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 a 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 vacuum 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. 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 environment is. 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 710°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 atmosphere.

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 differences. 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 at about 325°C. Electronic breadboard designs for operation at this temperature are presently being constructed and tested at JPL. The second flies between 50 and 48 km where the temperature does not exceed 150°C. Here, 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 or 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 280°C. A number of interesting experiments could be accomplished from this remarkable peak including all the traditional weather measurements, atmospheric turbulences, 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, 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 make short time studies in either temperature or pressure environments distinguished 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 consider 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 Hackman (1978), Palmer (1979), and Prince et. al. (lWG) 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 weight 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>
<thead>
<tr>
<th>Energy Device</th>
<th>Type</th>
<th>Manufacturer</th>
<th>Temperature Range</th>
<th>Wh/kg</th>
<th>Wh/cc</th>
<th>Max Watts</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium/Carbon</td>
<td>Primary</td>
<td>Power Conversion Inc.</td>
<td>-50° to 60°C</td>
<td>270 0.41</td>
<td>0.90</td>
<td>NA</td>
<td>D-size tested available</td>
</tr>
<tr>
<td>Lithium/Carbon</td>
<td>Primary</td>
<td>Electrochem Industries</td>
<td>-30° to 150°C</td>
<td>515 0.98</td>
<td>9.60</td>
<td>NA</td>
<td>D-size tested available</td>
</tr>
<tr>
<td>Sodium/Sulfur</td>
<td>Secondary</td>
<td>EIC</td>
<td>130°</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Experimental</td>
</tr>
<tr>
<td>Sodium/Sulfur</td>
<td>Secondary</td>
<td>General Electric</td>
<td>260° to 350°C</td>
<td>150</td>
<td>-</td>
<td>-</td>
<td>Experimental</td>
</tr>
<tr>
<td>Lithium/Carbon</td>
<td>Secondary</td>
<td>Rockwell International</td>
<td>400° to 450°C</td>
<td>79</td>
<td>-</td>
<td>-</td>
<td>Experimental</td>
</tr>
<tr>
<td>Sodium/Sulfur</td>
<td>Secondary</td>
<td>Marcoussis</td>
<td>260° to 350°C</td>
<td>200</td>
<td>-</td>
<td>10.6</td>
<td>80%</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>Silicon</td>
<td>Many</td>
<td>&lt; 150°C</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>-12% @ 20°C</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>GaAs</td>
<td>Rockwell International</td>
<td>&lt; 300°C</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>-14% @ 20°C</td>
</tr>
<tr>
<td>Thermal Electric Gen.</td>
<td>Pyro-technique</td>
<td>Aerospatiale</td>
<td>-40° to 50°C</td>
<td>-20</td>
<td>&lt; 0.07</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Radio Isotope Generator</td>
<td>Pt 238</td>
<td>General Electric</td>
<td>&lt; 100°C</td>
<td>&gt; 0.5 x 10⁶</td>
<td>-</td>
<td>0.25%</td>
<td>Requires Custom Design</td>
</tr>
</tbody>
</table>

Table 1. High Temperature Energy Sources
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 tempera-
ture ranges. Certain special mechanical and electro-
mechanical storage systems have not been included. For 
example atomic engines, compressed gas, internal combus-
tion engines, and windmills. The use of such systems 
should not be discounted, as a few of these may be 
etirely practical. For example, the atmosphere of 
Jupiter is mostly hydrogen. The operation of a internal 
combustion engine fueled on hydrogen is quite prac-
tical if an oxidizer is carried on the probe. Table I, 
then, concentrates on direct electrical power systems 
not requiring the conversion from mechanical to electric 
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 capabili-
ty, 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 land-
ers. 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, Mittoff, 
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 
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 100°C, although work is being done to 
examine their use at higher temperatures. 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. Al-
though these cells survived the 350°C testing, their 
efficiency at this temperature went to zero.

Thermionic cells or generators operate by establish-
ing 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 po-
tentially operate to a higher temperature than the pri-
mary cells. Commercially available cells are rated 
only to 65°C. These generators operate only for a short 
time after ignition (3 seconds to a few hours). During this time the energy must be used or it is lost. The Radiolysotope 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 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 tempera-
tures 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 re-
quires 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 multi-
plying 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 ratio of 
the multiplier stages. The purity of these 
oscillators, derived from the 
USO's, is high. Ultra stable oscillators have already been tested at 280°C with off-the-shelf crys-
tals. This circuit operated without failure during the 
two-week test period. The stability of crystal oscil-
lators at high temperatures depends on the stability of the crystal and its Q, but on 
the drifts in the other electronic components. Care-
fully, components will age faster at high temperatures, and 
instabilities 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 commu-
nications channel is via radio. The choice of wave-
lengths is dictated by the transparency of the atmo-
sphere, 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 microwave range, so the one-way trans-
mission loss of 5 dB is encountered for terrestrial 
sources. Since Venus has no appreciable ionosphere, longer wave-
lengths pass freely. The physical size of antennas for 
wave lengths longer than a few meters probably restricts 
the low frequency range to 100 MHz. The radio back-
ground noise is contributed by the emission of 
the planet and the radiation from free space.
free space background radiation becomes smaller as the wavelength is shortened, so shorter wavelengths are generally preferred. Therefore, any transmitter technology that can operate at frequencies in the 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 TWT's have been tested to temperatures of 350°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 or 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 noticeable deterioration of the S-band performance. Operation of these devices at 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 higher 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. Transistors 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 at JPL 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 electromechanical 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 pyrotechnic devices such as exploding bolts. All pyrotechnic 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 fusable 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 a wide variety of 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, ultrastable 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 Gp 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 seems 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.

References


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