LONG-LIVED VENUS LANDER TECHNOLOGIES

A Brief Discussion Of Technologies Relevant To Long-lived Landers For Venus Exploration

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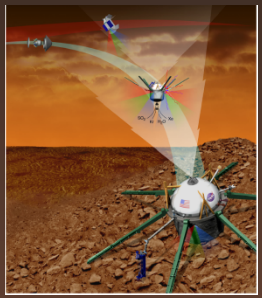
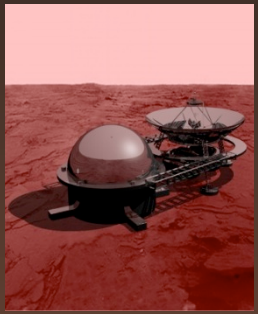
From the STDT Final Presentation
Surface Science Enhancements



Seismometer and Meteorological Network

- Require long-lifetime measurements on the surface to
- Provide measurements of the size-frequency distribution of seismic events
- Surface meteorology with measurements such as temperature, wind speed and direction, and pressure
- Provide correlation between observed planetary events and changes in weather conditions



Long-Lived (months) Landers

- Sample multiple sites and multiple depths for a complete survey of the elemental composition, mineralogy, and chemistry of the landing site
- Acquire long-duration observations in time-varying phenomena like seismometry, meteorology, and wind
- Decrease mission risk and optimize science return by providing missions with complete instruments operation for extended period of time
- Humans in the loop during mission operation

Required technologies: Refrigeration, high temperature sensors and high temperature electronic components, balloon materials

OUTLINE

- INTRODUCTION
- STIRLING BASED POWER AND COOLING
- HIGH TEMPERATURE ACTUATION AND MOTORS
- HIGH TEMPERATURE ELECTRONICS AND COMMUNICATIONS
- HIGH TEMPEATURE POWER
- HIGH TEMPERATURE SENSORS
- VENUS METEOROLOGY
- VENUS SEISMOMETRY
- POSSIBLE SCENERIO

A BRIEF OVERVIEW WILL BE GIVEN OF THESE TECHNOLOGIES HIGHLIGHTING THE MORE ADVANCED DEVELOPMENTS AND NOTING TECHNICAL CHALLENGES

A RANGE OF APPROACHES MAY BE EXAMINED. FURTHER STUDIES ARE NECESSARY FOR AN OPTIMAL CONFIGURATION.

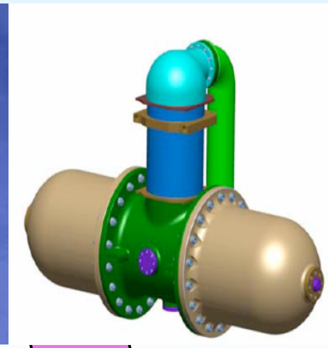
LONG-TERM POWERS SOURCES (500 WE & 1200W HEAT LIFTED FOR 117 DAY MISSION).

Approach	Properties
Radioisotope Thermoelectric	Efficiency ~3% on Venus (T_{hot}=850ºC, T_{cold}=500ºC) Difficult to couple with efficient active cooling Demonstrated in space, and will be used on Mars (MSL) Thermoelectric (Chmielewski 1989, Wong 2004) conversion approaches are possible
Radioisotope Brayton/Rankine	Requires high speed turbomachinery Speed reduction for mechanical coolers (Mason, 2006)
Radioisotope Free-Piston Stirling	Overall efficiency ~17% on Venus (T_{hot}=850 ºC, T_{cold}=500 ºC) Duplex system couples engine with active cooling (Schreiber 2006, Shaltens 2006)
Radioisotope Thermo-Acoustic Stirling	Overall efficiency ~13% on Venus, (T_{hot}=850 ºC, T_{cold}=500 ºC) Duplex system couples engine with active cooling (Abelson et al. 2005) Eliminate displacer with some reduction in performance. (Schreiber, 2006)
Solar Array	Efficiency of known photovoltaics is near zero at Venus surface temperatures at standard optical frequencies. (Landis, 2008)
Battery	Secondary batteries require charging (Harrison and Chapman, 2008) Primary batteries limit mission duration (Kolawa et al., 2007; Cutts et al., 2007 ; Balint et al., 2007)
Microwave beamed power	Station in atmosphere produces solar power; power is transmitted to surface by microwaves Not demonstrated in Venus environment Very low technology maturity, with many technical questions need to be answered; not yet considered a viable option

Principles of Stirling Convertor Operation

Sunpower Advanced Stirling Convertor

Northrop Grumman Thermo-Acoustic Convertor



The Stirling cycle engine, when integrated with a linear alternator, becomes a Stirling cycle power convertor

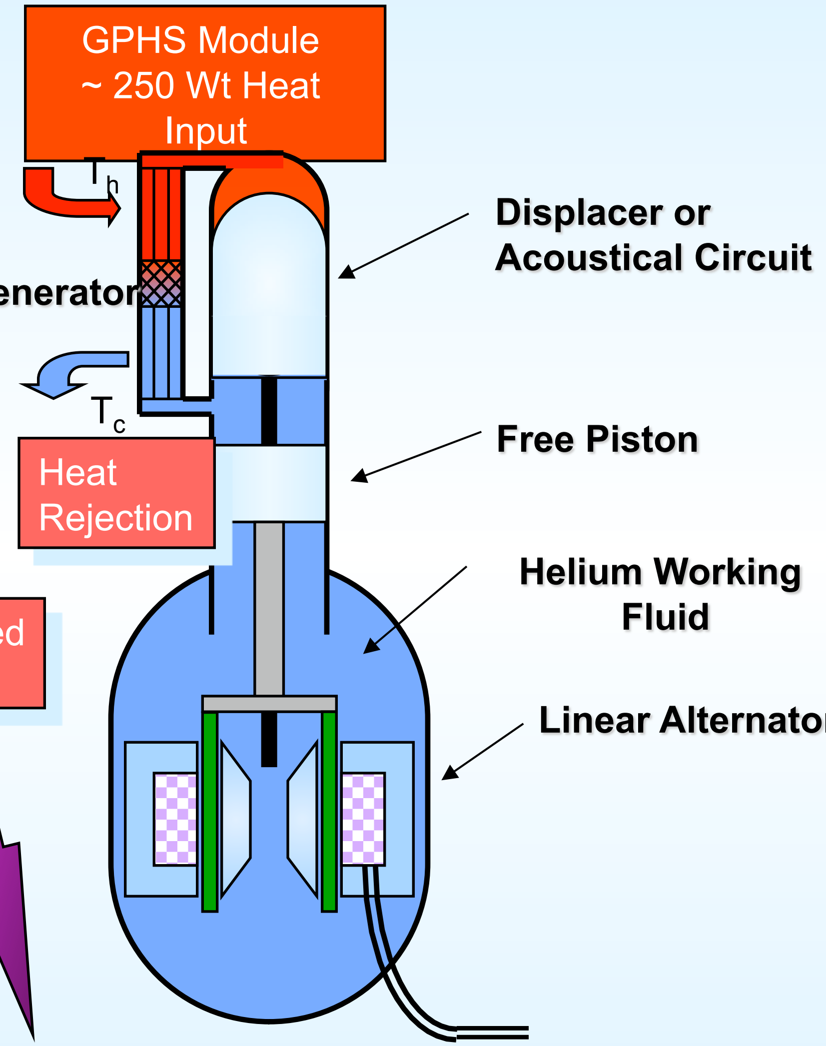
With proper masses, spring rates and damping (dynamic/acoustic tuning), the convertor will resonate as a Free-Piston or Thermo-Acoustic Stirling Thermodynamic Cycle Convertor

- All Wear Mechanisms Have Been Eliminated By Design
- Long Life Operation Is Based On Non-Contacting Operation

Heat In

Is Converted To

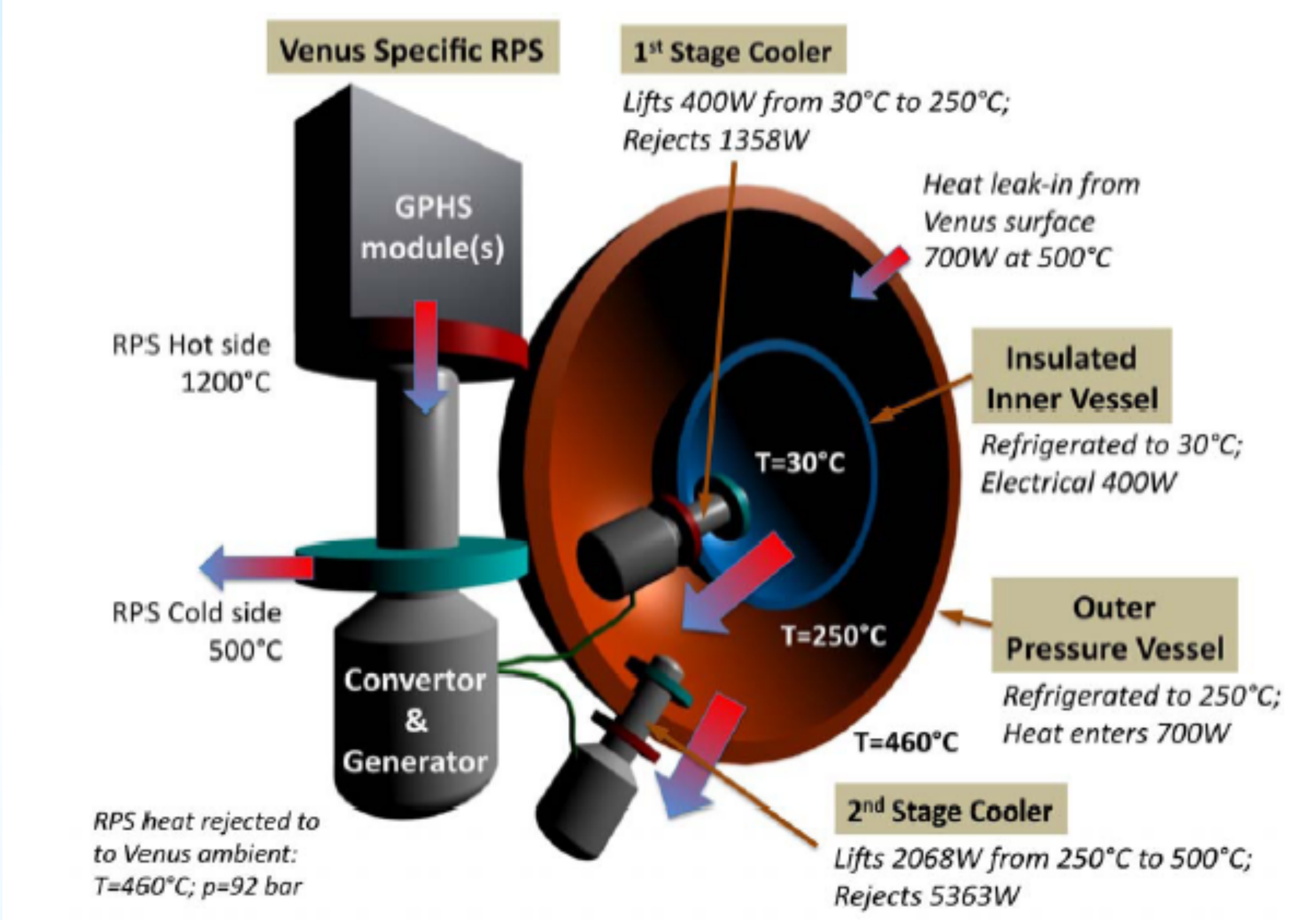
Electric Power Out



A BRIEF REVIEW OF VENUS COOLING OPTIONS

Approach	Characteristics
Thermoelectric	Inefficient at Venus temperature ratios (<1% of Carnot)
Reverse Brayton	High speed turbomachinery as is currently operating on Hubble Space Telescope, but less efficient than Stirling cycle
Free-Piston Stirling	Rotating or free piston linear configurations are possible Cryocooler currently operating on NASA spacecraft(25% of Carnot)
Free-Displacer Stirling	Novel concept being developed under SBIR activities [Sun Power SBIR contract,] . Hybrid between free-piston and thermo-acoustic Stirling (22% of Carnot)
Thermo-Acoustic Stirling	Eliminates the need for a displacer Many are currently operating on NASA/DOD/NOAA spacecraft (17% of Carnot)
Multi-stage Rankine/Brayton	High speed turbomachinery, high temperature motors Requires staging integrated into design (not yet developed)
Mixed Refrigerant Cycle	Terrestrial systems commonly used for natural gas liquefaction. High temperature Venus systems require different refrigerants, early development work in progress

MULTISTAGE STIRLING BASED POWER/COOLING ON VENUS



Heating and Cooling Load	# Cooling Stages	# GPHS Required
Case 1: Complete Lander (400 W Heating/700 W Cooling)	1	94
	2	72
	3	54
Case 2: Lander Subset (100W Heating/700 W Cooling)	1	65
	2	31
	3	17

VENUS POWER AND COOLING TECHNOLOGY

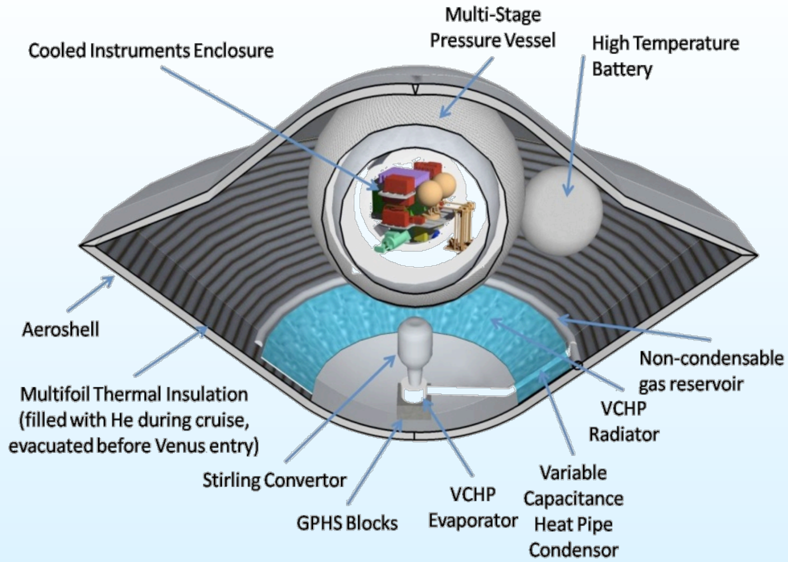
Long-lived Venus lander mission is possible with Stirling duplex technology but technical challenges remain

STATUS

- **Hot-end temperature of 850 ºC demonstrated for 300 hours without failure.**
- **Cryocoolers successfully operated in space since 1991 for thousands of hours at temperature ratios similar to Venus**
- **Introductory Work Has Begun In FY10 Related To Integrated Stirling Heat Engine And Refrigerator Into A Long-lived Duplex Machine**

TECHNICAL CHALLENGES INCLUDE:

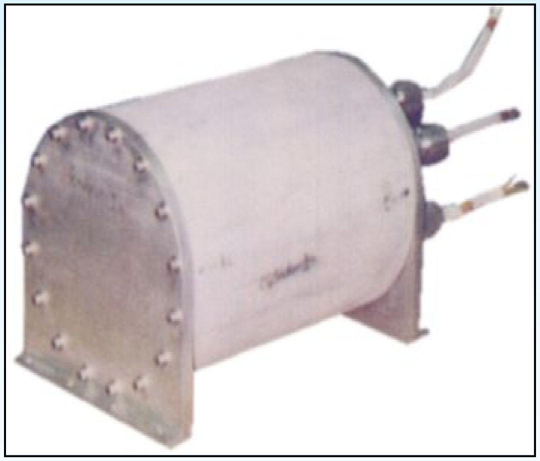
- **Combine a Stirling heat engine and refrigerator into a long-lived duplex machine with at least two stages of cooling**
- **Achieve a high thermodynamic efficiency that will keep the GPHS module requirements manageable**
- **Create a complete system design with the multi-stage refrigerator integrated into the Venus platform (lander, rover, balloon) and mitigate potential mechanical vibration effects**



Courtesy R. Dyson, NASA GRC

VENUS BATTERY POWER

- A RANGE OF BATTERIES CAN BE CONSIDERED FOR VENUS OPERATIONS
- ONE EXAMPLE BATTERY CHOICE IS SODIUM SULFUR
  - OPERATION DEMONSTRATED AT VENUS TEMPERATURE AND PRESSURE
  - COMMERCIALLY AVAILABLE FOR TERRESTRIAL APPLICATIONS; 220 W-HR/KG (EXISTING)
  - FLIGHT-TESTED IN SPACE
- CAN PROVIDE POWER FOR LOW POWER SYSTEMS, BUT PROBLEMATIC FOR LONG-TERM HIGH POWER OPERATIONS



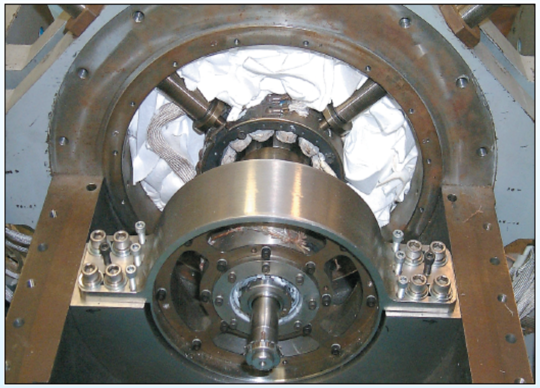
Sodium Sulfur battery flown on STS-87 10 day space shuttle demonstration experiment in 1997

Characteristic	LiAl–FeS2	Na–NiCl2	Na–S
Operating temperatures (°C)	400–475	220–500	290–450
Open circuit voltage (V)	1.73	2.58	2.08
Discharge voltage range (V)	1.2–1.8	2.1–2.5	1.7–2.0
Theoretical specific energy (Wh/kg)	490	800	755
Specific energy for batteries (Wh/kg)	Near 100	90–130	80–220
Energy density for batteries (Wh/l)	Near 150	70–130	90–150
Cycle life (cycles)	>1000	>1000	2000
Energy efficiency (%)	80	80	80

Significant improvements feasible with technology development

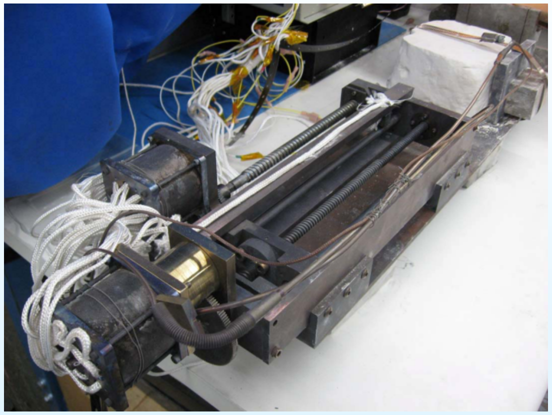
HIGH TEMPERATURE ACTUATION AND MOTORS

- HIGH-TEMPERATURE MOTORS, DRILLS, AND ACTUATORS WILL BE ENABLING FOR ROCK DRILLING AND FOR OTHER ELECTROMECHANICAL MISSION ELEMENTS OPERATING AT VENUS TEMPERATURES
- A RANGE OF SYSTEMS UNDER DEVELOPMENT
- MOTOR SYSTEM DEMONSTRATED TO BE OPERATIONAL AT VENUS TEMPERATURES
    - A SWITCH RELUCTANCE ELECTRIC MOTOR HAS BEEN SHOWN TO RUN INDEFINITELY, DRILLING INTO CHALKS WITH NO GEAR REDUCTION AT VENUS TEMPERATURES (HONEYBEE)
    - BRUSHLESS DC MOTORS ARE ALSO UNDER DEVELOPMENT
- LIMITED WORK HAS BEEN PERFORMED ON HIGH TEMPERATURE LUBRICANTS AND KEY DRIVE-TRAIN COMPONENTS, SUCH AS PLANETARY GEAR HEADS AND HARMONIC DRIVES
- TARGETED DEVELOPMENT AND TESTING FOR VENUS TEMPERATURES AND PRESSURES NECESSARY



Switched-Reluctance Motor: 8,000 rpm at 540°C (NASA GRC)

Brushless High-temperature DC motor (Honeybee)



High-temperature drill

MEDIUM TEMPERATURE ELECTRONICS

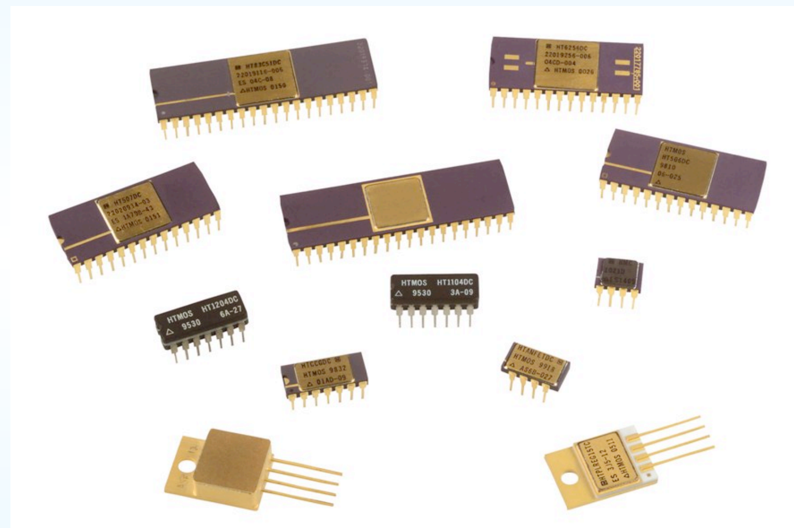
- A RANGE OF PARTS ARE AVAILABLE BASED ON SILICON ON INSULATOR (SOI) TECHNOLOGY
- OPERATIONAL TO 300˚C FOR EXTENDED TIMES

High Temperature SOI Part Availability from Honeywell
(Courtesy of Dewey Benson, Honeywell)

Standard Catalog Products:

- HTOP01 Dual Precision Op Amp
- HT1104 Quad Operational Amplifier
- HT1204 Quad Analog Switch
- HTPLREG Voltage Regulators
- HT83C51 8-bit Micro Controller
- HT6256 256Kbit SRAM (32K x 8)
- HT506 Analog Multiplexer (16:1)
- HT507 Analog Multiplexer (8:2)
- HTCCG Crystal Clock Generator
- HTNFET N-channel power FET

2 Million Device Hours Worth
Of Life Test Data

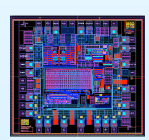
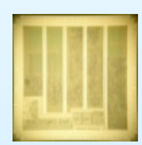


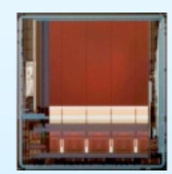
Custom Capabilities:

- Gate Arrays
- MCM (Multi-Chip Modules)
- High Temperature Design Services

Products in Development:

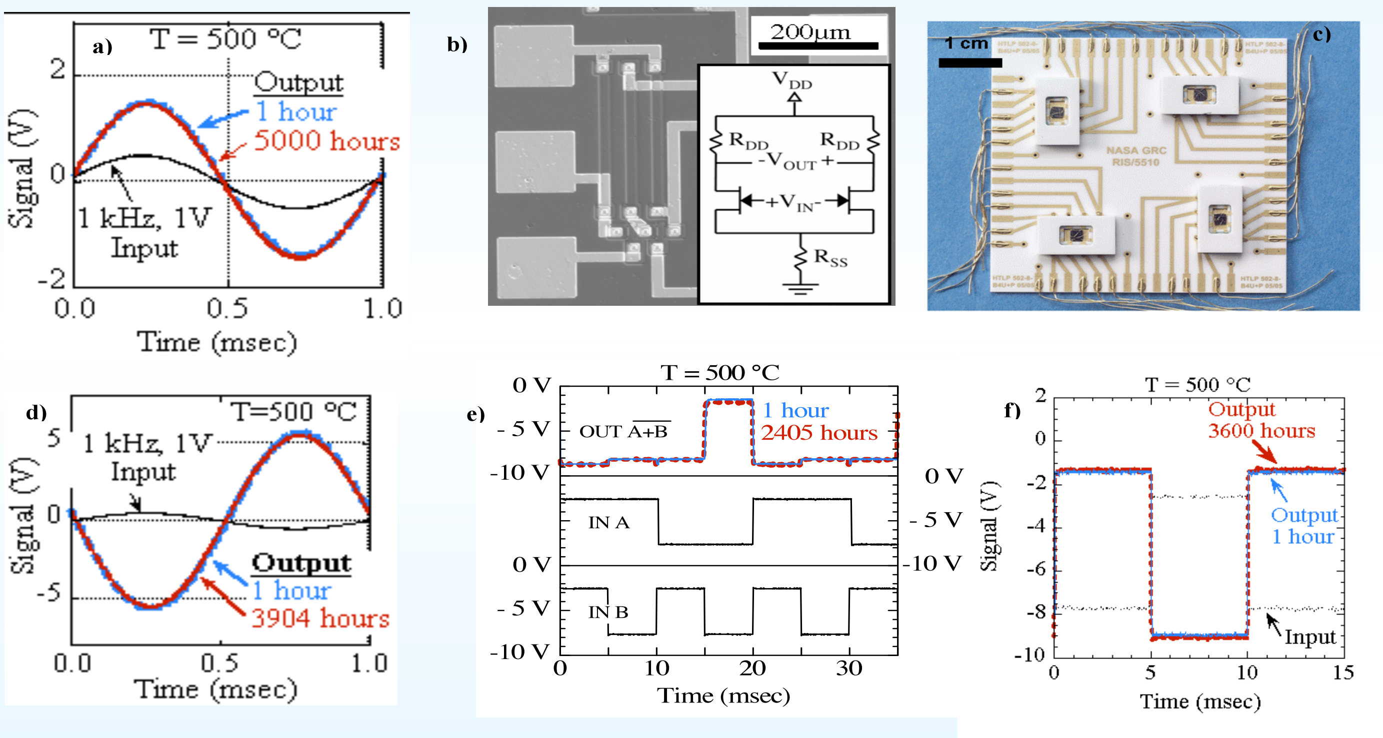
- HTA/D Converter (12 and 18 bit)
- HTEEPROM
- HTFPGA
- Reconfigurable Processor for Data Acquisition (RPDA)



HIGH TEMPERATURE ELECTRONICS

- BASIC ELECTRONIC COMPONENTS DEMONSTRATED IN SILICON CARBIDE ELECTRONICS WITH LONG TERM OPERATION AT 500°C
  - ➢ONE OF THE TOP 10 NASA DISCOVERY STORIES IN 2007
- OTHER ACTIVITIES ONGOING IN GALLIUM NITRIDE AND VACUUM TUBES
- MORE ADVANCED CIRCUITS UNDER DEVELOPMENT WITH INCREASED INTERCONNECTIVITY



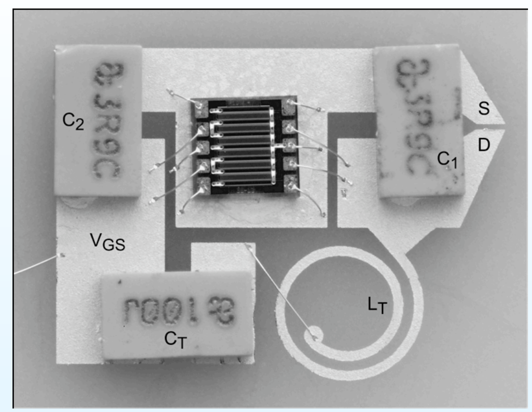
a) Differential Amplifier IC output at 5000 hours and 500°C
b) Picture of Differential Amplifier IC and schematic
c) High temperature packaging for SiC electronics
d) Inverting Amplifier IC output
e) NOR logic gate output
f) NOT logic gate output

HIGH TEMPERATURE WIRELESS DEVELOPMENT

- CASE WESTERN RESERVE UNIVERSITY: WIRELESS TRANSMISSION OF SENSOR DATA AT 400˚C AT 31.5 MHZ USING COMMERCIAL TECHNOLOGY FOR LIMITED TIMES
- NASA GRC DEMONSTRATED 1 GHz OSCILLATOR\ANTENNA TRANMISSION WITH CREE MESFET AT 270°C
- SOFTRONICS WORK ON HIGH TEMPERATURE SIC RF AMPLIFIER FOR WIRELESS TRANSMISSION
- VACUUM TUBES AND GALLIUM NITRIDE PROVIDE THE POTENTIAL FOR HIGHER FREQUENCY OPERATION
- HIGH POWER, HIGH-FREQUENCY TRANSMISSION WITH HIGH TEMPERATURE COMPONENTS, FOR EXAMPLE USING SILICON CARBIDE CIRCUITS FROM THE VENUS SURFACE TO THE ORBITER, SIGNIFICANT TECHNICAL CHALLENGE

High Temperature SiC RF Amplifier Prototype (Softronics)

High temperature vacuum triode including heater, cathode, grid, and anode



High temperature oscillator comprised of SiC MESFET, ceramic chip capacitors, and a spiral inductor

WIRELESS TRANSMISSION AND HARSH ENVIRONMENT SMART SENSOR SYSTEMS

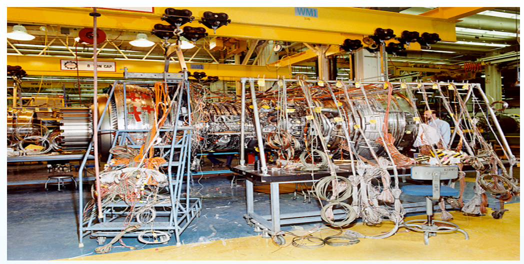
OBJECTIVES: HIGH TEMPERATURE WIRELESS TELEMETRY, DISTRIBUTED ELECTRONICS OVER A BROAD OPERATING RANGE

CHALLENGES: DEVELOPMENT OF RELIABLE HIGH TEMPERATURE TELEMETRY ELECTRONICS, POWER SOURCES, REMOTE COMMUNICATION ELECTRONICS, AND PACKAGING

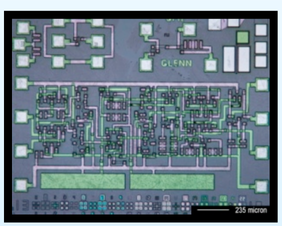
MILESTONE: DEMONSTRATE HIGH TEMPERATURE SENSING, WIRELESS COMMUNICATION, AND POWER SCAVENGING FOR PROPULSION HEALTH MANAGEMENT: 8/30/2011

METRIC: DEMONSTRATE INTEGRATED SELF POWERED WIRELESS SENSOR SYSTEM AT 500˚C WITH DATA TRANSMISSION WITH OPERATIONAL LIFE OF AT LEAST 1 HR

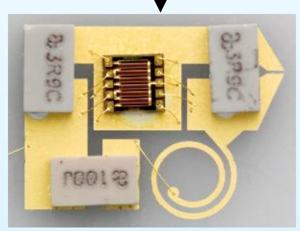
Significant wiring exists with present sensor systems



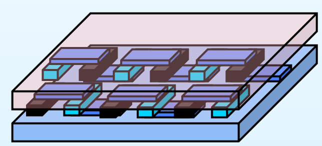
Allow Sensor Implementation by Eliminating Wires



World Record High Temperature Electronics Device Operation



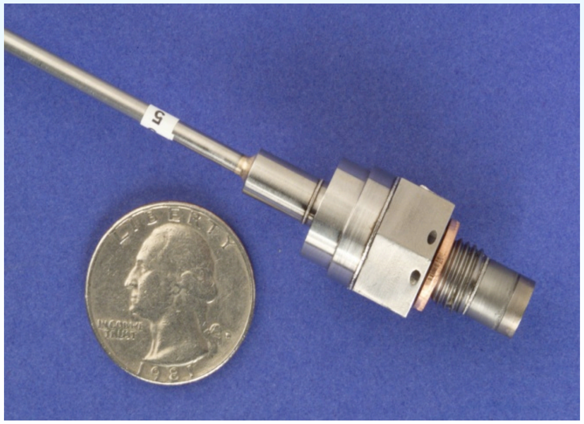
High Temperature RF Components



Energy Harvesting Thin Film Thermoelectrics

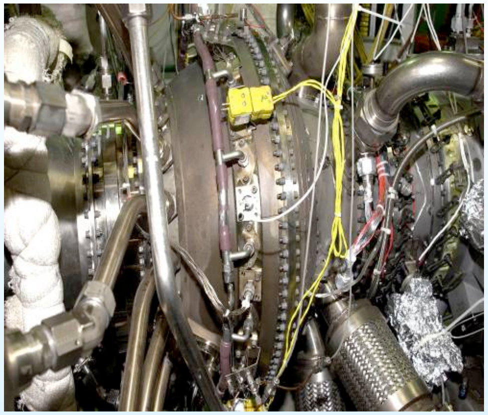
SiC-BASED PRESSURE SENSORS

- SiC HAS EXCELLENT MECHANICAL PROPERTIES FOR USE AS A HARSH ENVIRONMENT PRESSURE SENSOR (T > 500°C, SILICON UNDERGOES PLASTIC DEFORMATION)
- FORM DIAPHRAM OF SiC AND INTEGRATE WITH ELECTRONICS
- WIDE RANGE OF APPLICATIONS
    - AERONAUTIC ENGINE APPLICATIONS
    - AUTOMOTIVE APPLICATIONS
    - MATERIAL PROCESSING
- ENGINE OPERATION DEMONSTRATED AT 500 C
- CAN BE INTEGRATED WITH FLOW VELOCITY AND TEMPERATURE FOR A VENUS HIGH TEMPERATURE WEATHER MONITORING DEVICE



500 °C SiC pressure sensor

SiC High Operating Temp. Probe (HOTProbe): SiC chip to simultaneously measure flow velocity, pressure, and temperature;

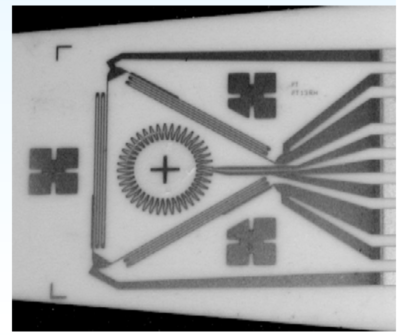


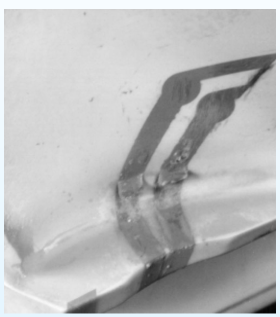
Real World Application: Pressure Sensor Installed in Engine Test

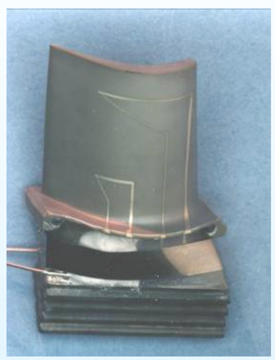
THIN FILM PHYSICAL SENSORS FOR HIGH TEMPERATURE APPLICATIONS

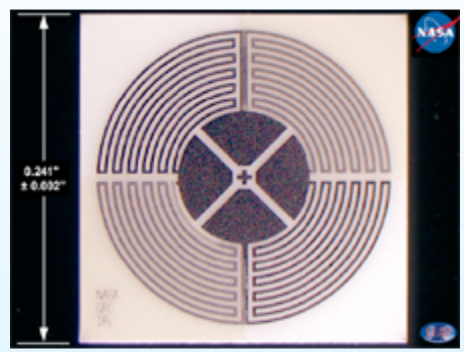
- **ADVANTAGES FOR TEMPERATURE, STRAIN, HEAT FLUX, FLOW & PRESSURE MEASUREMENT:**
    - ♦ Negligible mass & minimally intrusive (microns thick)
    - ♦ Applicable to all materials including ceramic based materials
    - ♦ Minimal structural disturbance
    - ♦ Intimate sensor to substrate contact & accurate placement
    - ♦ Multiple sensor fabrications, full-field measurement
    - ♦ High durability
    - ♦ Capable for operation to very high temperatures (> 1000°C)

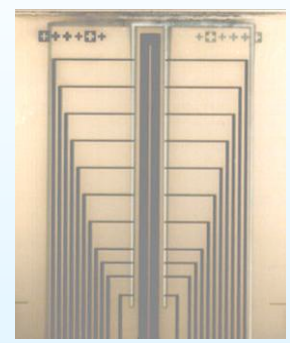
- **MULTIFUNCTIONAL SMART SENSORS BEING DEVELOPED**
- **CAN BE USED TO MEASURE VENUS SURFACE CONDITIONS AS WELL AS MONITOR VEHICLE CONDITIONS**


Multifunctional Sensor Array


PdCr strain sensor
On Alloy to T=1000°C


Pt- Pt/Rh temperature
sensor to T=1200°C

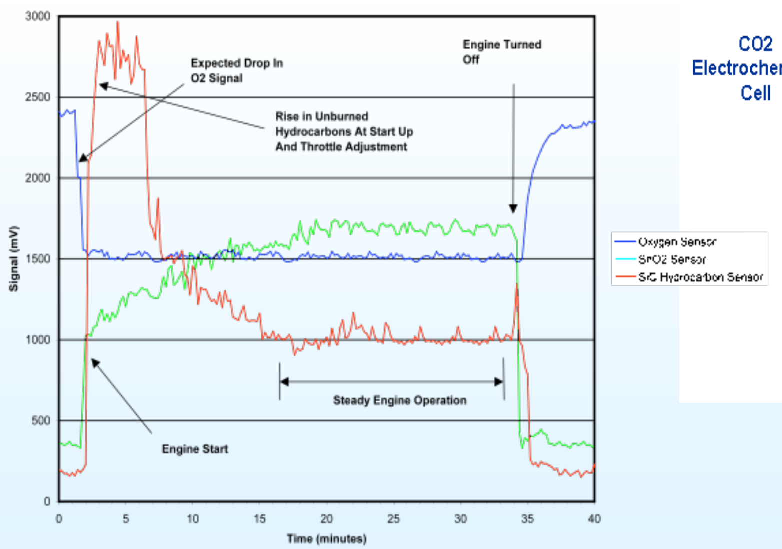

Heat Flux Sensor Array
to T=1000°C


Flow sensor
to T=1000°C

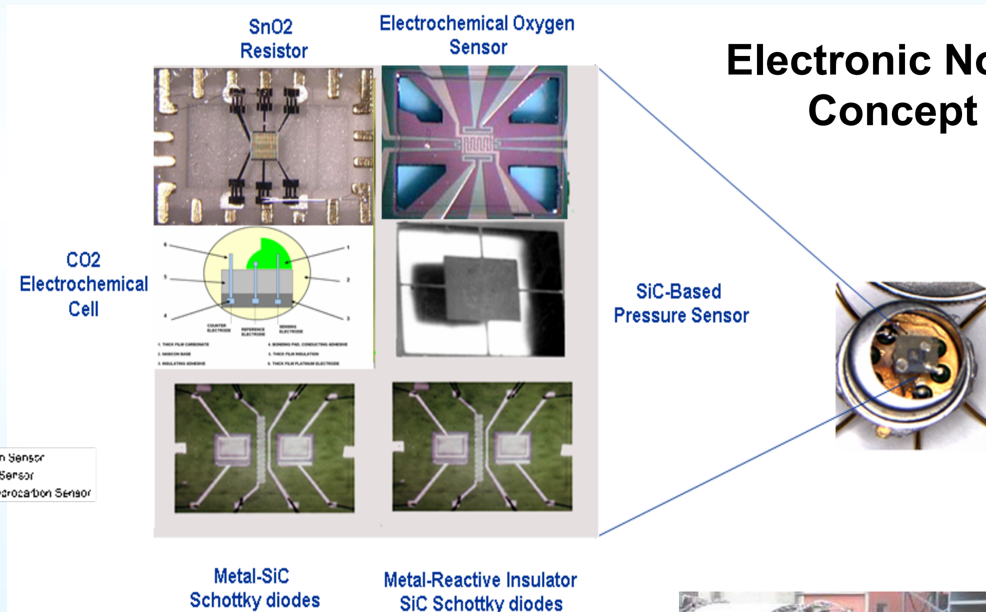
HIGH TEMPERATURE GAS SENSOR ARRAY
HIGH TEMPERATURE ELECTRONIC NOSE

- HIGH TEMPERATURE MEMS BASED GAS SENSORS DESIGNED FOR SELECTIVE DETECTION
- MULTIPLE CHEMICAL SPECIES CAN BE MEASURED/SENSORS CAN BE TAILORED FOR THE APPLICATION
- RECENT TESTS AT HONEYWELL ON A JET ENGINE SHOWED OPERATION OF A CO, CO_2, O_2, NO_X, AND HYDROGEN/HYDROCARBONS ARRAY WITH SENSOR OPERATION ABOVE 500˚C
- MULTIPLE SPECIES OF INTEREST TO VENUS APPLICATIONS CAN BE DETECTED

Automotive Engine Sensor Testing



Electronic Nose Concept



Jet Engine Sensor Testing

THE OHIO STATE UNIVERSITY | CWRU | MEI Makel Engineering Inc. | NASA | NASA

VENUS METEOROLOGY

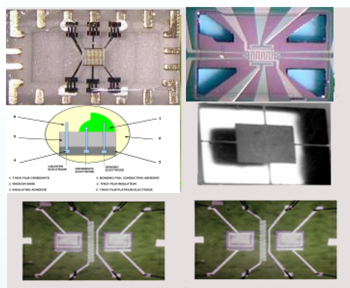
EXAMPLE POSSIBLE MISSION: Venus Integrated Weather Sensor (VIWS) System

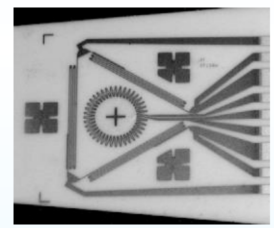
Sensor Suite to Monitor Venus Weather Conditions including:

Data Processing and Communication, Wind Flow, Pressure/Temperature/Heat Flux, Chemical Environment

- **ALL OF THE TECHNOLOGIES BELOW HAVE BEEN DEMONSTRATED AT 500˚C AND OFTEN SIGNIFICANTLY ABOVE**
- **CAN BE OPERATED FROM A LANDER SYSTEM WITH FEEDTHROUGHS TO CONVENTIONAL ELECTRONICS**
- **INTEGRATION WITH HIGH TEMPERATURE ELECTRONICS\POWER\COM WILL ALLOW INDEPENDENT, DISTRIBUTED OPERATION**

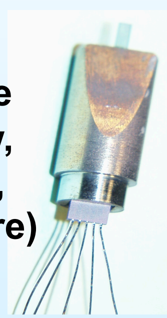
HIGH TEMPERATURE ELECTRONIC NOSE (Chemical Species)



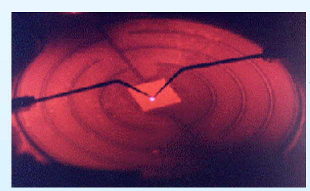


MULTIFUNCTIONAL PHYSICAL SENSOR ARRAY (Temperature, Heat Flux)

HOTProbe (Wind flow, Pressure, Temperature)



PRESSURE SENSOR (Pressure)

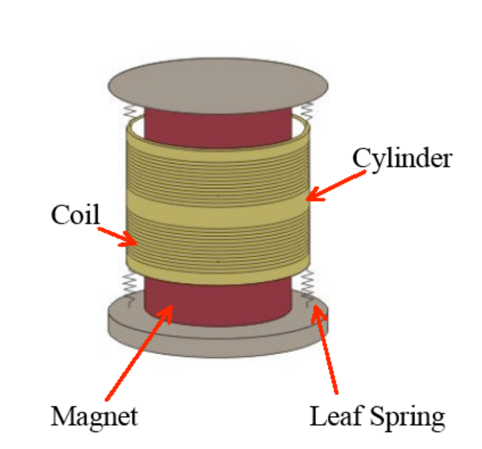


SiC ELECTRONICS (Data Processing and Com)

SEISMOMETER

- ONE OF THE FUNDAMENTAL QUESTIONS IN VENUS STDT DISCUSSIONS INVOLVED WHETHER VENUS SEISMOMETRY WAS VIABLE
- MAJOR TECHNICAL HURDLE IS THAT IN ORDER FOR A SEISMOMETER TO BE EFFECTIVE IT MUST BE COUPLED IN SITU TO THE PLANET
  - THIS IMPLIES HIGH TEMPERATURE OPERATION OF LEAST SOME SYSTEM COMPONENTS
  - EXTENDED OPERATION OF AT LEAST 117 DAYS DESIRED
- SEVERAL POSSIBLE DIFFERENT ARCHITECTURES WERE DISCUSSED
  - STAND-ALONE SYSTEM
  - SEISMOMETER SYSTEM COUPLED WITH LANDER POWER
  - SEISMOMETER SYSTEM COUPLED WITH LANDER POWER AND COOLED SUPPORT SYSTEM
- MODERN INSTRUMENTS USE COMPLEX ELECTRONICS SO THAT THE MASS IS HELD NEARLY MOTIONLESS RELATIVE TO THE FRAME
- GEOPHONE: A SIMPLER INSTRUMENT THAT MEASURES AND RECORD MOTIONS OF THE GROUND USUALLY FOR HIGHER FREQUENCIES
  - USE OF MAGNETIC MATERIALS MAKE STANDARD GEOPHONES QUESTIONABLE FOR VENUS MISSIONS

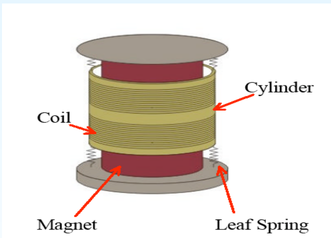
Geophone Design



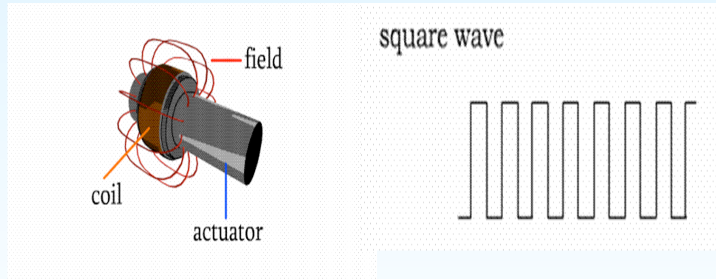
HIGH TEMPERATURE SEISMOMETER FOR VENUS APPLICATIONS

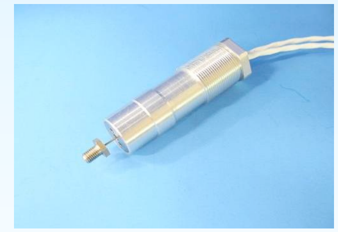
INPROX TECHNOLOGIES

- HIGH TEMPERATURE VARIABLE INDUCTOR IS PRESENTLY A SPECIALIZED COMMERCIAL PRODUCT- AEROSPACE POSITION SENSOR
- DEMONSTRATED OPERATION TEMPERATURE UP TO 650˚C; NO MAGNETIC MATERIALS



Geophone Design





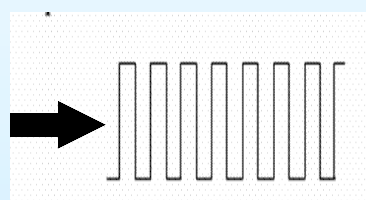
ITC Captive Field Linear Direct (CFLD4) transducer operational to 650°C and core of the project's seismometer.

PLANETARY INSTRUMENT DEFINITION AND DEVELOPMENT PROJECT

COMBINE INPROX SENSOR WITH SILICON CARBIDE ELECTRONICS FOR A PROOF-OF-CONCEPT SEISMIC MEASURING INSTRUMENT OPERATIONAL AT 500°C IN THE 1-30 Hz RANGE

- YEAR 1: FABRICATE AND DEMONSTRATE A SIC BASED ELECTRONICS SYSTEM TO CONVERT THE 1-30 HZ SEISMOMETER SIGNAL.
- YEAR 2-3: FABRICATE AND DEMONSTRATE A SIC BASED ELECTRONICS SYSTEM TO CONVERT THE 1-30 HZ SEISMOMETER SIGNAL AND WIRELESSLY TRANSMIT THE DATA, EXTENDING THE FREQUENCY EVEN INTO THE MHZ FREQUENCY RANGE.

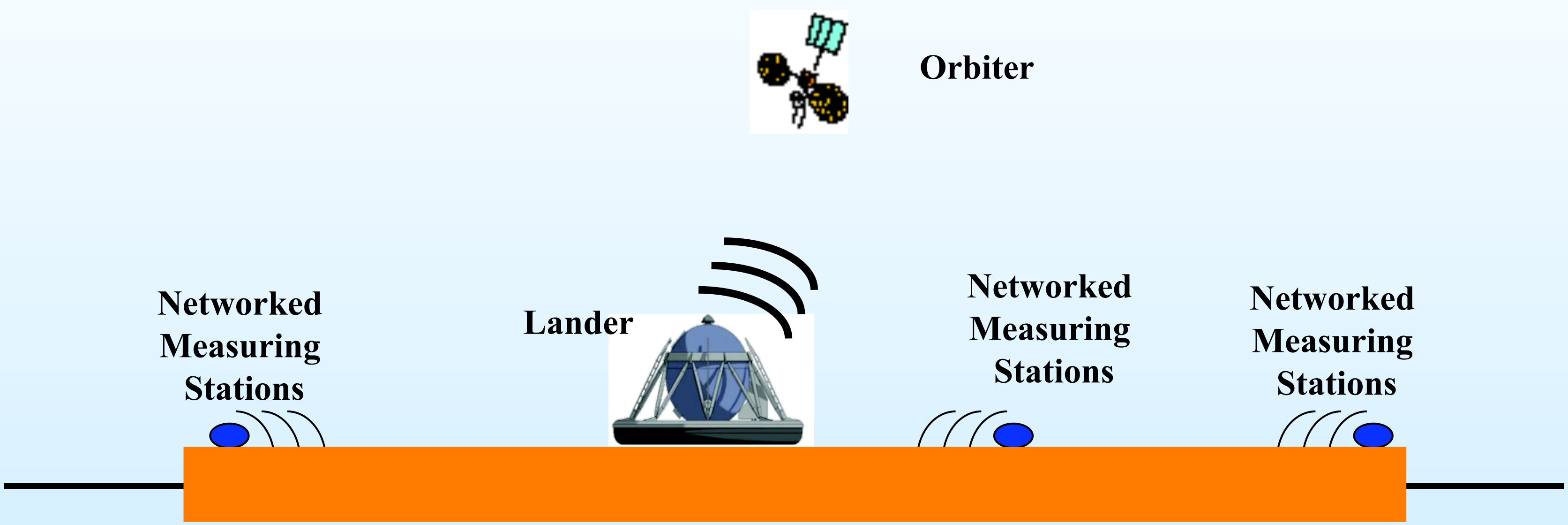
Inprox Sensor → SiC electronics and oscillator circuit →



→ Oscillations produce FM signals (up to MHz transmission)

ONE POSSIBLE SCENARIO: LONG-LIVED LANDER COUPLED WITH NETWORKED MEASURING STATIONS

- **LONG-LIVED LANDER POWERED AND COOLED WITH STIRLING DUPLEX SYSTEM**
  - **Sample multiple sites and multiple depths for a complete survey of the elemental composition, mineralogy, and chemistry of the landing site**
  - **Decrease mission risk and optimize science return by providing missions with complete instruments operation for extended period of time**
  - **Humans in the loop during mission operation**
- **SEISMOMETER AND METEOROLOGICAL NETWORK**
  - **Provide measurements of the size-frequency distribution of seismic events**
  - **Surface meteorology with measurements such as temperature, wind speed and direction, and pressure**
  - **Provide correlation between observed planetary events and changes in weather conditions**
- **OTHER TECHNOLOGIES SUCH AS DROP SONDES ALSO COVERED IN THE REPORT**
- **SYSTEM AND TRADE STUDIES NEEDED TO DETERMINE OPTIMAL APPROACH**



BACKUP SLIDES

GENERAL SUMMARY OF HIGH TEMPERATURE TECHNOLOGIES

Capability	Requirements	State of the art (TRL level)	Development focus
Refrigeration	- long life in Venus environment (months) - high efficiency - capable of ~3kW total heat rejection - suitable for integration with lander and low altitude balloon pressure vessels - minimized mechanical vibration	**TRL~3** - high temperature operation not demonstrated at the system level	- Stirling machines need to be adopted for Venus environment - duplex Stirling machine must be produced that integrates the heat engine and refrigerator functions into a high efficiency and high reliability device.
High-temperature power system	- long life in Venus environment - high conversion efficiency - low mass	**TRL~3** - demonstrated single Stirling converter for 300 hours operation with a 850 °C hot-end temperature and 90°C cold-end, 38% efficiency and 88 W power output with heat input equivalent to 1 GPHS.	- cold end operation needs to be raised from 90 °C to 480 °C with high conversion efficiency preserved - material testing, system development and validation for reliable operation in Venus surface environment.
High-temperature energy storage	- long life in Venus environment (117 days min.) - high specific energy - rechargeable and primary batteries	**TRL 4** - demonstrated LiAl–FeS_2, Na–S, and Na–metal chloride secondary batteries with specific energy in the 100-200 Wh/kg range	- adapt cell and battery designs for space applications - stability of seals and terminals - minimize the corrosion of current collectors at high temperatures - optimize the electrolyte composition to improve performance and reliability

Capability	Requirements	State of the art (TRL level)	Development focus
Medium-temperature electronics (300 °C)	- low power dissipation at 300 °C -l ong life and reliability	**TRL 4** - medium temperature components developed for automotive and oil drilling industry	- HTSOICMOS electronic components - low power - test, validation, and reliability
High-temperature telecom	- long life at Venus environment (117 days min.) - high data rate (~4.5 kbs)	**TRL 2** - demonstrated 2 GHz operation at 275 °C using SiC - SiC and vacuum tube based oscillator demonstrated at ~500 °C	- SiC based RF components for transmitters - miniaturized vacuum tube technology for power amplifiers - SiC based RF components for transmitters
High-temperature sensors	- long life in Venus environment (117 days min.) Seismometers: - 0.3 mHz to 10 Hz frequency range - 10^{-8} to 10^{-9} $msec^{-2}Hz^{-1/2}$ amplitude sensitivity Other sensors: - pressure, temperature, wind speed, gas species variation in time	**TRL 2-6** - geophones operating up to 260 °C - high-temperature pressure, temperature, and anemometers used on Venera/VEGA and Pioneer	- high-temperature MEMS technology for seismometers - SiC and GaN high temperature sensors
High-temperature electronics (500 °C)	- long life at Venus environment (117 days min.) - data acquisition, processing, and storage capability - power management	**TRL 2-3** - limited integrated circuit capability demonstrated - limited electronics packaging - data storage, ADC, power converters, and other needed components never demonstrated	- SiC-based electronics - GaN-based and miniaturized vacuum electronics - high-temperature electronic packaging, passive components - reliability, long life

VENUS SEISMOMETER REQUIRMENTS

	Proposed Venus Requirements	State-of-the-Art	Proposed System Development
Frequency Range	0.3 mHz to 30 Hz	N/A	1-30 Hz
Minimum Amplitude Limit	10^{-8} to 10^{-9} m sec^{-2} $Hz^{-1/2}$	N/A	10^{-8} to 10^{-9} m sec^{-2} $Hz^{-1/2}$
Operation Temperature	~500°C	N/A	500°C
Pressure	~ 90 bars	N/A	N/A
Duration	117 days to 1 year	N/A	90 days
Supporting Technologies	Communication of data	N/A	Low Frequency Wireless

WHAT IS NEEDED TO MAKE SEISMIC MEASURMENTS

- COMPLETE RANGE OF MEASUREMENTS COVERS WIDE FREQUENCY RANGE
  - SHORT-PERIOD (SP) SEISMOMETERS AND GEOPHONES MEASURING SIGNALS FROM APPROXIMATELY 0.1 TO 100 HZ. – GENERALLY USING VARIABLE INDUCTOR OR VARIABLE CAPACITIVE MASS-SPRING DESIGNS.
  - BROADBAND SEISMOMETERS (BB) HAVING A FLAT GROUND VELOCITY PROPORTIONAL RESPONSE FROM APPROXIMATELY 0.01 TO 50 HZ .
  - VERY BROADBAND SEISMOMETERS (VBB) MEASURE FREQUENCIES FROM BELOW 0.001 HZ TO APPROXIMATELY 10 HZ.

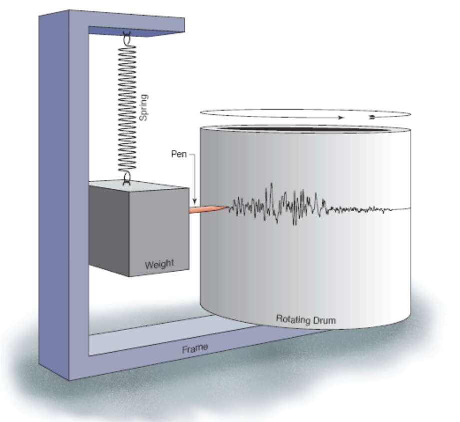
- THESE DESIGNS STANDARDLY INCORPORATE MULTIPLE SENSORS TO ACHIEVE THESE VERY BROAD RANGES.

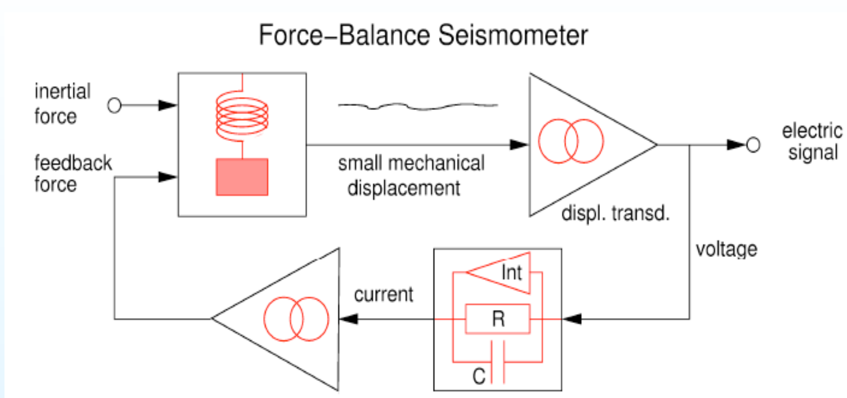
- BASIC COMPONENTS INCLUDE:
  - SENSOR
  - MECHANICAL INTERFACE (SPRINGS, LEVERS, ETC)
  - ELECTRONICS
  - COMMUNICATION
  - POWER
  - IMPLEMENTATION AND PLANETARY INTERFACE

WHAT IS A SEISMOMETER

Instruments that measure and record motions of the ground

- **Vibrations affect an inertial mass or sensor attached to an instrument by a mechanical system (involving e.g. springs). The mechanical system as well as the sensor needs to be specially designed for frequency range**
- **Modern instruments using electronics so that the mass is held nearly motionless relative to the frame by an electronic negative feedback loop**
- **The feedback loop applies a magnetic or electrostatic force to keep the mass nearly motionless. The voltage needed to produce this force is the output of the seismometer**
- **Sensors and electronics not viable for Venus missions as-is.**





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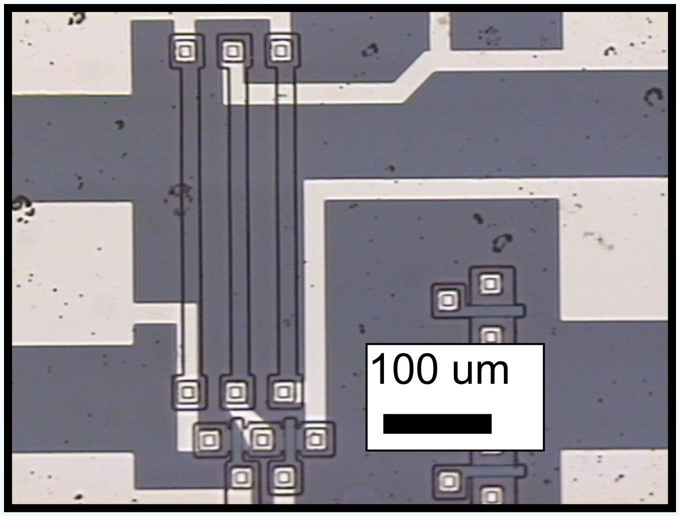
NASA Glenn Silicon Carbide Differential Amplifier

World's First Semiconductor IC to Surpass
5000 Hours of Electrical Operation at 500 °C

Demonstrates CRITICAL ability to interconnect transistors and other components (resistors) in a small area on a single SiC chip to form useful integrated circuits that are durable at 500 °C.

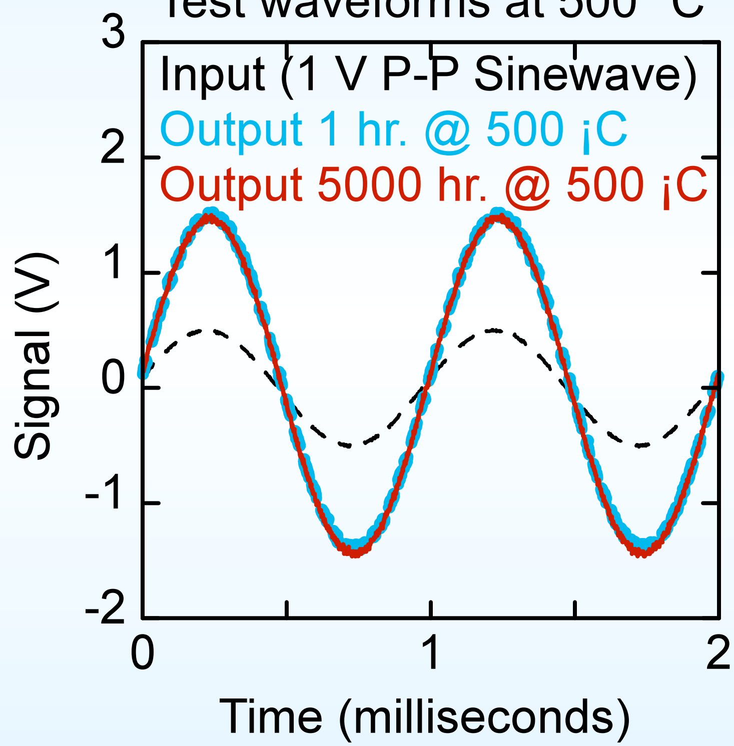
Optical micrograph of demonstration amplifier circuit before packaging



2 transistors and 3 resistors integrated into less than half a square millimeter.

Single-metal level interconnect.

Test waveforms at 500 °C

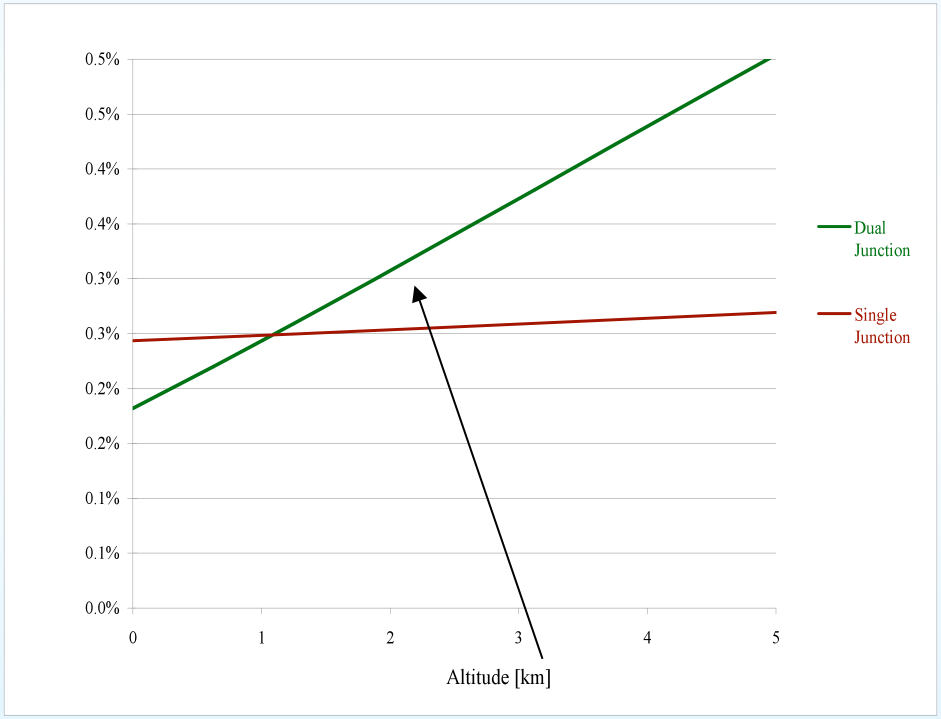


Less than 5% change in operating characteristics during 5000 hours of 500 °C operation.

Recent Work: Solar Cells Are A Possibility
Effective cell efficiency at low altitudes

•**note: this will require technology development to avoid thermal degradation** (technology exists in the lab, but has not been applied to commercially available cells

Technology development needed below 28km



Single junction GaAs cell best very close to surface (due to lack of blue light)

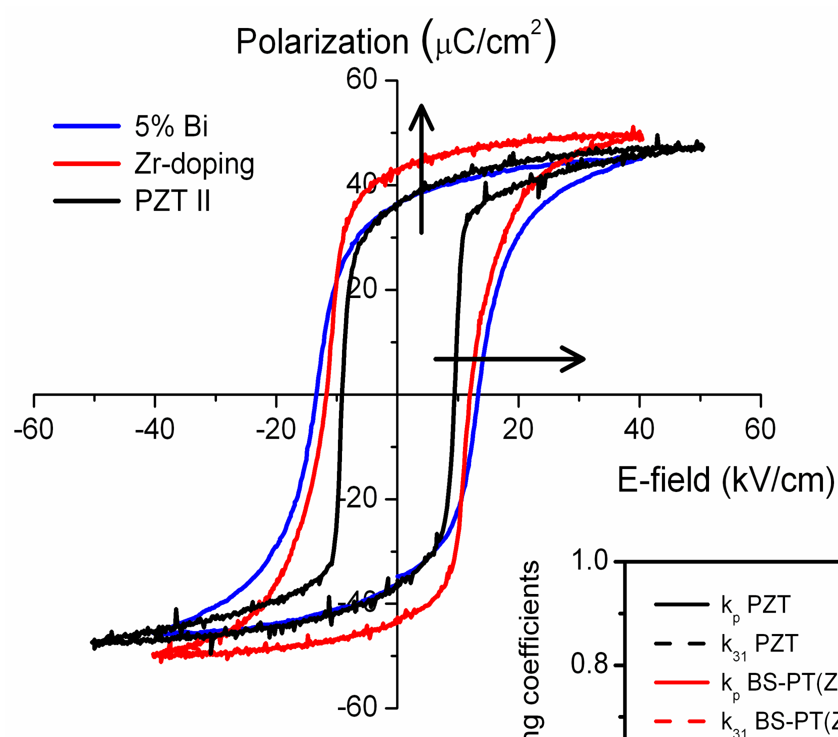
Altitude	Triple junction	Dual Junction	Single Junction
(km)	A (m^2)	A (m^2)	A (m^2)
0	-	2.34	1.75
10	2.01	0.55	1.46
20	0.71	0.3	0.95
30	0.12	0.13	0.48
40	0.07	0.06	0.38
50	0.03	0.04	0.26
60	0.01	0.01	0.13

Example: solar panel area required to produce 1.5 watts

High Temperature Piezoelectric Actuators

Zr^{4+} is added as a donor in place of Sc^{3+}

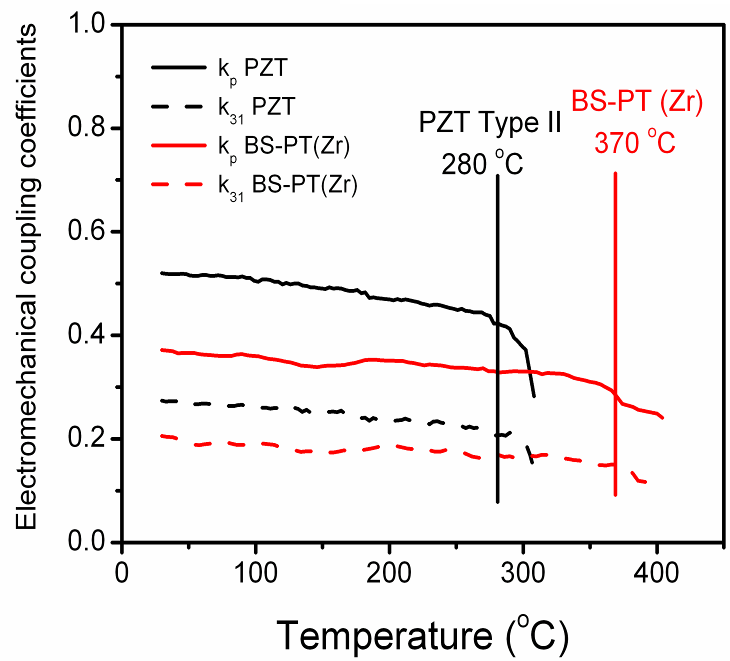
$0.37Bi(Sc_{0.98}Zr_{0.02})O_3$-$0.63PbTiO_3$

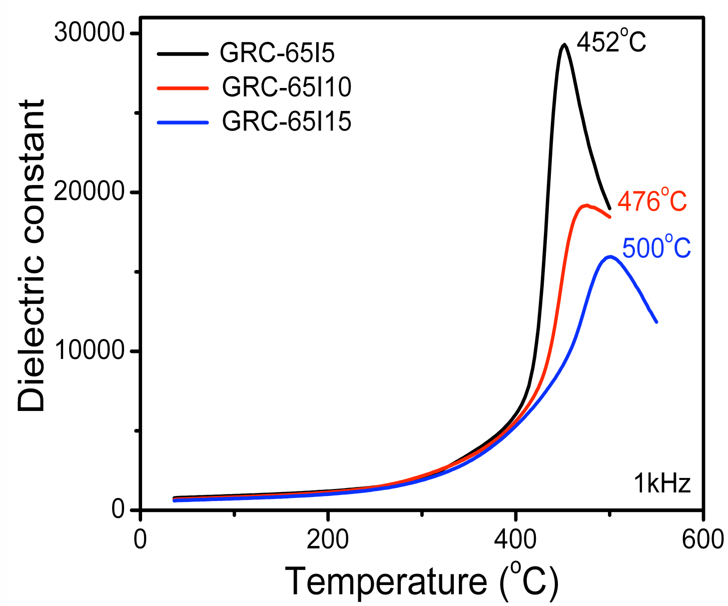


	GRC Zr-doped BS-PT	GRC LPS BS-PT	PZT Type II
T_C (°C)	404	430	315
d_{33} (pC/N)	500	408	585
E_C (kV/cm)	21	23	12
P_R ($\mu C/cm^2$)	43	24	44
ρ_{DC} (Ω.cm)	$\approx 10^{11}$	$\approx 10^{11}$	$\approx 10^{11}$

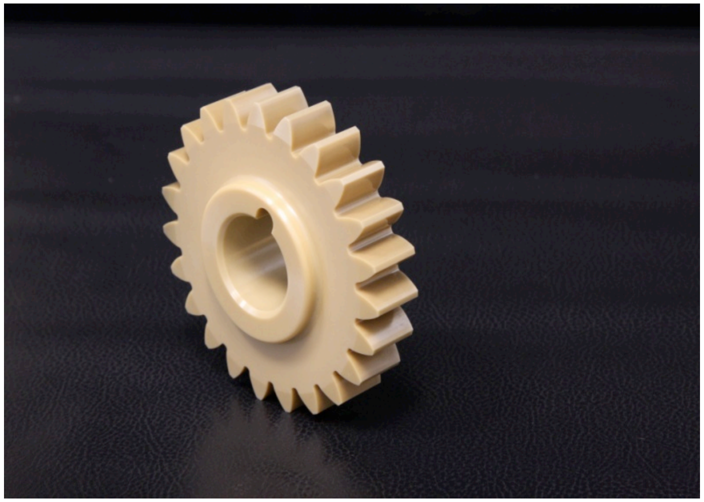
- Improved operating temperature
- Improved coercive field
- Improved remnant polarization

PUSHING THE TEMPERATURE LIMIT ABOVE 500 °C



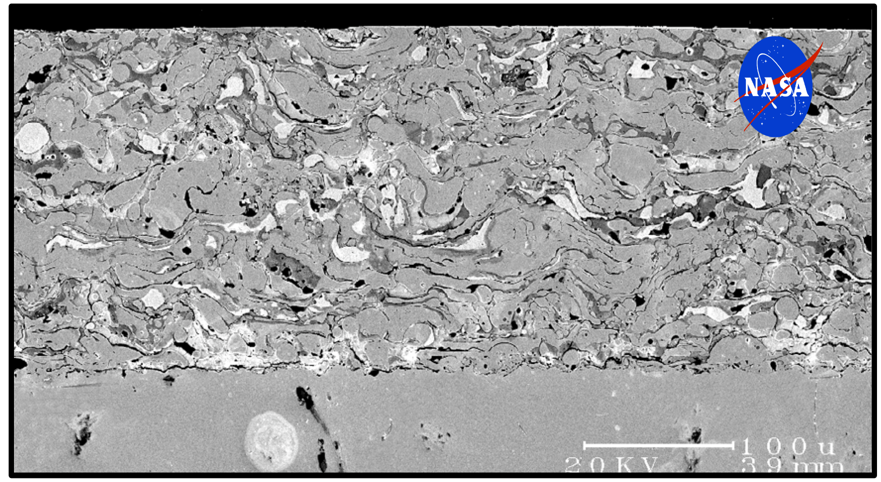


High Temperature Gears and Lubricants Development



Ceramic gear with potential for operating at Venus operating temperature

High temperature solid lubricant coating with capability for operating up to 850°C



Foil bearings with solid lubricant successfully tested at high loads for 100,000 start/stop cycles from 100°C to 650°C

Operation of high temperature gears and lubricants under Venus operating conditions need to be demonstrated for actuation applications

Courtesy of A. Mishra, NASA GRC