Extreme Electronics for In-situ Robotic/Sensing Systems

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Abstraa

NASA's desire to study and characterize the solar system and small bodies like comets and asteroids will be done by in-situ robotic systems in the near term. Work has already begun on the design of Mars and Europa mole penetrators, ultra-sonic coring systems for Venus, and corers for comet nucleus sampling. Along with these in-situ sampling systems come miniature science instruments that allow samples to be imaged microscopically, or sensor suites that break down and examine the chemical composition and DNA of samples. Both sample acquisition and instruments will be exposed to extreme radiation, temperatures, corrosion, or pressures. This paper describes these intended extreme mission environments, and discusses technologies being developed to enable systems to operate in extreme conditions.

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Introduction

The projected flight time between Earth and Europa is on the order of 3-4 years. Expected de-orbit periods are on the order of 1 year. During this time interval spacecraft and payloads will be exposed to total dose radiation levels over 20Mrad, most of which is seen in the Jovian de-orbit phase. Once on the surface, not only will radiation levels be extremely high, but surface ice temperatures will be around -170degC. At the opposite extreme, robotic spacecraft visiting Venus will be exposed to a CO2/sulfuric acid atmosphere during descent, and surface temperatures on the order of 450degC. These extreme environments clearly represent a significant challenge to spacecraft, sampling, and science instrument engineers if they are to design systems which can not only survive, but reliably report back data resulting from the in-situ sampling and science data collection. A small group of government, university, and private sector organizations have been doing research in the areas of high radiation/temperature, and low temperature tolerant electronics which hold promise for application to these extreme environments. This paper describes the work being done at JPL/NASA to characterize these environments, and design viable in-situ sampling missions for these environments. An overview of technology development activities in the field of extreme electronics that have direct application to these environments is also provided.

Description of Europa and Venus Extreme Environments

Europa-

Recent images and remote sensing data received from the Galileo spacecraft (1) show Europa to be covered by a highly fractured ice sheet. The signs of fracturing and up-welling of material are very similar to that experienced in the polar sea ice pack on Earth. Other areas with smoother surfaces are indicative of resurfacing and freezing of liquid water. Cratering data suggests that the smooth interior of the depressions was caused by liquid refilling and re-freezing after impact. Ice ridges and lateral fractures caused by crustal fracturing and butting, not only suggest on-going ice dynamics, but also indicate a possible thinner ice crust than originally predicted. Conservative assumptions about Europan ice crust dynamics indicate that an ice layer on the order of 10's of kilometers thick could experience 30 meter tides every 3.5 days (2). It is unclear at this time whether these tides are driven by hydro-thermal vents, currents, gravitational pull, or a combination of all of these forces. We know from empirical data collected here on Earth, that deep hydro-thermal vents, and gas bubbles trapped at the ice-water interface provide a source of nutrients for microorganisms. If these theories about Europa are correct, and experience with similar Earth environments apply, then the possibility of an ice liquid interface presents an opportunity for the presence of past or extant life. Cryo-hydrobot probes which might melt through the ice to reach the ice-liquid interface will therefore experience a dynamic high pressure ice pack environment on the order of 100's of atmospheres.

Surface ice temperatures have been measured at -170degC. The unique radiation environment around Europa is caused by the intense radiation field generated by Jupiter. Radiation modeling of the complete spacecraft intransit and deorbit time shows that the spacecraft and payload will be exposed 25Mrad total dose (3). This level of exposure approaches radiation levels found in Earth nuclear reactor systems. The combined high radiation, high pressure, and cryo-temperatures expected on Europa therefore represent one end of the extreme environmental spectrum.

Venus-

At the other end of the extreme environmental spectrum is Venus. The images obtained from the Russian spacecraft, Venera, which visited Venus and survived for a brief interval of time showed a landscape of barren, weathered, tectonic plates. The dense atmosphere of CO2 and sulfuric acid does not allow heat to escape. Resulting surface temperatures vary only between 470degC at the level of the plains, to 400degC at the higher slope elevations (4). The dense atmosphere on Venus is equivalent to about 100 Earth atmospheres. Although the radiation environment is benign, the 400degC+ temperatures far exceed what most electronic components can withstand. The only option currently available for an in-situ sampling mission to Venus is one in which the sampling and subsequent in-situ science is completed within hours after touchdown.

Summary of In-situ Sampling Mission Scenarios

Because these two extremes represent an opportunity to find life (Europa) and study extreme climatalogical/geological changes (Venus), both of these solar system bodies have been picked by NASA as high priority mission targets. It is considered essential to obtain in-situ samples from these bodies to better understand the state and evolution of our solar system. Two missions have been designed to obtain samples. The Europa mission utilizes a Cryo-Hydro Integrated Robotic Penetrator System (CHIRPS), and the Venus mission employs a stationary lander with an ultra-sonic coring device.

Europa-

The CHIRPS probe is a one (1) meter long, tapered cylindrical vehicle powered by an advanced radio-isotope power system (ARPS) (5). Figure (1) shows the primary components of the mole penetrator, and Figure (2) shows the ice/liquid descent sequence. The system operates quasi-statically and melts at a rate of approximately 10m/day. The total temperature range experienced by the probe during its descent is -170degC at the surface, to -5degC at the ice-liquid interface. Figure (2) shows the lander with probe in its stowed/locked orientation. After touchdown the lander bay doors open under the lander and pyro's blow the release locks. Telescoping struts provide a means of controlling the vertical alignment of the probe so that as the probe touches the surface it enters along the gravity vector. As CHIRPS initiates the thermal melt control cycle, surface material sublimates into the Europan vacuum. The mass of the lander communication avionics provides the axial pre-load necessary to keep the probe in contact with the ice and offset the sublimation pressure. The communication electronics module follows the probe into the ice and settles in the evacuated depression where a shape memory doughnut inflates and acts as a radiation cap/ anchor. Once in the ice, the avionics and probe are protected from the high surface radiation levels. The only structures remaining on the surface are the lander, primary lander antenna, and umbilical between the antenna and communication avionics. Once in the ice void, a twenty (20) centimeter receiver/transmitter is snapped open before the melt region re-freezes. As CHIRPS proceeds to melt through the ice, a short range acoustic imager helps steer the vehicle while melt-water is passively sampled via capillary action and transferred to internal science instruments. Transceiver modules powered by a radioisotope heater unit (RHU) power stick and configured about the size of a hockey puck contain quad-dipole antennas on both the top and bottom. These modules act as communication relays for transmitting vehicle state/science data back to the surface. The ice transceivers are ejected out of the rear of the vehicle into the slush plume using a heat activated shape memory lever where they then refreeze as the vehicle continues to descend. In cold ice (i.e., -100 degC to -170degC), even with salt impurities it behaves like an insulator, thus allowing radio-

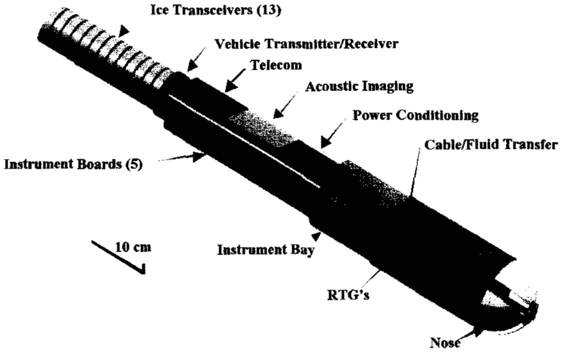

Figure 1: Europa Mole Penetrator

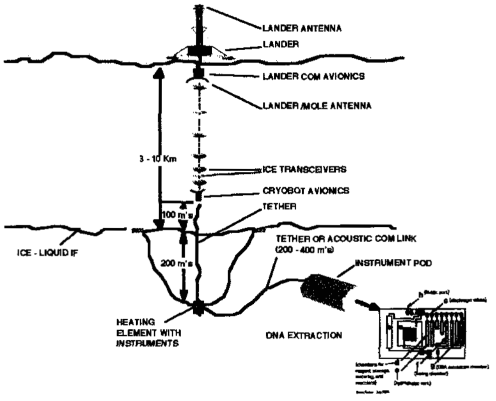

Figure 2: Cryo-Hydro Integrated Robotic Penetrator System

wave signals to transmit large distances (100's of meters to a kilometer) through the ice (6). As the temperature increases the signal strength decreases because the ice acts less and less like an insulator. Therefore, the transceivers are deposited as a function of signal strength and ice temperature. As the ice-liquid interface is approached and the ice temperature increases, the relays are deposited closer together to mitigate the signal attenuation problem(7).

As the mole approaches the ice-liquid interface, a slush plume of the order of 10's of meters in length is created behind the vehicle. Using the acoustic imager to locate the ice-liquid interface, the vehicle separates into two pieces at 100m from the ocean. At this distance, the primary vehicle antenna and avionics are able to refreeze in the ice and act as an anchor for the tethered instrument bay and heater module as it proceeds to punch through the ice and drop into the Europan ocean. The total length of the tether is only 300m. The instrument bay contains three pods which float to the ice-liquid interface. Each pod contains a micro-laboratory which passively samples liquid at the interface for DNA strains. The pods, powered by RHU's, transmit their science data back to the main tether also via short tethers (see Figure (2)). After careful examination of the state of technologies needed to support this design and facilitate a 2008 or 2010 Europa lander mission, it became clear that one of the most critical technology elements was electronic components which could survive the extreme ice/pressure and radiation environment expected for both the mole control system, ice transceivers, and science instruments.

Venus-

The decision to consider ultra-sonic coring technology for Venus was driven by three primary factors:

1. Ultra-sonic coring systems which displace material by tuning ultra-sonic energy input frequency to the resonance frequency of a given material can achieve higher drill rates than standard mechanical drilling approaches;
2. Application of ultra-sonic energy to disintegrate rock does not require the high axial pre-loads typically needed for standard mechanical drilling techniques;
3. Current tests of ultra-sonic coring in "basalt-like" materials expected on Venus, indicate coring rates on the order of 1mm/min at 80w of power input (8). These rates would allow the system to obtain sufficient rock sample before the extremely high surface temperatures would cause the system to fail;

The Venus basalt coring system is powered by a 150w battery pack. In order to survive long enough for the 100gm basalt core to be obtained, both the battery pack and control electronics are insulated by a phase change material for cooling. The coring tool is one (1) cm in diameter with a knife-edge energy transfer surface. The nominal coring tool length is 15 cm with the total resulting core sample (assuming the density of basalt) being approximately 100-120gms. The coring tool is held in place by gravity and a retaining ring inside a 30cm long cylindrical spindle that is interfaced to the ultra-sonic drive via a spring loaded locking collet/transducer. When the spindle is driven downwards the collet locks around the coring tool and ultra-sonic energy is transferred through the transducer to the coring tool. When the spindle is raised the collet stays locked until the "home" position is reached at which time energy transfer is interrupted.

The spindle vertical motion is controlled by three wire cables spaced 120 degrees apart on the outside diameter of the spindle. The cables are laterally flexible, but stiff axially and are permanently seated in grooves which run axially along the cylinder. Three actuators with encoders are hard mounted around the circumference of the spindle at the 120 degree spacing, and spool-out, or reel-in, the cables for up/down position control. By differentially spooling-in one side and reeling-out the other side the spindle orientation can be controlled. The complete corer/spindle assembly hangs like a pendulum on a gimbal so that as the actuators control the cable pay-out, the whole assembly can be oriented to accommodate lander tilt or surface irregularities. Figure (3) shows the complete corer/spindle assembly along with the sample canister (9).

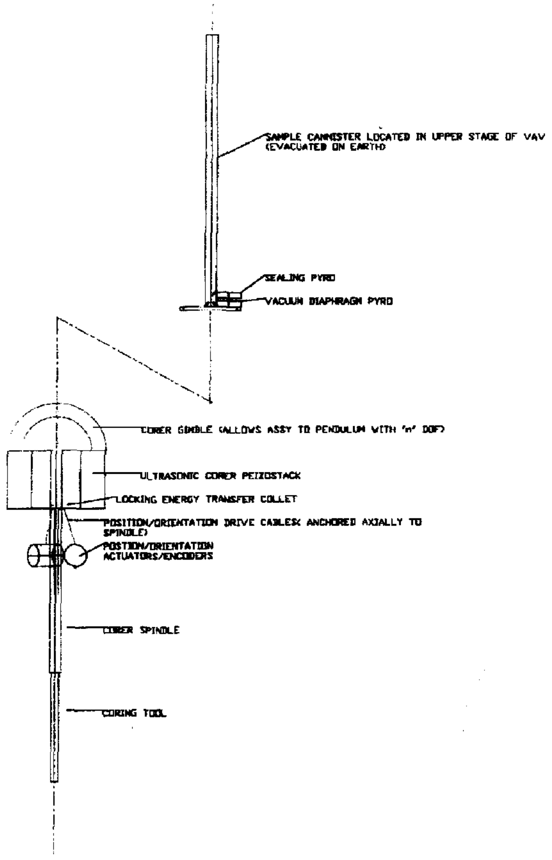

Figure 3: Venus Ultrasonic corer assembly sample canister.

Once the core has been extracted, the spindle/corer are retracted and moved upward to the original home position. The controller shuts off the piezo-stack which generates the ultra-sonic energy. The controller now moves the spindle/corer to the "retrieve" position which places the spindle partially inside the opening to the sample canister located directly above in the ascent vehicle. The sample canister has been evacuated and sealed on Earth prior to launch. At the retrieve position, a contact switch activates a pyro which punctures the canister seal. The large pressure differential between Venus ambient and the evacuated canister causes the corer tool with sample to be driven up into the canister. At full travel, the corer tool trips a contact switch which activates another pyro to reseal the canister. Once the sample is in the canister, the ascent vehicle is decoupled from the lander and allowed to ascend via a balloon, leaving the complete lander/payload on the surface. After carefully examining the technologies required to support moving the design to full flight capability by 2007-2008, it became clear that one of the most critical technologies was electronic components which could survive the extreme heat and corrosive atmosphere of the Venus environment.

Impact of Extreme Environments on Sampling/Science Components

As a result of the above engineering studies done for in-situ sampling on Europa and Venus, and the conclusion that control system, communication system, and instrument electronics could not be adequately protected by standard shielding, cooling, and packaging technologies, it was decided to sponsor an international workshop on "Electronics for Extreme Environments" at JPL. That conference was sponsored by JPL/NASA and held on February 9-11, 1999 (10). Researchers from industry, government, and academia were invited to participate with the following primary goals:

1. Assess the state of maturity of related technologies;
2. Determine if the technology development rate is in synch with the planned 2007-2010 launch window for Venus and Europa;
3. Assess the major hurdles to getting the technology in place to support these missions;

In the area of extreme cold, researchers emphasized that the key issues effecting device reliability are long term thermal cycling, synergistic effects between single event upset (SEU) and temperature cycling, and interconnect failures. Long term thermal cycling at extremely low temperatures and/or, over large temperature ranges, impacts carrier mobility (e.g., devices start behaving like superconductors), threshold voltages (e.g., less voltage is required to bias devices-too much voltage can result in hot-carrier induced damage), and current gain. Additionally, at low temperatures interconnect and solder junction reliability becomes suspect due to variable shrinkage/expansion rates and subsequent cracking. Energy storage devices like batteries generally exhibit lower internal discharge rates at lower temperatures which is favorable. However, at extremely low temperatures electrolytes become sluggish and start behaving like insulators rather than charge conductors.

The primary effects of exposure to high doses of radiation revolve around SEU and internal device damage due to energy transfer of high energy particles impinging/passing through semi-conductor materials. Semi- conductor devices will not only breakdown, but they will not retain their original design characteristics in terms of threshold voltages, currents, gains, and state retention.

In the area of high temperatures, the researchers stressed that extreme heat causes a substantial increase in internal resistance of devices. Again, as internal resistance increases, device behavior deviates from the original design characteristics. Exposure to extreme heat also causes internal structural changes to occur in semi-conductor devices (e.g., internal device lattice structures become reordered or breakdown). And finally, as with extreme cold, device interconnect failures rise substantially. Energy storage devices like batteries are greatly effected by extreme heat. Internal discharge rates rise exponentially, causing the device to breakdown and the net stored energy to decrease.

Overview of Technology Advances to Mitigate Extreme Effects

Extreme Cold Temperature Technologies-

Characterization of Ge, Si, and GaAs devices at liquid nitrogen temperatures suggest that GaAs is particularly robust to extreme low temperatures (11, 12). Additionally, testing has shown GaAs to offer speed and stable current gain at low temperatures. Silicon on insulator (SOI) has also been tested and found reliable down to -200degC. CMOS integrated circuit technology is suited for low temperature operation, but MOSFET's experience significant degradation in life due to hot-carrier induced damage. Experimental work done on hot carrier physics shows that stabilizing the bias voltage below 3 volts, using higher gate voltages for channel lengths not greater than 2.5um's, and doping both the source and drain to prevent excess charge fluxes, help mitigate hot carrier induced damage (13). NASA Glen Research Center has done significant experimentation with off-the-shelf technologies and found that careful selection of device materials and combinations can allow operation down to -140degC. NASA Glen has contructed and operated power conditioning circuits like DC-DC power converters and oscillators down to -140degC (14). Unfortunately, experiments with battery materials has shown that the lowest temperatures feasible are with custom Li batteries down to -80degC (i.e., Deep Space 2 (DS2) batteries currently being flown on Mars98 Polar Lander) (15). The final conclusion drawn from this research is that cold electronic component technology is, indeed, maturing towards a needed Europa lander/probe technology freeze by 2005. This freeze date would enable the flight system to be designed/built for launch by 2008 or 2010.

Extreme Radiation Technologies-

Most off-the-shelf rad-hard military standard technologies available today are hard up to 100's of Krads. Available silicon-on-sapphire substrates have been shown to be radiation resistant up to 1Mrad with analog degradation on the order of only 1 part in 10000 (16). Technology like this is particularly attractive to commercial satellite companies looking for a reasonably priced solution to periodic Sun spot flare-ups and subsequent impact on Earth orbiting systems. The nuclear reactor industry has taken a multi-faceted approach to solving the problem of high-energy particle interactions with semi-conductor materials.

TEMIC corporation designs and fabricates complete ASIC's (integrated circuits) for use in the nuclear reactor industry. Using a combination of SOI, trenching to prevent charge propagation to surrounding devices, oxide absorption layers to suppress inter/intra-device leakages caused by high energy particles, and redundant CMOS, NPN, and PJFET devices, they have come up with an extremely rad-hard system which can operate reliably under exposures of 10Mrad total dose with no latch-up (17). Tests made with one 16 bit microprocessor showed the device still operating after 350Mrad total dose irradiation. This same design for digital and analog-to-digital conversion has recently been qualified for up to 100Mrad environments in the nuclear industry. Other industry players are also using custom buried oxide layering (e.g., ADVANTOX-170) to further harden SOI technology to 10Mrad total dose (18). Extending the oxide hardening process further, a gate-all-around (GAA) MOSFET has been developed which protects the entire channel area from particle penetration. An SRAM was built and tested and shown to be operational at doses of 85Mrad (19). This same device also shows promise for high temperature operation as well.

Diamond can be doped for semiconductor or resistive devices, or can remain undoped as a capacitive device. Diamond offers the advantage of being extremely stable and largely immune to high radiation effects. Being extremely stable, diamond is also immune to cold, heat, corrosion, and pressure. High temperature diamond switches have been developed and tested at temperatures approaching 365 degC (20,21). Although promising, unfortunately diamond is still in the basic research stages of development and will probably not be mature by the 2005 technology freeze date when actual flight electronics have to be designed and built. However, overall, it appears that in the area of extreme rad-hard fully integrated circuits, the SOI oxide hardened, redundant device technology is on a reasonable intersection course with the Europa lander timeline.

Extreme Hot Temperature Technologies-

Perhaps the most significant development in the area of reliable high temperature devices is the large test database now developed for SOI. SOI technology has been tested sufficiently now to say that it is mature for operating reliably at temperatures around 200degC. Some components have performed reliably up to 300degC for limited periods of time (i.e., up to 100hrs) (22). This large database now confirms that the primary life limiting high temperature factors are:

1. Increase in internal leakage currents;
2. Lower tolerance to conductive thin film electron migration (somewhat related to (1) above);
3. Breakdown between interconnects due to mismatches in wiring materials;

The interconnect issue has historically been a major life limiting variable. Researchers have experimented with different interconnect materials and found that if the proper high temperature tolerant materials are selected (e.g., tungsten, aluminum wires bonded to gold bond pads, platinum) then component life can be increased by an order of magnitude at >/= 200degC (i.e., increase life from 100hrs to 1000hrs) (23).

In the area of larger scale integrated circuits (ASIC's) SOI technology has been used to build motor/ actuator controllers. A CMOS SOI ASIC with 21000 gates has been packaged into a high temperature 208 pin ceramic gate array. This ASIC has been functionally tested for a continuous 60hrs up to 250degC and found to be fully operational (24). Silicon-carbide has stability properties approaching diamond and therefore looks very promising for extreme high temperature use. As a semiconductor material it exhibits high thermal conductivity, wide bandgap, and high breakdown electric field (25). Because of its stability it is resistant to micro-pipe flaws formed at high temperatures (i.e., this is the above issue related to internal lattice structure reordering or breakdown). As an example, SiC-CMOS high power switches and piezoelectric pressure sensors have been operated for limited periods of time with no degradation in electrical properties up to 600degC. Overall, although devices like diamond and silicon-carbide exhibit ideal properties for high temperature environments like Venus, these devices are still in their early development stages and not likely available by the technology freeze date of 2005-2006 for start of the Venus flight system build. Most likely, the SOI technology will be the likely candidate for the flight build. Given that its stable reliability envelope has been proven to be in the 200degC-250degC range, it will not allow any sampling, communication, or science instrument control system to survive the extreme Venus 450degC environment for any significant period of time.

Conclusions

The above discussion provided an assessment of the state of development of some of the key electronic component technologies needed for the Europa lander and Venus lander missions. It is essential that the reader understand that we cannot build reliable spacecraft, in-situ sampling, and instrument communication and control systems without the building blocks in place which allow us to construct the power supplies, computers, memory, sensors, and supporting circuitry which form control systems. Since a large number of the extreme electronics community were present, JPL/NASA took the opportunity to distribute a questionnaire which specifically addressed the issue of technology readiness. The results of this questionnaire are provided as a conclusion to this paper. The following is a summary of the responses:

1. **Which of the two missions is the most likely to be flown?**

- Majority of the responses suggested that the Europa lander/CHIRPS mission had the best chance of success due to the maturity of cold/rad-hard electronics as compared with hot electronics;
- Relative to Venus, the majority of the responses indicated that component technology which could survive 400degC+ temperatures would not be ready by the technology freeze dates of 2005-2006;
- Relative to Venus, the respondents unanimously felt that a Venus sampling and sample return mission would have to be done on a "grab-and-go" or "limited-

life" basis (i.e., only allow surface exposures on the order of "hours");

2. **What are key limiting components to meet the 2005 technology freeze date?**

Europa-
- Power storage/conversion;
- Component characterization (e.g., synergistic effects of cold and high radiation);
- Building in radiation margin/tolerance to ensure radiation hardening meets required life;

Venus-
- Interconnects;
- Non-volatile memory;
- Power storage/conversion;
- Limited analog component availability for >400degC;

3. **What are relative levels of maturity of devices?**
- For >/= -200degC—Many prototype devices/ASIC's have been built and tested at levels that would allow most components to move to a flight ready configuration;
- For -200degC and >10Mrad hardness—Many prototype devices/ASIC's built and tested with technology showing maturity for terrestrial applications like the nuclear power industry. The technology is ready to move to flight configuration if an investment is made in large scale component integration for space systems;
- For </= 200degC—Many SOI components/ASIC's have been built. This technology is ready to move to flight ready configuration;
- For >/= 300degC—Some limited success has been obtained with SOI, but the technology is primarily in an advanced research and development stage with prototype devices;
- For >/= 400degC—Most technology is still at the basic research stage, particularly in the areas of SiC, diamond, and GAA-MOSFET's.

4. **Is the private sector manufacturing infrastructure in place to enable NASA to obtain needed device technologies?**
- SOI is in place now for electronic components operating between -200degC and +200degC;
- SOI is in place now for electronic components operating at -200degC and up to 20Mrad, but investment is still needed in developing ASIC designs and dies which meet spacecraft volume, mass, and power constraints;
- No infrastructure is in place to produce electronic components for temperatures approaching 400degC, or radiation environments approaching or exceeding 40Mrads;

5. **What is your best estimate of when a manufacturing infrastructure could be in place?**
- For technologies that allow in-situ sampling systems to operate reliably in environments >/= 400degC and >/= 40Mrad total dose it might be feasible to have a limited infrastructure in place by 2005 if NASA were to make a significant investment now;

6. **What are the current hurdles to getting the manufacturing infrastructure in place?**
- The primary hurdle is that NASA does not represent enough of a market for the private sector to invest in developing the manufacturing infrastructure—accordingly, NASA will have to assume a large overhead for the development and delivery of custom extreme environment electronic devices;

The above survey results clearly show that the robotic designs generated for in-situ sampling in the Europa ice and just below the Venus surface are scoped properly based on the current and expected level of technology readiness.

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Biography

Wayne Zimmerman has been a senior engineer at the Jet Propulsion Laboratory, California Institute of Technology, for almost two decades. He received his B.S. in Fluid Dynamics with a major in Aerospace Engineering from Case Institute of Technology, Cleveland, Ohio in 1969. He received his M.S. in System Engineering/Management from the University of Southern California, Los Angeles, California in 1972. He has been working in robotics for 19 years. Wayne was the Project Element Manager (PEM) for the Mars98 Polar Lander robotic arm. He is currently the Lead Avionics Engineer for the Mars01 microrover and robotic arm. Wayne is also the Lead Engineer for the JPL Center for In-situ Exploration and Sample Return (CISSR). Wayne has been responsible for spearheading advanced sampling, sample handling, and sample return system designs which will enable out-year in-situ missions to extreme environments like Europa, Venus, Titan, and comets.