

HIGH TEMPERATURE ELECTRONICS APPLICATIONS IN SPACE EXPLORATIONS *

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Electronic instruments and systems used for space exploration have not generally been exposed directly to harsh environments of outer space or the dense atmospheres of several of our planets. Instead, protective enclosures, insulation, shielding, and small heating systems are provided to control the environment. Also the design of spacecraft systems and instruments are carried out with fairly conservative design rules, because the cost of a mission is high, and failure is easy to achieve. The design of electronic instruments for use within the wide range of the earth's environment is difficult enough, and extension of our electronic technology to operate at very high or low temperatures or great pressures is no small challenge.

Operation of electronic systems in environments having temperatures or pressures beyond the capability of the electronics requires systems to protect or insulate the electronics from the environment. The maintenance of the protection requires energy, and the energy source itself may require protection. In vacuous space, the energy transfer to the spacecraft is entirely dependent upon radiative transfer, and temperatures can be controlled by varying the reflectivity of the spacecraft surfaces. This form of control may require little energy since it often can be accomplished with little more than the rotation of the spacecraft or the reorientation of reflective panels. Pressure differences are seldom larger than the difference between that of the earth and vacuum. In these respects, the exploration of space is considerably less difficult than the exploration of the earth's inner space where temperatures and pressures are high.

The exploration of the planets having large atmospheres is entirely a different matter. In the case of Venus, for example, the surface temperature is near 730°K and the atmospheric pressure 90 bars. The atmospheric profiles of the large outer planets are relatively unknown, but one thing is sure, both the pressure and temperature will increase well beyond our technical capability to design instruments before any surface is likely to be found. The depth to which these atmospheres can be studied depends on one of two things, 1. our ability to design probes that can withstand the great temperatures and pressures, 2. the ability to transmit the information through the dense absorbing atmospheres.

The problem of protecting electronic systems from the great temperatures and pressures of these atmospheres is a very different problem from that of outer space. Here the thermal energy transfer is caused primarily by conduction to the atmosphere. The atmospheric pressures may be hundreds of times greater than those of the earth's atmosphere, so our spacecraft may look more like a craft designed for deep ocean exploration. We have two choices as to the design of our craft, either we design our systems to withstand the high temperatures and pressures, or we maintain temperature and pressure differences within the craft. The maintenance of temperature and pressure differences requires energy, and energy is always a very expensive and a scarce commodity on any space probe. Therefore it is very important that we minimize or eliminate the need to maintain such dif-

ferences. The extension of range of operating temperatures of electronic components and systems is a start in that direction.

Missions

The exploration of the atmosphere of Venus will probably be the first example of the use of high temperature electronic systems in space applications. Studies of the Venusian atmosphere could be accomplished by the use of balloon borne instruments. The simplest sort of experiment might be one that determines only the circulation properties of the atmosphere at various altitudes. All that is required here is a beacon of sufficient power to be tracked by either orbiting spacecrafts or from ground-based radio telescopes. A more advanced probe might contain a radar transponder. The localization of the balloon, for example, could be accomplished by VLBI, Doppler tracking, range tracking in the case of a transponder, and all combinations of these. Two missions are presently being studied. The first carries only a simple beacon transmitter and flies at 18 km altitude where the temperature is about 325°C. Electronic breadboard designs for operation at this temperature are presently being constructed and tested at JPL. The second flies between 40 and 48 km where the temperature does not exceed 150°C. Here, more advanced instrument packages are presently within the available technology. Possible instruments include pressure, temperature, differential temperatures, light fluxes, lightning detectors, and sound pressure levels. Balloon missions are likely to last no longer than a few days to a few weeks, therefore only short term studies can be carried out (These are much longer, however, than the present Venera and Pioneer-Venus probes). Longer missions are desirable and would most likely have to be carried out from the surface.

If a landing probe could sit on the highest part of Terra Ishtar (about 10 km above the mean surface level) the temperature would be about 380°C. A number of interesting experiments could be accomplished from this remarkable peak including all the traditional weather measurements, atmospheric turbulence, light scattering from dust particles, and so on. Equally as interesting are measurements related to planetary and solar systems dynamics. For example, very accurate measurements of the rotation rate, direction of the spin axis, and orbital motion could be made. These measurements could easily establish whether the rotation is in synchronous lock with the earth or if some form of precession exists. As the planet rotates, two occultations could be observed per revolution as viewed from the earth. An orbiting spacecraft could observe several occultations per day. Such measurements not only aid in establishing the variation of the atmosphere but give a measure of the turbulence which establishes the ultimate "seeing" capability through the Venusian atmosphere at microwave frequencies.

Going to our outer planets, there is much work to be done. The first direct measurements of the Jovian atmosphere will be made by the Galileo space probes. These probes, like the PV probes, will last a short time until they are either crushed or their signal extinguished by the absorption in the atmosphere. The data

they return will ultimately determine if other methods of exploration are possible. Among the most exciting might be a hot air balloon mission to explore the circulation below the visible cloud regions. Though it is too early to know what might be possible, high temperature electronics will most likely be required.

Going towards the inner part of our solar system we find Mercury and the Sun. The Mariner 10 spacecraft measured surface temperatures on Mercury ranging from 90 to 460°K. Radiative transfer models indicate that temperatures as high as 650°K (377°C) exist when Mercury is closest to the sun. The precession of the perihelion of Mercury has been used to test the general theory of relativity, however, this rate of precession is also partly caused by the solar oblateness which distorts the gravity field of the sun. Further tests of the general relativity theory could be facilitated by placing a transponder on the surface of Mercury or by placing a close orbiter around the sun. The solar orbiter could map the gravity field, measure the oblateness, and carry out other measurements of fields and particles. Measurement of the perihelion precession of orbiter could give an even better verification of the general relativity theory.

Electronic Hardware

Most conventional military electronics will operate to 100°C. Therefore, at 100°C it is simpler to ask what won't work than what will. Even though many components will still function to 150°C, very few electronic systems will function properly. Therefore, electronic systems must be designed specifically to reach this temperature. As we go beyond 200°C, many standard components and packaging techniques begin to fail. By 300°C, very few silicon semiconductor devices continue to operate. As we go beyond 150°C it is especially important to consi-

der what is really needed for space exploration, as every good designer would like to have everything, and everything could be much too expensive.

There are on our list of components and systems many of the same things that are required for well-logging instrumentation, so to the degree that instrumentation requirements are more or less identical, operation to 300°C should be possible using hybrid circuit techniques developed for well-logging. A fairly good summary of the limits of electronic components was given by Veneruso (1979). Much work has been reported by Palmer (1977), Palmer and Heckman (1978), Palmer (1979), and Prince et. al. (1980) describing tests, design rules, and fabrication of electronic circuits suitable for many instrumentation systems. However, our list contains some items not essential to the well-logging industry. These are:

1. High temperature power sources
2. Ultra stable oscillators and clocks
3. VHF, UHF, and Microwave transmitters
4. Antennas
5. Electromechanical actuators, motors, and guidance systems
6. Special deployment components and systems

The power source is so important that it is placed first in the list. An effective way to evaluate power sources for space applications is by figures of watt hours per kilogram, watt hours per cubic centimeter, and watt hours per dollar. The last measure is often the most difficult to obtain as most high temperature

Table I. High Temperature Energy Sources

Energy Device	Type	Manufacturer	Temperature Range	Wh/kg	Wh/cc	Max Watts	Efficiency	
Lithium/Carbon	Primary	Power Conversion Inc.	-50° to 60°C	270	0.41	0.90	NA	D-size tested available
Lithium/Carbon	Primary	Electrochem Industries	-30° to 150°C	515	0.98	9.60	NA	D-size tested available
Sodium/NiPS ₃	Secondary	EIC	130°	-	-	-	-	Experimental
Sodium/Sulfur	Secondary Fused Salt	General Electric	280° to 350°C	150	-	-	-	Experimental
LiSA/FeS	Secondary Fused Salt	Rockwell International	400° to 450°C	79	-	-	-	Experimental
Sodium/Sulfur	Secondary Fused Salt	Marcoussis	280° to 350°C	200	-	10.0	80%	Experimental
Photovoltaic	Silicon	Many	< 150°C	NA	NA	NA	-12% @ 20°C	Available in many sizes
Photovoltaic	GaAs	Rockwell International	< 300°C	NA	NA	NA	-14% @ 20°C	Experimental .25cm x .25cm
Thermal Electric Gen.	Pyro-technique	Aerospatiale	-40° to 50°C	< 20	< 0.07	-	-	Available in many sizes
Radio Isotope Thermionic Generator	Pt 238	General Electric	< 500°C	> 0.5 x 10 ⁶	-	-4w/kg @ 300°K	0.25%	Requires Custom Design

power sources are not commercially available. Table I summarizes some of the power sources that are either available or are known to operate at extended temperature ranges. Certain special mechanical and electro-mechanical storage systems have not been included. For example steam engines, compressed gas, internal combustion engines, and windmills. The use of such systems should not be discounted, as a few of these may be entirely practical. For example, the atmosphere of Jupiter is mostly hydrogen. The operation of an internal combustion engine fueled on hydrogen is quite practical if an oxidizer is carried on the probe. Table I, then, concentrates on direct electrical power systems not requiring the conversion from mechanical to electrical energy.

The primary batteries listed in Table I have very high energy densities compared to most primary or secondary cells. They also have good storage capability, which is essential since many missions require six months to several years to arrive at their intended target. The present temperatures limit for commercially available primary batteries is about 150°C. The fused-salt batteries listed do not begin to operate until the materials fuse. These batteries can be stored in the charged state indefinitely below the temperature of fusion. Since the lowest temperature battery is the sodium-sulfur type which begins to operate near 280°C, there is a range between 150° and 280°C for which no batteries are presently available. Fused salt batteries can operate to 500°C, so they are ideal for Venus landers. Although a large number of experiments on various fused salt cells have been run, only two types of cells have received sufficient study to be manufactured. The work on Sodium-Sulfur cells has been reported by Mitoff, Breiter, and Chatterji (1977) and Chatterji, Mitoff, and Breiter (1977). Work on the Lithium-Silicon/Iron Sulfide batteries has been reported by Sudar, Heredy, Hall, and McCoy (1977). Most work since then has been directed at manufacturing large cells for industrial load leveling and for electric vehicles, therefore, a wide range of sizes are not available.

Energy sources that could support longer missions than possible with batteries are: 1. photovoltaic cells, and 2. thermionic cells. Photovoltaic cells may be usable if the power requirements are not too large. High light intensities are generally not available deep in the atmosphere of Venus and at the outer planets, thus the solar cell array sizes would have to be fairly large to provide even 20 to 30 watts. Silicon cells are not useful above 200°C, although work is being done to extend the temperature range for use with large concentrators. GaAs cells show the greatest promise for operation above 200°C, although their efficiency will decrease. Tests of a few samples of GaAs cells supplied by Rockwell International showed a near linear decrease in terminal voltage with increased temperature. Although these cells survived the 350°C testing, their efficiency at this temperature went to zero.

Thermionic cells or generators operate by establishing a temperature difference on two junctions formed of dissimilar metals. Two types of thermionic generators are listed in Table I. The pyrotechnique generators suffer from a low energy to weight ratio, but could potentially operate to a higher temperature than the primary cells. Commercially available cells are rated only to 65°C. These generators operate only for a short time following ignition (30 seconds to a few hours). During this time the energy must be used or it is lost. The Radioisotope Thermionic Generator (RTG's) suffer from many of the same problems, but their energy/weight ratio is much greater than any other power source. The life-time of these generators is controlled by the half-life of Pu 238 which is the most common heat source (86 years). A typical power source, such as the ones used

on the Voyager spacecraft, generate about 150 watts over a ten-year period and weigh about 40 kg. The efficiency of thermionic generator is proportional to some fixed percentage of the Carnot efficiency, thus the efficiency decreases linearly with increased temperature on the cold side of the junction. Typical high-side temperatures are near 1280° K. If the high-side temperature remains fixed, the Carnot efficiency would be about 2.5 times poorer on the surface of Venus than on earth. Higher efficiencies, of course, are possible if the high-side junction temperature can be raised. This requires either higher powered radioactive materials or ways to reduce the heat transfer through the thermionic converter. Higher powered radioisotopes probably imply shorter half-lives, so the total energy may not change greatly. In spite of this, the future for RTG's looks good when long missions are to be considered, as no other power source is presently available.

Ultra Stable Oscillators

Ultra stable oscillators (USO's) are used to control the frequency and timing of all signals in the space probe. Microwave signals are generated by multiplying the basic oscillator or some lower frequency derivative of it by a series of simple multiplier stages. As a result, any phase jitter or frequency variation of the USO is multiplied by the same ratio. Thus, the purity of the final signal is controlled by the USO. Lower frequencies are usually generated by counting the USO frequency down with digital counters. The short term stability is most important for the transmission of information, while the long term stability is most important for maintaining timing of sequences of operations and for guidance and tracking. High quality USO's maintain long term stabilities of a few parts in 10¹⁰ and short term stabilities several orders of magnitude better. Relatively little is presently known about the stability at temperatures above 100°C. In order to determine what might be possible, several experimental oscillators are being designed at JPL for operation at 325°C. These units use special crystals cut to have a zero temperature coefficient at that temperature. The oscillator electronics is being fabricated with the standard hybrid circuit techniques. Experimental oscillators have already been tested at 280°C with off-the-shelf crystals. This circuit operated without failure during the two-week test period. The stability of crystal oscillators at high temperatures depends not only upon the stability of crystal and its Q, but on the drifts in the other electronic components. Clearly, components will age faster at high temperatures, and stabilities are sure to be poorer than obtained at room temperature or with the best oven controlled crystal oscillators. Just how much poorer is a question that remains to be answered.

Transmitters

The measurements of scientific data in a high temperature environment is of little use unless the information can be sent out of the environment. In the case of planetary exploration, the only feasible communications channel is via radio. The choice of wavelengths is dictated by the transparency of the atmosphere, the feasibility of the antenna structures, the availability of receiving equipment, and the background noise level. In the case of Venus, the atmosphere becomes opaque in the cm range, and a one-way transmission loss of 5 dB is encountered for 4 cm waves. Since Venus has no appreciable ionosphere, longer wavelengths pass freely. The physical size of antennas for wavelengths longer than a few meters probably restricts the low frequency range to 100 MHz. The radio background noise is contributed by the thermal radiation from the planet and the radiation from free space. The

free space background radiation becomes smaller as the wavelength is shortened, so shorter wavelengths are generally preferred. Therefore, any transmitter technology that can operate in the frequency range from 100 MHz to 3 GHz is a potential candidate for our purposes. If we restrict our study to devices that could operate above 150°C, we find only vacuum tube and GaAs semiconductor devices. In the case of vacuum tubes, there is no reason to believe that a wide variety of devices would not work if special precautions were taken in fabrication. Included as possibilities would be Klystrons, TWT's, and standard ceramic vacuum tubes. Of these only the ceramic triode vacuum tubes have been tested to temperatures of 450°C and found usable. A small pulsed oscillator is being designed and fabricated by General Electric for testing at JPL. This oscillator could be used as a beacon, a simple telemetering device, or possibly a radar altimeter. Vacuum tube devices have the potential of operating at either continuous low power or high peak pulse power, thus they are ideal for pulsed radar and beacon applications.

GaAs transistors are available and provide the possibility of higher efficiencies than vacuum tubes, since no heater power is required. GaAs transistors supplied by Microwave Semiconductor Corporation have been tested at JPL to temperatures as high as 210°C for a period of 10 days with no noticeable deterioration of the S-band performance. Operation of these devices to higher temperatures is likely to be possible with reduced efficiency.

Antennas

Given that a suitable transmitter can be designed and fabricated, the power must be radiated to the observer. Antennas are passive devices constructed of metal and insulators. They must be structurally solid enough that the deformations are small compared to the scale size of the wavelength. In general, the more directive the antenna is, the more important is the structural integrity. Also important is the resistivity of the metal surfaces at high frequencies, that is, the losses in the antenna are contributed by the currents flowing near the surface of the metal, therefore, since the resistivity increases with temperature, the losses will be larger at high temperatures. Exposed antenna surfaces will most likely have to be gold plated to insure that active gasses in the atmosphere will not react with the metal raising the resistivity and increasing the losses. Some antenna components employ ferrite devices for switching, isolation, hybrid combiners, and so forth. Many ferrites reach their Curie point at fairly low temperatures, and devices dependent upon high frequency magnetic materials may not be available to the designer. Otherwise, the antenna system is not considered to be a serious problem, but systems to point it are likely to be a greater problem.

Electromechanical Devices

Electromechanical devices include such things as motors, solenoids, relays, resolvers, synchros, and so forth. Transformers are also usually included as simple machines even though they do not employ mechanical motion. Both adequate magnetic materials and magnet wire exist for fabrication of transformers for operation to 500°C. Transformers have been built for even higher temperatures, however, commercial suppliers are scarce. Recently, transformers have been built by General Magnetics for testing at JPL for temperatures to 350°C. These transformers have operated for several hundred hours at temperatures between 200°C to 300°C. As a result, we believe that electromagnetic devices of all types can be designed. Presently under testing

are several transformers and reed switches. High temperature motors were demonstrated by General Electric in the 1950's, but apparently this technology has been lost. At the present time, few high temperature electromechanical devices can be found, but modifications of standard designs should be possible simply by substituting high temperature materials for the standard materials.

Deployment Devices

Spacecraft designers have a number of favorite devices for deploying spacecraft systems. Among these are various pyrotechnique devices such as exploding bolts. All pyrotechnique materials become increasingly unstable as the temperature increases, and the use of such devices at high temperatures seems out of the question unless insulation or cooling is provided. A number of other deployment techniques seem applicable. For example, since the temperature increases as we enter the planetary atmospheres, various fusible pins and plugs can be used to initiate deployment. Pressure sensitive devices may also be practical.

Conclusions

There are many applications requiring high temperature electronics for space exploration. Presently, there seems to be no applications requiring systems operating above 500°C, where very few electronic components continue to operate. A number of important missions can be carried out with 300°C electronics, most interesting would be the low altitude balloon studies of the Venus. Even more extraordinary would be a low altitude airplane imaging system flying only a few hundred meters above the surface. Although it may be several years before such missions could be considered seriously, a balloon system to study the Venusian atmosphere at an altitude of 40 km is being designed by the French Space Agency and initial studies of 300°C electronics are being carried out at JPL for a possible balloon mission near an altitude of 18 km.

Electronic systems that are required include instruments, modulators, ultra stable oscillators, transmitters, power supplies, and power sources. Many of these systems would benefit from further work in high temperature semiconductors. Especially lacking are high temperature diode rectifiers and microwave transistors. New developments in GaAs and GaP devices would greatly aid in simplifying the design of high temperature systems. The ultimate 500°C applications will require new technology. Further work on SiC semiconductors seem appropriate. The integrated thermionic circuits being developed by McCormick (1978) at Los Alamos Scientific Laboratory coupled with ceramic triode transmitters by General Electric could provide the basic building blocks for the first entry into the area of 500°C exploration.

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