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# Chapter 11

# Metrology Requirements of Future Space Power Systems

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Anticipated metrology requirements of future space power systems have been researched in a program initiated at the National Institute of Standards and Technology. These requirements have been compared with existing state-of-the-art measurement capabilities and inadequacies in present measurement techniques are discussed. Particular attention is paid to the difficulties of determining measurement reliabilities for long-term, unattended sensor operation.

## Introduction

The Strategic Defense Initiative (SDI) accelerates the existing trend toward larger, more versatile, multipurpose power systems in space. In the earlier days of the U.S. space program, power systems had largely been developed to support single-purpose, limited-duration, low-power missions. At present, higher-power civilian applications, such as the space station, are requiring a reassessment of the most appropriate design for space-based power systems. In addition, military applications, such as those envisioned by the SDI, will require power systems with sophistication and complexity far in excess of anything which has gone to space to date.

Anticipated SDI space-based power systems will be analogous to terrestrial power systems in that they will consist of the following components:

1. An energy source,
2. One or more generators,
3. Converters to change the generator output to the appropriate level and waveform,
4. A power distribution system,
5. A variety of loads, and
6. An automated control system.

Modern land-based systems are intensively instrumented and computer controlled to maximize system reliability. Because of the high cost of repair or any other type of human intervention, space-based power systems will incorporate the best features of automated system diagnosis and control which have been developed for land-based systems as well as features particular to the space environment.

Design and development work are in progress for a wide range of future space power control systems for which reliable measurement techniques and systems are a necessity. In addition to the obvious need for accurate measurements of electrical quantities, the instrumentation and control system for the prime power sources will require information about many other parameters including temperature, pressure, and radiation. During ground-based development and testing, the design of these measurement systems needs to be performed in parallel with other aspects of the power system development. Doing so will avoid costly retrofits.

A fundamental requirement is the coordination of the various measurement approaches so that combined outputs of the sensors for the various space-based subsystems can be used to assess the system integrity, status, and operational capability. This requirement makes it obvious that development and application of measurement systems and techniques in an *ad hoc* manner is counterproductive. The developers of the various subsystems clearly must have the freedom to develop the most appropriate diagnostic systems, but guidance must be provided concerning interface requirements as well as the reliability, calibration capabilities, and space worthiness of various measurement approaches.

While metrology requirements for present ground-based developmental and operational testing are less stringent than for anticipated future applications, some measurement problems already clearly exist. Any required extension of existing measurement techniques to larger magnitude parameters will only aggravate any sensor or instrumentation shortcomings, and further extension of these techniques to space environment applications will not be straightforward.

## Study Design

The existing trends in space power indicate that the evolution of space power systems will cause measurement problems. In an attempt to identify future problems, the following study was conducted. The objectives were to

1. Characterize the metrology requirements of various space power programs;
2. Compare these requirements with present state-of-the-art measurement capabilities;

3. Identify possible problem areas; and
4. Identify areas where additional research in emerging measurement technologies may allow development of measurement techniques capable of meeting the extreme requirements of SDI space power applications.

The first two objectives required the gathering of information. Objective 1 was the more difficult because the newer power systems are in the very early stages of development and the measurement needs which will finally evolve are not yet determined. In an attempt to develop reasonably reliable information, interviews were conducted with staff from many of the presently active space power programs. These interviews focused on identifiable measurement needs and not on measurement system designs.

Having identified the quantities of interest, their range of values, and their required measurement uncertainties, the next step was to compare the present and future needs with existing state-of-the-art measurement capabilities. For the purposes of this study, the state of the art was defined as the accuracy with which the U.S. National Institute of Standards and Technology (NIST), formerly the National Bureau of Standards, performs calibrations. This defined the best level at which measurements could be compared among various laboratories, or equivalently, the level at which an infrastructure exists by which government and industry can assure measurement accuracy. It is possible that an individual laboratory, including NIST, could make a specific measurement with better accuracy than reported in this report. The measurement could not, however, be disseminated and assured with a smaller uncertainty without significant research and development.

Areas in which existing state-of-the-art measurement techniques are inadequate to meet anticipated requirements were highlighted with suggestions made for possible solutions to various measurement problems. In the course of this information gathering, the participants were also asked about novel measurement techniques which were under development which might eventually be appropriate for various space power applications. Particular attention was paid to systems which were, in some sense, "self-calibrating."

**Table 1** *Partial Listing of Anticipated Parameters requiring Measurement in Future Space Power Systems.*

| Parameter | Range |
|---|---|
| DC Voltage | 1 mV to 120 kV |
| AC Voltage | 100 V to 250 kV |
| Pulsed Voltage | 10 V to 10 kV |
| DC Current | 1 mA to 1.1 kA |
| AC Current | up to 1 kA |
| Pulsed Current | 1 MA to 4 MA |
| Electric Fields | undetermined |
| Magnetic Fields | 0.3 Tesla to 10 Tesla |
| Power | up to megawatts |
| Temperature | 20 K to 2500 K |
| Pressure | $10^{-7}$ Pa to 8 MPa |
| Neutron Flux | up to $10^{16}$ neutron/cm$^2$·s |
| Gamma Fluence | up to 2.7 × $10^8$ Rad |
| Flow | 5.2 kg/s to 2000 kg/s |
| Frequency | 4 Hz to $10^{15}$ Hz |
| Electron Beam Characteristics | N/A |
| Ion Beam Characteristics | N/A |
| Acceleration | 1000 to 2000 km/s$^2$ |
| Velocity | 0 to 10 km/s |
| Position | 1 $\mu$m to 10 m |
| Vibration | undetermined |
| Strain | undetermined |

## Selected Results

The complete survey identified more than twenty different physical parameters which must be measured for the operation of various space power systems. These quantities and the ranges determined by the survey are summarized in Table 1. Because of the large amount of information, it is not possible to detail all of the parameters in this paper—only representative samples are discussed. The complete survey results are available for distribution (Olthoff and Hebner 1989).

### Voltage Measurements

Accurate long-term voltage measurements will be essential for the control of space power systems which support anticipated SDI weapon platforms. Some of the most stringent dc-voltage measurements may be required for the operation of space-based neutral-particle beam (NPB) systems. Low dc-voltage measurements (<1000 V) may be required with 5 parts-per-million (ppm) uncertainties. These measurements can presently be performed with less than 10 ppm uncertainty by state-of-the-art digital voltmeters using multi-slope integrating analog-to-digital converters under controlled conditions. However, yearly drifts of less than 10 ppm cannot presently be obtained without periodic recalibration, thus making this technique inappropriate for some long-term applications. A limited amount of remote calibration is possible by using voltage standards such as precision reference-voltage zener diodes. However, this approach is appropriate only if the cause of the voltmeter decalibration (such as radiation damage) does not also affect the standard. For more accurate calibrations, a Josephson array standard could be used in the 10 mV to 10 V range (Hamilton et al. 1987). However, a 3-K temperature environment, a 90-GHz, tunable microwave source, and a control system would be required.

Space-based NPB systems may also require large-magnitude dc-voltage measurements (>1000 V) with long-term uncertainties of 0.1%. Terrestrial high-voltage dc-measurements can presently be made with ±0.01% uncertainty under clean laboratory conditions for short periods of time using high-voltage dc-resistance dividers (Misakian 1985). However, no adequate method presently exists for making low-uncertainty measurements of high voltages on space platforms. There has been little experience with measuring high voltage for days (or years) with low uncertainty, and voltage drifts due to corona, leakage current, and temperature changes (~5 ppm/K) would make a long-term 0.1%

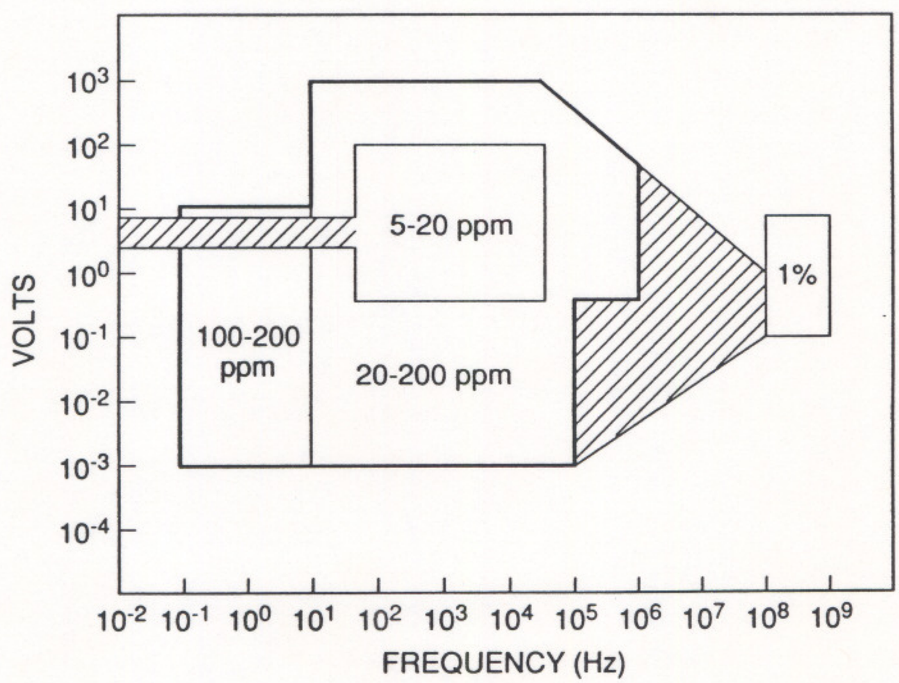
measurement very difficult. An additional difficulty is that state-of-the-art high-voltage dividers are quite large (~0.5 cubic meters for 100-kV measurements). Also, high-accuracy dividers are constructed using low-magnitude, high-precision, wire-wound resistors which draw fairly large currents (milliamperes) from the test system. Space-based dividers would necessarily have to be constructed from high-impedance film resistors which are smaller and draw less current, but are also less precise and are more susceptible to surface and radiation damage.

Many anticipated SDI weapon systems will require megawatts of radio frequency (rf) power thus necessitating the determination of large rf voltages. For example, free-electron laser (FEL) systems and NPB facilities require measurements of rf voltages with magnitudes exceeding 100 kV. Presently, high-magnitude rf voltage measurements are made with uncertainties ranging from 5 to 10%, while 1% uncertainties are desirable. To the author's knowledge, no method presently exists for measuring 100-kV rf voltages with 1% uncertainties, and furthermore, no calibration technique presently exists for high-voltage rf signals (or high-voltage ac signals) at any frequency other than 60 Hz. Existing *low-voltage* calibration uncertainties using state-of-the art thermal ac-dc transfer techniques are summarized in Figure 1.

An alternative voltage measurement technique, which appears promising for many space applications, uses the Pockels effect (Hebner et al. 1977). With this electro-optic technique, the change in the index of refraction of a crystal is measured as a function of the applied voltage. This technique is desirable since the apparatus can be designed to be quite small, the device draws no current from the test circuit, and the output signal is electrically isolated from the test voltage. However, the technique is still developmental and present uncertainties approach ±5% depending on the application. Also, Pockels cells typically exhibit large temperature and stress coefficients, and additional research needs to be done in order to determine the effects of crystal aging, radiation damage, and the long-term suitability for space applications.

### Current Measurements

Anticipated SDI current measurement requirements are extremely broad (see Table 1), but the accurate characterization of the current pulses required by space-based electromagnetic launcher (EML) facilities is perhaps the most difficult. The required pulse amplitude may eventually exceed 4 MA, with a 5 second duration, and millisecond rise and fall times. For targeting purposes it is necessary to control the projectile velocity to within 0.5%, thus implying that the current pulse should be measurable to within 0.1%. Present determinations of the pulse profile using current shunts are inaccurate (~10%) because of voltages induced on the signal lines by the rapidly-changing magnetic field surrounding the apparatus and because of the difficulty in characterizing the resistance of the shunt at such high current levels. Rogowski coils (Heumann 1966), whose output are proportional to the derivative of the current, are suitable for characterizing the rapidly-varying portions of the pulse, but it is difficult to perform a sufficiently accurate integration of the signal to characterize the low-frequency portion. The use of magneto-optic sensors which utilize the Faraday effect (Chandler et al. 1986) appears to be a more promising



technique. The output of a Faraday effect device is proportional to the square of the current, hence, unlike for the Rogowski coil, no integration is required and both high and low frequency portions of the pulse can be characterized. The use of flexible optical fibers is also well suited to the unusual geometries of the EML apparatus, and allows the output signal to be electrically isolated from the test system. However, significant development is still required in order to make these measurements to within the required 0.1% uncertainty, and such systems presently require fairly sophisticated optics and electronics, introducing their own stability and reliability problems.

### Temperature Measurements

SDI temperature measurement requirements range from 20 K for coolants of EML systems and superconducting alternators, to 2500 K for interior reactor temperatures of the multimegawatt (MMW) program. Required uncertainties usually range from 1% to 2%, with a few high accuracy requirements (±0.1%) such as the source temperature of a NPB accelerator. State-of-the-art temperature measurements are made using several different techniques depending upon the required range and accuracy. The calibration uncertainties of these techniques are summarized in Figure 2. However, given that many of these techniques are presently inappropriate for space applications, it is anticipated that thermocouples will become the primary temperature sensor for space power systems.

Various types of thermocouples are available covering temperature ranges (3 K to 3000 K) exceeding those anticipated for space power applications. With careful calibration, a thermocouple can offer a short-term uncertainty level of ±0.1 K over a small temperature range, while over a larger range, temperatures may be interpolated to within ±2 K. Difficulties in using thermocouples for high-accuracy measurements can be numerous. A few which may cause problems in SDI applications are kinked or work-hardened sections of wire, electrical-leakage paths, electromagnetic interference, unmatched extension wires or switching apparatus at variable temperatures, reference-temperature drift, long-term drift in high-radiation environments, and long-term drift in high-temperature service. These last two difficulties are perhaps the most critical in light of the long-term measurement requirements of space-based nuclear reactors.

Many other emerging thermometry techniques exist which may eventually prove appropriate for selected measurements. Optical-fiber-based radiation thermometers evade the non-blackbody difficulties of other radiation thermometers by affixing a radiator of known emissivity to the end of a fiber-optic cable. Johnson-noise thermometers have commercial applications at many temperatures and are being further developed for use on the SP-100 space nuclear reactor. Laser-based thermometry, while still developmental, is increasingly promising for high-temperature measurements. The best developed of the laser-based methods, known as Coherent Anti-Stokes Raman Spectroscopy (CARS) (Taran and Péalat 1982), measures the local temperature of a gas by determining the vibrational and rotational spectra of a polyatomic species. Long-term calibration of this technique may not be so difficult since the vibrational and rotational spectra are intrinsic properties of the gas. However, CARS systems are very sophisticated and at present are unsuited for space applications or for the measurement of interior reactor temperatures. One last technique which appears promising is nuclear quadrupole resonance (NQR) thermometry (Ohte and Iwaoka 1982). The variation of the NQR frequency of $^{35}Cl$ in a $KClO_3$ crystal

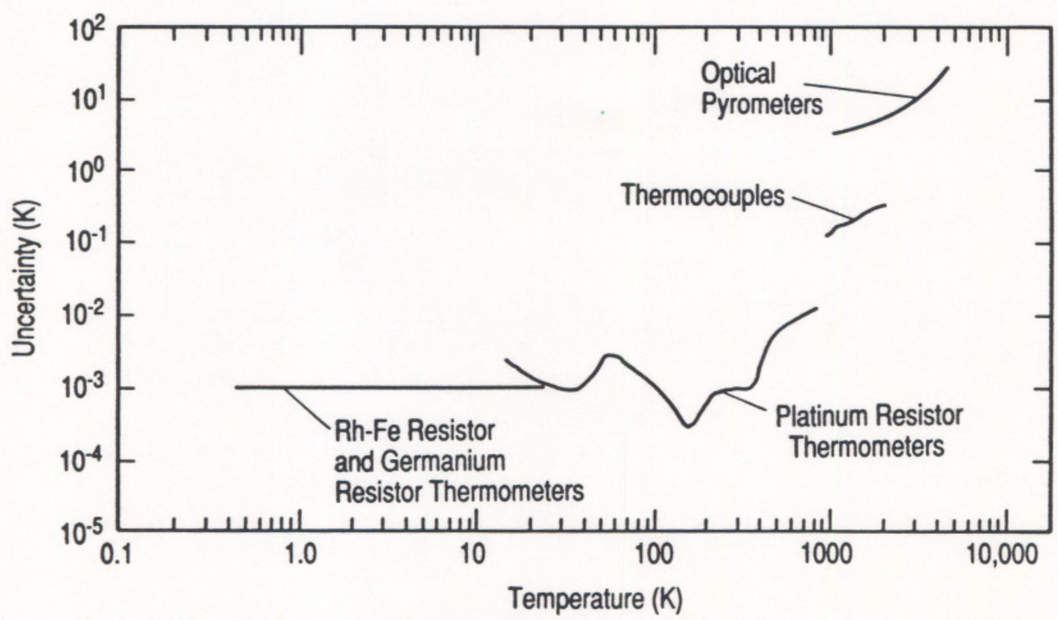



***Figure 2*** *Uncertainties of NIST Temperature Calibrations.*

is the basis for very precise thermometry in the range of 50 K to 400 K. The upper temperature limit is determined by the melting point of the $KClO_3$ crystal so it is conceivable that higher temperature limits could be achieved by using reference crystals with higher melting points. The fact that the NQR frequency is an intrinsic property of the crystal and can be measured with extreme accuracy indicates that NQR thermometry may be the most promising method of achieving an accurate thermometer which does not require extensive calibration or exhibit long-term drift. The long-term effects of interaction with radiation and/or the space environment have yet to be determined.

### Pressure Measurements

As with other parameters, space power requirements for pressure measurements are extremely diverse. Reactor coolant pressures may exceed 8 MPa (80 atmospheres), while the ambient pressure surrounding the space platform may range from $10^{-2}$ to $10^{-7}$ Pa. Most anticipated static-pressure measurement requirements could be met using present-day sensors in ground-based situations. However, severe problems develop when attempting to make dynamic (fast changing) measurements for long periods of time under harsh environmental conditions. In a remote or contaminated environment, long-term calibration will require redundant sensors and a program of intercomparisons. Some of the sensors may have superior capabilities and be designated as reference standards, but reliability of all sensors obviously becomes a paramount concern. The achievable uncertainty of a particular pressure sensor can only be determined when one considers the particular operating environment. However, the uncertainty of a field measurement certainly cannot exceed the uncertainty of the primary calibration standards which are summarized in Figure 3. A desirable alternate or supplement to the intercomparison of redundant sensors is periodic *in situ* calibration at fixed pressures, preferably ones that are constants of nature. An embryonic program exists to develop this capability, starting with the triple point of argon (Pavese 1982), since the pressure at the triple point will be independent of location or environment.

### Radiation Measurements

Radiation measurements are critical for monitoring reactor power and operation. The anticipated full-power neutron fluxes of multimegawatt space reactors are near the upper limits of present state-of-the-art measurements ($\sim 10^{16}$ neutrons/cm·s). Due to the reactor geometry, it is desirable to measure neutron flux inside the reactor vessel, but no neutron detectors currently exist that can withstand the anticipated core temperatures of the MMW reactors. The development of fission chambers using ceramic housings, high-temperature conductor impurities or conductive coatings, and fissionable oxides might provide a solution. Additionally, low-neutron-flux detectors are needed which will be able to survive full-power flux conditions and continue to provide accurate readings. No detector presently exists with these capabilities. Further, once neutron detectors are designed to withstand the high-flux, high-temperature conditions of the MMW core, their accuracies must be improved by nearly a factor of three over current state-of-the art measurement uncertainties to meet anticipated SDI requirements. Self-powered neutron detectors (SPND) may be appropriate for some space applications because they

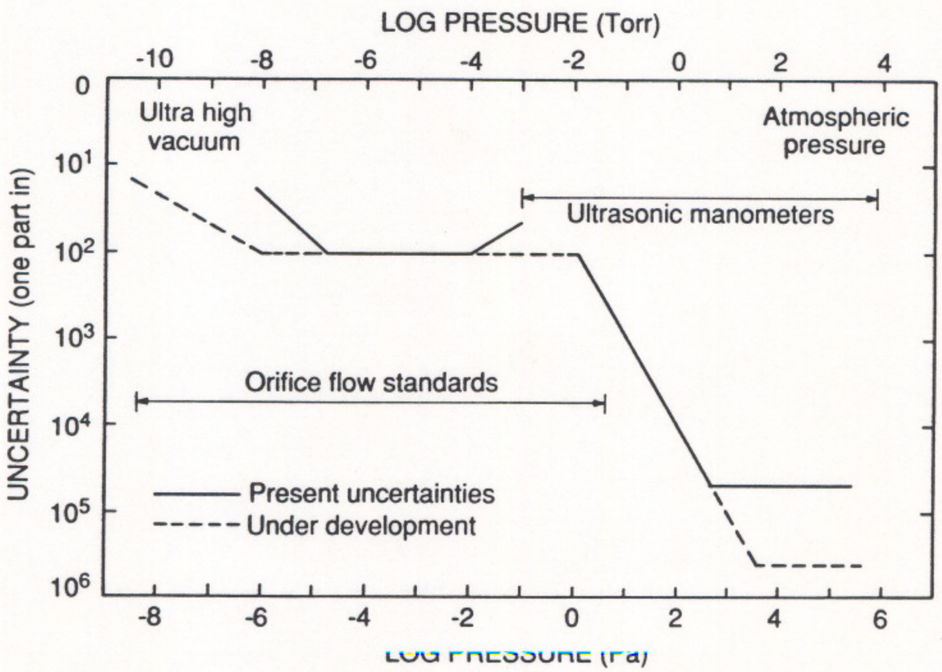



*Figure 3 Uncertainties of NIST Low-Pressure and Vacuum Standards.*

require no support electronics at the sensor location, are appropriate for high-flux applications, and exhibit fairly low uncertainties (1–2%). However, the uncertainties tend to rise rather dramatically when SPND's are used at higher temperatures (>650 K).

It is very important to note, that, in addition to the aforementioned needs for sensor development, space nuclear-reactor control will require significant development of high-temperature, radiation-hardened support electronics. Presently, only a limited number of semiconductor devices exist which can survive the anticipated environment of a space nuclear-reactor platform and provide the instrumentation requirements of the MMW and SP-100 programs. Substantial modifications to signal conditioners, cables, transmitters, multiplexers, converters, and control system interfaces will be required before adequate long-term control of space nuclear power systems can be provided.

## Long-term Measurement Reliability

In addition to the shortfalls in measurement capabilities summarized above, a critical measurement problem that exists for all future space programs, both military and civilian, is the maintenance of reliable sensor calibrations over long periods of time. SDI platform lifetimes, for example, are anticipated to be on the order of ten years. All measurement systems exhibit variations in their responses over time, and typically these variations are significant over times short compared to ten years. Thus, it will be necessary to recalibrate each sensor periodically to ensure reliability. In the unattended situations envisioned for SDI space platforms, however, most calibration standards would also experience substantial drift over a long time period. Only calibration standards that can be telemetered to the platform (such as frequency) or that are intrinsic properties of a material (such as radiation or nuclear quadrupole resonance) are suitable as long-term calibration standards. However, these standards are scarce, and additionally, may themselves require support electronics which prevent them from being completely drift free.

It should also be emphasized that the problem of accurate measurement and sensor recalibration is not unique to the monitoring of space power systems. The same problems arise, to a greater or lesser extent, in the long-term operation of sensing systems, communication systems, thermal-management systems, or life-support systems. Although these systems will ultimately be developed independently, it is likely that they will share any on-board calibration capability.

The most promising solution to the problem of long-term assurance of the power system is detailed modeling of the power and measurement systems and complementary sensor redundancy. A sufficiently powerful computer model of the entire space power system would permit one to monitor sensor output and perform internal calibrations using data from other sensors. This coherent approach to measurements could also detect faulty sensing devices and even predict incipient failures of system components. It is likely that the development of these types of computer-monitored capabilities is the only solution to long-term, high-reliability measurements.

An automated "self-calibrating" measurement system can only be constructed if two complementary sets of knowledge are available. The first is an hierarchical control system which may be based on an expert system, a state estimator, and/or a system model. This control system is a set of software rules which permit failures, drifts, or incipient failures to be identified and corrective action to be taken. Critical to the successful operations of this control system is the second set of information—good knowledge of the physics and chemistry of failure of the components of both the measurement system and the power system. This knowledge base will have to be developed through extensive testing of the components prior to space flight.

The need to know realistic failure scenarios raises serious problems in the design of any space-based system for two reasons. First, it is prohibitively expensive, and probably impossible, to have comprehensive knowledge of the failure mechanisms of all of the components of the systems. Thus, decisions will, of necessity, be made on the basis of a combination of laboratory data and engineering judgment. Considerable effort must be put forth to identify an appropriate mix of fact and judgement. Second, many of the components of space power systems are new devices, built specifically for space applications. The fundamental conundrum in the prediction of the failure of a new system is that the ten-year failure mechanisms, for example, cannot be determined with confidence until a large number have failed. One cannot accelerate aging unless one knows the failure mechanism. A microcircuit may fail, for example, due to radiation damage, to vibration, or to mechanical stresses resulting from thermal cycling. Unless one knows the dominant source or sources of failure in the particular application, it is *impossible* to design an accelerated aging test.

## Conclusions

The necessity for longer-term versatile space missions is generating the need for improved measurements. The needed improvements can be classified as two types. The first is the measurement of a specific physical quantity stimulated by a particular mission requirement. These requirements lead to the need to develop light-weight, rugged, space-qualified instrumentation and calibration techniques. Second is the need to assure the reliability of the aforementioned power and measurement systems. This requirement leads to the development of strategies to deploy and calibrate measurement systems to obtain the maximum amount of high-quality information.

### Acknowledgments

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