduction

RADIOISOTOPE power systems (RPSs) have been used for decades in space to enable scientific missions to the farthest reaches of our solar system except in the most extreme high-temperature environments such as occur on the surface of Venus, Jupiter, Mercury, Io, or near the Sun. Of those extreme environments, Venus is in many ways the most challenging to operate within due to the high-temperature, high-pressure, and corrosive atmosphere. All of the currently proposed Venus missions have a very limited technology base to enable even short duration (5 to 10 hour) surface exploration The power and cooling requirements are particularly challenging. Fortunately, Glenn's Advanced Stirling Duplex, which is being supported by the RPS Program Office's Technology Development Project, can provide both the electrical power and cooling protection required for long-term exploration (>1 year), while reducing the overall development costs of the spacecraft.

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A. Stirling Triad of Enabled Missions Overview

Stirling systems have been selected as the power conversion technology for the Advanced Stirling Radioisotope Generator (ASRG), Fission Surface Power (FSP), and the Advanced Stirling Duplex (ASD) project because of their high efficiency. These three technology development efforts will enable long-duration missions to any location in the solar system. Often non-nuclear power technologies such as solar and chemical are preferred whenever solar radiation is available or the mission is of short duration. But in many cases, space exploration requires radioisotope- or fission-based power systems.

1. *ASRG*

ASRG and its lower and higher power cousins provide modest power levels (100's W to about 1 kW) in difficult environments such as the outer planets and moon. For example, as shown in Fig. 1, ASRG enables radioisotope electric propulsion (REP) outer planet exploration and it also enables a long-lived international lunar network. A higher power convertor based on the same basic technology is also being considered. The ASRG is designed to operate for 14 to 17 years to support outer planet science missions.

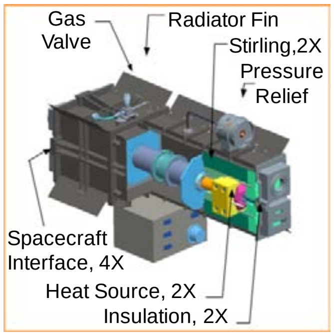


Figure 1. ASRG

2. *FSP*

FSP (shown in Fig. 2) provides high power levels (1 kW to 100's kW) in difficult environments such as the moon, Mars, and outer planets for human outposts or large flagship missions. It utilizes the heat from a fission reactor to provide very high power levels. It is intended to operate for at least 8 to 10 years and is the only viable power option for high power levels.

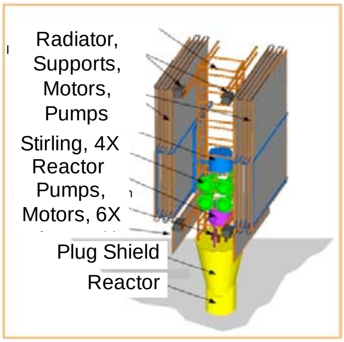


Figure 2. FSP

3. *ASD*

ASD (shown in Fig. 3) enables exploration in areas no other power technology can provide due to excessively high temperatures. ASRG and FSP systems cannot operate in hot environments since they do not provide cooling and their organic and magnetic components would fail. Nearly all other power technologies cannot survive either in the extreme environments that exist on Venus, Mercury, Jupiter, and Io. One exception is high-temperature batteries, which can operate at high temperatures for a limited time. However, any long-lived mission in an extreme environment would benefit from ASD technology to provide not only a long-lived power supply, but to refrigerate other sensitive components such as electronics, sensors, and motors.

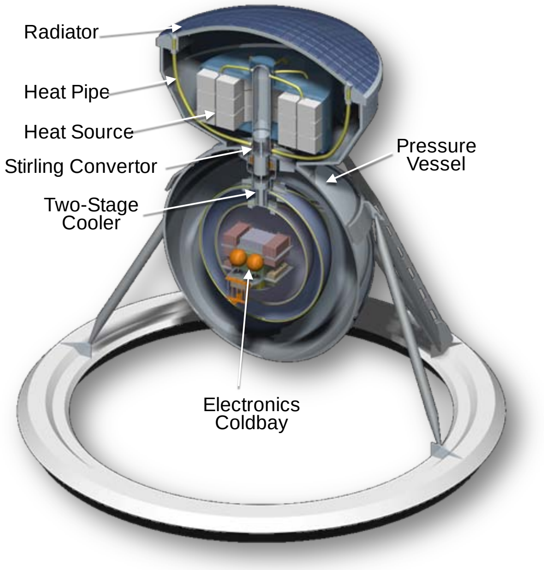


Figure 3. ASD

B. RPS Technology Roadmap

As shown in Fig. 4, the development path is defined by the technology readiness level (TRL). The current plan envisions the use of ASRG for outer planet missions over the next decade. FSP is anticipated for mission use starting in the next decade. Notice ASD is intended to be demonstrated in the 2016 timeframe to TRL 6 and would be flight qualified by 2020.

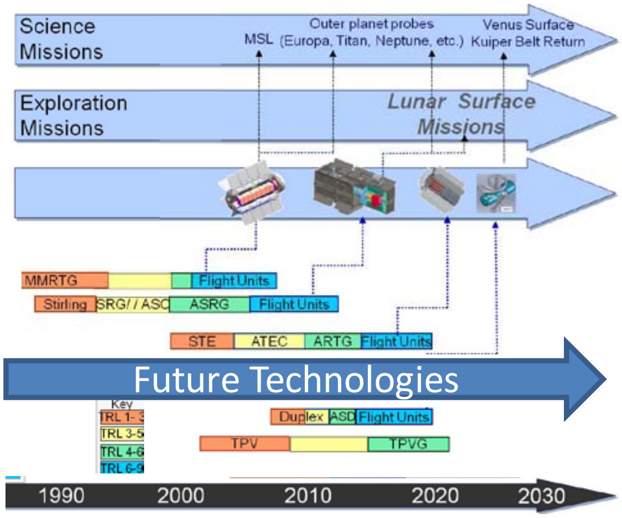


Figure 4. RPS Technology Roadmap

C. Advanced Stirling Duplex Team

The ASD Team comprises NASA, industry, and academia. The stakeholders include the mission planning organizations, project office, technology development organizations, and research management. The team makeup is designed to quickly develop and test a working duplex prototype. Multiple parallel efforts are underway to develop both power and cooling technologies that can operate at high power and high temperature on the surface of Venus. The supporting technologies being developed by this team include a free-displacer Stirling power convertor, a high-power thermoacoustic power convertor, a multistage Stirling cooler, control system, thermophotovoltaic power convertor, variable conductance heat pipe, extreme high-temperature materials, full-scale extreme environment test chamber, and spacecraft-cooling-related integration technologies such as insulation, radiator, and heat collection systems. The mission planning centers, which include Jet Propulsion Laboratory, Goddard, and Applied Physics Laboratory have provided challenging requirements that must be met for this technology to be useful under a variety of Venus mission scenarios. Several space grant consortium projects from Arizona, North Carolina, and Maryland have also contributed to the lander design. The National Research Council's planetary science subcommittee and decadal survey have also highly ranked missions to Venus. The Venus Exploration Advisory Group (VEXAG) have proposed specific missions requiring the ASD.

Clearly, many organizations have a stake in the successful development of this duplex system, and a team consisting of discpline leaders have been formed to expeditiously demonstrate this new enabling technology.

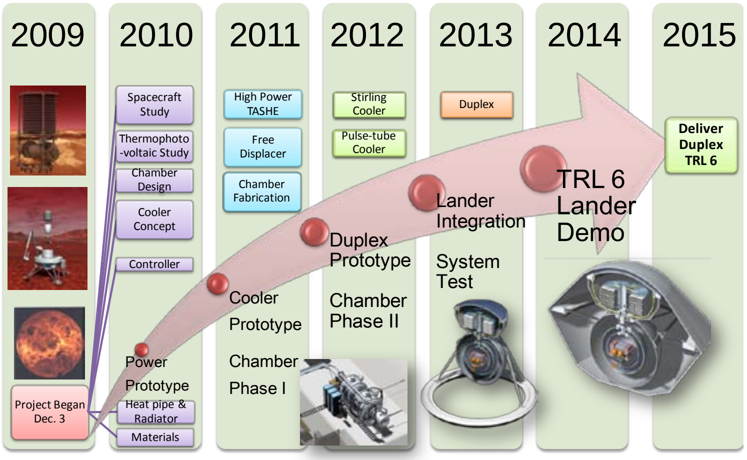


Figure 5. Schedule and Milestones

D. Development Schedule and Milestones

As shown in Fig. 5, the technology development project is expected to cost $15 million over a 5-year development period. The test chamber and power convertors are being developed initially, followed by coolers that are then integrated into a duplex and eventually integrated into a mock lander and aeroshell for a complete system demonstration.

E. Venus Exploration Approach

While Venus has been explored in the past, the ability for extensive scientific return has had to wait until new technologies could be developed to answer some key questions including the following: "Was there ever an ocean on Venus? "; "Why does Venus not have a magnetic field? "; and "Did Venus ever have plate tectonics? ". Perhaps more significant is the runaway greenhouse gas effect causing the planet to overheat. Some of the lessons learned about Venus may apply to Earth as well. Venus is not considered to be habitable due to the high-pressure, high-temperature, and corrosive atmosphere, however, as Landis has suggested, floating cities in the mild climate above the sulfuric acid clouds are a distinct possibility.

The approach for returning to Venus has been the development of multiple mission scenarios by independent teams in which new technology is assumed to be available. A Venus mission was already recommended in the last decadal survey and more recently, a Discovery mission announcement opportunity has Venus ranked in the top three. Some technology development has begun for these proposed missions including the ASD, high-temperature electronics, and balloon bellows for Venus Mobile Explorer.

Since current technology only permits very short-lived missions, it is critical that ASD be demonstrated soon so these missions can be properly baselined.

F. Past and Proposed Missions

Numerous missions to the Venus surface have been attempted. The longest surviving was the Soviet Venera 13. It lasted for 127 minutes and was cooled with a phase change material and utilized batteries for power.

Several mission scenarios have been proposed for exploring the surface of Venus including rovers, landers, and bellows. In addition, long-lived weather stations and seismometers on the surface have been proposed. One of the most significant studies was recently completed by the Venus Science and Technology Definition Team in which a flagship mission was proposed for launch in the 2025 timeframe. In that mission, two landers, two balloons, and an orbiter were proposed. Since the Stirling duplex technology has not been demonstrated, the baseline mission assumed the landers would only survive for 5 hours. In a separate mission study, the Venus Mobile Explorer is proposed in a decadal white paper in which a bellows system inflates and deflates to enable hopping across the planet. In this system, the ability to actively cool the lander enables extensive time on the surface.

In all of those studies in which only passive cooling is used, the near surface vehicle must exercise all of its instruments in a concerted dash to complete its science mission. This requires a much higher peak power load than if only some of the instruments are operating at a time. Since the Stirling duplex will enable at least a year's worth of operations, the electrical power requirement is likely to be considerably less than the baselined missions currently require.

G. Venus Environment

Venus is perhaps the most challenging exploration target in the solar system as shown in Fig. 6. In addition to the hot surface and high pressure, the environment contains potentially very corrosive and reactive species. On the surface the atmosphere is mostly supercritical carbon dioxide and nitrogen, but it also contains trace amounts of sulfur dioxide, argon, water, carbon monoxide, helium, neon, hydrogen chloride, and hydrogen fluoride. Hydrogen sulfide and sulfuric acid are found above the surface. The dense atmosphere also limits the planetary entry angle permitted and limits the solar radiation reaching the surface. The surface of the planet is basalt and rocky. It is thought the thick atmosphere is due to extreme volcanic activity. The lack of old craters on the surface suggests a sublimation occurs every million years or so.

The challenging Venus environment requires new technology development to fully explore it. These new technologies must be demonstrated in a simulated Venus environment for flight qualification. Since Venus is in many ways the harshest environment in the solar system, any technology developed to survive there can likely be used in other challenging locations in which high temperature limits mission life such as Mercury, Jupiter, Io, and near the Sun.

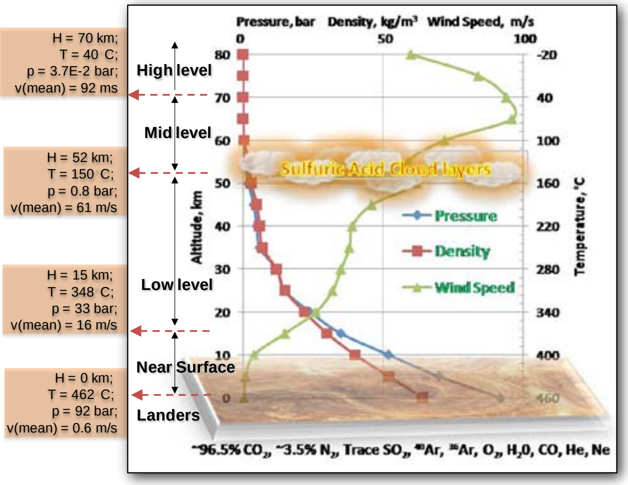


Figure 6. Venus Environment

II. Extreme Environment Test Chamber

All eight of the currently proposed missions to Venus would benefit significantly from active cooling. But key to demonstrating component and system performance is testing in a suitable Venus environment. While a few organizations have very small testing chambers suitable for low TRL test tube and coupon testing, the international community is in need of a larger facility.

The capability for testing and validation of technology systems in extreme environments such as on the surface of Venus, Jupiter, Mercury, and on Jupiter’s moon, Io, does not currently exist. Several mission studies have concluded the need for developing surface exploration technologies such as Stirling duplex for power and cooling, high temperature sensors, electronics, motors, telecom, and sample acquisition systems for operating in those extreme environments. This section provides a brief description of a proposed test chamber that would enable the development and flight qualification of these critical technologies.

A. Background

Of all extreme environments, Venus is in many ways the most challenging to operate within due to the high-temperature, high-pressure, and corrosive atmosphere. Mission planners have a very limited technology base from which to choose to achieve near planetary surface scientific goals. An ASD has been identified as a key technology development priority since it will provide both the electrical power and cooling necessary to enable long-lived surface missions. But key to demonstrating component and system performance is testing in a suitable Venus environment.

B. Proposed Facility

Since the initial need is for materials characterization and power system performance testing in a Venus environment, a small 3- by 4-foot chamber would be fabricated the first year as shown in Fig. 7. A larger chamber would subsequently be added to this smaller chamber to allow complete system testing. The modular nature of this design also allows for simultaneous tests from several organizations and the addition of much larger chambers if required by the Agency.

C. Features

As shown in Fig. 7, the test chamber facility will include test article controls, DAQ, and PLC racks for test chamber control, optical port holes, removable liner, rolling door access, and overhead crane access. Notice the chamber consists of several sections to allow for modular construction that is consistent with budget and testing requirements. Shown in Fig. 7 are the approximate sizes of each test chamber. The small test chamber enables component and materials testing, the phase II chamber enables testing of a complete lander with the duplex system, and phase III is a larger option available for full-scale flight testing.

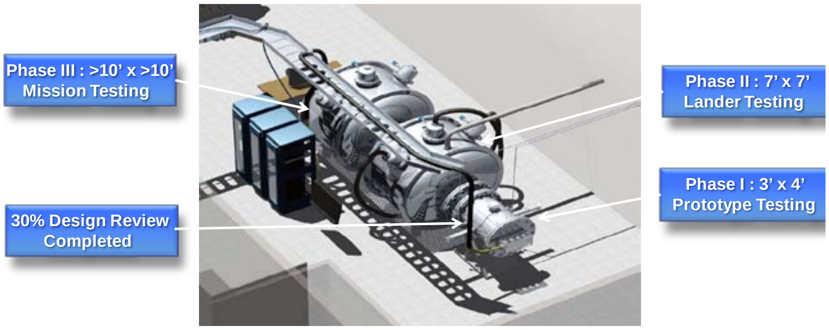


Figure 7. Extreme Environment Phased Construction

D. Mission Phases

The test chamber will be capable of supporting both a vacuum and high pressure to simulate the entire mission sequence including launch, cruise, entry, descent, and surface operations. The chamber can support both on surface testing and higher atmospheric operations. The pressure, temperature, wind speed, and atmospheric composition can be varied within the chamber. The wind speed is below 1 m/s at the surface, but significantly impacts radiator sizing, seismometer, weather, and lander stability considerations.

E. Lander Concepts

Shown in Fig. 8 are four proposed lander concepts[2,3,10,11] that could be tested in the extreme environment chamber. Originally, the VISM Team proposed a lander in which the seismometer was attached to an actively cooled pressure vessel in 1993. Next, the Arizona Space Grant Consortium recommended a hybrid dual chamber approach in which only some of the instruments were cooled. The NASA Science Technology Definition Team developed a passively cooled lander in 2009. Most recently, the ASD Team developed an actively cooled lander similar to the original VISM concept, but without a seismometer attached. The pressure vessel size is approximately 3 feet in diameter and the landers are typically are less than 1000 kg. The test chamber is intended to initially test only the power, cooling, and materials components in the smaller 3- by 4-foot chamber. Later, the lander will be tested in the phase II chamber. Note that it is necessary to include the entire lander in the Stirling duplex test because the exact parasitic heat load into the vessel is not known at this time. Moreover, the multistage cooling requires separately cooled and insulated compartments to be successfully tested.

This project is tasked with demonstrating Stirling duplex operation on the surface of Venus in a lander. However, it is also necessary to show how a lander can be stored inside an aeroshell with a duplex onboard. The phase III chamber is large enough to testing the cruise condition and planetary entry. Also, since Venus has approximately the same gravity as Earth, the test chamber can very realistically simulate all known physics occurring on the Venus surface.

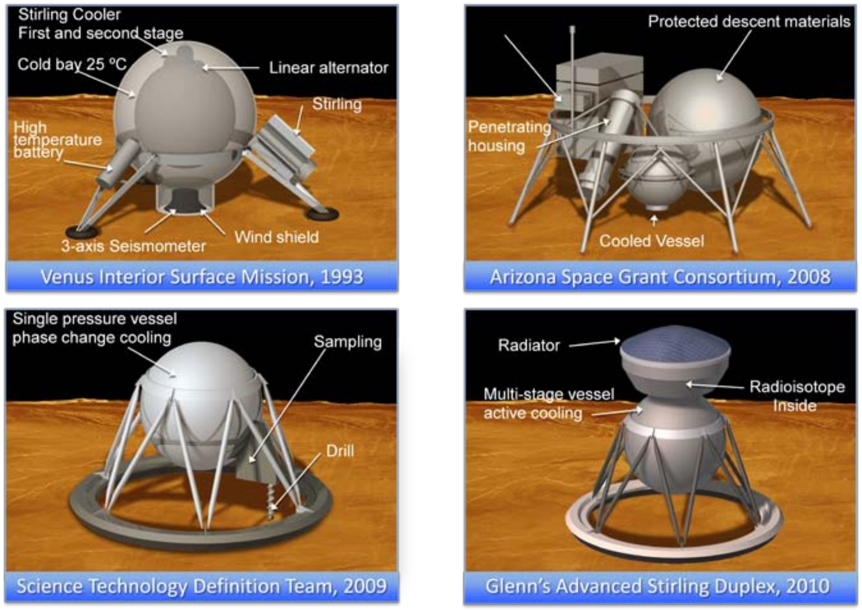
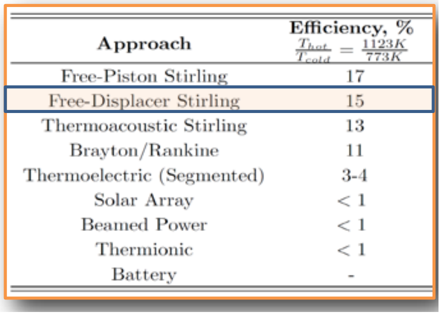


Figure 8. Lander Concepts

III. Advanced Stirling Duplex

The high temperatures on Venus require a high-efficiency power and cooling system. Since the refrigerated temperatures are approximately 30 °C, and the environment is approximately 460 °C, most power technologies cannot operate efficiently enough to be useful.

Table 1. Power Options



Approach	Efficiency, % $\frac{T_{hot}}{T_{cold}} = \frac{1123K}{773K}$
Free-Piston Stirling	17
Free-Displacer Stirling	15
Thermoacoustic Stirling	13
Brayton/Rankine	11
Thermoelectric (Segmented)	3-4
Solar Array	< 1
Beamed Power	< 1
Thermionic	< 1
Battery	-

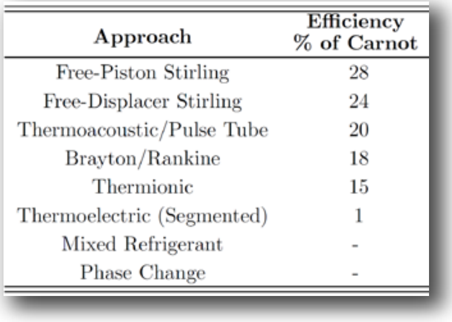
A. Power and Cooling Trade-Space

Shown in Tables 1 and 2 are a comparison of power conversion options and cooler options. Notice all the Stirling cycle power and cooling systems have a higher overall efficiency. One of the properties of Stirling convertors is their ability to maintain high efficiencies even when the temperature ratio gets small. Another important consideration is in how to join the power and cooling systems into a single duplex. For example, a Stirling cycle has an oscillating gas whereas a Brayton cycle has rotating gas. Attempting to join an oscillation with a rotation can limit the overall system efficiency.

1. Effect of Hot-End Temperature

Notice in the figure on the right a comparison is made of three power convertors based on the Stirling cycle: free-piston, free-displacer, and thermoacoustic. It is currently believed that free-piston is the most efficient power conversion option available, followed by free-displacer, and then by thermoacoustic. However, as the dashed line shows, the free-piston convertor cannot be operated with a temperature hotter than 950 °C due to having moving parts in the hot-end. However both the free-displacer and thermoacoustic designs can be operated at much higher temperatures since they have no moving parts at the hot-end. The dashed line shows the free-displacer will eventually out-perform the free-piston at 1025 °C and the thermoacoustic outperforms the

Table 2. Cooling Options



Approach	Efficiency % of Carnot
Free-Piston Stirling	28
Free-Displacer Stirling	24
Thermoacoustic/Pulse Tube	20
Brayton/Rankine	18
Thermionic	15
Thermoelectric (Segmented)	1
Mixed Refrigerant	-
Phase Change	-

free-piston at 1130 °C. For these reasons, these alternative technologies are being developed under this project with a goal of 1200 °C at the hot-end.

It should also be noted that thermophotovoltaic technology is not shown as a power system since it cannot operate at Venus temperatures unless refrigerated. It is potentially possible to combine a thermoacoustic duplex with a thermophotovoltaic system to provide cooling and power with no moving parts.

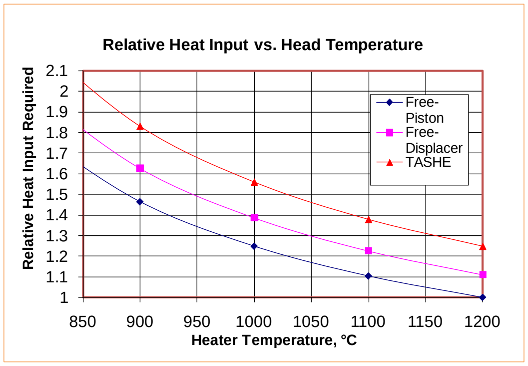


Figure 9. Efficiency Comparison

B. Life-Limiting Mechanisms

The Stirling cycle devices have been improved over the past decades to the point they are extremely efficient and reliable. Some potential life-limiting mechanisms include wear, fatigue, creep, permeation, and radiation. Fortunately, as shown in Fig. 10, some of these mechanisms have been mitigated since noncontacting operation is now possible using either flexures or gas bearings.

Notice that the free-piston configuration does not have a mechanical connection between the displacer and the piston. The relative motion of these elements is determined by physical resonance conditions and the non-contact operation is achieved with gas bearings in the figure. This configuration is currently the world's most efficient heat engine achieving 55% of Carnot efficiency.

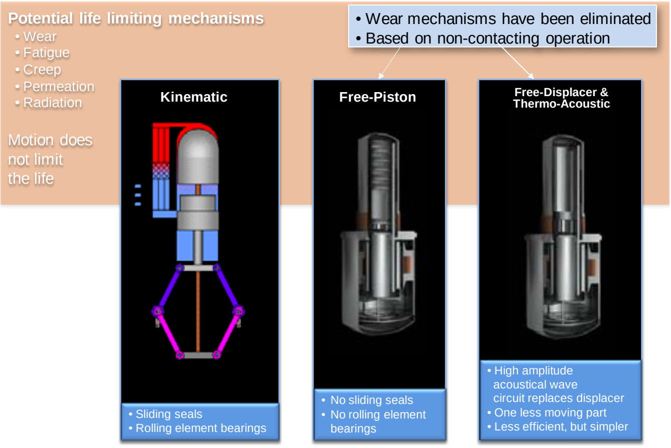


Figure 10. Life Limiting Mechanisms

In the last example shown in the figure, a free-displacer convertor is depicted in which the displacer is shortened. In that case, the efficiency of the engine decreases due to the increased dead volume. A related technology is the thermoacoustic convertor in which the displacer is entirely removed and replaced by an acoustical circuit.

One of the design issues is the working fluid. Often helium is used, but in the case of the Stirling duplex, there appear to be advantages to utilizing alternative working fluids instead. One of the challenges of using alternative fluids is they tend to permeate through the walls or can damage magnets. If a suitable material is identified for fluid containment then significant improvement in system efficiencies are possible for the heat engine and cooler.

Another design issue is the thickness of the heater head. Ideally, the walls would be thin to reduce thermal losses from the hot-end to the cold-end. Thin walls can lead to excessive material creep, especially at the high temperatures. This creep can cause the oscillating flow to bypass the regenerator.

The operating frequency is another consideration. A high frequency results in smaller resonators for thermo-acoustic convertors, but makes it more difficult to fabricate heat exchangers. Most convertors operate between 50 and 120 Hz.

Fatigue can occur on the moving parts, especially those on the hot-end of the convertor due to the repeated oscillating pressure forces acting on them. Also, parts such as springs or flexures have to be carefully designed for millions of oscillations over the entire operating cycle. Finally, radiation is potentially a concern, particularly for magnets and organics. Preliminary tests indicated minimal impact at expected exposure limitations. Also, one of the benefits of the thick Venus atmosphere is minimal radiation actually reaches the surface.

C. Principle of Operation

The Stirling duplex can be designed with a variety of power and cooling configurations. Each of those power and cooling technologies can be joined into a duplex using either a pneumatic, electrical, or mechanical mode. The least desirable is the mechanical mode due to the need for lubrication and the frictional losses. The electrical mode requires converting the mechanical motion into electrical and then back into mechanical. Each of those conversion steps results in overall energy losses due to the imperfect efficiency of linear alternators and compressors. The most desirable is the pneumatic mode because the acoustical energy is directly used for cooling.

D. Cooling System Staging

One of the keys for developing a successful Venus lander cooling system is to take advantage of the thermodynamic efficiency of a multistage cooler.

1. *Single-Stage Cooler*

In a single-stage cooler, the heat is removed from the payload bay in a single step. Most previous Venus lander studies assumed a single-stage cooler would be utilized and this resulted in very inefficient designs. As shown in Fig. 11, all the electronics are contained within a single pressure vessel. This is the same basic pressure vessel structure used for all previous Venus landers.

Notice that the cooler has to reject the heat produced by the electronics in the payload and the heat that enters from outside the pressure vessel due to the hot Venus environment. Shown in this figure is the original design from 1993 in which a double acting Stirling engine with 8 GPHS was assumed. The cooler has a piston that was activated from the helium pressure wave and the piston then acted through a gear system to power the cooler. The heat absorption fins were used to collect the heat so the cooler could pump it out. The heat rejection fins would reject the cold-end waste heat from the Stirling convertor. Notice this duplex had a pneumatic coupling but connected to a kinematic cooler. This original design was overly optimistic in the heat engine and cooler efficiencies assumed, the electrical payload requirements were understated, and uneven cooling in the payload was never addressed.

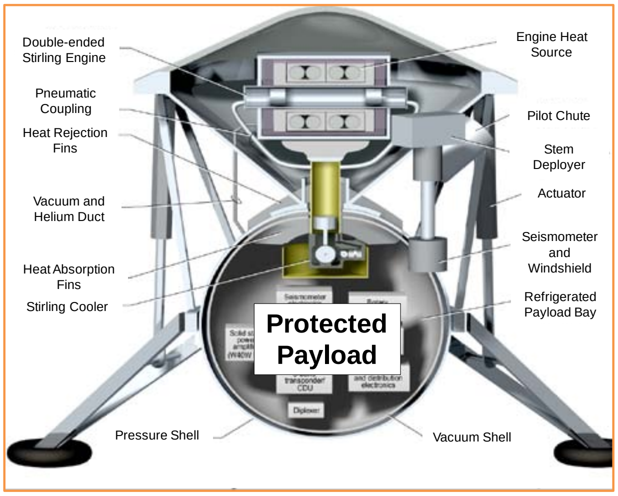


Figure 11. Single-Stage Cooling System

2. *Two-Stage Cooler*

The two-stage cooler configuration shown in Fig. 12 is a much more recently designed configuration. Notice the number of GPHS modules has increased from 8 up to 40. Now the overall efficiency of the duplex is higher because of the significant thermodynamic advantage that occurs by intercepting the heat coming from the Venus environment at a higher temperature. The heat collection and rejection is also enhanced via modern variable conductance heat pipes. This allows the payload bay to be evenly cooled.

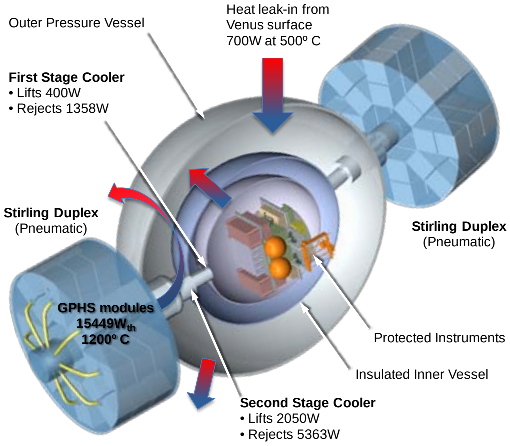


Figure 12. Two-Stage Cooler Integration

IV. Prototype Convertors

A number of prototype heat engine convertors have been developed in the past under different projects that demonstrate high hot-end operating temperatures are currently possible.

A. High-Temperature Stirling

A Component Test Power Convertor (CTPC) was developed under the SP-100 program to operate at 777 °C while producing 12 kWe and operating with a mean pressure of 15 MPa. Since the Venus environment is approximately 460 °C, it is possible to use this engine on Venus if the cold-end were protected as in a duplex configuration. Moreover, the high operating pressure actually exceeds the Venus atmospheric pressure. This was demonstrated nearly 20 years ago.

More recently, the Advanced Stirling Convertor was demonstrated to operate at 850 °C while achieving 55% of Carnot efficiency with over 2000 hours of continuous operation. It is anticipated that this convertor would operate with 17% efficiency on the surface of Venus if the cold-end were protected in a duplex configuration. It is thought the highest temperature possible with ASC technology is 950 °C due to cyclic fatigue on the moving hot-end parts.

Most recently, several attempts at eliminating moving parts in the hot-end were successful by developing small power convertors utilizing thermoacoustic technology. While they operated at only around 600 °C on the hot-end, they demonstrated the efficiency that is possible with this approach. In general, they are about 80% as efficient as the free-piston-based Stirling cycle commonly used when operated at the same temperatures. However, as mentioned previously, since their hot-end temperature may approach 1200 °C, their overall efficiency may surpass the ASC. Higher power thermoacoustic engines have also been demonstrated as discussed in the next section.

Clearly, high-temperature and high-pressure Stirling systems have already been demonstrated, and an approach for raising the temperature further has been demonstrated. The cold-end temperatures are less of a concern because they can be cooled in a duplex configuration.

B. High-Power Thermoacoustic

A thermoacoustic engine/driver that was initially developed under an Air Force Small Business Innovation Research (SBIR) phase II effort, was successfully tested as shown in Fig. 13. This proof-of-concept prototype operates at the high power levels required for a Venus mission. It is unique in that it was designed to operate as a duplex for the ARES upper stage rocket's cryogenic propellant densification system. It is the second largest thermoacoustic engine ever constructed and it is designed to be mated with a two-stage cryocooler. Due to funding cancellation, the engine and cryocooler were never operated and have sat in mothball for over 2 years. The Advanced Stirling Duplex project was able to leverage this previous work to quickly assemble and test this hardware. Since the engine is the first at the higher power levels required for Venus, it is an ideal risk reduction tool to confirm our analytical models so we can confidently design for the Venus environment.

Figure 13. High-Power Thermoacoustic Milestone Completed

Shown in Fig. 13 is the thermoacoustic engine with one of the consultants on the project, Dr. Greg Swift. The engine operates at 30 Hz with 500 psi mean helium pressure. It is designed to accept 12000 W of thermal energy and convert that to 4000 W of acoustical energy. This engine/driver can be connected to linear alternators and pulse tube coolers to provide electrical power and refrigeration.

While this engine is not designed to operate at Venus temperatures, it provides an important proof-of-concept for understanding the physics of these large engines. Moreover, the already fabricated cryocooler can be quickly added to this engine to form a prototype duplex early in our project to help guide future development efforts.

Also shown in the figure are a large resonator and dummy masses to contain the inertial forces. Note that since this engine was originally designed to provide cryogenic cooling, its operating frequency is 30 Hz to allow time for heat transfer at the liquid hydrogen temperatures. This low frequency induces vibration and requires a large resonator. However, for our Venus application of this technology, the cooler can operate at much higher frequencies since the refrigerated temperatures are much higher. This significantly reduces vibrations and reduces the size of the resonator required. The closeup of the engine shown in Fig. 13 shows the electrical heating leads and liquid cooling lines.

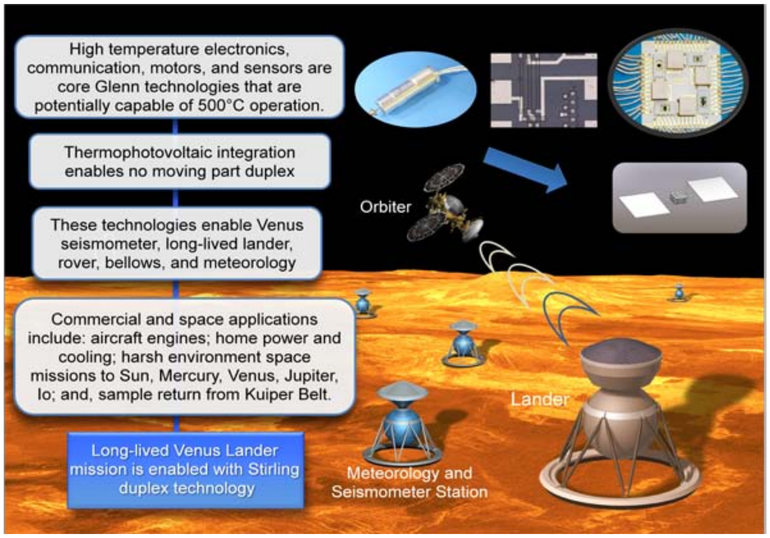
One of the critical components of any thermoacoustic engine is the jet pump. This component prevents Gedeon streaming from occurring within the engine and it is very difficult to analytically predict its behavior. The jet pump on this engine will be resized several times to optimize the performance of the engine. After that, the next step for this early prototype demonstration effort is the addition of a cryocooler to confirm the duplex operation matches analytical predictions. Once all physical behavior can be explained and our analytical predictions are validated, then this duplex can be cost effectively and confidently modified to operate under Venus conditions.

Shown in the figure are the dummy mass and dummy load. These are only needed for this preliminary prototype test; a mature ASD design will not include them. Note the engine test cell is located in a separate building from the control room.

V. Technical Challenges

Many technical challenges remain to be addressed under this current effort. First, a Stirling cycle heat engine must be developed that can operate at a high hot-end temperature with high efficiency, and be compatible with the Venus environmental conditions. Second, a high-efficiency Stirling cycle multistage cooler must be developed that can fit within the lander's pressure vessel and operate at very high efficiency with minimal vibration. Third, the heat engine and multistage cooler must be compatible with each other, share the same working fluid, and maintain an overall high system efficiency. Fourth, the variable conductance heat pipe technology must be developed to efficiently transport heat energy to the heat engine and cold fingers while rejecting heat to radiators that are exposed to the Venus environment. Fifth, the entire system must operate within the pressure vessel of the lander while being mass efficient. Finally, the Stirling duplex, heat pipes, radiator, and insulated pressure vessel, as shown in Fig. 14 must be demonstrated to operate within the Venus environment for up to 1 year.

Two novel heat engine and cooling technologies are being developed to support a variety of Venus operations. It is anticipated that a system with no moving parts will have less vibration and may be suitable for a Venus seismometer. The free-displacer duplex will have no moving parts in the hot-end and will be maximally efficient, but may exhibit more vibrations rendering it more useful for a lander vehicle.



High temperature electronics, communication, motors, and sensors are core Glenn technologies that are potentially capable of 500°C operation.

Thermophotovoltaic integration enables no moving part duplex

These technologies enable Venus seismometer, long-lived lander, rover, bellows, and meteorology

Commercial and space applications include: aircraft engines; home power and cooling; harsh environment space missions to Sun, Mercury, Venus, Jupiter, Io; and, sample return from Kuiper Belt.

Long-lived Venus Lander mission is enabled with Stirling duplex technology

Figure 14. Strategic Technologies and Commercialization

VI. Conclusion

Clearly the development of a Stirling duplex is possible and desirable for a host of reasons including solar system exploration in harsh environments, commercial opportunities, and environmental benefits. This technology development project is anticipated to continue for the next several years with a demonstration unit scheduled for completion by 2015. Success of this effort will be when the Stirling duplex can operate at TRL 6 in a Venus-like environmental test chamber for 1 year while maintaining the payload bay of a mock Venus lander within acceptable refrigerated limits.

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