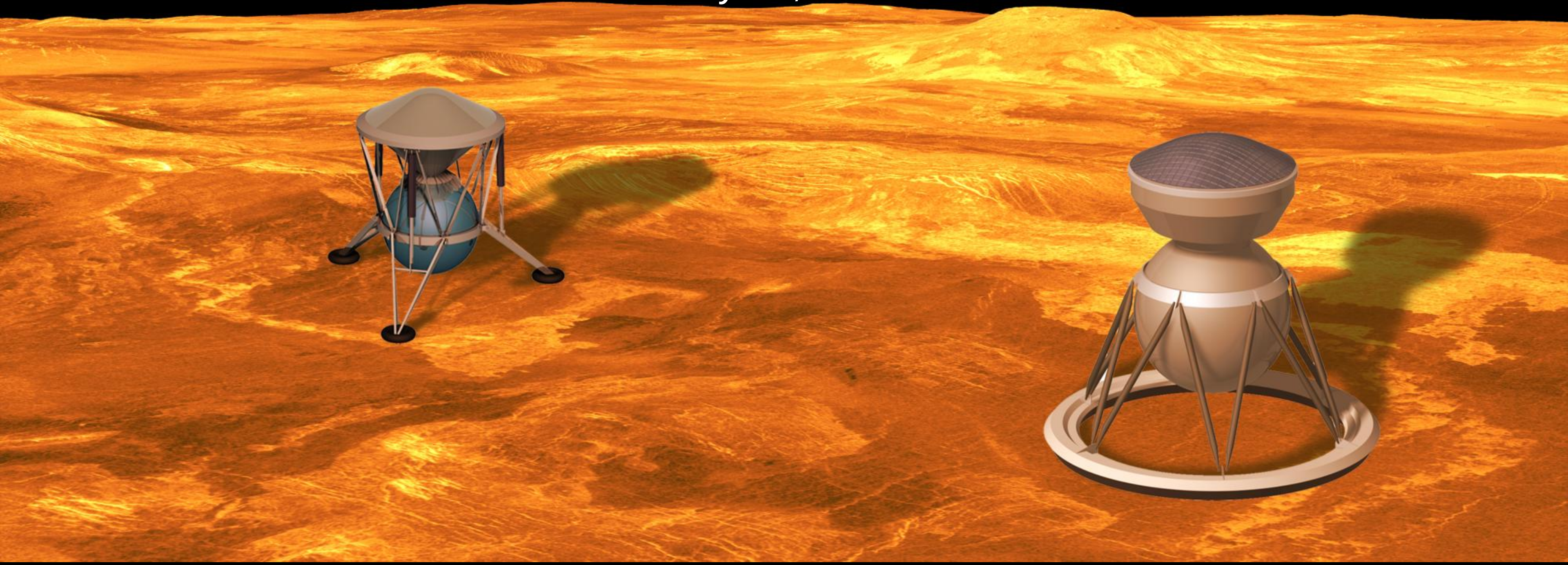
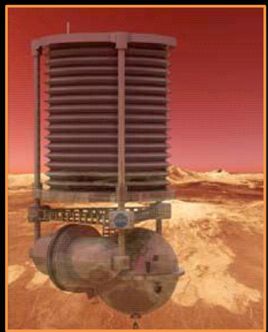
Progress Towards the Development of a Long-Lived Venus Lander Duplex System

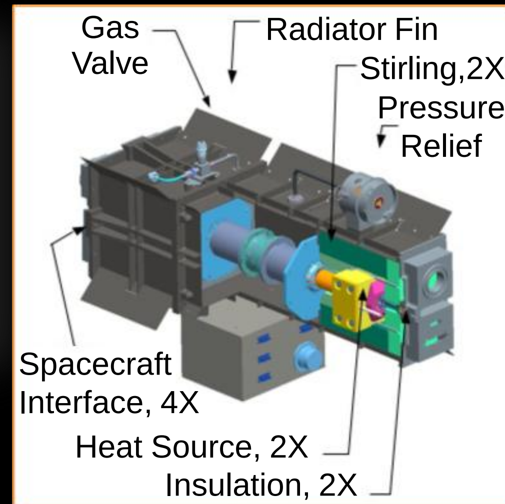
Rodger W. Dyson and Geoffrey A. Bruder
Thermal Energy Conversion Branch
NASA Glenn Research Center

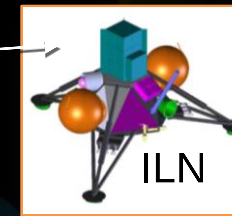
8th AIAA IECEC, Session 126-APS-4
July 27, 2010

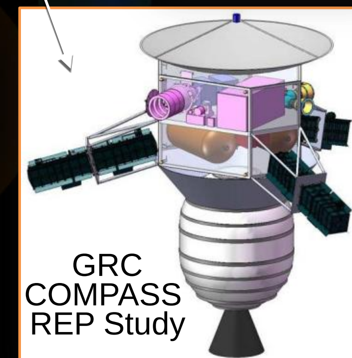


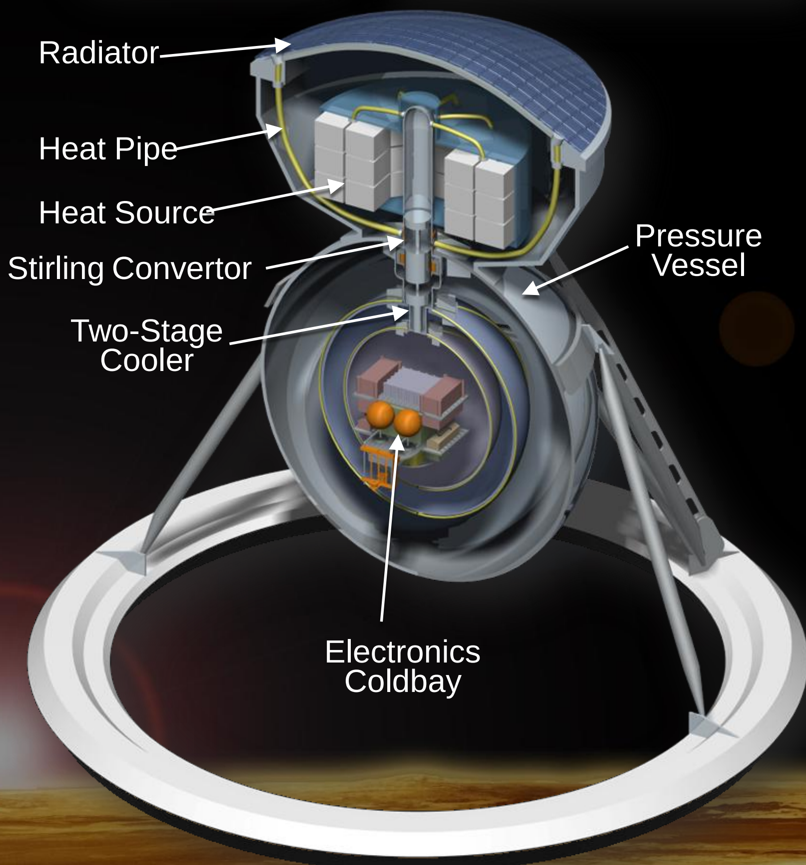
Stirling Triad of Enabled Missions Overview

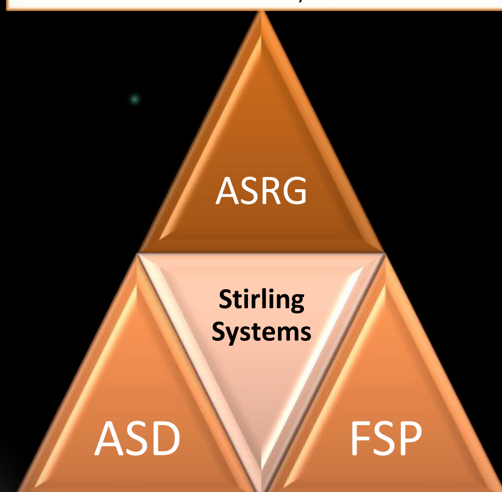


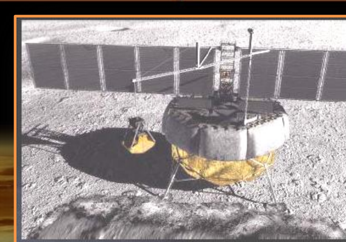


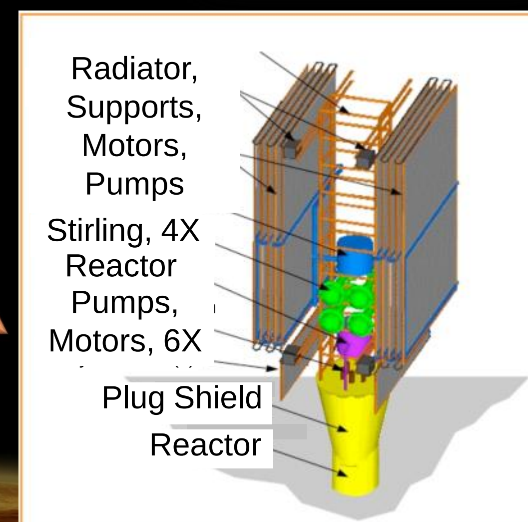












Advanced Stirling Duplex Team and its Stakeholders

Project
L.Dudzinski
J. Hamley
T. Rodgers

Technology
G. Hunter
G. Landis

Mission
T. Balint
J. Hall
C. Baker
L. Glaze
E.Stofan
R. Gold
P. Ostdiek

Supervision
J. Lei
G. Schmidt
V. Lyons
D. Shaltens

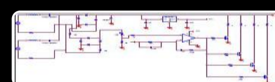
ASD Team


RPT–Task Management, Planning and Integration
(Dyson, Shaltens)

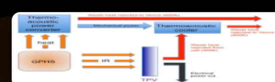

Sunpower–Free Displacer
(Wood, Gedeon)

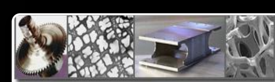

Sierra Lobo–High Power TA
(Haberbusch, Nguyen, Swift)


Lockheed Martin–Cooler Concepts
(Olson, Nast, Li)


Case Western Reserve University–Duplex Controller
(Newman)


Advanced Cooling Tech.–Variable Conductance Heat Pipe
(Tarau, Anderson)


RPV–Thermo-Photovoltaic Integration With ASD
(Clark, Wolford, Landis)

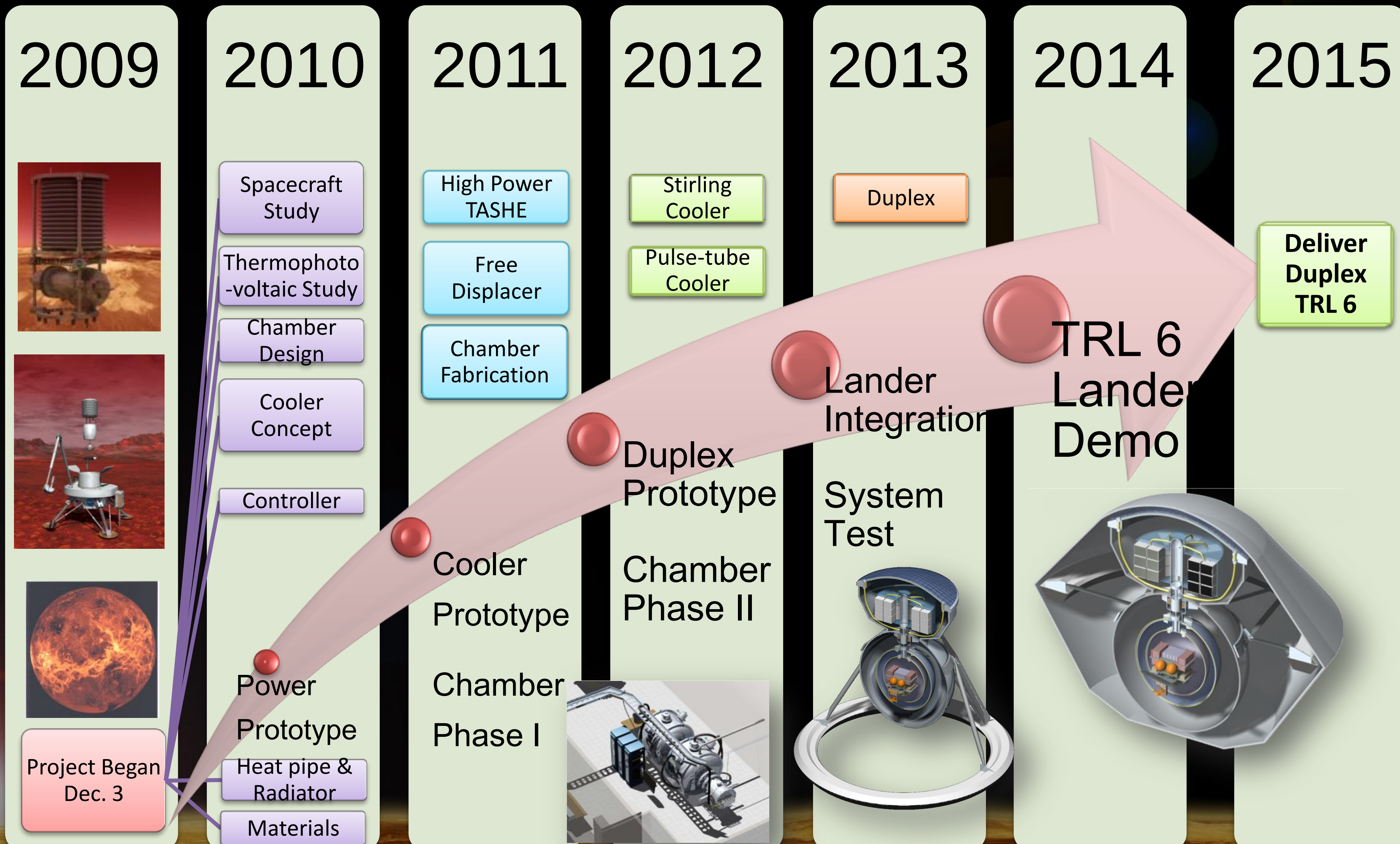

RXA,RXD–Extreme Materials Development
(Ritzert, Bowman, Nathal, Dever, Ellis, Locci)


FTF, FTK, RPT–Facility Development/Testing
(Nowlin, Lalli, Vickerman, Elonen-Wright, Bruder, Swiatek)


PCS, Sest–Spacecraft Trade Study
(Penswick, Schmitz)

MARYLAND SPACE GRANT CONSORTIUM
NORTH CAROLINA space grant
Arizona Space Grant
Planetary Science Subcommittee
Goddard SPACE FLIGHT CENTER
APL The Johns Hopkins University APPLIED PHYSICS LABORATORY
VEXAG Venus Exploration Analysis Group
JPL

Schedule, Cost, and Milestones



Venus Exploration Overview

The Evolution of Venus

– Why did Venus evolve so differently from Earth?
– Was there ever an ocean on Venus, and if so, when did it exist and how did it disappear?
– Did Venus ever have plate tectonics?
– What caused the extensive resurfacing of Venus during the last Gy?

Venus Today

– Is Venus currently geologically active?
– Why doesn’t Venus have a magnetic field?
– What absorbs sunlight in Venus’ atmosphere?
– How do the surface and atmosphere interact chemically?

Advocacy & Exploration Approach

– Return to Venus with New Technology
– Discovery, New Frontiers, and Flagship
– Only Short-lived Missions Possible Now
– JPL, Goddard, APL Mission Studies
– Decadal Survey Input
– Project and PIDDP Funded Development

Exploring the Inner Solar System

	Inner Solar System Targets			
Fundamental Science Questions	**Mercury**	**Venus**	**Moon**	**Mars**
How did the Sun’s family of planets originate?	⬡	⬢	⬢	⬢
How did the Solar system evolve to its current state?	⬡	⬢	⬢	⬢
Solar System that led to the origin of life?		⬢	⬢	⬢
Does life exist elsewhere in the Solar system?		⬡		⬢
Opportunities for expansion of human presence?			⬢	⬢

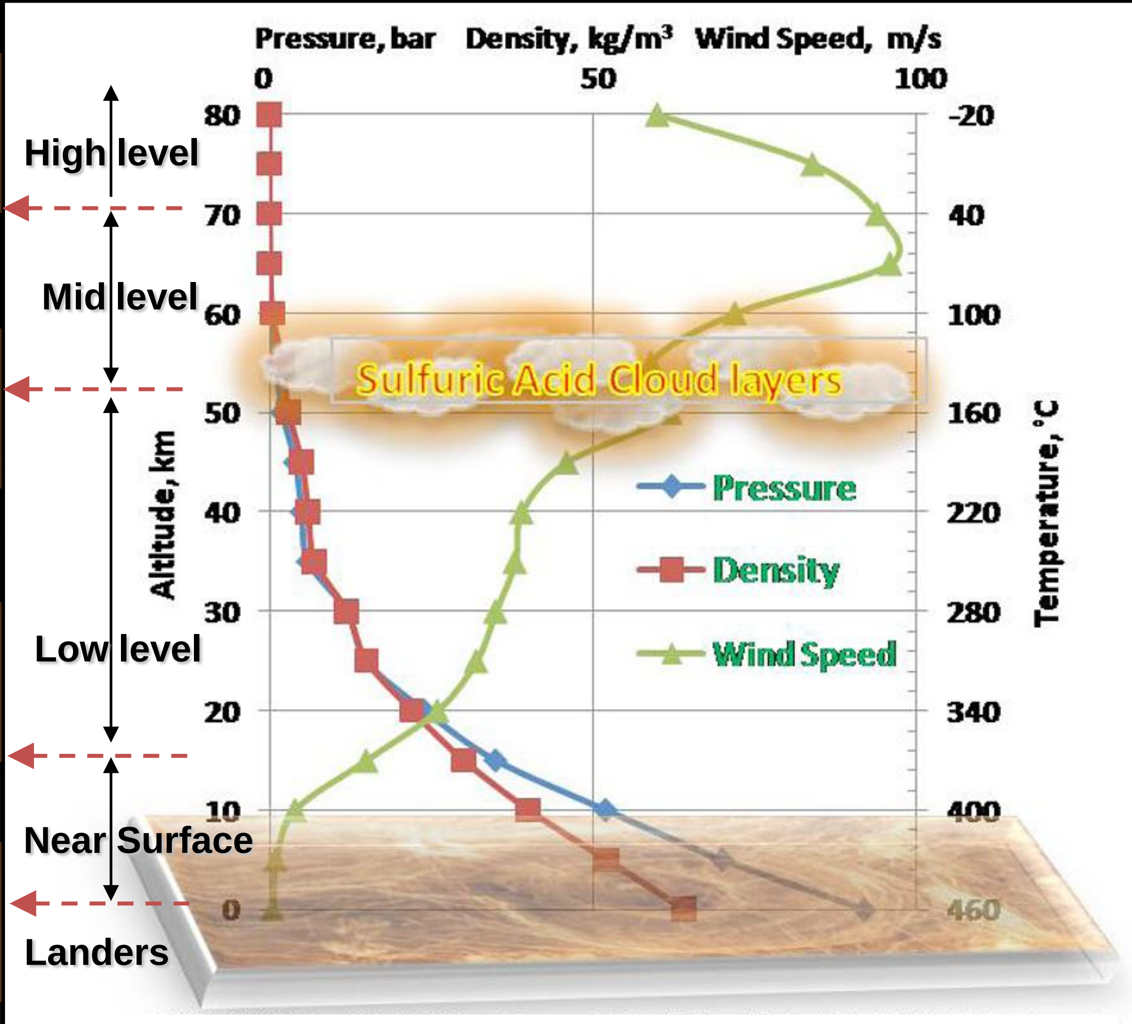
Venus Environment

H = 70 km;
T = 40 C;
p = 3.7E-2 bar;
v(mean) = 92 ms

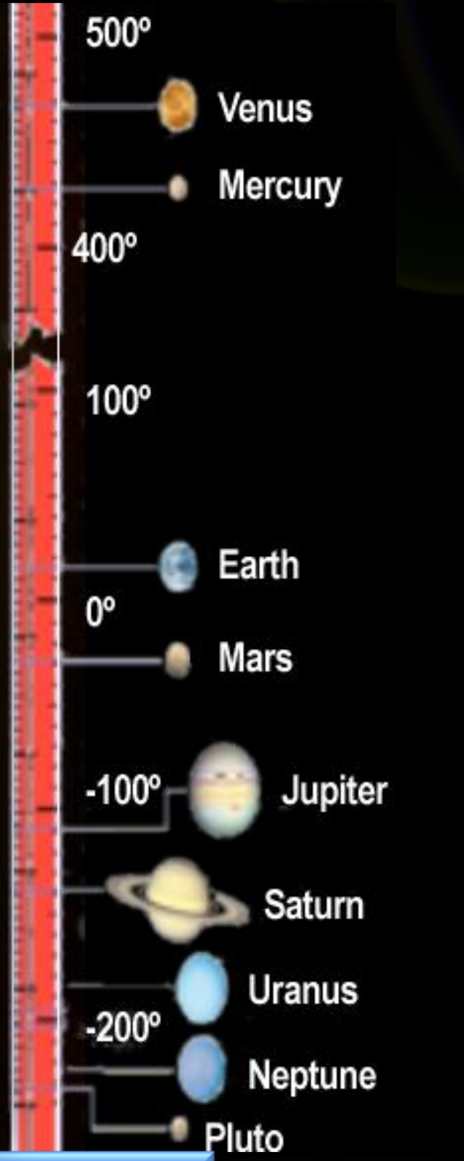
H = 52 km;
T = 150 C;
p = 0.8 bar;
v(mean) = 61 m/s

H = 15 km;
T = 348 C;
p = 33 bar;
v(mean) = 16 m/s

H = 0 km;
T = 462 C;
p = 92 bar;
v(mean) = 0.6 m/s



95.5% CO_2, 3.5% N_2, Trace SO_2, Ar, H_2O, CO, He, Ne, OCS, HCl, HF



Venus environment is the most inhospitable in the solar system. Extended duration surface missions require active lander cooling.

Past and Proposed Venus Surface Missions

NRC Decadal Survey

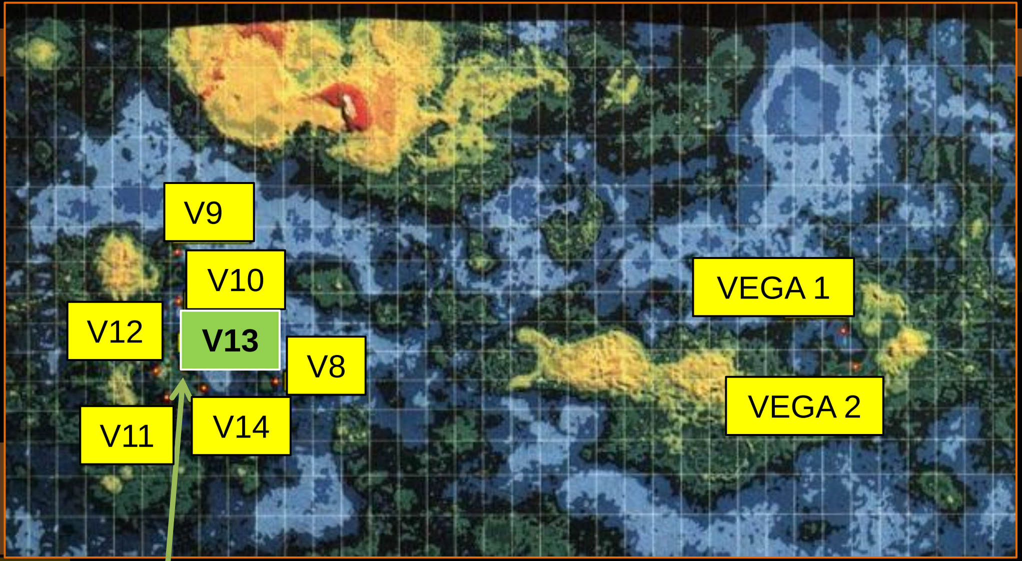
(New Frontiers 2013)

1. South Pole–Aitken Basin;
2. Jupiter Polar Orbiter with Probes;
3. Venus In Situ Explorer (2015); and
4. Comet Surface Sample Return

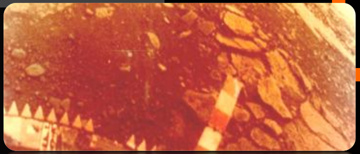
VEXAG/STDT Proposed Flagship Mission 2020

Venus Mobility Explorer –
Several Months Mission
(Air Mobility vs. Rover)
Decadal Survey White Paper

Search for granitic and sedimentary rocks, in-situ analysis of the crust, measurements of oxidation/ mineralogical state of iron

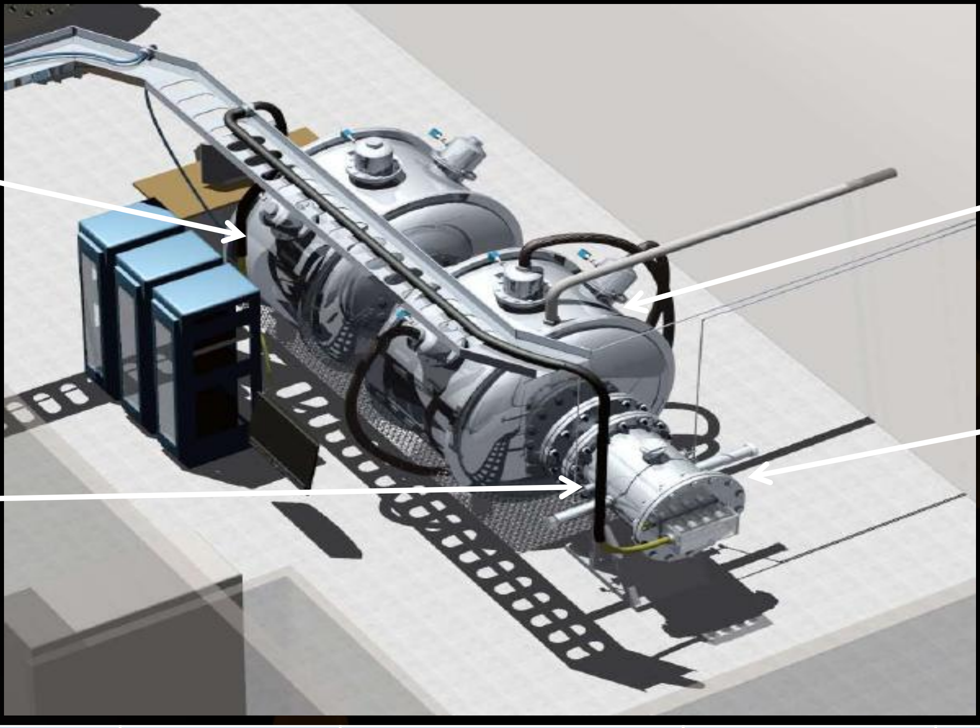


	Launch Date	Arch.	Temp. (°C)	Pressure (bar)	Phase	Alt. (km)	Duration (min)
	1964	Probe	80	5	-	-	-
	1965	Probe	80	5	Entry	200	-
	1967	Probe	300	20	Descent	25	93/0
	1969	Lander	320	27	Descent	20	53/0
	1969	Lander	320	27	Descent	20	51/0
	1970	Lander	460	92	Landed	0	55/23
	1972	Lander	460	92	Landed	0	55/50
Venera 9	1975	Lander	460	92	Landed	0	55/53
Venera 10	1975	Lander	460	92	Landed	0	55/65
Pioneer	1978	Lander	460	92	Landed	0	55/68
Venera 11	1978	Lander	460	92	Landed	0	60/95
Venera 12	1978	Lander	460	92	Landed	0	60/110
Venera 13	1981	Lander	460	92	Landed	0	55/127
Venera 14	1981	Lander	460	92	Landed	0	55/57
VEGA 2	1984	Lander	460	92	Landed	0	55/56



Venus has a history of short-lived surface missions and is being studied as a potential destination for a flagship mission.

Venus Mission Testing Facilities



Phase III : >10' x >10' Mission Testing

Phase II : 7' x 7' Lander Testing

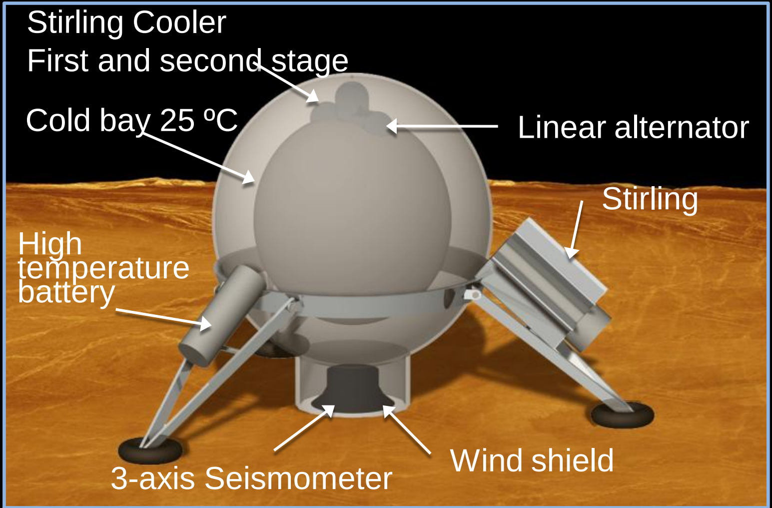
Phase I : 3' x 4' Prototype Testing

30% Design Review Completed

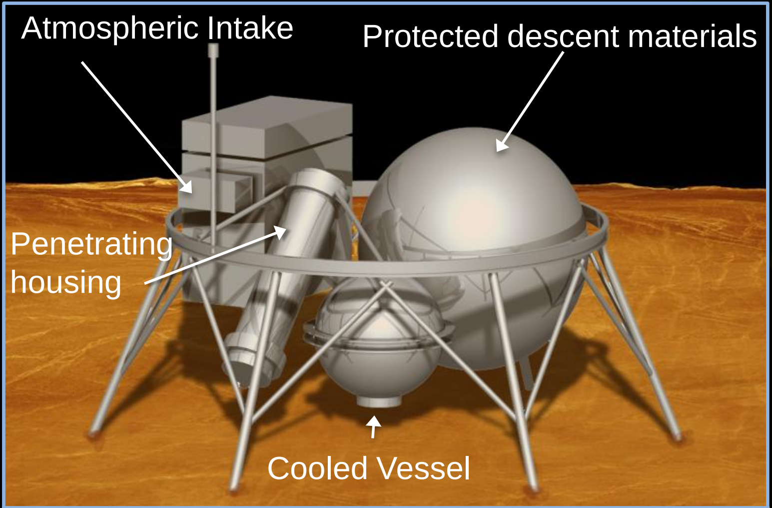
Location	Size (in.)	Pressure(bar)	Temp. (°C)	Gas
Georgia Inst. Tech.	12 x 12	100	343	Variable
Goddard	5 x 12	90	500	CO_2
Jet Propulsion Lab	4 x 54	92	500	CO_2, N_2,trace
M.I.T.	1 x 48	200	700	CO_2

All mission phases can be tested once proposed facility is completed. Note some small facilities currently exist at some universities and Goddard.

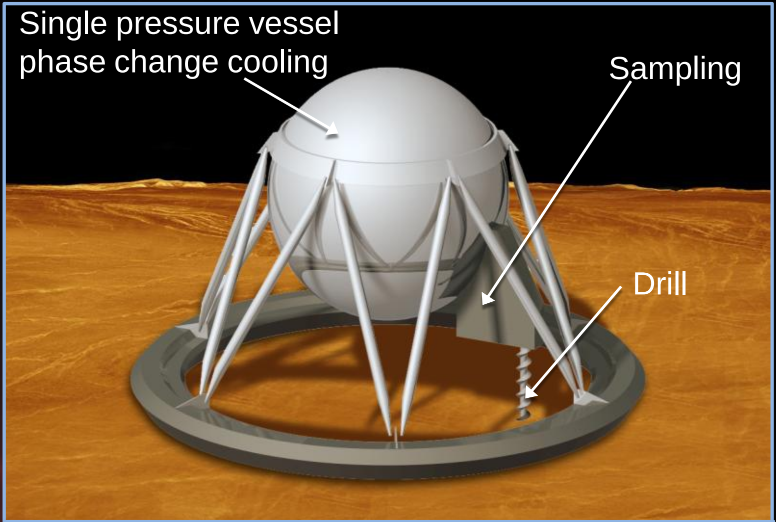
Lander Concepts



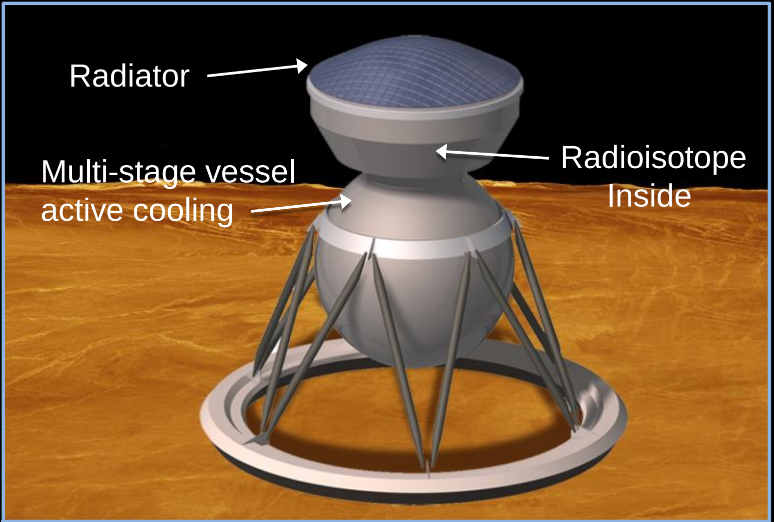
Venus Interior Surface Mission, 1993



Arizona Space Grant Consortium, 2008



Science Technology Definition Team, 2009

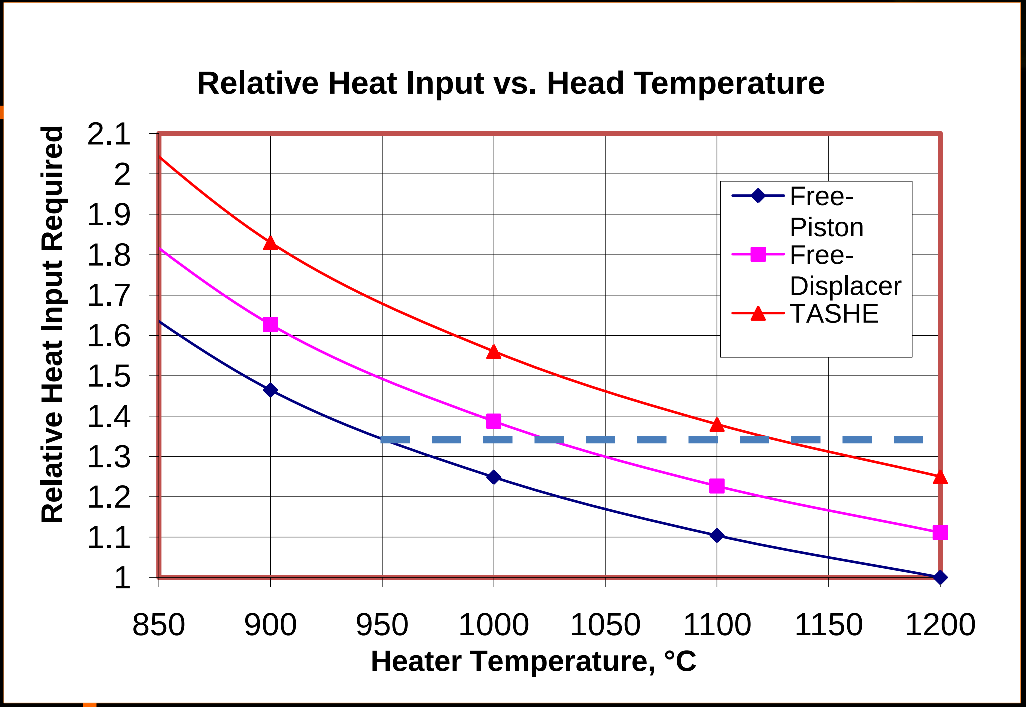


Glenn's Advanced Stirling Duplex, 2010

Power and Cooling Trade-Space

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	-

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	-



Stirling power and cooling offers most potential when combined into duplex

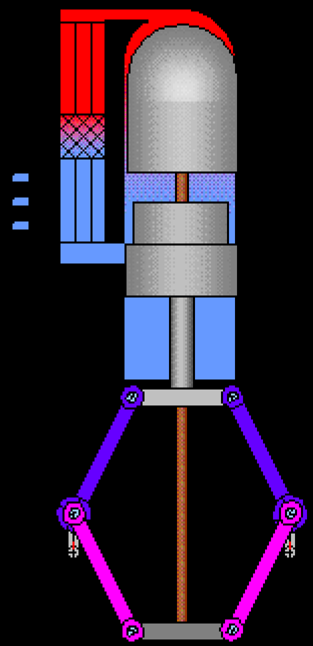
What are the Life Limiting Mechanisms?

Potential life limiting mechanisms
- Wear
- Fatigue
- Creep
- Permeation
- Radiation

Motion does not limit the life

- Wear mechanisms have been eliminated
- Based on non-contacting operation

Kinematic



- Sliding seals
- Rolling element bearings

Free-Piston

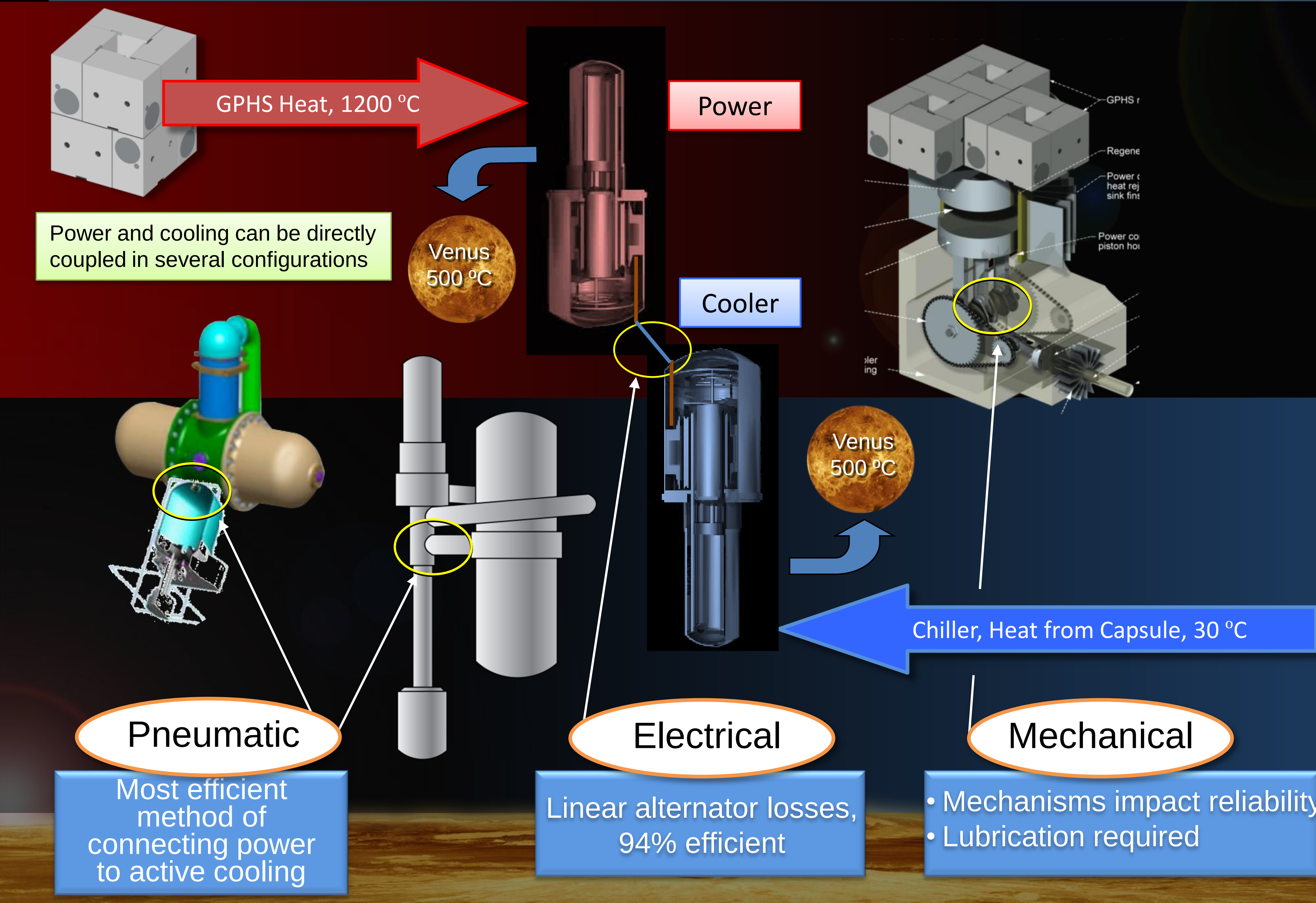
- No sliding seals
- No rolling element bearings

Free-Displacer & Thermo-Acoustic

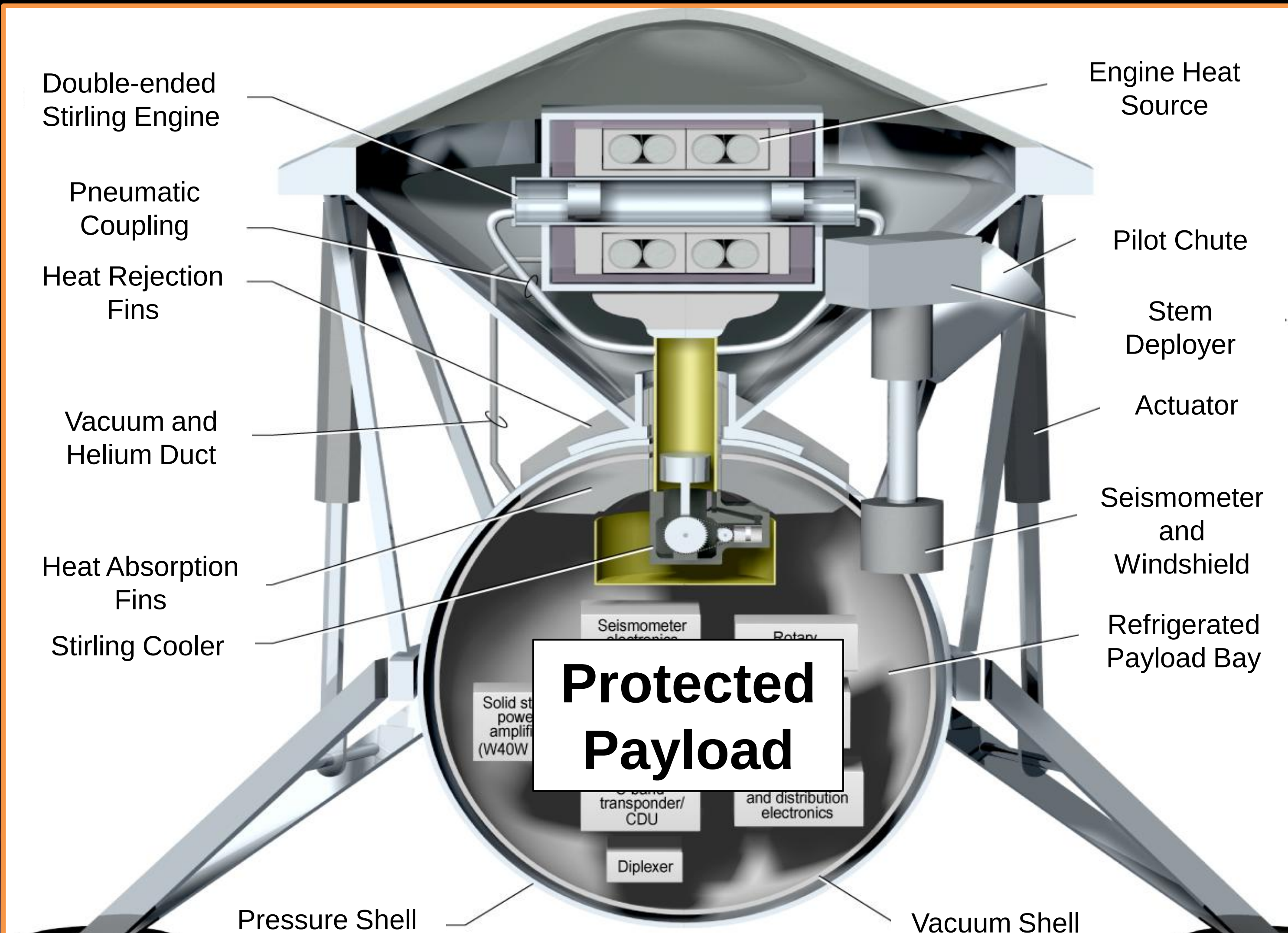
- High amplitude acoustical wave circuit replaces displacer
- One less moving part
- Less efficient, but simpler

Can minimize number of hot moving parts if necessary.

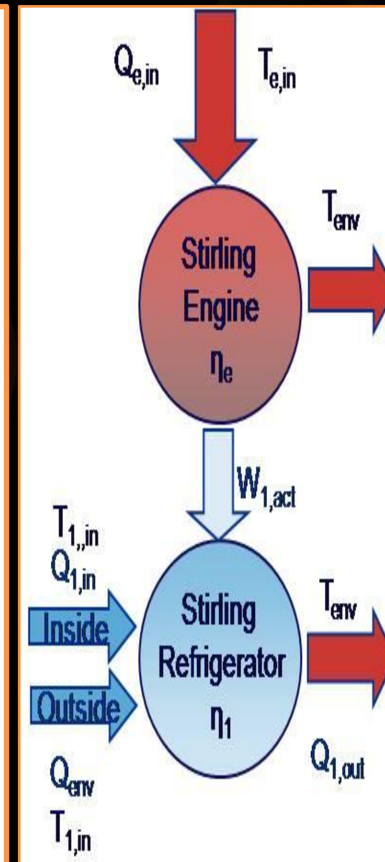
Stirling Duplex Principle of Operation

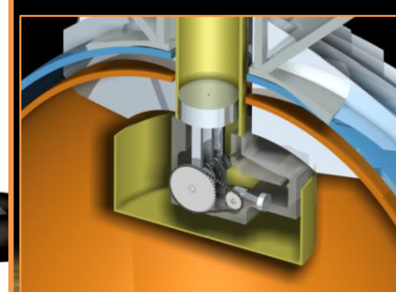


Single-Stage Cooling System

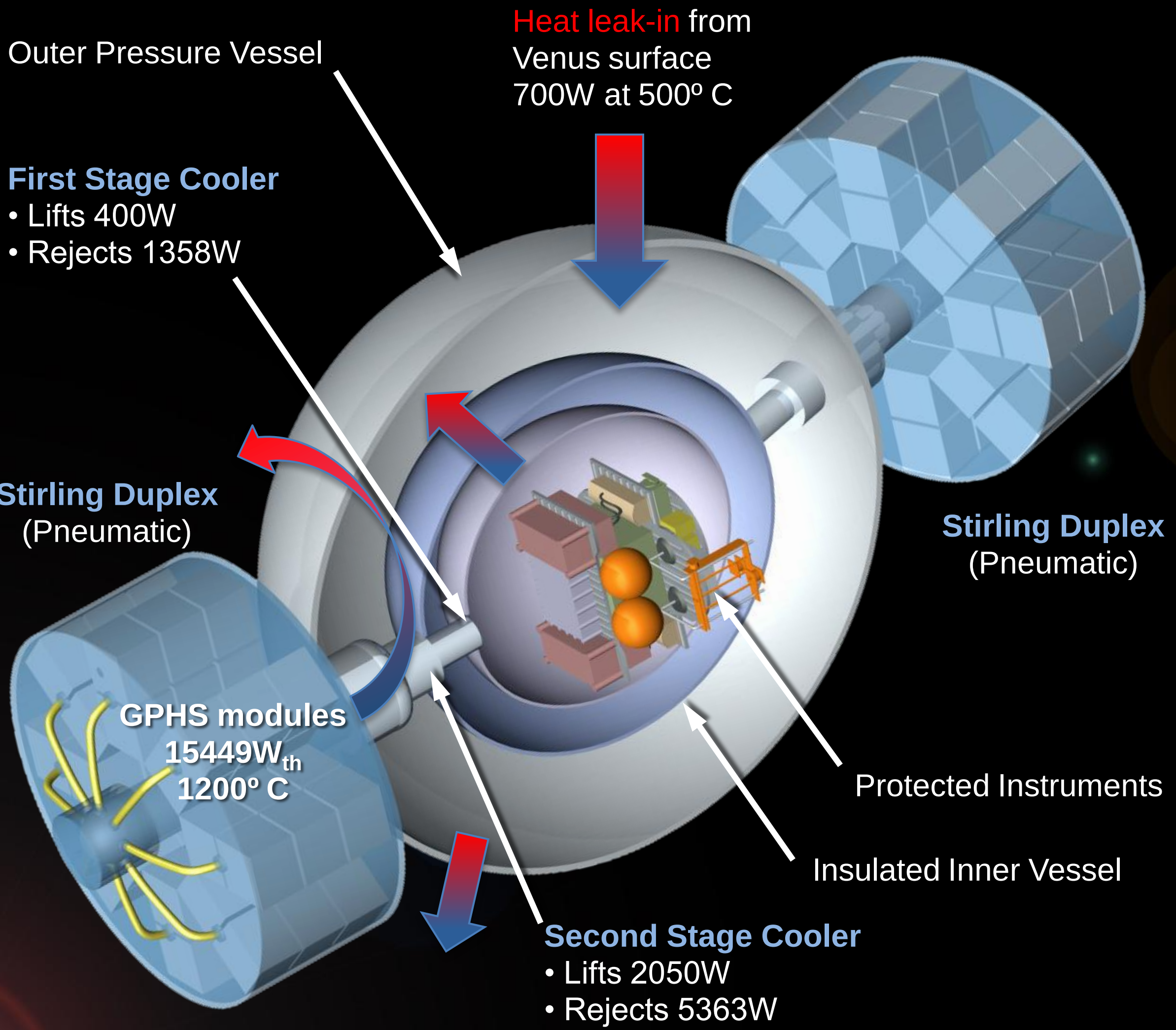


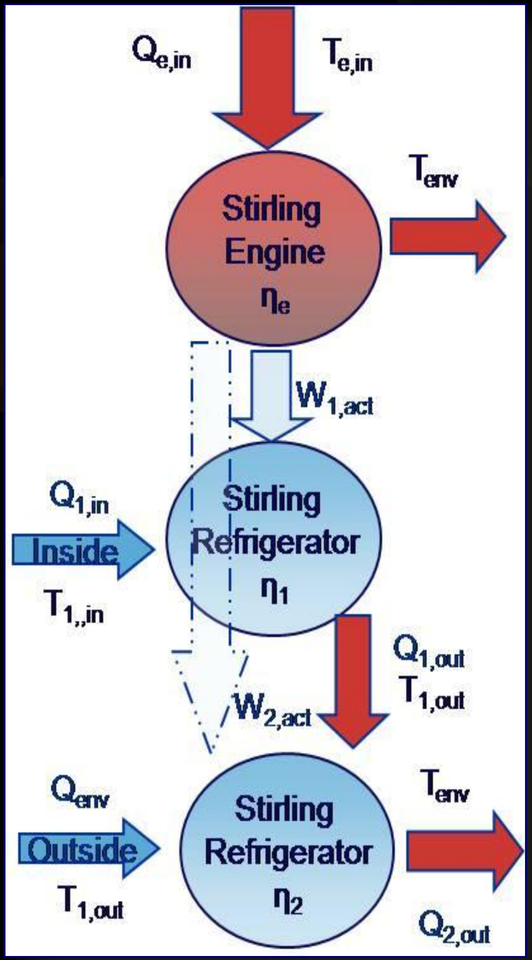
All previous studies assumed single-stage cooling.
Most detailed study was Venus Interior Surface Mission, 1993





Two-Stage Cooler Integration



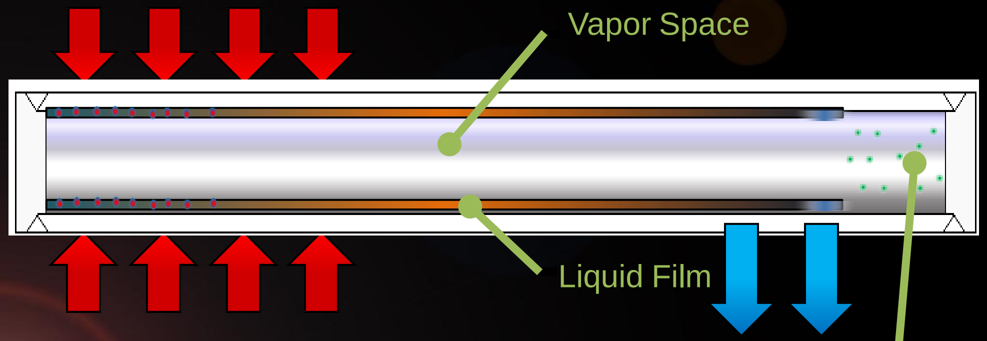


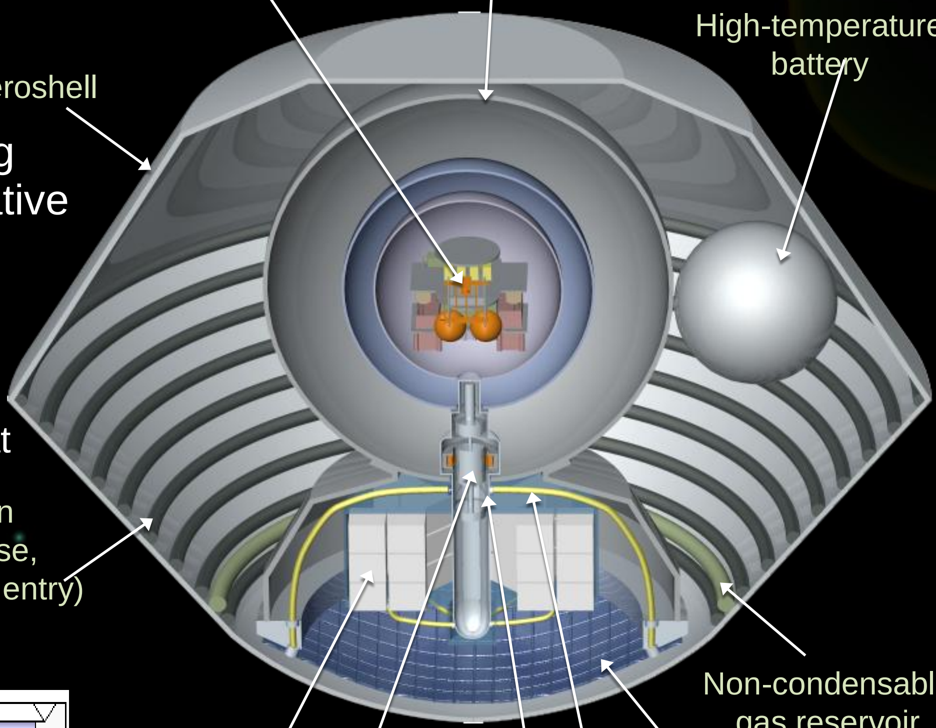
By staging the cooling, the power requirements drop considerably. Shown here are two stages, two additional stages may be optimal

Variable Conductance Heat Pipe

- *Allows option of commanded stop and restart of Duplex for GPHS installation and taking sensitive science data with zero vibration and minimal EMI*
- Ability to protect Duplex heater head during cruise, commanded stop/restart, and alternative isotope intentional over-capacity.

VCHP off during normal operation (NCG covers condenser) –if Duplex overheats, temperature and alkali-metal vapor pressure increase to uncover condenser and remove GPHS heat

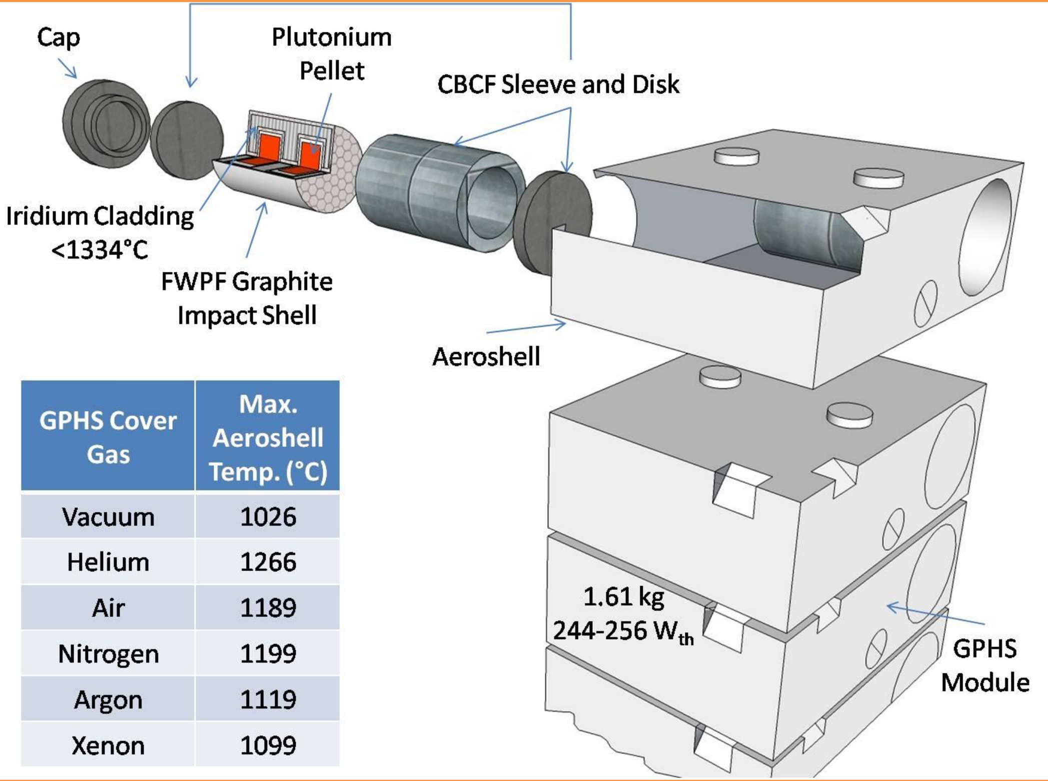




When coupled with energy storage technology, enables quiet seismometer and magnetic field measurements. Also allows the use of alternative isotopes.

Ref. Advanced Cooling Technologies, Inc., W. Anderson & L. Thieme

GPHS Temperature Limits



GPHS Cover Gas	Max. Aeroshell Temp. (°C)
Vacuum	1026
Helium	1266
Air	1189
Nitrogen	1199
Argon	1119
Xenon	1099

- Iridium cladding temperature limit determines GPHS aero-shell max. temperature
- **1266°C maximum possible**

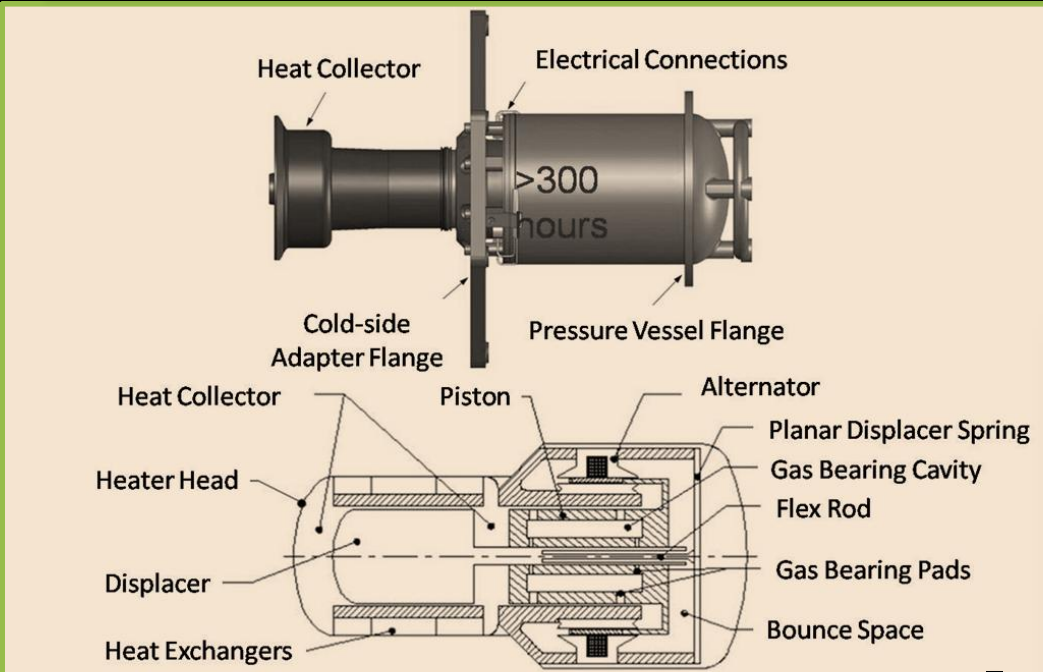
- DOE seeks authorization for new US Pu^{238} production (FY11)

✓First output in 2016, full production by 2018 (1/2 capacity to NASA), 2 to 5kg/yr,

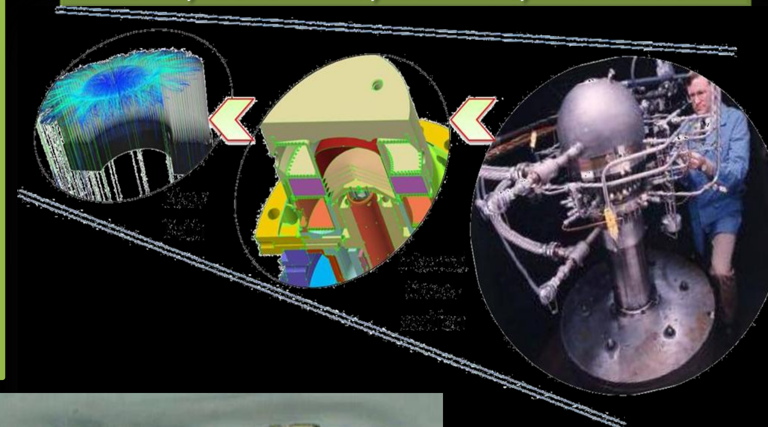
✓3 to 8 GPHS/year

Isotope	Half-life	W/cc	W/g	Cost
Pu-238	89.8 y	3.5	.55	$$$$$
Po-210	138 d	75	141	$
Cm-242	163 d	75	120	$$$$
Cm-244	18.4 y	26.4	2.74	$$$

High-Temperature Stirling Convertors



CTPC Operated at:
777 °C hot-end, 252 °C cold-end,
3-4 hours at max. temp. 1500 hours
total testing (527/127 °C)
70Hz, 15.0 MPa, 12 kWe, Nov. 1992



ASC-1 and ASC-1HS
Single Convertor Operating over 2000 hours
Total hours on all convertors: 3257
850 °C hot-end, **90 °C** cold-end
38% efficient, 1.3 kg, 102 Hz, ~3.6MPa,
88 W up to 114 W, 2005

Venus-like hot-end temperature already demonstrated.

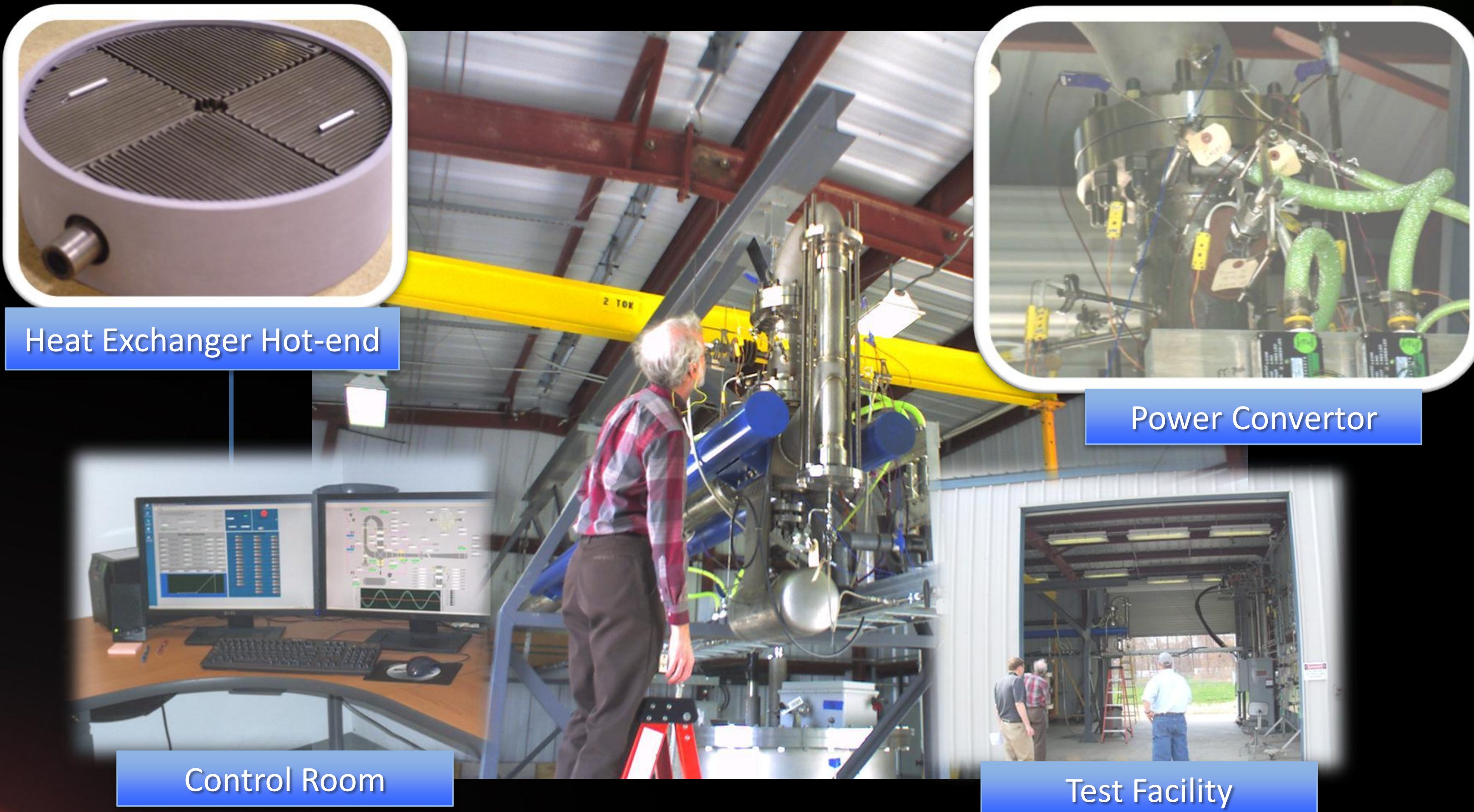
Ref. G. Wood and M. Tward

Northrop Grumman

Sunpower

TASHE Demos	Sunpower	Northrop Grumman
Pressure	3.65 MPa (530 psia)	5.28 MPa (765 psia)
Frequency	100 Hz.	125 Hz.

High Power Thermo-Acoustic Milestone Completed



Successful test of 12000W Full-Scale Heat Engine

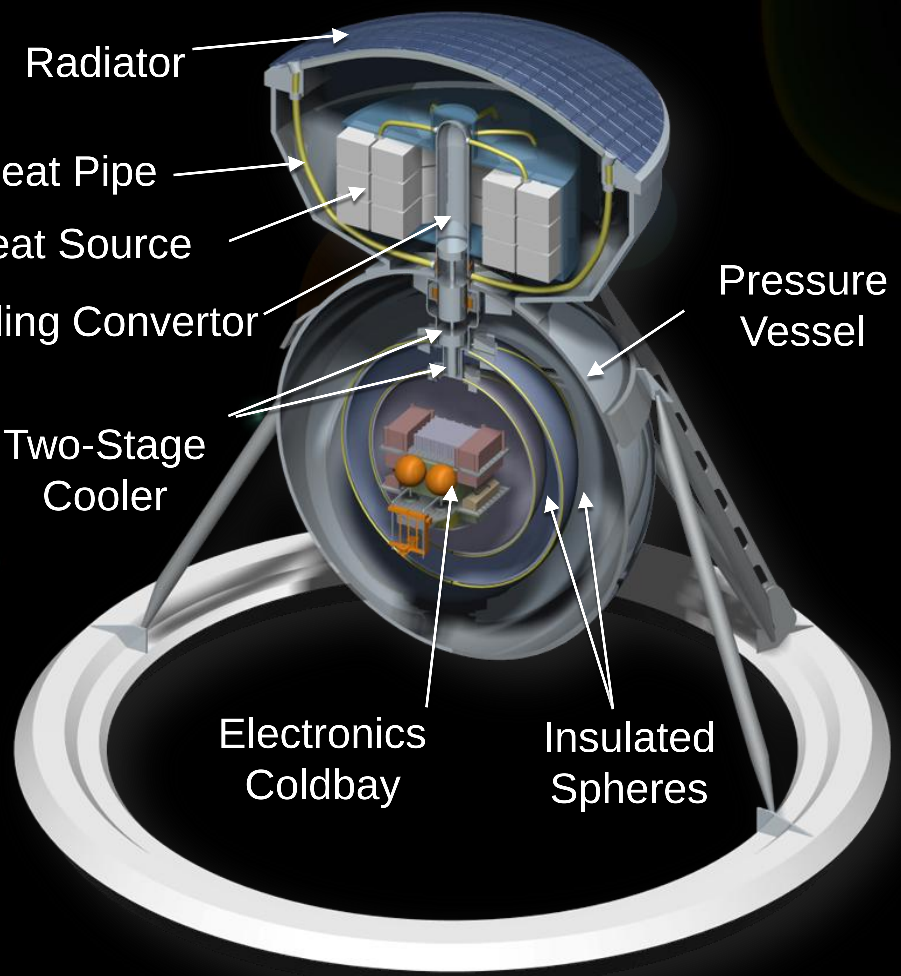
Concluding Technical Challenges

To combine a Stirling heat engine and refrigerator into a long-lived duplex machine with at least two cooling stages.

To achieve a high thermodynamic efficiency that will keep the GPHS module requirements manageable.

To create a complete system design with the multi-stage refrigerator integrated into the Venus platform.

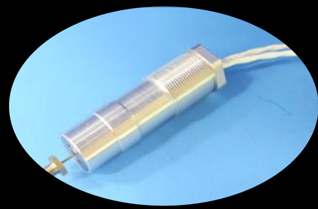
To mitigate potential electromagnetic or mechanical vibration effects.

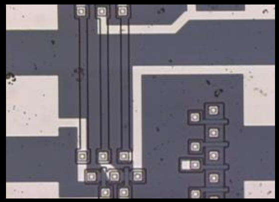


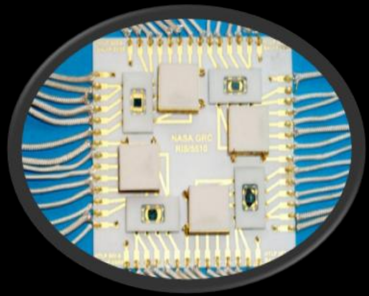
Long-lived Venus Lander mission is possible with Stirling duplex technology

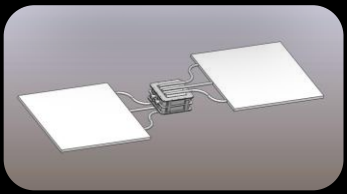
Strategic Technologies and Commercialization

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



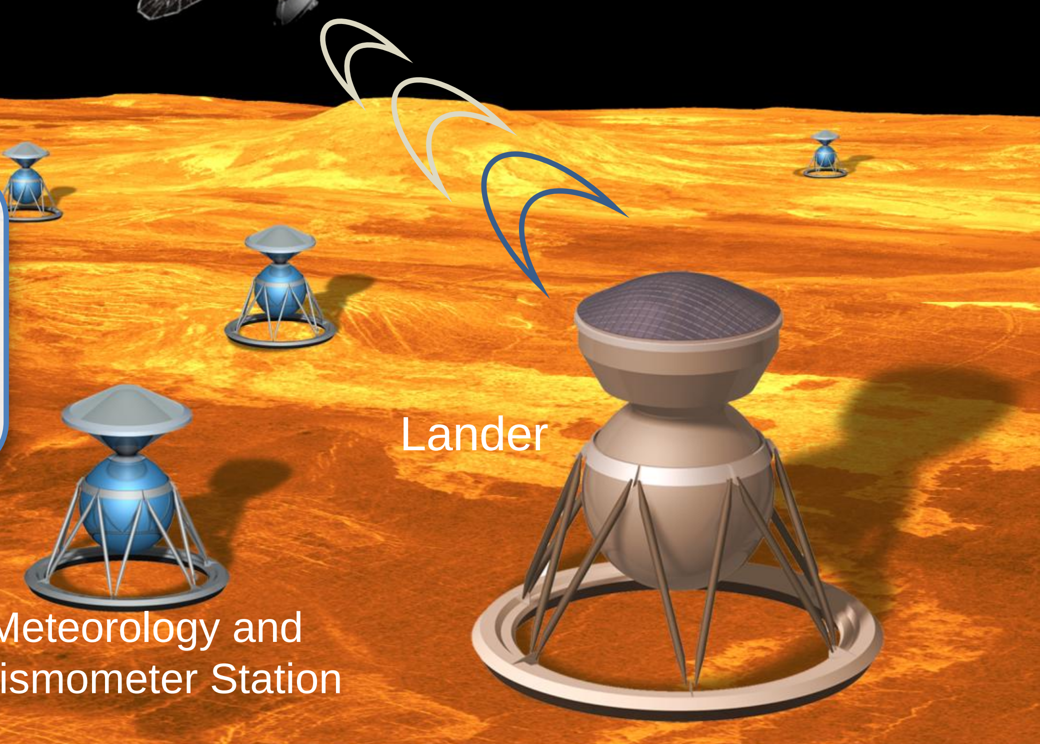






Thermophotovoltaic integration enables no moving part duplex

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

For more information visit:

http://www.grc.nasa.gov/WWW/ASDT

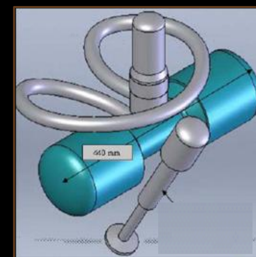
APPENDIX MATERIAL

Advanced Stirling Duplex Technology Development
Science Mission Directorate

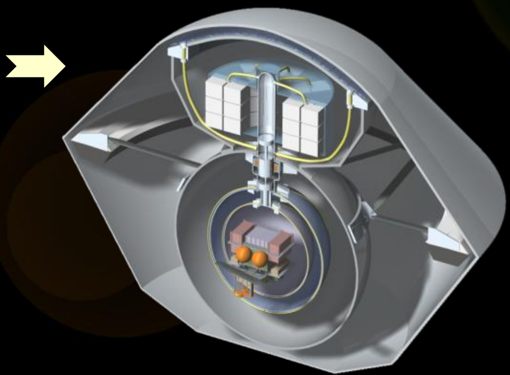
Objective

- Develop the Advanced Stirling Duplex (ASD) to provide power and cooling for long-lived in situ elements on the surface of Venus and other extreme environments.
- Provide 100-400 W_e of power and 1100 W_{th} of cooling for spacecraft electronics and sensors.
- Achieve 55% of Carnot power and 30% of Carnot cooling to minimize use of Pu 238.
- Demonstrate technology by 2015 (TRL 6),

Multi-Stage Vehicle Integration



ASD
By GRC/Industry



Approach

- Develop lower efficiency low vibration thermo-acoustic duplex for long-lived, low power seismometer operation
- Develop higher efficiency free-displacer duplex for Lander, rover, and bellows craft long-lived operation
- Validate design of ASD (materials, structures, etc.)
- Demonstrate use of ASD in Multi-stage Vessel
- Demonstrate reliability of ASD in situ Venus chamber

Key Milestones

- Thermoacoustic Stirling Heat Engine Test – Apr 2010
- Free-displacer Stirling Heat Engine Test –Sept 2010
- Pulse-Tube Stirling Cooler Validation –July 2011
- Free-displacer Stirling Cooler Validation –Sept 2011
- Initial Duplex Testing (Power & Cooling) –June 2012
- Extended Testing in Venus Chamber –Sept 2013
- Deliver TRL 6 Advanced Stirling Duplex –Sept 2015

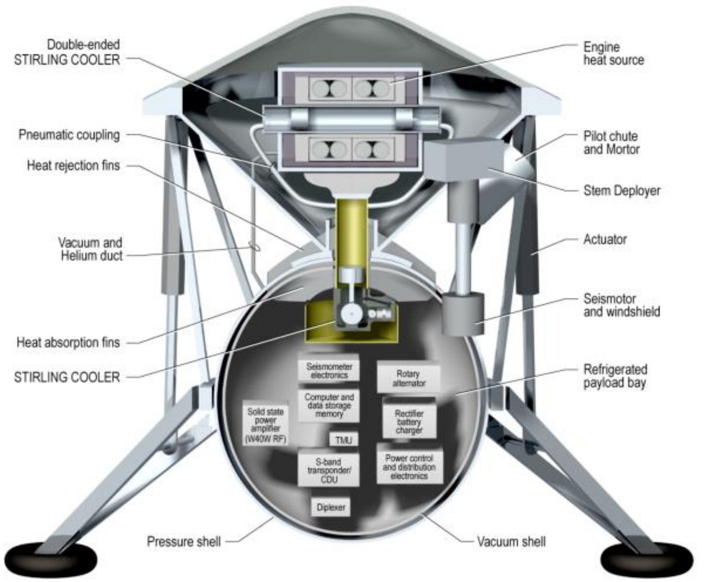
Partners/Co-Investigators

- Sierra-Lobo, Lockheed Martin, Sunpower, Gedeon Assoc.
- Case Western Reserve University, Advanced Cooling Tech.
- Jet Propulsion Laboratory, Goddard Space Flight Center, John Hopkins Applied Physics Lab, Northrop-Grumman

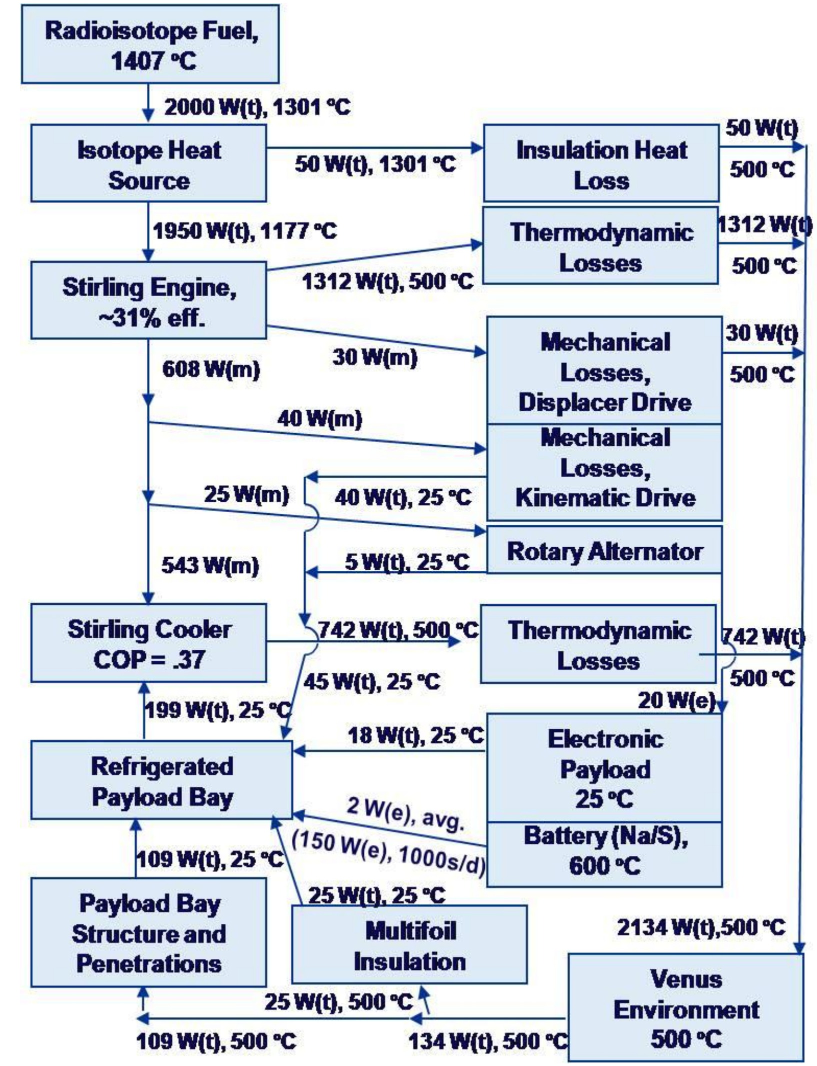
Potential Missions for ASD

	Power	Cooling	
• New Frontiers ~	100 W_e	1100 W_{th}	~ 2018 timeframe
• Venus Flagship ~	400 W_e	1100 W_{th}	~ 2020 timeframe
• Kuiper Return ~	400 W_e	600 W_{th}	~ 2025 timeframe

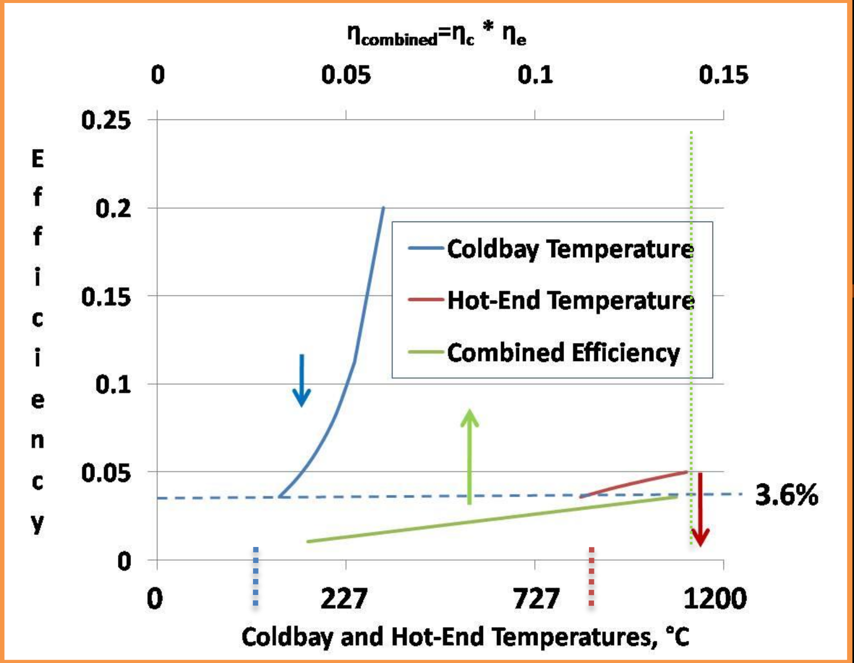
VISM Lander Configuration, 1993

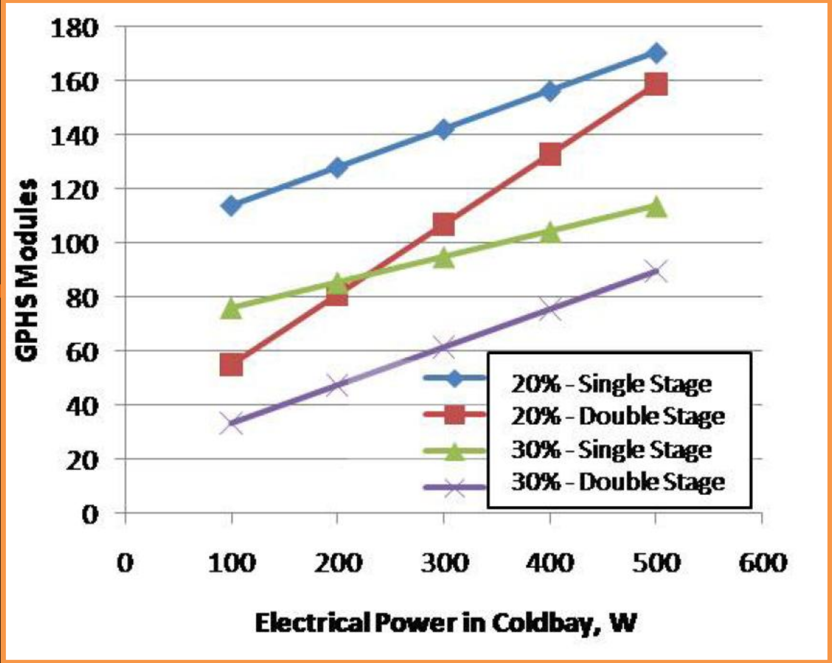


Radioisotope Heat Source (8 GPHS)	**11.6**
Heat Source Canister (Ir)	**4.0**
Multifoil Thermal Insulation (Mo,0.0003", 60 layer)	**1.5**
Heat Source Pressure Shelf (Tl, 0.25" wall, five 0.20" stiffeners)	**9.6**
Stirling Engine (Mo)	**10.0**
Pneumatic Coupling (Tl)	**0.5**
Stirling Cooler & Alternator	**9.1**
Heat Pipes and Radiators	**7.0**
Payload Bay Canister (Tl, 15" dia., 0.025" wall, 25 °C)	**1.3**
Multifoil Thermal Insulation (Nl)	**1.8**
Payload Bay Pressure Shell (Tl, 0.165" wall, 500 °C)	**9.4**
TOTAL Mass (kg)	***65.8***



GPHS Requirements





Single-Stage Duplex Performance

- Assuming 30% of Carnot refrigerator
- Achieves 3.6% system efficiency
- Achieves 5% at max. temp (1200°C)
- Achieves 20% with warmer coldbay

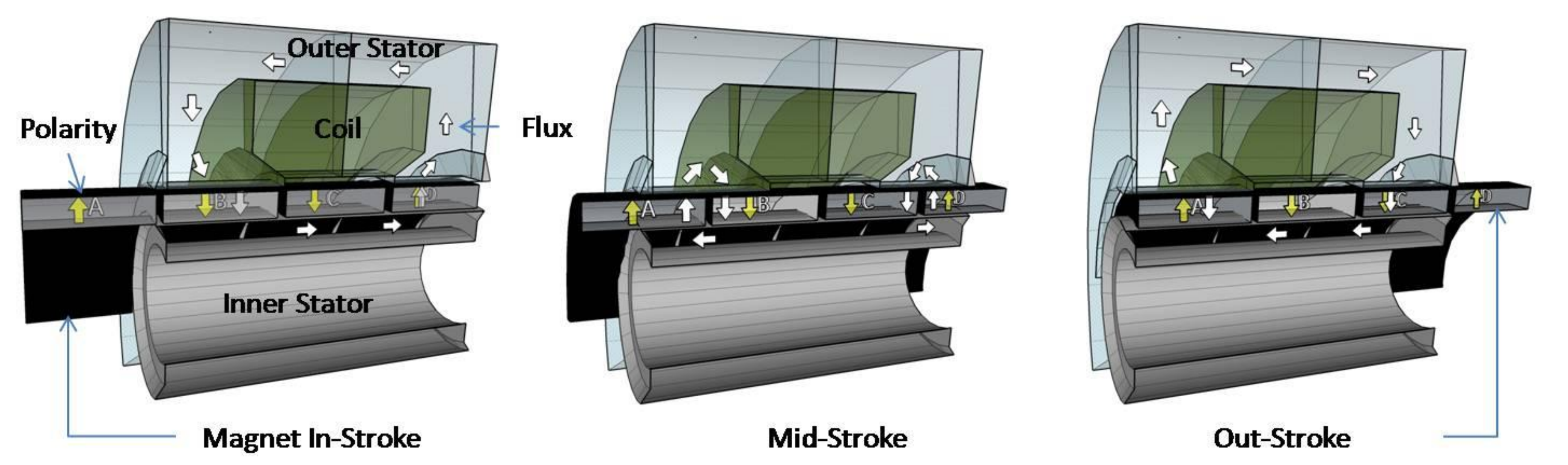
Multistage vs. Single-Stage Cooling

- 55% of Carnot Convertor
- 20 vs. 30% of Carnot cooler
- 700 W heat leak in, 1200°C Hot-end, 250°C Buffer, 30°C Bay

High temperature electronics are important!

High Temperature Alternator Development

- **Option 1: Permanent Magnet Type**
  - Venus ambient temperature ≈ 460 °C
  - Known SmCo type magnets may be used potentially up to 300 °C
    - Magnet Remanence declines with increasing temperatures
- **Option 2: Electromagnet Type**
  - Based on induction generator technology
    - Battery or some other external power source needed during start-up
    - Coil provides magnetic field, not used yet in Stirling industry.



GRC has an existing laboratory for the evaluation and development of high-temperature linear alternators. Wire insulation is primary limiting component, but ceramics could be considered. Fortunately, duplex design can refrigerate itself!

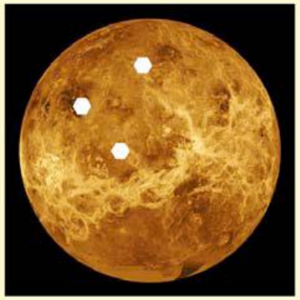
Mission Capability Summary

Flagship Class Mission Concept

Venus Geophysical Network

Scientific Objectives

- Determine the internal structure and seismic activity of the planet
- Monitor the circulation of the atmosphere

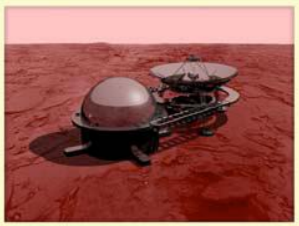


Exploration Metrics

- At least three stations on the surface of Venus
- Operate for at least one Earth year

Science Payload

- Camera, descent imager
- Seismometer network
- Meteorology station with pressure, temperature and wind velocity sensors



Technology & Heritage

- Extreme-environments technologies (pressure vessel, thermal management, corrosion)
- High-temperature electronics for telecom / high-data volume
- Radioisotope power system w/ active cooling
- Long-duration operations in situ
- Passive insulation and survival technology from VISE

Mission & LV Class

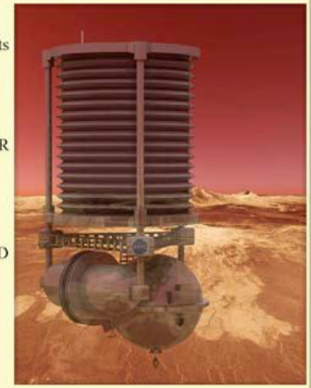
- Flagship Class Mission
- Launch Vehicle(s): TBD

Flagship Class Mission Concept

Venus Mobile Explorer

Scientific Objectives

- Composition and isotopic measurements of surface and atmosphere
- Near IR descent images
- Acquire and characterize core samples at multiple sites
- Demonstrate key technologies for VSSR



Exploration Metrics

- Operate in Venus surface environment for 90 days+
- Range and altitude if aerial vehicle TBD
- Range across surface if rover TBD

Science Payload

- Neutral-mass spectrometer with enrichment cell
- Instruments to measure elements and mineralogy of surface materials
- Imaging microscope

Technology & Heritage

- Extreme-environments technologies (pressure vessel, thermal management, corrosion)
- High-temperature electronics
- Sample acquisition and handling in Venus near-surface environment
- Air-mobility system (e.g., metallic bellows)
- Radioisotope power system w/ active cooling
- Long-duration operations in situ

Mission & LV Class

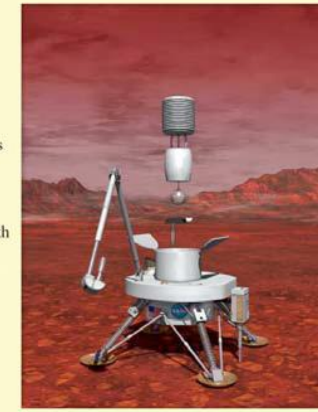
- Flagship Class Mission
- Launch Vehicle:
  - Delta-IV-H
  - Atlas V

Flagship Class Mission Concept

Venus Surface Sample Return

Scientific Objectives

- Measure isotopic composition of oxygen in surface rocks
- Measure isotopic composition of trace elements to characterize core-and-mantle formation
- Determine the age of returned rocks



Exploration Metrics

- Return samples of Venus rock soil and atmosphere for analysis on Earth
- Mission duration: TBD
- Time on surface: TBD (short lived)

Science Payload

- Camera and Descent imager
- Sample identification as needed
- Sample-acquisition system
- In-situ instrumentation

Technology & Heritage

- Extreme-environments technologies (pressure vessel, thermal management, corrosion)
- High-temperature electronics
- Sample acquisition and handling in Venus near-surface environment
- Multi-stage ascent air-mobility system to lift sample to launch altitude
- Rendezvous and sample-return systems inherited from Mars Sample Return
- Heritage from prior Venus missions: e.g., VISE, Venus Geophysical Network, VME

Mission & LV Class

- Flagship Class Mission
- Launch Vehicle: TBD

- Stirling duplex enables both power and cooling.
- Hot-end temperature of 850 °C has been demonstrated for 300 hours without failure.
- Cryocoolers have successfully operated in space since 1971 for thousands of hours at similar to Venus temperature ratios

VEXAG flagship class missions specifically suggest the use of a radioisotope power system with active cooling for **three out of the four concepts,** including Venus Surface Sample Return.

- Numerous studies over the past 15 years have indicated the need for duplex Stirling power/cooling on Venus.
- GRC and Industry partnered to develop flight convertors for the radioisotope generator and are primed to begin development for the Venus application.

Ref. VEXAG report

Contributors

Randy Bowman, GRC
Rodger Dyson, GRC
Steve Geng, GRC
Jan Niedra, GRC/ASRC
Paul Schmitz, GRC/PCSI
Jeff Schreiber, GRC
Eugene Shin, GRC/OAI
Roy Tew, GRC
Lanny Thieme, GRC
Wayne Wong, GRC

Scott Backhaus, LANL
Pete Chapman, FM
John Corey, CFIC
David Gedeon, GA
Barry Penswick, Sest, Inc.
Mike Petach, NGST
Jeff Raab, NGST
Ellen Stofan, VEXAG
Nick Vitale, FM
Tom Walters, FM
Gary Wood, Sunpower