Extreme Environment Technologies for Space and Terrestrial Applications

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ABSTRACT

Over the next decades, NASA's planned solar system exploration missions are targeting planets, moons and small bodies, where spacecraft would be expected to encounter diverse extreme environmental (EE) conditions throughout their mission phases. These EE conditions are often coupled. For instance, near the surface of Venus and in the deep atmospheres of giant planets, probes would experience high temperatures and pressures. In the Jovian system low temperatures are coupled with high radiation. Other environments include thermal cycling, and corrosion. Mission operations could also introduce extreme conditions, due to atmospheric entry heat flux and deceleration. Some of these EE conditions are not unique to space missions; they can be encountered by terrestrial assets from the fields of defense, oil and gas, aerospace, and automotive industries. In this paper we outline the findings of NASA's Extreme Environments Study Team, including discussions on state of the art and emerging capabilities related to environmental protection, tolerance and operations in EEs. We will also highlight cross cutting EE mitigation technologies, for example, between high g-load tolerant impactors for Europa and instrumented projectiles on Earth; high temperature electronics sensors on Jupiter deep probes and sensors inside jet engines; and pressure vessel technologies for Venus probes and sea bottom monitors. We will argue that synergistic development programs between these fields could be highly beneficial and cost effective for the various agencies and industries. Some of these environments, however, are specific to space and thus the related technology developments should be spearheaded by NASA with collaboration from industry and academia.

Keywords: Solar system exploration, extreme environments, technology, NASA

1. INTRODUCTION

In 2003, the National Research Council recommended in its Solar System Exploration Decadal Survey (NRC DS) [1] that "NASA commit to significant new investments in advanced technology so that future high-priority flight missions can succeed." These proposed high-priority flight missions were further discussed in NASA's 2006 Solar System Exploration Roadmap [3], targeting planets, moons and small bodies, where spacecraft would be expected to encounter diverse extreme environmental (EE) conditions through their various mission phases. In support of these roadmapping activities, a series of studies were undertaken to assess the state of these relevant technologies. The findings were reported in an extreme environments technologies report [2]. NASA's Science Mission Directorate (SMD) Science Plan [4] – published in May 2007 – also identified technologies for extreme environments, as high-priority systems technologies needed to enable exploration of the outer solar system and Venus.

In these studies, environments are defined as "extreme," if they present extremes in pressure, temperature, radiation, and chemical or physical corrosion. In addition, certain planned missions would experience extremes in heat flux and deceleration during their entry, descent and landing phases (EDL), leading to their inclusion as missions in need of technologies for extreme environments. These EE conditions are often coupled. For instance, near the surface of Venus and in the deep (~100 bars) atmospheres of giant planets probes experience comparably high temperatures and pressures. In the Jovian system, for example near Europa, low temperatures are coupled with high radiation. Other environments include thermal cycling, and corrosion. Mission operations could also introduce extreme conditions. During atmospheric entry the spacecraft could experience high heat flux coupled with deceleration loads. Some of these extreme environment conditions are not unique to space missions; they can be encountered by terrestrial assets from the fields of defense, oil and gas, aerospace, and automotive industries. (It should be noted that there are many instruments and system technologies exist, which can be readily transferred between space and terrestrial applications. However, these are not closely related to EE technologies and therefore will not be addressed here.)

The primary focus of this paper is to discuss key findings of NASA's Extreme Environments Study Team, including discussions on environmental protection, tolerance and operations in EEs. We will also highlight cross cutting EE mitigation technologies, for example, between high g-load tolerant planetary impactors and instrumented projectiles on Earth; high temperature electronics sensors on Jupiter deep probes and sensors inside jet engines; and pressure vessel technologies for Venus probes and sea bottom monitors. We will argue that synergistic development programs between these fields could be highly beneficial and cost effective for the various agencies and industries. Some of these environments, however, are specific to space and thus the related technology developments should be spearheaded by NASA with collaboration from industry and academia.

2. DEFINING EXTREME ENVIRONMENTS

According to the definitions used in [2], a space mission environment is considered "extreme" if one or more of the following criteria are met: (a) *Heat flux:* at atmospheric entry exceeding 1 kW/cm^2; (b) *Hypervelocity impact:* higher than 20 km/sec; (c) *Low temperature:* lower than -55°C; (d) *High temperature:* exceeding +125°C; (e) *Thermal cycling:* between temperature extremes outside of the military standard range of -55°C to +125°C; (f) *High pressures:* exceeding 20 bars; and (g) *High radiation:* with total ionizing dose (TID) exceeding 300 krad (Si). Additional extremes include (h) *Deceleration:* (g-loading) exceeding 100g; (i) *Acidic environments:* such as the sulfuric acid droplets in Venusian clouds and (j) *Dusty environments:* as experienced on Mars.

A summary of planetary destinations and their relevant – and sometimes coupled – extreme environments are shown in Table 1, Typically, high temperature and pressure are coupled – e.g., for Venus *in situ* and deep entry probe missions to the two gas giants, Jupiter and Saturn. High radiation and low temperature can be also coupled, as experienced by missions to the Jovian system. Low-temperatures could be associated with surface missions to the Moon, Mars, Titan, Triton, and comets. Thermal cycling would affect missions where the frequency of the diurnal cycle is relatively short – e.g., for Mars (with a similar cycle to Earth), and for the Moon (with 28 Earth days).

3. PLANETARY MISSIONS TO DESTINATIONS WITH EE

Within NASA, the primary objective of the Science Mission Directorate is to implement a set of science-driven strategic and competitive missions. Planning for these missions can take many years and even decades in advance. To prioritize the related technology investment areas, it is necessary to understand NASA's planning activities and the mission concepts currently under consideration. Among SMD's three mission classes, strategic Flagship class missions are usually directed and larger in scope, with a projected cost cap of ~$1.5B to $3B. Smaller Discovery and Scout class and medium class New Frontiers missions – capped at ~ $425 M-$475 M and ~ $750 M, respectively – are competitive and selected through periodic NASA Announcements of Opportunity (AO).

Technology planning for large missions is reasonably well defined and the mission impacts are comparatively straightforward to determine. On the other hand, smaller missions are only planned a few opportunities ahead, translating sometimes to five years or less of planning, which introduce limitations to technology development. Therefore, technology development plans for these smaller missions are harder to forecast.

As discussed in NASA's 2006 SSE Roadmap [3], among the Flagship class missions the Europa Explorer would be the leading candidate to fill the first programmatic slot, with an earliest launch date of 2015. Second decade missions would include the Titan Explorer and the long-lived Venus Mobile Explorer (VME). For the third decade, the options could be influenced by the findings of the Europa Explorer mission, leading to a selection between the Neptune/Triton Explorer or a Europa Astrobiology Lander. The initial New Frontiers class missions included the 2006 New Horizons Pluto-Kuiper Belt mission (launched in January 2006), and Juno (a Jupiter Polar Orbiter mission without probes), planned for a 2011 launch. Potential New Frontiers missions for the 2015 opportunity are still under consideration, but could include concepts for: Comet Surface Sample Return (CSSR), Lunar South Pole Aiken Basin Sample Return, Venus In Situ Explorer (VISE) (short-lived), or Saturn Flyby with Shallow Probes (SFSP). Further details on these mission concepts are provided in [3].

4. SYSTEMS ARCHITECTURES AND TECHNOLOGIES FOR EE

Systems architectures for extreme environments can be categorized by the (1) isolation of sensitive materials from hazardous conditions; (2) the development of materials, which are tolerant to hazardous conditions; and an appropriate combination of isolation and tolerance, we termed hybrid systems. Isolation of all electronics and sensitive components in an environmentally controlled vessel could be difficult to implement, due to potential cost and mission architecture constraints, especially if some of the *in situ* components – e.g., sensors and sample acquisition systems – need to be directly exposed to the environment. Similarly, while the concept of environmentally tolerant technologies is appealing – e.g., removing the need for a pressure vessel and thermal management, – actual technology developments may not be able to answer these challenges due to fundamental physical limitations. For example, development of silicon electronics that could operate beyond its physical limit of 350°C is not possible, while some other EE technology approaches could result in impractical investment strategies. In contrast, hybrid architecture would use hardened components which would be exposed directly to the environment, and in parallel not-hardened components would be protected. In a high temperature environment, for example, this approach would result in a simpler and lighter thermal control, and would be more cost-effective.

Table 1: Extreme environments in the solar system [2]

Target Destination	**Radiation (krad/day)**	**Heat flux at atm. entry (kW/cm^2)**	**Deceleration(g)**	**Pressure (bar)**	**Low temperatures (°C)**	**High temperatures (°C)**	**Rotational period (Earth days)**	**Chemical corrosion**	**Physical corrosion**
High temperatures									
Venus		2.5	300	92	482	243		Sulfuric acid clouds	
Jupiter (upper atmosphere)		30	228	22		230	0.4		
Low temperatures									
Lunar permanently shadowed regions					−230				Dust
Comet (nucleus)		0.5[a]			−270				
Titan		0.01	15	1.5	−178		16	CH4	
Enceladus (equator)					−193				
Enceladus (south pole)					−188				
Low temperatures and high radiation									
Europa (orbit)	40								
Europa (surface)	20				−180		3.6		
Europa (sub-surface)	0.3 at 10 cm				~0 at 5 km				
Thermal cycling									
Moon					−233	+197	27		Dust
Mars		0.05 –0.1		0.007	−143	+27	1		Dust
[a] refers to Earth return									

Technologies can be categorized as heritage, enhancing, or enabling. Heritage technologies are flight qualified and do not need significant technology investments. Enhancing technologies would benefit the mission, but without them the mission could still be successful, although with a less optimum configuration or reduced utility. Without enabling technologies the mission could not be executed at its conceived way. In formulating technology roadmaps to handle the extreme environments of these future planetary missions, it is important to understand not only what has been done previously in planetary missions, but also to consider emerging technologies not previously used in space. Emerging technologies have been categorized into three general areas, namely: (a) environmental protection technologies; (b) environmental tolerance for exposed components; and (c) robotics in extreme environments, which includes technologies like mobility or sample acquisition, providing capabilities to operate in extreme environments in order to achieve mission science objectives. These three areas will be discussed below in more details.

5. PROTECTION SYSTEMS

Under protection systems we will outline technologies related to hypervelocity impact and entry, high temperatures and pressure, low temperatures, and ionizing radiation.

5.1 Hypervelocity impact

All long-duration missions in the solar system would be subjected to hypervelocity impact hazard, but among the roadmapped missions a return to the Saturn system and the exploration of active comets would most likely involve the most difficult challenges. Cassini's ability to cross Saturn's ring plane and to conduct a close-up reconnaissance of the plumes of Enceladus is limited by the design of the spacecraft. Advances in shield technology might enable more aggressive sampling of the icy plumes in a potential future mission to Enceladus.

In the past, all three NASA Discovery-class missions to active comets - Stardust, CONTOUR, and Deep Impact - were equipped with shielding to cope with the environment. Stardust and CONTOUR used multilayer Whipple shields composed of a multilayer Nextel "bumper" to disrupt particles, and included a Kevlar backup layer. The Deep Impact mission, which consisted of two spacecraft, employed the most complex approach to protection, because of the need to observe the comet throughout the encounter. The Flagship-class Cassini mission protected vulnerable parts of its vital propulsion system from the low-level, but still mission-threatening, ambient micrometeoroids flux during its long cruise phase by exploiting the particle disruptive properties of multilayer insulation (MLI). Particularly vulnerable components, such as the rocket nozzles, were protected with a retractable cover that is withdrawn during the operation of the engines. For the much more intense, but highly directional fluxes experienced in crossing the narrow ring plane, the spacecraft is oriented in the least vulnerable attitude.

Future technology investments could address new environmental models for meteoroids, cometary, planetary ring, and debris models above 2000 km for the outer planets; standardized, validated empirical cratering and penetration models and validated hydrocodes capable of modeling complex shielding geometries for impacts of 5-40 km/s; techniques for rapidly and cheaply testing new shielding configurations for particle masses up to 1 mg and for velocities up to 40 km/s; shielding technologies for light shielding designs for 1 mg particles impacting at 5 to 40 km/s; and standardized methodology for evaluating the efficiency and reliability of complex shielding schemes.

These advances could reduce the risk of spacecraft damage or destruction, and by utilizing more accurate environmental impact models – validated by ground tests – could potentially permit significant savings in mass and mission complexity, and possibly increase performance.

5.2 Hypervelocity entry

Entry environments experienced in planetary missions range from the comparatively benign at Mars and Titan, to the more severe at Venus and Earth (required for sample return), to the most severe environments at the giant outer planets. For example, the Galileo entry probe entered the atmosphere of Jupiter at ~47 km/s, more than four times the entry velocity of the Pioneer-Venus probes, while the ablative heat shields of these probes were protected with a dense carbon phenolic material.

The SSE Roadmap [3] recommended a Saturn entry probe mission, for which the entry velocity (~26-29 km/sec) could introduce a heat flux significantly lower than experienced by the Galileo probe. Other mission concepts to Titan and Neptune may use aerocapture technology to reduce their approach velocity and to get into orbit with a single pass, thus requiring extended hypervelocity sustained flight through the atmosphere. Aerocapture places new demands on the performance of the thermal protection system (TPS) and requiring other new technologies as well, related to guidance, navigation and control, and thermal management. (These high entry velocities into dense atmospheres could also result is high deceleration loads, which must be tolerated by the subsystems – e.g., electronics, power sources, and science payload – either directly, or by using other mitigating or damping techniques. For example, entry probes to Venus and Jupiter could experience g-loads up to 300-400 g. In comparison, impactors and penetrators – proposed Europa, Enceladus and lunar exploration missions – could encounter g-loads well over 2000-3000 g.)

Most of the development in TPS technology over the past two decade has been targeted at improving the payload mass fractions. New ablative and reusable materials have been developed and evaluated through arc jet testing. For a better understanding of their performance, aeroshell TPS can be instrumented – e.g., as planned for the 2009 Mars Science Laboratory mission – in order to characterize local conditions and entry shell ablation rate during planetary entry.

Future investments in TPS should address dense ablative materials for the environments of the outer planets – such as Jupiter and Saturn – to reduce TPS mass fraction from today's 50-70%, thus increase payload mass fraction for the same entry mass. Surface sample return and Venus *in situ* missions would also benefit from lower TPS mass fractions. However, the testing of these materials for the outer planets would require major facility investments. While pressure and temperature sensors are commercially available, development is needed for measurements of heat flux and recession rates. Finally, physics-based models are needed to validate experimental measurements.

5.3 High temperatures and high pressures

These environments have been encountered by Soviet and U.S. missions at the deep atmosphere and surface of Venus, while being also exposed to the corrosive aspects of the atmosphere (i.e., sulfuric acid in the upper and supercritical carbon dioxide in the lower atmosphere). Pioneer-Venus, NASA's only Venus *in situ* mission to date, included 1 large and 3 small atmospheric probes, which were not designed or equipped for surface observation. Among all the successful *in situ* Venus missions the longest lifetime on the surface, of 127 minutes, was achieved by the Venera 13 lander.

The proposed VISE mission, which would investigate surface chemistry at one location on Venus, would be enhanced by passive technologies (advanced pressure vessels, insulation, phase-change materials), designed to extend Venus surface mission lifetime. These technologies would also be applicable to deep probe missions to Jupiter and Saturn. Missions, such as the long-lived VME, would also require internal power generation coupled with active cooling technologies, and high-temperature electronics to achieve the long-lifetime objectives. Sample acquisition mechanisms would necessarily be exposed to the environment and advances in components would have major mission impact.

This area has the broadest potential for progress of any of the protection technologies considered in [2]. For protection from high pressure, high buckling strength beryllium and titanium matrix materials could enable much lighter pressure vessels than those used previously. Their creep resistance also permits longer-duration missions in the elevated temperature environment at the surface of Venus or for outer planet deep probes.

For protection from elevated temperatures, a number of different approaches show potential. New insulating materials and architectures for employing those insulating materials have been identified. Phase-change materials (PCM) offer a mixed prognosis. While there is only limited potential for advances in using the liquid-solid phase transition beyond those achieved with lithium nitrate (195 kJ/kg), a water lithium system exploiting the water-vapor transition with venting to the Venus environment could permit up to 700 kJ/kg. However, these essentially passive or "one-shot" approaches can only prolong surface operations from hours to perhaps days on the surface. For months of operation, an active cooling system (a heat pump), powered by a suitable Radioisotope Power System (RPS), would be needed.

Future investments could address pressure vessel designs, which may introduce mass savings up to 50-60% compared to a standard monolithic titanium shell; a thermal energy storage system with twice the specific energy capacity of the current state of the art; a thermal energy storage system integrated with the pressure vessel with a tenfold improvement in storage capacity relative to the current PCM module technology; and a scaleable powered active cooling system capable of providing a temperature lift of ~400°C, while removing 80 W for a system mass of 60 kg (including an RPS), giving an effective cooling density of about 5 kJ/kg. [2]

5.4 Low temperatures

Severe low-temperature environments are inherent to exploration of the outer solar system and are experienced in the inner solar system during the exploration of airless bodies (Moon, Mercury, asteroids) and Mars (a body with a thin atmosphere and extreme diurnal temperature changes). Short-duration missions, such as the Huygens probe to Titan, have coped with environments as cold as -178°C. The still active Mars Exploration Rovers (MER) experience diurnal temperature cycles with lows near -143°C, which is well below the operating temperature limits. However, they protect the electronic components in a warm electronics box (WEB), where the temperature is controlled within the normal operating range. The MER rovers use lithium-ion batteries with an advanced electrolyte, permitting operation down to -40°C.

In situ missions to these low-temperature environments present significant challenges because of their power constraints and thermal control complexities. Low-temperature batteries and low-temperature electronics could enable extended operations on cold targets. For mobile vehicles with motors and actuators exposed to the surface environment, cold electronics can greatly simplify cabling. Thermal-cycling due to the diurnal cycles of slowly rotating bodies, such as the Moon and Mercury, could impact electronic components and must be designed to tolerate the resulting cyclical stresses.

Protection against cold-temperature environments involves extension of the WEB technologies used on MER. In addition to this purely passive solution, radioisotope heater units (RHU) could be used to avoid demands on scarce electrical power. For those missions using RPSs, excess (waste) heat from the RPS could provide further protection against the cold environment. Protection from cold environments would not be as challenging as protection and isolation from high temperatures.

5.5 Ionizing radiation

While ionizing radiation environments are ubiquitous in space, the most severe radiation is encountered in the radiation belts of Jupiter. In its multiyear mission, the Galileo orbiter not only provided the most complete characterization of this environment, but was exposed to a much higher cumulative dose (~600 krads) than any other planetary spacecraft, before the mission was ended by sending the spacecraft to impact Jupiter. Galileo employed an extensive use of shielding, radiation-tolerant electronic parts, and operational methods for recovering from radiation damage.

The broad base of experience from the Galileo mission on the nature of the Jovian environment, its effects on spacecraft components, and methods of mitigating these effects, is being applied to the Juno mission, currently in formulation phase, and to other missions that are still in the study phase. The Europa Explorer mission – proposed in [1] and [3] – would have a typical mission profile to orbit Jupiter for two years, followed by a 90-day orbiting mission around Europa. This is expected to result in radiation doses about five to ten times that of the Galileo mission. The proposed Europa Astrobiology Lander (EAL), conceived as a follow-on mission to the Europa Explorer, may experience lower dose rates than an orbiter, due to Europa's self-shielding. However, landed missions would be much more mass constrained than orbiters, so it is possible that the requirements on the components would be even more demanding.

Protection from ionizing radiation environments could include shielding by the target body under investigation, shielding by spacecraft systems, such as propellant tanks, as well as dedicated shielding for sensitive components. Recent work has indicated that self-shielding by both Europa and Ganymede is significant and should be accounted for in the design of both orbital and landed missions. There has been a great deal of work on the development of radiation codes, but high-fidelity codes for predicting radiation effects in spacecraft and tests of the effectiveness of different shielding materials are lacking.

Future investments could include improved models of the Jovian, Neptune, and Uranus systems, and modeling of the solar charged particle environments near Venus and Mercury; development of shielding effectiveness; and conducting ground testing. Radiation transport codes should also be validated against ground test results, and by comparing them against other codes, such as NOVICE, MCNPX, GEANT4.

6. COMPONENT HARDENING

Developing components that can tolerate extreme environments is a complementary approach to protecting the components of a system from the environment. Component hardening is particularly relevant for dealing with environments with extreme temperatures and ionizing radiation effects, where complete protection may not be practical for meeting mission objectives.

6.1 High-temperature electronics

NASA has not implemented a mission to a high-temperature solar system *in situ* environment since the Pioneer-Venus and Galileo probes, although neither of them was equipped with electronic components to tolerate elevated temperatures.

Nevertheless, developments within NASA and the commercial drivers of deep subsurface access have resulted in significant progress on components tolerant of high-temperature environments.

Large-bandgap semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN), as well as vacuum tube active components, have the potential for operating at 500°C, but so far this potential has only been validated for SiC. A SiC transistor designed and packaged for high temperature has demonstrated 1000 hrs of operation at 500°C. In addition to the active devices, passive components (resistors and capacitors) have been demonstrated and progress has been made on development of thermally compatible substrates. A key challenge is the development of interconnects that can survive extended exposure to these temperatures.

On proposed Venus surface missions, high-power electronics and telecommunications systems act as internal heat sources. Placing these systems outside the thermally protected vessel may reduce internal heating and extend the life of the mission. Small-scale integrated SiC, and GaN high-temperature technologies and heterogeneous high-temperature packaging can support this need and provide components for power conversion, electronic drives for actuators, and sensor amplifiers. Another architectural approach is the use of devices that operate at an intermediate temperature of 300°C, such as commercially available silicon-on-insulator (SOI) devices. Electronics operating at medium temperatures can reduce the difference between the outside environment and inside the thermally protected system, significantly reducing the associated power requirements for cooling. High-temperature batteries have also demonstrated significant progress and can enable and/or enhance future missions to high-temperature environments.

Future investments could address: high-temperature, long-life (500 hrs) SiC, GaN, and vacuum tube active components; small-scale, high-temperature (500°C) SiC, GaN, and microvacuum device-based integration technologies; high-temperature passive components and packaging technologies; device characterization and modeling capability that result in a tools that enables extreme environment electronics designs; high-temperature integrated systems; medium-temperature (300°C) LSI-scale ultra-low-power SOI CMOS; and integrated medium-temperature electronic systems, such as solid-state recorders, flight microcomputers, and actuator/sensor controllers.

6.2 Low-temperature electronics

Avionics systems, components (such as sensors, transmitters), and *in situ* systems (using wheels, drills, and other actuators) that could directly work at cold temperatures (down to about -230°C) would enable the elimination of the warm electronics box and the implementation of distributed architectures that would enable the development of ultra-low-power, efficient and reliable systems. Developments in cold temperature electronics are currently being sponsored to support the needs of the Mars Science Laboratory mission and future lunar robotic missions. Commercial development of silicon germanium (SiGe) components is also showing a great deal of promise.

Future investments could include: design methodology for making reliable, ultra-low-power, wide-range low-temperature and low-temperature very large scale integrated (VLSI class) digital and mixed-signal application specific integrated circuits (ASIC); low-temperature and wide-range low-temperature radiation-tolerant, VLSI class, ultra-low-power, long-life Si and SiGe-based electronic components for sensor and avionics systems; wide-range low-temperature passive components and high-density packaging technology; research and modeling tools that produce the models that enable low-temperature and wide-range low-temperature radiation-tolerant electronic design; and low-temperature integrated systems, such as solid-state recorder, flight microcomputer, and actuator/sensor controller.

6.3 Radiation-tolerant electronics

In addition to DoD developments, NASA has carried out focused investments in rad-hard technology aimed specifically at missions to the Jupiter system under the X-2000 program in the late 1990s, and as part of NASA's Prometheus program between 2002 and 2004, with its flagship Jupiter Icy Moons Orbiter (JIMO) concept (now canceled). As a result, many components are currently available rated at 1 Mrad total integrated dose (TID), and a broader range of components to 300 krads.

At present, the space industry relies on three distinct sources for radiation-tolerant components: (1) commercial components, which are determined to be – perhaps serendipitously – radiation tolerant; (2) radiation hard by process (RHPB) components, which are manufactured with radiation hardened material processes at specialized foundries; and (3) radiation hard by design (RDBD) components, which are built on commercial lines with commercial materials and processes, but designed to tolerate high radiation doses.

One major gap in this technology has been dense nonvolatile memory (NVM). High-density solid-state recorders (SSRs) used for Earth orbital missions use commercial flash memory devices, which are inherently rad-soft. Even massive vaults may not provide the level of shielding needed for operation in the Jupiter system. However, recent progress on chalcogenide random access memory (CRAM) and magneto-resistive memory (MRAM), for which the memory elements are rad-hard, may provide a solution.

Future investments will require NASA to initiate a significant effort in this area to evaluate and characterize the options for avionics systems in a methodical fashion. Electro-optical components for science instruments would need particular attention, since the ability to successfully execute scientific measurements is inherent to the success of the future missions, including the proposed Europa Explorer mission.

6.4 High-temperature energy storage

Primary batteries that release their electrical charge by thermal activation are in routine use on NASA and DoD programs. In the 1970s and 1980s, there was active research on high-temperature rechargeable batteries that operated at 300°C to 600°C because of the prospects of achieving high energy densities. Progress in lithium-ion technology removed that impetus, but still provided a foundation for several technologies that could be applied to future Venus surface missions, such as an all solid-state battery developed by DoE's Sandia Laboratory for oil drilling applications. Longer-range possibilities include a primary battery concept from JPL using a calcium (Ca) metal anode, nickel-fluoride (NiF_2) cathode, and fluoride-ion based solid-state electrolyte. Not having to cool the batteries will significantly lower the thermal load on a Venus *in situ* mission, and if the battery can be moved outside the temperature-controlled housing, the size of the enclosure can be reduced.

Future investments could include: characterization of the performance and stability of existing primary batteries at high temperatures (500°C) and if a promising candidate is found, selecting it for advanced development; development of an intermediate-temperature secondary battery (250°C) based on current lithium ion technology; and selection of the most successful components and creation of a flight-qualifiable primary and secondary battery for the 250-500°C temperature range.

6.5 Low-temperature energy storage

Low temperature batteries could enable effective operation of rovers/probes/landers in cold environments through mass and volume savings, associated with the heavy thermal systems that are needed with state-of-practice space batteries. This technology could also introduce corresponding cost savings. Storing energy at low temperatures using devices based on chemical energy is challenging, since the chemical reactions needed to release electrical energy slow down at low temperatures. There is potential for reducing the operating temperature from the -40°C, achieved in the batteries on the MER mission, to perhaps -100°C. Other chemistries with potential for low-temperature operation are lithium-sulfur and lithium-copper chloride. For energy storage at lower temperatures than -100°C, other approaches, such as flywheels and superconducting magnetic storage would need to be pursued. However, it is not clear that these approaches would be practical or the needs of Roadmap missions would warrant the investment.

Future investments could address: search for electrolytes that have good lithium conductivity at low temperatures; improvement to lithium electrode/electrolyte interfacial properties for enhanced charge transfer; and demonstration of technology feasibility with experimental cells at appropriate rates of charge and discharge.

7. ROBOTIC SYSTEMS

Robotic systems are essential for *in situ* mission goals to be met and to enable the collection and direct examination of samples. Technologies include mechanical systems, required for *in situ* sample acquisition and analysis, as well as aerial mobility systems on Venus or Titan, where atmospheric conditions provide the opportunity for broad survey operations.

7.1 High-temperature mechanisms

Motors and actuators are required for a variety of functions, such as opening and closing valves, deploying landing gear, and operating robotic arms and antenna gimbals. Motors are also required for operating drills, and the acquisition of un-weathered samples from at least 20 cm below the surface layer of Venus (e.g., VISE). For VME, motors and actuators would also be needed for the mobility systems and would require reliable operations for at least hundreds of hours.

Standard actuators, based on ferromagnetic or ferroelectric materials, face an intrinsic challenge at high temperatures since at the Curie temperature the phase transition causes them to lose their actuation capability. In response to this need, NASA has sponsored the industry development of a switched reluctance motor, which operates without permanent magnets and it has been successfully tested at 460°C [2]. No other motors are currently known that could operate under Venus conditions for any significant period of time.

Future investments could include: the development of a sample acquisition system operable at 500°C; development of mechanisms associated with aerial mobility; and extended operations up to tens of hours in this environment.

7.2 Low-temperature mechanisms

Cold-temperature mechanisms are needed to provide many of the same functions identified for the hot mechanisms discussed above. Low-temperature motors and actuators would be needed for the proposed Titan Explorer, for rovers associated with the Lunar South Pole Aitken Basin Sample Return mission concept, and for the proposed Europa Astrobiology Lander. The motors would be required for sample acquisition systems, mobility systems, robotic arms, and other applications. Current operation of gears bearings and lubricants at -130°C is limited to 1,000,000 cycles, while drive and position sensors are also limited to operation at -130°C.

Future investments could include: an integrated wheel/ballute motor, with appropriate lubrication, capable of operation down to -180°C and 50,000 revolutions; a low-temperature robotic arm for sample acquisition; and integration with technologies hardened to 1 Mrad of radiation.

7.3 High-temperature mobility

High-temperature mobility systems are required for future missions to the surface and lower atmosphere of Venus. For a Venus Surface Sample Return (VSSR) mission, it would be necessary to raise samples from the surface to altitudes of 50 to 60 km. Efforts to develop a single stage polymer balloon for this application have been unsuccessful, however, a two stage balloon with a metal bellows first stage appears practical. The metal bellows approach has been tested at Venus temperatures. The metal bellows technology also appears to be applicable to the proposed VME mission and would easily permit operations over an altitude range of 10 km.

Future investments could include: design, fabrication and testing of large-diameter bellows balloons, deployment and inflation mechanisms, and including systems integration.

7.4 Low-temperature mobility

Low-temperature mobility systems would be primarily needed for the proposed Titan Explorer mission. There has been significant progress over the last several years in aerial mobility systems. Balloon envelope materials have been developed that can tolerate the low Titan temperatures and various architectures for controlled mobility have been investigated. A thermal Montgolfiere balloon – capable of multiyear operation – looks particularly attractive, although it has not yet been demonstrated in a relevant environment. Autonomous control systems capable of responding to unpredictable conditions in the environment have also been evaluated.

Future investments could target: low-temperature mobility to mature the technology to the point that it could be adopted for the Titan Explorer mission. This technology would have several sub-components including cryogenic balloon materials, balloon fabrication, aerial deployment and inflation, aerobot autonomy, and surface sample acquisition and handling. The technology needs are currently being updated in a NASA sponsored flagship class mission study in order to define the technology needs for a Titan Explorer mission.

8. CROSS CUTTING BETWEEN SPACE AND TERRESTRIAL EE TECHNOLOGIES

In this section we provide a limited number of examples to illustrate the similarities and differences between extreme environment technologies in space and on Earth. This is not a comprehensive list, rather a snapshot of certain applications, which may demonstrate the difficulties with directly transferring technologies from one domain to another.

For a start, natural extreme environments on Earth are much more benign than those in space. The recorded highest and lowest temperatures on Earth were +58°C and -91°C, while the pressure at the deepest place in the ocean – at 11 km below sea level – is 1110 bars. Although this pressure is very high, it is not coupled with high temperatures, as on Venus or in deep giant planets atmospheres.

In comparison, “man made” operating environments in aeronautics can reach over 1000°C, where simple high temperature tolerant components – such as pressure sensors, thin film thermoelectrics, and high-T RF components, with demonstrated operations up to 500°C – could enable new capabilities, including intelligent engines, which are self-monitoring, self-correcting, self-modifying or morphing. These sensors can also enable high temperature wireless communications, but they are still at an early development phase [5]. High temperature components face technology challenges and limits, as shown in Fig.1. For instance, connectors start to develop problems at ~150°C, and soft solders melt at ~180°C. Magnets and actuators and silicon based electronics reach their operational limits at ~300 to 350°C. (This impacts high temperature electric motor designs, envisioned for proposed Venus surface drills.) Teflon, which could be used on Venus balloons, degenerates at 370°C. This could point to a metallic bellows design for VME, operating near the surface. Even hard solders melt at ~400°C. It is acknowledged, however, that most of the technologies used by commercial industries and military applications fall below the current limit of ~350°C. Furthermore, even if some of the terrestrial applications would encounter extreme environments comparable to that in space, the resources to mitigate them would not be bound by the same limitations as those for space missions. For example, high radiation environments inside nuclear reactors are very effectively shielded by concrete. This, on the other hand, is not suitable for space applications due to mass limitations [6]. Radiation tolerant electronics, developed for military use, could benefit future missions to Europa, as discussed in Sec.6.3, and the gains should be weighted against potential shielding mass savings, which in turn could be re-utilized as payload mass.

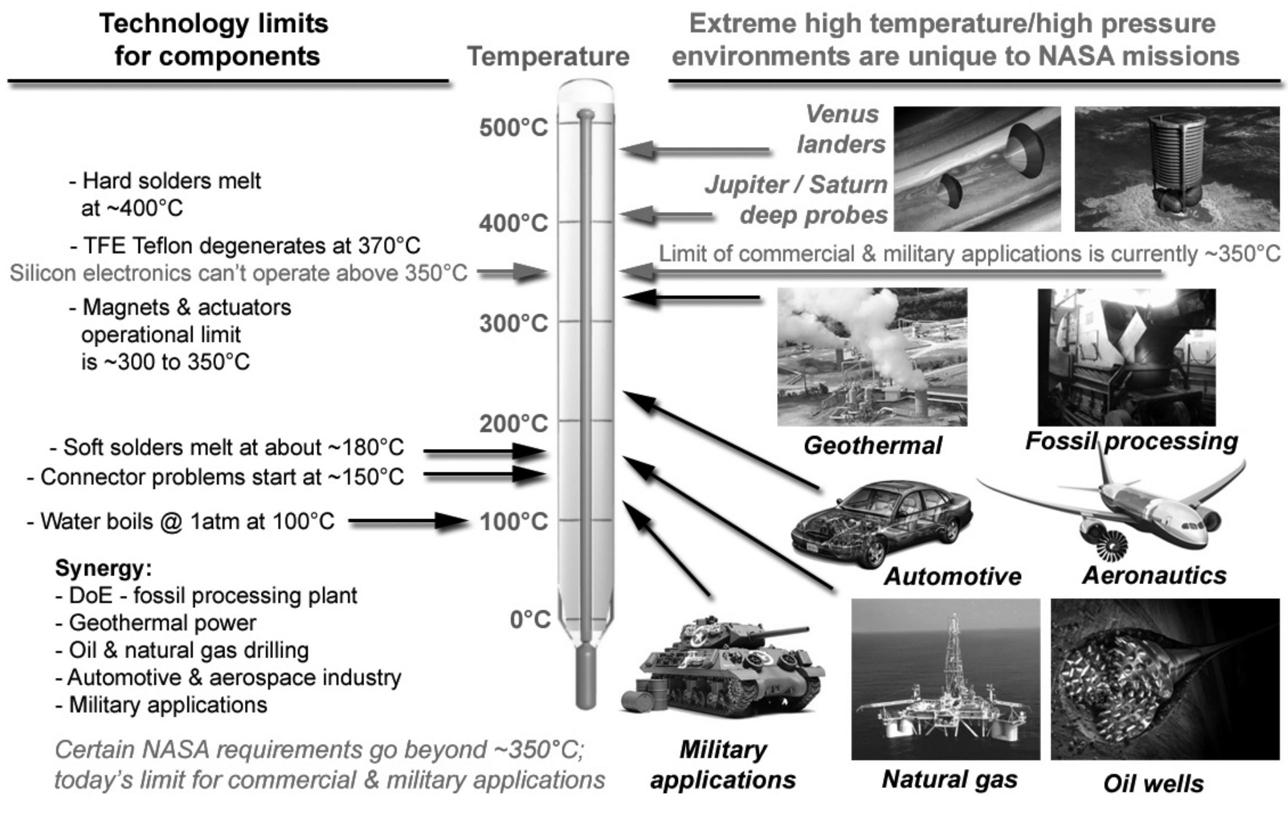

Fig. 1. High temperature limits of conventional components

In certain fields and industries market drivers may not encourage the development of extreme environments technologies, once suitable alternatives are found. This is discussed in Sec.6.4, where high temperature battery developments by DoD and NASA was showed to slow down after the emergence of Lithium-Ion batteries. There are also technologies, which seem to overlap between space and defense fields, and while they may look comparable, the environmental regimes might be significantly different. For example, thermal protection systems on intercontinental ballistic missiles could encounter very high convective heating rates, but without the simultaneous radiative heating experienced by the Galileo probe [7]. This impacts TPS material selection and the shape of the entry shell, among other design parameters. Similarly, planetary impactors and penetrators may experience comparable deceleration loads to the acceleration loads on projectiles used by the military. Thus, g-load tolerant electronics (to ~20000 g) on instrumented projectiles could directly benefit space missions [8]. However, impactors may require longer lifetimes than projectiles, which could significantly increase power requirements on an already mass limited space mission. Furthermore, it is likely that not all of the instruments and subsystems required for an impactor would have direct technology heritage from the above mentioned application, and the development of new technologies may render the design unaffordable within given mission cost constraints.

In summary, technologies developed for terrestrial use typically don't require to tolerate extreme environments to the same level as experienced by spacecraft. Ground based application may not have the same stringent mass, volume and power limits as those imposed on space missions, nor the very long term and reliable operating requirements. Terrestrial applications can also exploit their environments. Radioisotope power systems (RPS) on deep ocean probes could use the surrounding water as a heat sink, while the pressure vessel design is not likely mass limited. In comparison, radioisotope power systems on deep space missions would be operating in a vacuum, therefore, the only available heat rejection mechanism for the RPS excess heat would be radiation, which would require large radiator fins, thus increasing mass and reducing specific power.

Finally, while practically all cutting edge defense-related technologies are developed internally by specific agencies and their supporting industry partners, while many of the civilian space exploration missions have international collaboration elements. This introduces a significant challenge to technology transfers and spinoffs between these entities, while complying with the International Traffic in Arms Regulations (ITAR), especially if the transfer is towards civilian space agencies and programs. Technology transfer from civilian space to defense is expected to be easier, but the technologies related to mitigating extreme environments in planetary environments are significantly above the range encountered by terrestrial applications and might not benefit these fields. Still, the experience and knowledge base from the various industries should be exploited to the overall benefit of all involved. NASA should build on the expertise of industry partners and academia, and lead the development of extreme environments technologies. In turn, these extreme environments technology developments could benefit terrestrial industries, ultimately broadening the boundaries of Earth based applications.

9. SUMMARY

Most planetary exploration targets of interest present multiple environmental challenges, requiring the development of technologies designed for multiple environmental extremes. In general, there may be several architectural approaches for coping with these environments, some involving protection, others environmental tolerance or a combination of both. Systems analyses and architectural trades would be needed to develop specific performance targets for the different technologies and to establish priorities in the technology investment program.

Over the first decade, a number of technologies are required to enable proposed planetary exploration missions. These could include: radiation-hard electronics for missions to the intense radiation environments of the Jupiter system; entry probe technology that could enable atmospheric entry into Saturn and Jupiter, and for operation down to 100 bars pressure depth; technologies for (short-duration) survival, operation, and sample acquisition on the surface of Venus; and drilling, sample manipulation, and storage at cryogenic temperatures for comet missions. For the subsequent decade, the NRC DS report [1] and the SSE Roadmap [3] identified the need for technologies to enable aerial vehicles for the exploration of Venus, Mars, and Titan; and long-lived high-temperature and high-pressure systems for operation on and near the surface of Venus.

Addressing these technology-needs within NASA made progress in certain cases, but also had some substantial setbacks. For example, the Aerospace Technology program was dissolved, and its funding was folded into the Exploration Systems Missions Directorate (ESMD). In contrast, some work has been funded by ESMD on components for operation at cold temperatures, and SMD is sponsoring technology development for high-temperature electronics; high-temperature motors; advanced pressure vessels; and thermal control systems as part of NASA's Small Business Innovative Research (SBIR) program for robotic exploration of the solar system. At this time, however, there is no program within SMD that directly supports development of the needed technologies by NASA centers, universities, and industries not qualifying for the SBIR program.

While terrestrial applications also require ongoing technology developments for defense, oil and natural gas, automotive, aeronautics, and geothermal industries, it can be concluded that the extreme environments encountered through theirs operations may not exceed or even reach the domain of NASA's deep space missions. Therefore, it can be concluded that planetary extreme environments and related technologies are unique to space agency driven missions, and thus space agencies are expected to take the lead in the development of these critical technologies, with support from industry and academia. In turn, such a partnership – benefiting from the resources and experiences of terrestrial industries and government entities – could support the formulation of a coherent program addressing future extreme environment technology needs.

10. ACKNOWLEDGMENTS

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. The authors of this paper wish to thank the Extreme Environments Study Team members at JPL, including: Ram Manvi, Gaj Birur, Mohammad Mojarradi, Gary Bolotin, Alina Moussessian, Eric Brandon, Jagdish Patel, Linda Del Castillo, Michael Pauken, Henry Garrett, Jeffery Hall, Rao Surampudi, Michael Johnson, Harald Schone, Jack Jones, Jay Whitacre, Insoo Jun, - in addition to the authors of this paper: Tibor Balint, Elizabeth Kolawa (study lead), James Cutts & Craig Peterson. Team members from other NASA centers included: Ed Martinez, Raj Venkapathy, & Bernard Laub from NASA-Ames Research Center; and Phil Neudeck from NASA-Glenn Research Center. Further thanks to Gary Hunter from NASA GRC for his support. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration.

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