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NIST Technical Note 1259

Assessment of Space Power Related Measurement Requirements of the Strategic Defense Initiative

James K. Olthoff and Robert E. Hebner

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[2]Some divisions within the center are located at Boulder, CO 80303.
[3] Located at Boulder, CO, with some elements at Gaithersburg, MD.

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ASSESSMENT OF SPACE POWER RELATED MEASUREMENT REQUIREMENTS OF THE STRATEGIC DEFENSE INITIATIVE

James K. Olthoff and Robert E. Hebner

Abstract

A survey has been performed to determine the measurement requirements of space power related parameters for anticipated SDI systems. These requirements have been compared to present state-of-the-art metrology capabilities as represented by the calibration capabilities of the National Institute of Standards and Technology. Metrology areas where present state-of-the-art capabilities are inadequate to meet SDI requirements are discussed, and areas of metrology-related research which appear promising to meet these needs are examined. Particular attention is paid to the difficulties of long-term, unattended sensor calibrations and long-term measurement reliability.

Key words: calibration; measurements; metrology; reliability; sensors; space power; Strategic Defense Initiative

1. INTRODUCTION

Space power requirements for Strategic Defense Initiative (SDI) weapon systems extend over many orders of magnitude of both amplitude and time, from quiescent station keeping to short-term burst conditions. Requirements range from tens of kilowatts (electric) for housekeeping use over time periods of years to hundreds of megawatts for periods of seconds. The power is produced and delivered at widely different voltage and current levels, from low-voltage primary power to pulsed power which may be at levels exceeding 1 MV and 1 MA. Characteristic frequencies range from dc to GHz. The development of power sources to meet these specifications requires extensive instrumentation to characterize components vital to power systems, and to validate the performance of these systems under anticipated operating conditions. The systems that control these power sources must be reliable, long-lived, automated, remote, autonomous, reconfigurable, and have other attributes that exceed the present requirements for terrestrial and space-based power plants.

SDI space-based systems will be analogous to land-based power systems in that they will consist of an energy source, one or more generators, power conditioning to convert the generator output to the appropriate level and waveform, a power distribution system, and a variety of loads. To develop, control, and verify the performance of these systems, a wide range of measurements is necessary. In addition to measurements of electrical quantities, the sources of prime power will require information about many parameters including temperature, flow rates, vibration, stress, and other physical quantities. If nuclear reactors or isotope sources are used, then radiation measurements will also be required. During ground-based development and testing, existing technology will obviously be used to the extent possible. The accuracy and reliability of these measurements need to be evaluated and, if necessary, modified as the program develops to later avoid potentially more costly retrofits. In addition, the various measurement approaches must be coordinated so that combined outputs of the sensors for the various space-based subsystems can provide an assessment of system integrity, status, and operational capability. During full-power operation, many of these measurements will provide critical information to control and command centers.

While not all measurements used in ground testing will be needed in space, the highly complex nature of the SDI weapon platforms will require significantly more sophisticated and greater numbers of diagnostics than are presently used on existing spacecraft. By comparison, present-day satellites and spacecraft are fairly simple systems with the number of maintenance diagnostics limited by power requirements and telemetry capabilities. Additionally, the usefulness of extensive diagnostics on present-day spacecraft is minimal in most cases, because of the inability to repair faulty components as indicated by the sensors. This lack of accessibility has led the current space program to emphasize long-term reliability rather than high-accuracy sensor technology, thus forcing most spacecraft to use "older", well-characterized technology and components. This situation has recently been aggravated by delays in the space program caused by the Challenger accident and by budgetary constraints. SDI measurement requirements are sufficiently more demanding than present space-based measurement technology that totally new measurement hardware and techniques will be needed in a number of cases, as noted in this report.

While existing ground-based instrumentation may be adequate for most ground-based developmental and operational testing, some problem areas clearly exist where present technology is simply inadequate to make certain ground-based measurements. Extrapolation of existing techniques to measure parameters over extended ranges will only aggravate any existing sensor or instrumentation shortcomings, and further extension of these ground-based techniques to space-environment applications will not be straightforward. Space operation imposes the additional demand of long-term operation with little or no direct human access, which pushes many SDI measurement requirements beyond present state-of-the-art calibration capabilities. Additionally, certain measurements unique to space operation will be needed. For example, it will be necessary to monitor the local environment surrounding the spacecraft to predict the degradation rate and useful life of components exposed to the space environment.

For the above reasons a program was initiated at the National Institute for Standards and Technology (NIST) whose objectives were to 1) characterize the metrology requirements of various SDI programs requiring or related to space power; 2) compare these requirements with present state-of-the-art measurement capabilities and identify possible problem areas; and 3) identify areas where additional research in emerging technologies may allow development of measurement techniques capable of meeting the extreme requirements of SDI space power applications. Space power metrology requirement information was obtained for many SDI programs from the available literature and from direct inquiries of project personnel. This information was then compiled in a data base, sorted by parameter (voltage, current, temperature, etc.), and distributed to scientists in various divisions of the National Institute of Standards and Technology (formerly the National Bureau of Standards). Personnel from NIST then evaluated the measurement requirements in light of state-of-the-art metrology programs at NIST, and made recommendations concerning anticipated difficulties and promising areas of further research. This report is a compilation of the information received from the SDI programs and of the recommendations made by NIST personnel.

It is appropriate to give a perspective to the information in this report. First, due to the volatile nature of the SDI program, stated measurement requirements are obviously subject to change since they represent extrapolations from preliminary project designs. They must therefore be treated as "best guesses" at this time. Second, the listing of SDI space power metrology requirements presented here cannot be considered complete since it is compiled solely from interactions with the programs listed in section 3. Third, the recommendations of the NIST personnel are obviously based on a background of terrestrial metrology, not space-flight experience. Thus, the report can identify limitations in present measurement technology, but it is less useful in the identification of areas in which the existing technology is adequate. Fourth, as stated previously, this report deals primarily with space power related measurements. The study does not include discussions of the metrology challenges of targeting, fire control, navigation, and other systems which are related to the operation of SDI weapon platforms. Each of these systems will have unique measurement requirements, many of which may equal or exceed the requirements discussed in this report.

The report is divided into eight sections. Section 1 is this introduction. Section 2 is a summary of state-of-the-art measurement techniques applicable to SDI space power measurement needs along with considerations for the suitability of the techniques for space deployment. Section 3 is a compilation of specific space power metrology requirements of various SDI programs and an assessment of the applicability of currently available techniques. The fourth section discusses the difficulties of long-term calibration and reliability requirements, and section 5 is a summary of major metrology problem areas. Section 7 is the list of references, and section 8 is an appendix containing a copy of the data base used to organize the information.

2. SDI RELATED MEASUREMENT CAPABILITIES

2.1 Introduction

This section contains brief summaries of the present state of the art in measurement capabilities for parameters which are related to SDI space power applications. The parameters discussed in this section are electromagnetic parameters (voltage, current, etc.), temperature, pressure, radiation, flow, frequency, laser power, vibration, and length. For the purposes of this report, the reference basis for the state of the art for a particular measurement will be the limitations of the calibration techniques available at NIST - the assumption being that the available calibration standards, by definition, must be significantly more accurate than the actual measurement techniques. A more extended discussion of the calibration facilities at NIST may be obtained from the *NBS Calibration Services Users Guide* [1] and a detailed discussion of commercially-available sensors and their capabilities may be found in References 2 and 3.

In most cases it should be noted that the state-of-the-art measurement techniques upon which calibration services are based are strictly laboratory techniques and are not easily transferable to space-based situations because of their size, complexity, fragility, or need for human operation and maintenance. Additionally, any sensor designed for SDI application must withstand long-term exposure to the harsh space environment encountered in low-earth orbit. This requires a resistance to debris impact, temperature variation, radiation damage, atomic-oxygen corrosion, charging due to the ionosphere, launch high-g forces, and gravity-gradient effects. In some cases improvements in existing techniques may be sufficient for future space-flight requirements, however, for many parameters the development of "emerging technologies" may be necessary to provide measurement techniques which are more suitable for long-term space use. Even in cases where a contractor claims to have the capability for making a particular measurement, the Department of Defense must also have this capability in place in order to verify the contractor's claims. A technique that is suitable for one of a kind measurements in a laboratory may not prove suitable for routine measurements of SDI hardware in a full-scale development and deployment mode.

2.2 Electromagnetic Measurements

2.2.1 Voltage

Voltage measurements fall into three basic categories a) dc voltages, b) ac voltages (a subset of which is rf modulated voltages), and c) pulsed voltages. For metrology purposes, each of these categories is divided into high and low voltage measurements with an arbitrary cut-off somewhere between 1 kV and 10 kV. In the SDI applications studied, dc voltages vary from millivolts to 100 kV, ac and rf modulated voltages range from millivolts to 300 kV, and pulsed voltages exist on the order of 10 kV (on millisecond time scales). Required measurement uncertainties range from a few parts-per-million (ppm) to several percent, thus covering practically the entire range of measurement possibilities.

Short-term, low-magnitude dc-voltage measurements ($<$ 1000 Vdc) can be performed accurately ($<$ 10 ppm uncertainty depending on voltage) by state-of-the-art digital voltmeters using multi-slope integrating analog-to-digital converters. Yearly drifts of less than 10 ppm can be obtained under controlled conditions thus making this technique appropriate for some long-term uses. Naturally, changes in environment will effect the overall calibration of the device. Since voltmeters contain semiconducting devices, radiation and high temperatures may adversely affect their operation or may damage them. Present silicon-based semiconductors usually exhibit a maximum operating temperature near 150 °C, but programs are in existence to develop high-temperature, radiation-hardened devices that would minimize this limitation. A limited amount of remote recalibration of voltage measurement devices is possible by using voltage standards such as precision reference-voltage zener diodes [4]. This approach is appropriate only if the cause of the voltmeter de-calibration (such as radiation damage) does not also affect the standard. For more accurate calibrations, a Josephson array [5, 6] could be used in the 10 mV to 10 V range with uncertainties of .01 ppm. However, a 3 K temperature environment, a 90 GHz tunable microwave source, and a control system would be required at present technology levels. Investigations are underway to develop arrays which would function at 10 GHz and would utilize high-temperature superconductors for operation at higher temperatures.

Low-magnitude ac voltage is measured most accurately at this time by comparison with a nominally equal dc reference voltage using a thermal voltage converter [7]. Measured uncertainties thus consist of the sum of the uncertainty of the thermal voltage converter and the uncertainty of the dc reference voltage ($\sim$ 5ppm). Uncertainties of the thermal ac-dc transfer standards vary from 10 ppm at audio frequencies to 100 ppm in the megahertz range [8] to about 1% as one approaches gigahertz frequencies. A detailed summary of the uncertainties of NIST thermal ac-dc transfer calibration is shown in figure 1. Presently, this technique is suitable only under controlled laboratory conditions with significantly larger uncertainties experienced under field conditions. The best commercial digital voltmeters quote uncertainties of approximately 40 ppm at audio frequencies and moderate voltages. At rf frequencies, commercial voltmeters quote uncertainties near 5% or greater. Very low frequency measurements, (0.1–10 Hz) are made at NIST with uncertainties of less than 200 ppm using an “ac voltmeter/calibrator” [9] which contains a high-resolution rms digital voltmeter and both ac and dc calibrators.

High-voltage dc (HVDC) measurements ($>$ 10 kV) can be made with $\pm$0.01% uncertainty under clean laboratory conditions for short periods of time (minutes) using high-voltage dc resistance dividers [10]. Longer measurement times (hours) with this accuracy are possible with very conservative divider designs, however, there has been no experience with measuring HVDC for days (or years) with 0.1% uncertainty as required by some SDI applications.

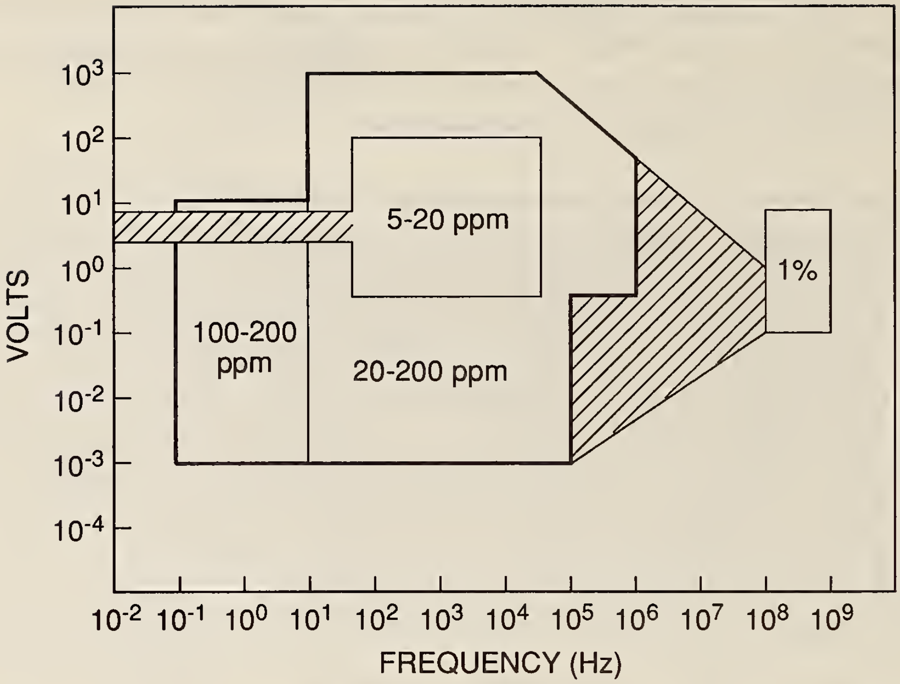

Figure 1. NIST uncertainties for calibrations of thermal ac-dc transfer standards. Shaded areas represent future capabilities.

Voltage drift due to corona, leakage current, and temperature changes (~ 5 ppm/°C) would make a long-term 0.1% measurement very difficult. An additional difficulty in the extension of this technique to space deployment is the large size of the divider (~ 0.5 cubic meters for 100 kV measurements) which is necessary to reduce corona and other leakage currents. Also, high-accuracy dividers are constructed using low-magnitude, high-precision, wire-wound resistors which draw fairly large amounts of current (milliamperes) thereby producing large amounts of waste heat. Space-based dividers would necessarily have to be constructed from high-impedance film resistors which are smaller, but are also less precise and are more susceptible to surface and radiation damage.

High-voltage ac (HVAC) measurements can be made using several different techniques, all of which are less accurate than HVDC measurements. Compensated resistance-capacitance voltage dividers are available for voltages from 1 kV to 1 MV in the frequency range from dc to 1 MHz. Stated uncertainties range from 0.2–3% depending on the voltage and frequency. These dividers suffer from the same difficulties as the HVDC dividers with regard to space deployment. HVAC measurements can also be made using high-voltage transformers [11]. However, these devices are large, heavy, expensive, and draw fairly large amounts of current from the test circuit. It should be pointed out that NIST offers calibration services for HVAC dividers (±0.05% uncertainty) and transformers (±0.01% uncertainty) only at 60 Hz. Determinations of uncertainties at higher frequencies are extrapolations from dc and 60-Hz measurements, or are extrapolations from measurable low-voltage, high-frequency signals, to high-voltage signals. Thus absolute uncertainties at frequencies exceeding 60 Hz are difficult to determine, but they are always greater than the uncertainty at 60 Hz. Above 1 MHz, in the radio frequency (rf) range, HVAC measurements are made with field detectors inside microwave cavities or waveguides. While low voltage rf devices can be calibrated to about 1%, no high-voltage rf calibration technique exists at NIST. It is assumed that the field-detector technique for measuring rf high voltages is only accurate to within ±5%.

Voltage measurements currently being made in space for the maintenance of spacecraft are very limited. Most voltages are dc with magnitudes of less than 200 volts, and with required measurement uncertainties of about 1%. These measurements are usually made using standard analog-to-digital technology. Very little work has been done involving space-based measurements of high-magnitude or rf voltages.

An alternate technique for voltage measurements, which may be suitable for high-voltage dc and ac applications in space, uses the Pockel's effect [12]. With this technique, the change in the index of refraction of a crystal is measured as a function of the applied voltage. This electro-optic technique is promising 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, Pockel cells typically exhibit large temperature and stress coefficients, and additional research needs to be done in order to determine the effects of crystal aging.

The state of the art in pulsed-voltage measurements varies with the magnitude of the voltage and the required bandwidth of the measurement. For low-voltage signals requiring a bandwidth from dc to not more 100 kHz, measurements between 0.001% and 0.1% can be made economically and easily using integrating and successive approximation analog-to-digital converters. Measurements over wider bandwidths (up to 100 MHz) can be achieved using flash-converter transient digitizers at the expense of increased size, complexity, cost and reduced accuracy (1–5%).

High-voltage (> 1 kV) pulse measurements require a voltage divider to attenuate the signal to levels which a transient recorder can accept. The frequency response of the divider usually limits high-voltage pulse-measurement uncertainties to about 1% for pulses up to 1 MV with rise and fall times on the order of a microsecond. Uncertainties become considerably greater for pulses with rise times of less than 1 μs. The electro-optic techniques discussed above may also be suitable for pulsed high-voltage measurements.

2.2.2 Current

For SDI applications, anticipated dc and ac current measurements vary from the milliampere range to greater than 1 kA with required uncertainties of approximately 1%, and pulsed currents may exceed 4 MA with required uncertainties of less than 0.5%.

State-of-the-art dc-current measurements are normally made using precision shunt resistors along with high-accuracy voltage measurement techniques. The uncertainty of the mea-

Table 1. Calibration uncertainties for NIST dc-resistance standards [1]

Nominal Resistance (ohms)	Maximum Power(mw)	Uncertainty ppm
1(Thomas)	10	0.08
10^4(Special)	10	1
10^{-4}	100	20
10^{-3}	100	12
10^{-2}	100	7
10^{-1}	100	5
1	100	3
10	100	4
10^2	100	4
10^3	100	5
10^4	100	7
10^5	100	10
10^6	100	15
10^7	*	20-2000
10^8	*	100-2000
10^9	*	2000
10^{10}	*	2000
10^{11}	*	2000
10^{12}	*	2000

*Resistors at this level are tested at voltages up to 1 kV.

surement is thus the combined uncertainties in the resistance and voltage measurements. Voltage uncertainties were discussed in the previous section and resistance-standards uncertainties for low-current requirements are listed in table 1. Long-term variations of standard resistors are typically characterized by temperature coefficients of $\simeq$ 10 ppm/°C and drift rates of $\simeq$ 5 ppm/year, although special standard resistors exist with yearly drifts and temperature coefficients of less than 1 ppm/year and 1 ppm/°C, respectively. For high-current conditions (up to 1000 amperes) normal uncertainties of high-current standard shunts are $\leq$ 0.04%. However, these high-current shunts tend to be quite bulky which limits their suitability for space deployment. Hall probe current sensors offer an alternative method of measuring large dc currents although accuracies are limited to approximately 1%. High-accurate dc-current measurements may also be made using specially-designed current comparators, or NMR techniques. Care must be taken when making accurate current measurements on spacecraft to account for induced currents due to the motion of the spacecraft through the earth's magnetic field. Accurate magnetometer measurements would be necessary to compensate for these induced currents.

For small ac-current magnitudes, state-of-the-art measurements can be made using precision ac resistors and a digital voltmeter. For large ac-current measurements (> 100 A), a current transformer may be used to scale the magnitude down to more easily measurable levels. Uncertainties in current transformer calibrations are approximately 0.01% at 60 Hz. Limited calibration support presently exists at 400 Hz and 1000 Hz.

The calibration of sensors to measure large current pulses (1 kA to $>$ 1 MA) is difficult due to the lack of sources with precisely known magnitudes. Measurements are usually performed using either a shunt resistor with a voltage digitizer, or a Rogowski coil. Shunt resistor measurements are limited by the frequency response of the resistor (which is often difficult to characterize in the megampere regime), grounding difficulties, and induced signals in the measurement system. A Rogowski coil is a non-intrusive measurement technique which determines the change in magnetic flux produced by a varying current [13]. The voltage output from the coil is proportional to the change in current and requires a precision integration in order to determine an accurate current magnitude. At 60 Hz, a high-quality Rogowski coil can be calibrated to within 1%. For pulsed applications no absolute calibration method presently exists, and estimated uncertainties would vary widely with the pulse characteristics.

An alternative technique for current measurements is the use of magneto-optic sensors which utilize the Faraday effect [12]. Magneto-optic sensors detect the change in polarization of a solid material, typically a glass, due to the magnetic field produced by a current. Since the output is proportional to the square of the current, no integration is required and magneto-optics are suitable for dc, ac, and pulsed current measurements. Commercial, 60-Hz ac sensors presently quote uncertainties of 1.5% [14], while experimental 100 kA, microsecond-pulse measurements have been reported to ±1% [15]. These devices can be made quite small and may be suitable for space applications, however additional research is necessary to determine long-term operation characteristics and the effects of adverse environmental conditions.

2.2.3 Electromagnetic Fields

Electromagnetic (EM) fields need to be measured in several SDI programs. Electric fields need to be monitored to characterize the local EM environment surrounding the spacecraft, in addition to measurements inside microwave cavities and ion sources. Low-level magnetic fields also need to be measured around the spacecraft, while high-magnitude magnetic fields need to be characterized inside homopolar generators, electro-magnetic launchers, and beam magnets. The required uncertainties of many of these measurements have not been specified at this time.

State-of-the-art magnetic field measurements are made using nuclear magnetic resonance (NMR) techniques over a range from less than a gauss to several tesla with uncertainties of less than 1 ppm. Calibrations are performed using extremely accurate low-magnitude fields (10 gauss) and then extrapolating to higher fields. These measurements are extremely stable since the NMR frequency is an intrinsic property of the probe material. However, this technique is relatively slow (millisecond response times), requires large amounts of equipment, and is primarily used for characterizing uniform magnetic fields (although special probes can be designed for nonuniform field environments). Hall probes are less expensive, smaller, and more versatile than NMR techniques. However, they are also less accurate and exhibit a strong temperature dependence. Calibration uncertainties of 0.01% to 0.1% are usual for these devices, with long-term stabilities on the order of 0.1% to 1% for field strengths ranging from 10^{-3} gauss to 2.5 Tesla. Hall probes are also appropriate for measuring time-varying fields, with frequencies ranging from dc to 100 kHz, and may be used in spatially non-uniform fields with a spatial resolution of 0.01 cm^2 [16]. Inexpensive, low-accuracy measurements of fast-changing magnetic fields can be made with single-turn pick-up coils, and more slowly varying fields can be measured with multiturn coils. Uncertainties of better than 1% are possible, but accurate calibration of these devices is more difficult because the coils measure the time derivative of the field. Low-magnitude dc magnetic fields (10^{-5} gauss to 2 gauss) have long been measured on spacecraft using fluxgate magnetometers. These devices are very stable and can have uncertainties as low as ±0.001% [17]. Some research is being done to design magneto-optics techniques to measure field strengths, but present techniques are still in the developmental stages.

AC electric fields are measured by determining the induced voltage on a detector plate. Ground-based 60 Hz ac electric fields are routinely measured to 0.5% uncertainty using this technique [18], but little work has been done at other frequencies. A similar system is often employed to measure electric fields in microwave cavities, however, accurate calibration techniques are unavailable at high frequencies, so rf field measurements of this sort are seldom more accurate than ±5%. Ground-based dc electric fields are more difficult to measure since induced dc voltages are critically affected by leakage currents. Thus devices are employed to produce an ac signal which is proportional to the field strength. These devices, called field mills or vibrating-plate field meters, are suitable for measuring dc electric field magnitudes of $> 100\,\mathrm{V/cm}$ to within ±0.5% [19]. Long-term reliability is suspect since the sensors are moving, mechanical devices.

Space-based electric-field measurements (both ac and dc) are usually made using either a dual-probe apparatus or long antennae, which are adequate for dc to megahertz applications with an uncertainty of 10%. However, these techniques are primarily used to measure low-magnitude fields (1–10 V/m) and the signals may be adversely affected by the local plasma surrounding the spacecraft. For accurate measurement of low frequency E-fields care must be taken to compensate for the induced potential on the probe due to the spacecraft's motion through the earth's magnetic field. This requires an accurate determination of the spacecraft velocity, the magnetic-field vector, and the length and orientation of the probe.

2.2.4 Power

Accurate power measurements are necessary in space applications because of the need for precise management of waste heat. Present high-power measurements (10 W to 10 kW) at NIST are limited to systems with frequencies ranging from 60 Hz to 100 kHz. Uncertainties

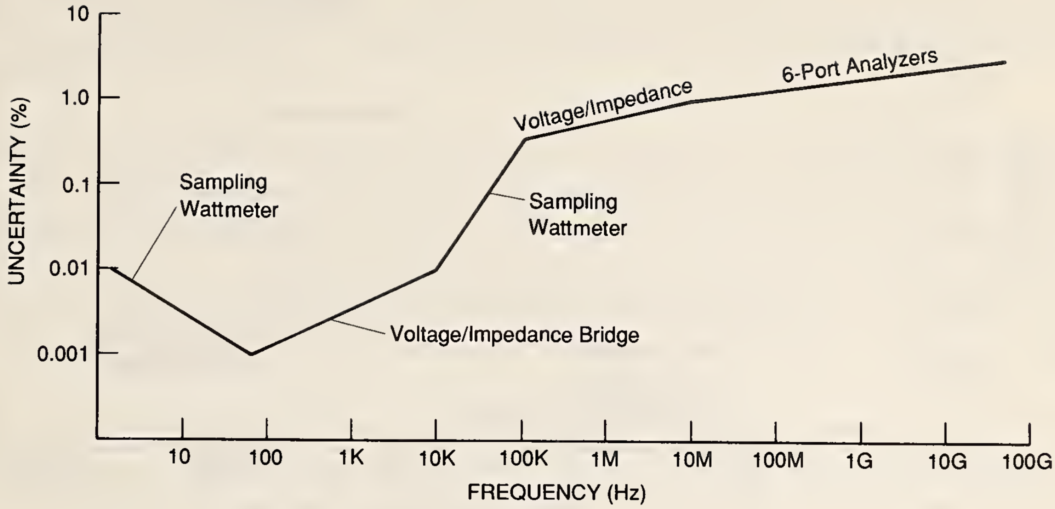

Figure 2. Uncertainties of NIST power measurements.

in the 0.001% range are achievable at 60 Hz [20], increasing to approximately 1% as one approaches 100 kHz [21]. A new service will soon be available for power measurements of up to 1 kW in the 1 to 30 MHz range and 1 W in the 30 to 400 MHz range with uncertainties of approximately 1–2%. RF power measurements are usually made using a directional coupler and/or a calorimeter detector. At very high powers (megawatts) no calibration techniques are available and estimated uncertainties vary between 5 and 10%.

At low rf power levels ($\sim$ 10 mW), NIST maintains standard calibration services from 100 kHz to 96 GHz (not continuous) with rated uncertainties between 0.2 and 3.5% [22]. From 100 kHz to 10 MHz power standard effective efficiencies are determined by the voltage and impedance technique [23]. In the 10-MHz to 18-GHz range and in the WR42, WR28 and WR10 waveguide bands single or dual six-port automatic network analyzers [24] are used as transfer systems with detectors calibrated using the NIST microcalorimeter as standards. However, extrapolations of low power calibrations to high power levels are often incorrect, particularly in rf cavities. Some level of spurious electrical activity is nearly always present in high-power cavities, and this activity can screen the sensor from the full fields present in the rf cavity. Errors due to these effects of up to 50% are commonly observed, thus indicating the need for improved high-power rf calibration techniques. A summary of the uncertainties of NIST power calibrations as a function of frequency is shown in figure 2.

Of particular interest are power measurements at 20 kHz, due to the interest of NASA in using 20-kHz power in the proposed space station. It is anticipated that 20-kHz power measurements in space may be required with uncertainties of better than $\pm 0.1\%$ at 75-kW power levels. Present state-of-the-art capabilities for 20-kHz power measurements at NIST have uncertainties on the order of $\pm 0.1\%$ at 1 kW power levels, with improvements to 200 ppm uncertainties planned for the future.

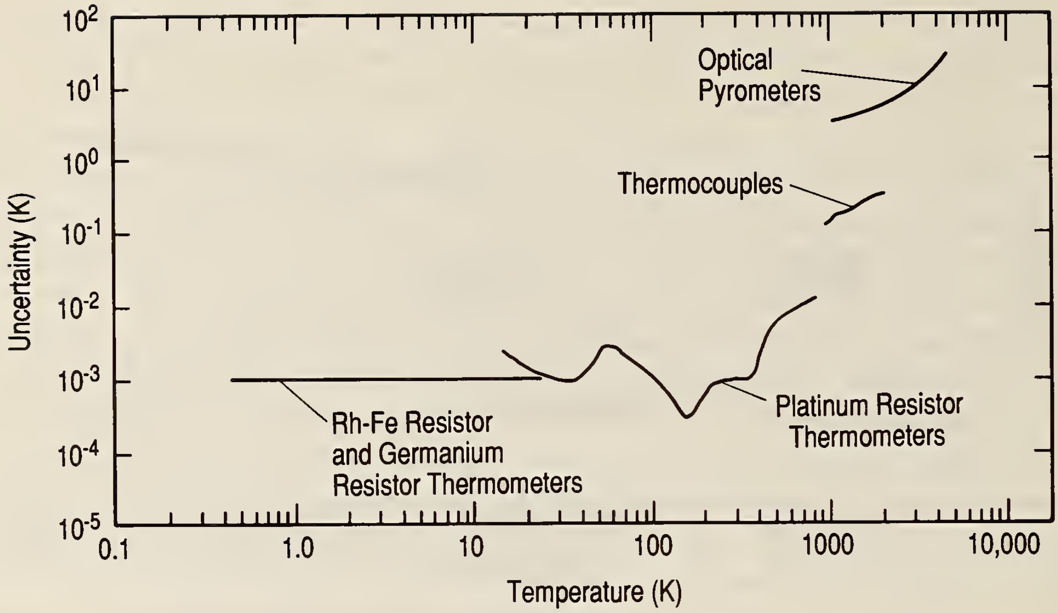

Figure 3. Uncertainties for NIST temperature calibrations.

2.3 Temperature

Temperatures which will require monitoring in various SDI programs range from 20 K for electromagnetic-launcher and nuclear-reactor coolants to 2500 K for interior reactor temperatures of the multimegawatt program. Required uncertainties range from 0.1–2%. Accurate, long-term temperature measurements will be especially important for monitoring the waste-heat management system and for determining heat-exchange efficiencies at the radiators. The determination of long-term temperature measurements on surfaces exposed to space is a particularly difficult problem because many surface-temperature sensors are susceptable to damage by the low-earth orbit space environment.

Ground-based state-of-the-art temperature measurements in the 0.5–1200 K region are made with resistance thermometry using iron-doped rhodium or high-purity platinum thermometers calibrated at various temperature reference points [25]. Uncertainties are about ±0.001 K up to 900 K and about ±0.2 K above that temperature. Above 1200 K, one uses a Planck-Law radiation thermometer calibrated at the silver or gold point (1240 K or 1335 K) with uncertainties of ±0.2 K at 1240 K. However, uncertainties involved in realizing and transferring the entire temperature scale (1070–4470 K) at NIST vary from ±0.5 K to ±2 K [26]. Uncertainties of routine high-precision optical pyrometer calibrations vary from ±3 K at 1240 K to ±30 K at 4470 K [1]. A more detailed presentation of uncertainties of NIST temperature calibrations for different devices is shown in figure 3.

All of the above mentioned state-of-the-art techniques are laboratory methods and any mechanical shock, radiation, extreme pressures, or severe temperature cycling will be disruptive to high-accuracy measurements. The degree of disruption is difficult to anticipate and would need to be determined on a case-by-case basis. Additionally, the radiation thermometry technique requires a true blackbody target for accurate measurements, and resistance thermometry is very slow, making it inappropriate for fast-changing time-dependent measurements.

Temperature measurements presently made on spacecraft also use resistance-thermometry devices (thermistors), although of a much less sophisticated nature than those discussed above. These devices are used extensively on the space shuttle and on deep-space probes to monitor temperatures ranging from 55–1150 K with accuracies of 1–3%. While these devices are of limited range and accuracy, they are extremely reliable. The thermistors used on the Voyager space probes, for example, are still operational 11 years after launch.

The thermocouple thermometer is a common, inexpensive, rugged, simple method for measuring temperatures over a larger range and with more accuracy than a thermistor. Various types of thermocouples are available covering a temperature range from −270 °C to 2760 °C. With careful calibration a thermocouple can offer an uncertainty level of ±0.1 °C over a small temperature range, while over a large range, temperatures may be interpolated to within ±2 °C if the calibration points are not more than 200 °C apart. Difficulties in using thermocouples for high-accuracy measurements can be numerous, but 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, temperature gradients, radiation sensitivity, and long-term drift in high-temperature service. This last difficulty is worthy of further comment in light of the long-term, high-temperature requirements of space-based nuclear reactors. Type K and Type N thermocouples are both rated for operation to approximately 1650 K, however, both exhibit substantial drifts when held at high temperatures for extended periods of time. Typical drifts of 15 °C and 4 °C, respectively, for Type K and Type N thermocouples, have been observed after being held at 1200 °C for approximately 600 hours [27]. Thermocouple thermometry techniques at higher temperatures are being developed using several refractory-metal thermocouple materials. One of the most promising is the tungsten-rhenium alloy which is rated to 2760 °C [27], but which still suffers from long-term, high-temperature drift. Additional research may eventually show that a molybdenum-neodymium alloy offers the best hope for a high-temperature, radiation-resistant thermocouple.

Many other thermometry techniques exist (some commercially available, others still developmental) which may 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. Commercial units are becoming available with stated uncertainties of approximately 1% at 2000 °C, but one must still consider the difficulties associated with the support equipment (lasers, data analysis, etc.) and with the detrimental effects of radiation on optical fibers and crystals. Johnson-noise thermometers also have applications at many temperatures and are also becoming commercially available. Under a wide range of industrial conditions, Johnson-noise thermometers have exhibited uncertainties of ±0.5% over a temperature range of −170 to 1000 °C [27]. Ultrasonic thermometers base their temperature determinations on the speed of sound in the sensor material. Some ultrasonic sensors have been used in terrestrial nuclear reactors, but the associated electronics are relatively complex and care must be taken when designing these devices for use in strong magnetic fields.

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) [28], measures the local temperature of a gas by determining the vibrational and rotational spectra of the 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. In principle this technique is suitable over a wide range of temperatures and can give picosecond response times. However, the complete analysis of CARS spectra is not a trivial task, and the entire apparatus would undoubtedly be quite complex.

One last technique which may be useful is nuclear quadrupole resonance (NQR) thermometry [29]. The variation of the NQR frequency of ^{35}Cl in a $KClO_3$ crystal is the basis for very precise thermometry between about 50 K and 400 K. A commercial version of this device is available and provides uncertainties of ±1 mK over the range of 90–393 K [27]. 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 extremely accurately indicates that NQR thermometry may achieve the goal of an accurate thermometer which does not require extensive calibration or exhibit long-term drifts.

2.4 Pressure

As with other parameters, SDI requirements for pressure measurements are extremely diverse. Reactor coolant pressures approach 8 MPa (80 atmospheres), while linear-accelerator flight tubes must be maintained at 10^{-5} to 10^{-7} Pa. Several required measurements must be made under rapidly-changing pressure conditions and others must be made in extremely harsh environments. External pressure sensors will be required to identify the species comprising the background gas surrounding the spacecraft in order to identify the presence of leaks or the decomposition of materials.

State-of-the-art static-pressure standards can be separated into three basic ranges. Vacuum standards, below 100 Pa, are generally McLeod gauges, volume-expansion devices, or orifice-flow systems. NIST maintains the latter type which generates a pressure by pumping a known flow of gas through a calculated conductance. From 0.1 Pa to 1 MPa, liquid-column manometers (generally mercury) are used. Manometers offer the lowest uncertainty of any pressure measuring device. From 1 kPa to 1 GPa, piston gauges or pressure balances can be

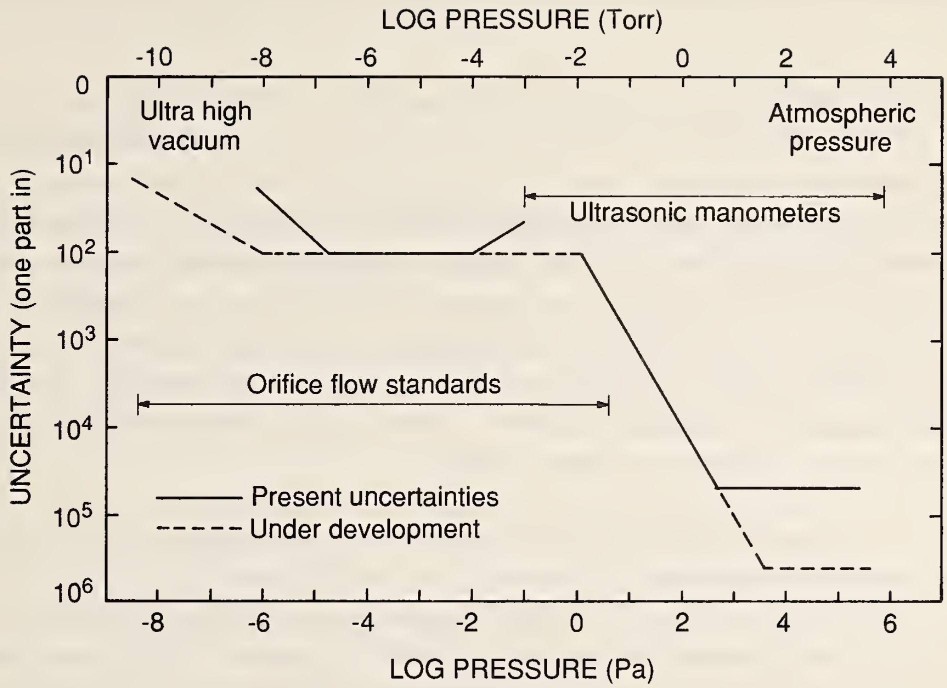

Figure 4. Uncertainties of NIST low pressure and vacuum standards [1].

used, and are the only practical standard for pressures much above a few atmospheres. All of these devices are inherently ground-based instruments. The uncertainty of the pressure standards currently maintained by NIST below a few atmospheres varies significantly with pressure, as indicated by figure 4. The diversity of commercial pressure gauges or transducers currently available is too great to attempt to summarize their capabilities here. It should merely be noted that their accuracy does not exceed that of the primary standards available to calibrate them, although in some cases the stability of the best transducers approaches the uncertainty of the primary standards. As a rule of thumb, state-of-the-art static pressure transducers can achieve accuracies in "field" use that are about an order of magnitude poorer than the uncertainties indicated for primary standards in figure 4. As examples, the best sensors used for aircraft altimetry can reliably operate at the level of 100 ppm. The better designed hot filament ionization gauges are reliable to within 10–20% in the high vacuum range.

Dynamic-pressure measurements are a particularly difficult problem. As the frequency range increases the correlation between transducer response and pressure units becomes increasingly tenuous. This is due in part to the difficulties in predicting energy transfer from the pressure media to the sensor. NIST does have a research program that uses coherent Anti-Stokes Raman Spectroscopy (CARS) to measure the temperature and pressure of gas molecules directly, and it is expected that this will form the basis for a calibration facility that initially will go to about 10 Mpa for frequencies up to a few kilohertz (frequency response is limited by signal and data processing). Since the optical technique is essentially non-intrusive it can profitably be used in situations where a mechanical intrusion is undesirable.

Very low-pressure (vacuum) measurements also present a number of special problems [30]. Interactions between the sensor and the "pressure fluid" can cause significant perturbations to the measurements, and in many cases, the development of less intrusive sensors, modified ion gauges or optical probes, would be highly desirable. In many cases, a measurement of the partial pressure or density of one or more atomic or molecular species is desired rather than the total pressure. This requires the use of mass analyzers (mass spectrometers or residual-gas analyzers), which tend to be rather complicated, require detailed calibration procedures, and currently exhibit extreme calibration drifts over short time periods. Species-specific measurement techniques are an alternative. They are not well developed at this time, although some optical techniques show promise.

Cold-cathode ion gauges have been flown on short-term space missions and have measured the ambient pressure surrounding a spacecraft to vary between 10^{-1} and 10^{-5} Pa. Cold-cathode devices were chosen for their rugged construction, but degradation of the field-emission cathode due to interactions with the atomic oxygen and contaminates surrounding the spacecraft has been observed. Work is presently taking place to develop corrosion-resistant cathodes.

Lack of gravity is a consideration for some mechanical devices such as manometers and piston gauges, but not for most pressure sensors. Extreme environmental conditions (high temperatures, temperature gradients, radiation, magnetic fields, and corrosives) significantly complicate most pressure measurements. A wide variety of devices have been developed to cope with these problems and their success has been varied. Again, the problems encountered and the attempted solutions are far too varied to summarize, but the fields that have addressed some of these problems include reactor instrumentation, chemical processing, semiconductor fabrication, and well logging (oil and geothermal). Within these areas several programs have been set up to develop or characterize transducers under extreme conditions. Commercial manufacturers are also active with development efforts, and while some problems have been solved, others remain.

As noted before, pressure sensors must be calibrated against a pressure standard. On the ground, under static conditions and for most pressures, this can generally be done in a fairly straightforward manner using well-understood standards. In a remote or contaminated environment, this may require redundant sensors and a program of intercomparison. Some of the sensors may have superior capabilities and be designated as reference standards, but the reliability of all sensors obviously becomes a paramount concern. 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. This is widely done in temperature metrology, but has been much more difficult to achieve for pressure. NIST has an embryonic program to develop this capability, starting with the triple point of argon [31], since the pressure at the triple point will be independent of location or environment. In all cases, the comparison or calibration of pressure sensors requires a mechanical link to transmit a common pressure to all devices.

2.5 Radiation

Accurate knowledge of neutron and gamma fluxes from the core of a reactor are essential for determining power densities inside the reactor. As a rule, detectors outside of the reactor vessel monitor average power, while interior sensors determine the power distribution inside the core and monitor for hot spots. The details of radiation measurement requirements anticipated for SDI space power platforms (ignoring hostile threat conditions) are dictated by the design of the nuclear power system. Probable designs for the multimegawatt space reactor program indicate the need to measure neutron fluxes up to 10^{16} neutrons/cm^2-s (10^{19} neutrons/cm^2 total fluence) and gamma fluences on the order of 10^8 Rads. Some systems may require measurements with uncertainties of better than 1%.

Present space-based radiation measurements monitor primarily high-energy electrons, protons, and ions. To the authors' knowledge no neutron-detection devices are currently operating on spacecraft. Thus one must rely on earth-based techniques to satisfy the radiation-measurement requirements of SDI.

Most on-line neutron flux measurements in commercial power reactors and in test reactors depend upon some form of fission chamber. Fission chambers are also used for state-of-the-art neutron measurements for the following reasons:

- Proper selection of uranium isotopes allows fission chambers to be selectively sensitive to either high energy or low energy neutrons.
- By selection of pulse-counting mode or current mode, the same fission counter (with different electronics) can be used for low- or high-power operation, respectively.
- Response time is fast. Even in the extreme case of a fast-pulse reactor, where start-up times are at the minimum possible for a controlled neutron fission chain (< 1 millisecond), fission detectors can follow the energy generation profile.
- Because of the relatively large amount of energy (180 MeV) associated with each fission event, pulse-height discrimination against instrument gamma sensitivity is relatively simple.
- Fission chambers can be of rugged construction, remotely positioned in high-radiation fields, and capable of precision operation in hostile environments.
- Response to low- and high-power operations may be intercalibrated over a middle range and verified by remotely moving a neutron source to the immediate vicinity of the chamber.

- Long-term calibration of fission chambers depends primarily on the reproducibility of the associated electronics and no loss of the ionizing gas. Under ground-based conditions, electronics operation may be periodically checked independent of the fission chamber operation. At temperatures below about 500 K degrees, gas leaks are ordinarily not a problem as long as the accumulate radiation exposure is less than 10^8 Rads.

The chief limitation for the application of fission chambers in SDI nuclear reactors is the anticipated core temperature (up to 2500 K) since most conducting electrical materials will melt at these temperatures. However, the development of fission chambers using ceramic housings, high-temperature conductor impurities or conductive coatings, and fissionable oxides might provide a solution.

Another type of neutron detector which has been used for many years in terrestrial reactors and may be appropriate for space nuclear reactors is the self-powered neutron detector [32]. These devices have several advantages in that they require no support electronics at the sensor location, they have long lifetimes (> 11 years), and they are appropriate for high-flux conditions ($> 10^{16}$ neutrons/cm^2-s). The detectors do experience some drift over time, but these drifts are well characterized and can be accounted for. Uncertainties of 1–2% are usual for these devices at low temperatures ($< 350\,°C$). However, at higher temperatures the contribution of thermal electrons becomes severe and the accuracy diminishes rapidly.

There is a wider variety of state-of-the-art gamma sensor instrumentation which can be used in very high radiation fields but they have the same temperature limitations as neutron detectors. Therefore, similar ceramic conductive electronics development would be necessary.

State-of-the-art fission detector calibrations and performance testing are performed at NIST with well-characterized radiation fields that use the 20 MW NIST Research Reactor as a neutron source. Absolute fission-rate measurements are also carried out using a compact double-fission chamber and the NIST set of fissionable-isotope mass standards. Fluxes of up to 5×10^7 neutrons/cm^2-s with uncertainties of 2% are available from well characterized ^{252}Cf fission neutron sources, while thermal neutron fluxes of up to 2×10^{11} neutrons/cm^2-s with uncertainties of 3% are available with cavity neutron sources. Uncertainties of present state-of-the-art fission-chamber sensors range from 3–5%, although there is no inherent obstacle to realizing 1% uncertainties with significant research effort.

2.6 Flow

SDI requirements for flow measurements are mostly related to the monitoring of coolant and fuel-flow systems. Possible coolants include hydrogen, nitrogen, lithium, and ammonia, with their physical states ranging from solids to cryogenic liquids and superheated gases. Some flow rates are anticipated to exceed 2000 kg/s.

State-of-the-art flow calibration and measurement services at NIST for liquids, such as water and/or hydrocarbons, utilize gravimetric and volumetric techniques. Measurement uncertainty levels for these facilities are quoted at the level of $\pm 0.13\%$. This uncertainty is composed of a precision level (three standard deviations) of $\pm 0.03\%$ plus an estimated systematic error of $\pm 0.1\%$ over the ranges of 10^{-5} to 1 m^3/s for water and 10^{-4} to 100 kg/s for hydrocarbons. Meter calibration services for cryogenic fluids (primarily, nitrogen) are available from NIST for flow rates of 76 to 757 liters/minute. For gases, such as air, volumetric and gravimetric techniques are available for calibrating a range of different types of flowmeters. Measurement uncertainty levels for these facilities are quoted at the level of $\pm 0.25\%$. This is based upon a laboratory precision having a three standard deviation of $\pm 0.15\%$ plus an estimated systematic error of $\pm 0.1\%$ over a range of 10^{-4} to 10 m^3/s.

For "point-velocity" air speeds, state-of-the-art measurements use both pitot-tube and laser Doppler velocimetry (LDV) techniques. The usual uncertainty level quoted for these techniques is $\pm 1\%$ for air speeds ranging from 0.05 to 50 m/s.

SDI measurement needs for fluid-flow rates that range beyond the above-described calibration capabilities would need to be addressed through the development of focused research programs. SDI needs for measurements in fluids other than those described can be addressed using surrogate fluid techniques. These techniques use specific parameters to document specific flow device characteristics in such a way as to predict performance in fluids other than those in which the actual calibration is done.

Specific flowmeter performance in specific installation and operation conditions varies widely, and *in situ* development and testing would obviously be required. However, as for pressure measurements, it should be noted the accuracy of flow sensors cannot exceed that of the primary standards discussed above. Performance data is conventionally obtained through meter calibration or testing procedures using standards such as those described above or transfer standards which are traceable to them.

2.7 Frequency

SDI frequency measurement requirements vary from a few hertz for electro-magnetic launcher firing rates, to microwave frequencies for rf linear accelerators, to approximately 10^{14} Hz for free-electron laser frequencies.

Frequency measurements into the gigahertz range can be made using commercially available counters with uncertainties of less than 1 ppm. If a known frequency signal is available as a reference, then uncertainties of 1 part in 10^{10} are achievable with "off-the-shelf" devices. One part in 10^{13} measurements may be made under laboratory conditions using more extensive equipment and more complex methods. Optical frequencies ($\sim 10^{14}$ Hz for 1 micron lasers) may be measured fairly simply using optical comparisons (or interferometric) techniques to uncertainties of one part in 10^8. Measurements of one part in 10^{14} (i.e. ± 1 cycle for 10^{14} Hz) is an extremely complex measurement, requiring a large laboratory facility. This capability is expected to be developed at NIST over the next several years. It should be pointed out that frequency is one of the few parameters which permits the use of an earth-based calibration for space applications [33]. This makes long-term frequency measurements significantly simpler than other metrology requirements.

2.8 Laser Power

Accurate laser-power measurements are obviously of interest to the free-electron laser programs. NIST maintains the U.S. standards for laser power and energy by using isoperibol (constant-temperature environment) calorimeters. The calorimeters compare absorbed laser radiation with equivalent quantities of electrical energy. Calibrated wavelengths vary from 400 nm to 10.6 μm, and continuous wave (CW) power ranges vary from 1 μW to 50 W. Some capabilities exist for CW calibration out to power levels exceeding 200 kW and pulsed power levels up to 15 kJ per pulse. Calibration uncertainties range from 1–5% depending on the power level and wavelength at which the calibration is performed [1].

A new program has been initiated at NIST to develop a national standard for laser power measurements in the megawatt regime. Construction has begun on a precision calorimeter to measure CW laser power in the 1–2 MW power range at wavelengths ($\sim$ 3 nm) which are suitable for large chemical lasers. This device is intended for ground-based testing of lasers for SDI applications, and uncertainties are anticipated to be better than 5%. However, the calorimeter will be extremely large and the developed techniques will not be directly suitable for space applications.

2.9 Shock, Vibration, and Acceleration

Vibration, shock, and acceleration are parameters of interest in SDI programs for a wide range of applications. They are dealt with together in this report because of the similarities of the sensors used to measure each parameter. Vibration transducers on SDI space power platforms will be needed to monitor for loose parts in primary power sources, to sense imbalances in rotating devices (i.e., turbines), to monitor the stability of mirrors inside a free-electron laser, and to determine overall stability of the space platform for locating and tracking operations. Also, accelerometers could possibly be used to measure the acceleration of a projectile being ejected from an electromagnetic launcher.

Most vibration measurements are made in order to determine system health or to predict component failure. Few vibration measurements are presently made in space since the continuing problem of limited human access to most space systems limits the usefulness of this information. There is, however, an ongoing program to investigate anticipated low-g vibrations of the proposed space station using laser interferometry. It is thought that the large, low-mass structure of the space station may be susceptible to low-frequency vibrations which would interfere with the aiming of deep-space observation equipment. However, these modal vibrations are difficult to simulate on earth in the presence of gravity.

The most common form of shock and vibration transducer is the piezoelectric accelerometer. Piezoelectric transducers are useful for measuring accelerations of magnitudes from $10^{-4}\,g$ to more than $10^{4}\,g$ [34]. A single accelerometer can provide measurements with a dynamic range of 10,000 to 1 or more, with excellent linearity under normal usage. At higher accelerations (depending on the design characteristics) nonlinearity may occur. Piezoelectric accelerometers are available which may be used in the temperature range of -254 °C to 760 °C, and resonance frequencies may exceed 100 kHz. However, the sensitivity of the transducer will decrease with increasing resonance frequency.

Piezoelectric accelerometers are also available with internal integrating electronics to measure velocities or displacement. These velocity transducers are small, have high resolution and frequency response, have no moving parts, and are relatively unaffected by magnetic fields. However, the electronics limit both the shock-acceleration limits and the temperature range.

Several types of optical-electronic transducer systems also exist. Laser Doppler vibration measurement systems provide real-time outputs proportional to the instantaneous velocity of the test surface. The technique is ideal for measurements requiring a non-contact method or remote monitoring. Currently the technique has a velocity dynamic range from 10^{-6} m/s to 3 m/s, and amplitude measurements from 10 nm to 1 m can be made in the frequency range from 0 Hz to 740 kHz [35]. Fiber-optic displacement sensors exist which are simpler and more compact than laser Doppler systems, and can measure displacements as small as 2×10^{-8} meters. However, they have limited dynamic range (100:1) and are very sensitive to rotation of the reflecting target.

Calibration of transducers over the entire range of operation is essential since sensor response may not be linear with increasing acceleration or frequency for all types of transducers. Calibration techniques at NIST include fringe-counting interferometry, fringe disappearance interferometry, and reciprocity methods. Uncertainties range from 0.25% [36] at low frequencies ($<$ 20 Hz) to 2% at higher frequencies ($<$ 10 kHz). For constant frequency, sinusoidal calibrations, the range of accelerations varies from 0.5–20 g, while comparison shock calibrations range from 50–10,000 g.

Static and dynamic torque are parameters related to shock and vibration. While most attention and engineering considerations are given to rectilinear motions (i.e., three-degree-of-freedom motion along the classical X-Y-Z axes), angular motion also occurs about an additional three degrees of freedom. Static torque is generally not too difficult to measure, however dynamic torques and angular accelerations may be extremely difficult to determine. There is a very limited number of sensors available for such measurements and accepted calibration methods have not generally been developed. Nonetheless, this is an area that deserves consideration in complex system designs such as the high-speed, balanced rotating devices (turbines, homopolar generators, etc.) envisioned for SDI space power production.

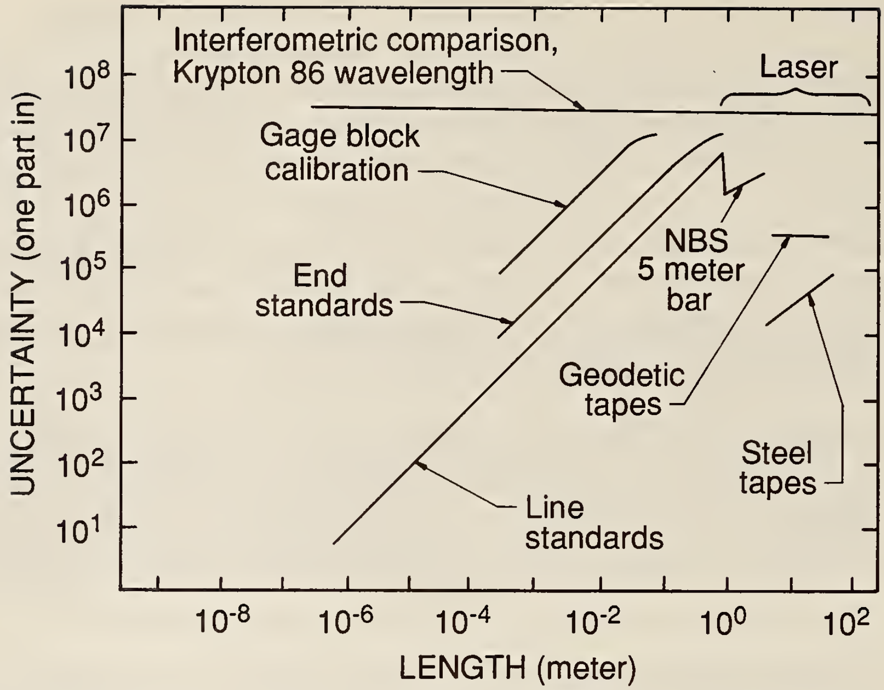

Figure 5. Uncertainty of length measurements at NIST [1].

2.10 Length

The requirements for length measurements in SDI programs vary from determining reactor control-rod positions to measuring the distance between two mirrors in a free-electron laser. State-of-the-art length measurements are presently made using interferometric-comparison laser techniques with uncertainties on the order of 0.1 ppm. The accuracies of length measurements made at NIST for various standards are shown in figure 5. The accuracy limits of the interferometric-comparison technique are due primarily to the uncertainties of the index of refraction of air. If measurements were made in a vacuum the uncertainty could be reduced to 1 part in 10^9.

3. SUMMARY OF SDI MEASUREMENT REQUIREMENTS

3.1 Introduction

As seen in the previous section, SDI measurement requirements include almost every imaginable parameter. However each measurement in each program is made under different conditions which affect the choice of the measurement technique. This section of the report discusses specific measurement requirements of various programs and examines the suitability of many of the measurement techniques presented in section 2. The most stringent metrology requirements are discussed for the following SDI programs and space power system components:

- Multimegawatt program
- SP-100 program
- Neutral-particle beam program
- Free-electron laser program
- Electromagnetic launcher program
- Turbines
- Homopolar generators
- High-voltage alternators
- Power conversion systems.

For a more complete detailing of SDI metrology requirements and anticipated measurement techniques, the reader is referred to the data base contained in the appendix of this report.

3.2 Multimegawatt Program

The multimegawatt space reactor (MMW) program has as an objective the determination of at least one space nuclear power system concept by the early 1990's that can meet SDI multimegawatt space power requirements including the resolution of all technical feasibility issues. The project is currently in the preliminary planning phase with six different concepts under consideration. The concepts have been grouped into three categories, each with different power generation, operating time, and cooling system requirements [37]. Some of the designs use liquid lithium coolants while others use hydrogen. Some of the reactors are designed to run continuously at low-power levels and then quickly ramp up to full power, while others are designed to be completely quiescent until their full power is needed. These design differences obviously produce variations in anticipated measurement requirements. In this section, we deal with the most difficult and extreme measurements which would be anticipated for the operation of the reactor portion of the MMW power system designs. The one operational aspect which is similar for all of the designs, is that each system must be capable of ramping up from its quiescent (or quasi-quiescent) state to full power in a matter of seconds. This implies the necessity of an extremely high level of control and, thus, the need for high confidence levels in sensor readings over a wide dynamic range for measured quantities.

Due to their extreme magnitudes, the most challenging metrology requirements of the MMW program are temperature, pressure, and radiation measurements. Three main temperature measurements need to be made on a MMW space platform including one of the most critical (and most difficult) – the interior reactor temperature. An accurate determination of this parameter is necessary to monitor the reactor conditions and to ensure the safety of the platform. Possible values for this parameter vary from 1200 K to 2765 K depending on the system design with possible uncertainty requirements approaching 2% (again dependent upon the design). The extremely high-temperature and high-radiation environment in which the temperature sensor must survive presently makes this long-term measurement impossible. It is conceivable that this problem could be solved by the development of high-purity or non-metallic thermocouples with low neutron cross sections. However, long-term drifts due to high temperatures and intense radiation would have to be eliminated and improved response times would have to be achieved in order to make thermocouples appropriate for this application. Other, possibly more suitable methods, might be Johnson-noise detectors, ultrasound time-of-flight, or optical-fiber methods. Any sensors employing these techniques would need to be constructed of low neutron cross-section materials to minimize radiation damage, and all of these techniques would require considerable development simply to survive in this harsh environment, let alone meet the long-term accuracy requirements.

A similar measurement requirement is the reactor coolant temperature. This varies from about 250 K at the reactor inlet to 2000 K as the coolant exits the reactor. Thermocouples may be appropriate for use where the temperature and neutron flux conditions are lower. However, the long-term drift problem would still need to be solved, a stable reference temperature maintained, and resistance to the corrosive coolants increased. Other possible methods are to measure the speed of sound through the liquid coolant or perhaps to detect eddy-current profiles in the heat pipes carrying the coolant. Both parameters vary with temperature.

The last main temperature measurement is the determination of the ambient temperature of the entire space platform. This measurement is important in order to monitor waste heat management and because some temperature sensors measure only temperature differences (thermocouples, for instance) not absolute temperatures. Estimated platform temperatures vary from 400–600 K with required uncertainties of about 1%. Since absolute temperatures are required it is conceivable that CARS or perhaps NQR thermometry would be most appropriate. Significant research and development, however, will be needed to determine which, if either, of these could be made suitable for long-term space use.

Radiation measurements are also essential for monitoring reactor power and operation, especially during fast start-up and shut-down procedures. Due to anticipated reactor geometries, it will be necessary to measure neutron flux inside the reactor in order to obtain an accurate indication of reactor activity levels. The anticipated in-core, full-power neutron fluxes of the MMW reactor ($\sim 10^{16}$ neutrons/cm^2-s) are within the upper limits of present state-of-the-art measurements, however, no neutron detectors currently exist which can withstand the anticipated core temperatures. Additionally, neutron detectors will be needed to measure low neutron-flux levels during start-up procedures, and because reactors will be cycled on and off many times during their lifetime, the low-flux detectors must 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 a factor of 2 to 3 over current state-of-the-art measurements to meet anticipated SDI requirements.

The pressure measurement requirements of the MMW program consist primarily of high-pressure coolant measurements under harsh environmental conditions (high temperature, corrosive coolants, radiation, etc.). Depending on the system, these measurements could possibly be made under static conditions using present technology. However, present technology does not provide a method to characterize the pressure-versus-time profiles of the anticipated rapid pressure changes of the MMW reactors. Further research into dynamic-pressure measurements will be required. The CARS technique discussed in the temperature and pressure portions of section 2 may provide a possible solution, however, as stated previously, this technique is nontrivial and the presently required apparatus is very complex.

Non-thermodynamic measurements are, of course, also required by the MMW program. The purity and radioactivity of the coolant must be monitored in order to detect leakage or corrosion inside the core, and coolant flow must be measured to detect blockages in the cooling system. Control rod or control drum positions must also be monitored.

It is very important to note that, in addition to the aforementioned need for sensor development, space nuclear-reactor control will require significant development of high-temperature, radiation-hardened support electronics. Presently, few semiconductor devices exist which can survive the anticipated environment of a space nuclear-reactor platform and provide the instrumentation requirements of the MMW program. 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.

3.3 SP-100 Program

The SP-100 space reactor program is a joint project supported by the Department of Energy, NASA, and SDI. The objective of the program is to design, construct, and test a space-based, nuclear reactor powered, electric generator in the tens to hundreds of kilowatts (electric) range by the mid- to late-1990s. This reactor is being designed in order to satisfy the future power requirements of NASA and the anticipated housekeeping-power requirements of SDI. While many of the measurement requirements of the SP-100 program are similar in nature to the requirements of the MMW program, the lower power requirements lower the ranges of many of the parameters. Unlike the MMW program, which is designing reactors for short-term, burst operation, the SP-100 reactor is being designed for long-term, continuous operation. It is expected to provide power for various types of space missions including space stations, space-based radar, lunar bases, and interplanetary rocket boosters. Present designs call for a fast-spectrum, liquid-lithium cooled, closed-loop system, with electric power being generated by thermo-electric converters. The system is designed to have a mission life of 7–10 years with the capability of approximately 20 start-up and stop cycles. Full-scale ground testing is scheduled for the early 1990's.

The fundamental control measurement on the SP-100 reactor is the temperature of the lithium coolant in the primary loop. This measurement will be used to limit the fuel temperature inside the reactor and to control the reactor start-up and shut-down procedures. It is anticipated that the coolant temperature will be measured at the reactor outlet by six tungsten-rhenium thermocouples and by six Johnson-noise thermometers at each location. Thus the measurement system is designed to be redundant and diverse. The coolant temperature will range from 800–1350 K, with measurement uncertainties of $\pm 1.4\%$ or 10 K (whichever is greater). The cold-junction reference for the thermocouples will probably be a thermostatically-controlled reference box which will be shielded from the radioactive environment and will be maintained at temperatures slightly above the ambient platform temperature (300–400 K). The reference-box absolute temperature will be determined to within 1% by a resistance-thermometer device (RTD). Calibration of the Johnson-noise thermometers signal processors will be maintained by reference resistors housed inside the reference box.

The coolant temperature is a very important measurement since no in-core temperature measurements will be made. No measurement technique has been developed which can withstand the high-temperature, high-radiation environment. However, the reactor vessel temperature will be monitored by thermocouples mounted to the outside of the reactor. Additionally, no incore radiation flux or pressure measurements are presently planned on the SP-100 reactor. However, on ground-based tests and on early flights, external neutron monitors will be used to monitor the reactor neutron level.

Anticipated coolant pressures in the SP-100 reactor are approximately 20 psi nominally with a maximum of 40 psi. To date, the method for measuring this pressure has not been determined due to the harsh environment in which the sensor must survive. It is possible that this measurement will not actually be made, but will be accomplished by using pressure switches which will determine if the lithium pressure is too high or too low.

Other measurements of interest include the coolant flow rate which will be measured on ground-based tests using electromagnetic flow meters. For space deployment, the flow rate will not be directly measured, but the presence of flow in the system will be detected in order to monitor the initial thawing process of the coolant. The control drums and rods positions will be measured on all systems by high-temperature resolver-type position sensors, and no plans are currently being made to monitor coolant purity or radioactivity to monitor corrosion or leakage.

3.4 Neutral-Particle Beam Program

Neutral-particle beams are being investigated as possible space-based weapon systems for the SDI program. The heart of a neutral-particle beam (NPB) weapon platform will most-likely be an rf linear accelerator (LINAC). The LINAC will accelerate a beam of H^- ions to hundreds of millions of electron volts and then strip the ions of their extra electron to form an intense beam of neutral hydrogen atoms. Primary metrology concerns in the NPB program are the long-term, accurate measurement of voltages to control the ion beam, and the determination of beam parameters.

The voltage measurement requirements for a ground-based NPB test facility are substantially different from those for a space-based NPB weapon platform. Ground-based systems require low dc-voltage stabilities of 5 ppm, high-dc voltage stabilities of 0.1%, and high rf-voltage stabilities of 0.5% in order to maintain continuous operation of the NPB over extended periods of time (hours) [38]. Absolute voltage values need only be known to within ±1%, because voltages are continuously adjusted to produce the highest quality beam output. The absolute voltage value is only necessary to provide a starting point from which to begin this tuning procedure.

Under space-deployment conditions however, a NPB facility would be run infrequently thus not allowing day-to-day tuning. Additionally, it would be required that the NPB start-up time be short (seconds), thereby not allowing much time for voltage and beam adjustments. It is therefore anticipated that absolute voltage measurements with uncertainties on the same order as the stability requirements may be necessary for space-based NPB facilities. Present dc-voltage measurement techniques are not adequate for measuring low dc voltages to 5 ppm over a 10-year period. At this point, accumulated errors on the order of 100 ppm would be expected over 10 years. As discussed previously, HVDC measurements of 0.1% using a resistive divider are also unlikely, and 0.5% rf high-voltage measurements are, at present, simply not possible.

Beam parameter measurements are of primary importance to an NPB facility since beam diagnostics are the best way to monitor the performance of the LINAC. Beam parameters of interest are beam current, energy, position, phase, spatial profile, emittance and loss. The current, position, phase, and energy of the beam can be measured using current-sensing toroids and microstrip probes. These provide adequate measurements in most cases. One difficulty is the measurement of the current-versus-time profile. A microstrip probe is an adequate sensor, but a signal recorder with a bandwidth of 500 GHz would be necessary to acquire the data. The beam's spatial profile (or cross section) and emittance are presently measured by devices which intercept the beam (such as viewing screens). This is adequate for ground-based test facilities but inappropriate for space deployment. Flying wire scanners have been developed which use a wire to scan across the beam and measure current distributions in one dimension. These devices are preferable to intercepting screens since they intercept only a small portion of the beam. Beam losses are measured by monitoring radiation produced by the divergent portion of the beam striking walls and apertures.

Many other measurements are necessary at a NPB facility. The rf power driving the LINAC is presently only measured to within 5–10% using directional couplers or calorimetric loads. This is adequate for test systems, but in a space-based scenario where waste-heat management is critical, a 5% measurement is not sufficient. Other measurements include the ion-source temperature, which must be monitored to maintain consistent performance. Ground-based systems presently monitor the source output (i.e., current) via a feedback circuit to control the temperature. Additionally, the flight-tube vacuum pressures must be monitored and maintained in the 10^{-5} to 10^{-7} Pa range.

3.5 Free-Electron Laser Program

A free-electron laser (FEL) facility is similar to an NPB facility since the basis of the apparatus is a particle accelerator. (It should be noted that the FEL programs contacted for this study at Los Alamos National Laboratory and at NIST both use rf LINACs.) The accelerator produces a relativistic beam of electrons which is then modulated by a well-defined spatially-oscillating magnetic field such that the beam radiates in a coherent manner. The wavelength of the emitted light can be varied by changing the energy of the electron beam. SDI's free-electron laser program is unique among the projected weapons systems because both land-based and space-based deployment is being considered. This, of course, makes an enormous difference in metrology needs, with the space-based requirements naturally being the more demanding.

FEL facilities basically consist of the accelerator portion (which creates the electron beam) and the laser portion (which creates the laser beam). Principal metrology requirements for the accelerator are voltage measurements and beam parameter determinations. Voltage requirements are very similar to those of a NPB facility, with uncertainties for space-based facilities approaching 0.1%. Absolute voltage measurement uncertainties can be greater for ground-based systems (1–2%) if fast tuning and constant sensor-monitoring capabilities exist. Required beam parameter diagnostics for an FEL facility are also similar to NPB requirements except the upper frequency response needed to monitor the electron beam is an order of magnitude higher than that needed for an ion beam. Multiplexing/heterodyning techniques allow microstrip detectors to determine average macroscopic properties of the electron beam, however, the frequency response is too low for the determination of microscopic beam-bunching characteristics.

To measure the beam position, spatial profile, emittance, and current-versus-time profile, a screen is usually inserted into the beam path and the subsequent radiation is observed by a detector or streak camera. While the radiation intensity is proportional to the electron current, absolute normalization is nearly impossible. Additionally, the quartz screens are interceptive and extremely fragile thus indicating that space-based applications and continuous-wave type lasers will require non-interceptive beam diagnostics. Possible non-interceptive methods are moving-wire scanners similar to those used by NPB facilities, wall-current monitors which measure induced voltage on a resistive wall coating, and split (multipole) wall current monitors which are a toroidal array of wall-mounted resistive sensors. To date, no adequate technique (interceptive or otherwise) has been developed to determine the current-versus-time profile of the electron beam with the sub-picosecond time resolution necessary to characterize the rf-modulated nature of the beam. Beam energy is usually determined by the magnetic deflection of the beam by a known field, or by measuring the frequency of the light emitted from a well-characterized magnetic wiggler. Both of these methods require well defined magnetic fields. The uniform field used for deflection would probably need to be measured using NMR techniques, and the rapidly varying field of the wiggler would be determined using a Hall probe which was calibrated against an NMR instrument. Other required measurements include the internal accelerator pressure (10^{-5} to 10^{-9} Pa), rf cavity temperature (0.1 °C regulation required), and rf power measurements. Of course, as mentioned before, power measurement uncertainties (and efficiencies) would be more critical for space deployment than for land-based facilities.

Laser frequency (or wavelength) and power are two of the most important measurements in an FEL facility since they characterize the final result: the laser beam. The frequency (or wavelength) may be determined either spectroscopically or by high-accuracy frequency determination, as discussed in section 2. Laser power is usually determined by pyroelectric detectors, and some research is obviously required to develop detectors which can withstand the extreme power densities anticipated for SDI applications. Other measurements critical to the operation of the optical portion of the FEL include accurate characterization of the magnetic field inside the wiggler. Also required is the determination of the distance between mirrors to within a micrometer over 10 meter distances. As can be seen from figure 5 in section 2, this one part in 10^7 measurement is just possible using multi-color interferometric technique. Additionally, it is necessary to monitor submicrometer vibrations of these mirrors, since vibrational amplitudes on the order of the laser wavelength will cause inconsistent laser operation.

3.6 Electromagnetic Launcher Program

Electromagnetic launchers (or rail guns) are kinetic-energy weapons which accelerate projectiles to high velocities using the force on a high-current carrier in a large-magnitude magnetic field. Measurement requirements for an electromagnetic launcher (EML) platform include electromagnetic, kinematic, and thermodynamic parameters.

Perhaps the most critical measurement for SDI applications is the accurate determination of the time profile of the large current pulse which powers the EML. The required pulse amplitude may eventually exceed 4 MA, with a 5-second duration, and millisecond rise and fall times. For targeting purposes in various SDI scenarios, it will be necessary to control the projectile velocity to within 0.5%, thus implying that the current pulse must be controlled to better than 0.5% and should be measurable to within 0.1%. Present determinations of the pulse profile using current shunts are inaccurate ($\sim$ 10%) because of voltages induced on the signal lines by the rapidly-changing magnetic field around the apparatus and because of the difficulty in characterizing the resistance of the current shunt in the megampere current regime. Rogowski coils 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 appears to be a promising alternative technique. Since the output of the sensor is proportional to the square of the current, no integration is required and the entire pulse can be measured. The use of flexible optical fiber is also well suited to the unusual geometries of the rail gun 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.

Other electromagnetic measurements required by the EML program are of magnetic-field intensities and pulsed-voltage measurements. The magnetic fields produced by a rail gun are of large magnitude (10 Tesla) and are rapidly changing (10^9 Tesla/s). These fields need to be accurately characterized inside the bore of the EML in order to control the projectile, and they need to be measured outside of the bore to determine the effects on other components and sensors. Because of the dynamic nature of the magnetic fields, Hall probes and pick-up coils are the most suitable sensors currently available. However, difficulties still exist when one attempts to measure the magnetic field inside the bore of the EML during a shot. Voltage measurements at the breech and muzzle of the EML are also necessary to characterize the processes which occur inside the bore during a shot. The measured pulses are on the order of 10 kV in magnitude with millisecond durations. However, accurate determination of these signals is also difficult due to large induced voltages in the signal leads. Electro-optic techniques may be more suitable here because the sensor is electrically isolated from the sensor electronics.

Required kinematic measurements include position, velocity, and acceleration of the projectile as a function of time. Bore velocities of a projectile can approach 10 km/s, and, as mentioned previously, the velocity must be *controlled* to within 0.5% for targeting purposes. No method has yet been determined which can even *measure* the velocity to that accuracy. Presently, break wires (or films) spaced along the bore of the EML are used, but this method is good only for one shot, and does not provide adequate time resolution. Optical techniques have also been used, such as intercepting laser beams and doppler-shift detection. However, these techniques are limited by the effects of the pressure surge preceding the projectile, by the effects of the residual plasma from the vaporized armature, or by difficulties in designing optical sensors such that they will not be destroyed by the emerging projectile. Other techniques such as x-ray photography through the bore walls simply do not have adequate time response. Acceleration measurements obviously suffer from the same constraints. One possibility is to attach velocity and acceleration detectors directly to the projectile. This, however, requires the development of electronics which can withstand the 2000 km/s^2 accelerations, operate in high-magnitude, transient magnetic fields, and telemeter data back to the laboratory while inside the bore, traveling at 10 km/s.

Thermodynamic parameters which must be measured in the EML project are coolant temperatures and transient bore pressures. To measure the coolant temperature accurately, the sensors would probably have to be removed from the high magnetic field region, or be non-electrical sensors such as gas or filled-system thermometers. These devices are less accurate ($\sim 1\%$) but they are unaffected by magnetic fields. The bore pressure measurement is a difficult problem because the pressure changes over many orders of magnitude in a matter of milliseconds, and the sensor cannot protrude into the EML bore. Attempts have been made using fast piezoelectric transducers with undetermined accuracy [39]. Extreme care must be taken to electrically isolate the transducer since induced voltages from the local magnetic fields can swamp the signal output. Naturally, this is a measurement of interest only in land-based testing since the presence of a vacuum within the bore would eliminate the need for this measurement.

3.7 Turbines

For several projected space power systems, it is anticipated that high-speed, counter-rotating turbines will be used to convert the thermal energy from the power source into mechanical energy. Many of the parameters which one would anticipate measuring at the turbines are similar to those discussed previously. For example, turbine inlet and outlet pressures and temperatures are similar to those quoted for the coolant parameters in the MMW program, and one would anticipate using similar measurement techniques. A different measurement parameter required for SDI turbine applications is the determination of the rotational frequency (6–20 krpm). This must be accurately determined since on each space platform an even number of balanced, counter-rotating turbines must turn with the same rotational velocity to preserve the mechanical and positional stability of the platform. This can be measured with relative ease using optically-isolated frequency-counting techniques.

3.8 Homopolar Generators

Homopolar generators (HPG) are devices which contain a conducting disc or drum rotating in a magnetic field, cutting field lines and generating a voltage. The generating rotor is large and can operate as a flywheel storing large amounts of rotational energy. It is anticipated that HPGs would be used to convert the rotational energy of the turbines into large current pulses for electromagnetic launcher use. The expected power output from SDI homopolar generators is between 80 and 150 MW, produced in the form of high-magnitude current pulses (> 1 MA) at low voltages (50–200 V) [38]. These current pulses will probably be measured using Rogowski coils or magneto-optic devices, while voltage pulse characterization can be adequately determined by transient recorders or successive approximation analog-to-digital converters. Internal magnetic fields (4–6 Tesla) [38] will most likely be measured using Hall probes. Since HPGs are rotational devices, like turbines their rotational velocity will have to be carefully measured and controlled. Dynamic torques and angular accelerations will also need to be monitored due to the anticipated pulsed operation of HPGs when used to power devices such as EMLs. A critical temperature measurement in an HPG system is the determination of the rotor temperature in order to monitor wear and friction. Eddy-current thermometry offers a non-contact capability with fairly fast response, but is still developmental.

3.9 High-Voltage Alternators

High-voltage alternators being designed for SDI applications are very similar to alternating-current generators commonly used today. They produce sinusoidal-voltage outputs at peak voltage levels ranging from 10–85 kV at frequencies ranging from 400 Hz to 5 kHz [38]. Present plans are for the alternators to be cryogenically cooled to improve efficiencies. Measurement requirements are in many ways fairly straightforward. Rotational frequencies can be determined in similar fashion to the other rotating devices, ac currents ($\sim$ 1 kA) can be measured using Rogowski coils or current transformers, and coolant temperatures must be maintained below cryogenic levels. The accuracy of the HVAC measurements are limited as discussed in section 2.2.1.

3.10 Power-Conversion Subsystem

The power-conversion subsystem will take the power output from the primary electrical power generator (i.e., homopolar generator, high-voltage alternator, etc.) and convert it into electrical signals suitable for driving the load (i.e., a FEL, NPB, EML, etc.). Obviously, a plethora of electrical measurements will be required in the power-conversion stage of the space power platforms. However, almost complete uncertainty presently exists in terms of the required inputs and outputs of this subsystem, making detailed metrology analysis impossible. However, one expects that the extreme electrical measurement requirements of the SDI program exist at each end of the power system (the power source and the load) and have therefore been addressed in the previous sections of the report. The obvious difficulties lie in the long-term, high-reliability electrical measurements required to maintain platform operation.

4. MEASUREMENT RELIABILITY

A critical measurement problem which exists in all SDI programs and has been touched upon in the previous sections is the maintenance of reliable sensor calibrations over long periods of time. SDI platform lifetimes are anticipated to be on the order of 10 years, and to expect present-day sensors to provide accurate, reliable measurements in a harsh environment over that time period is unrealistic. In electronics alone, a state-of-the-art passive resistor experiences $\sim$ 1 ppm/year drift in a controlled environment, while active electronic components experience drifts on the order of 10 ppm/year. Ideally, one would like to periodically recalibrate each sensor to ensure reliability, however, in the unattended situations envisioned for SDI space platforms, 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, nuclear quadrupole resonance, etc.) appear suitable for long-term calibration standards. However, these standards are scarce and, additionally, may themselves require support electronics which prevent them from being completely drift-free. In the final analysis, it is probably unrealistic to expect to develop every sensor required by the space power system such that it can meet the required accuracies over a 10-year period without some form of calibration.

The improvement of measurement effectiveness and reliability is an area of present research. Components of this research are being developed under such labels as "statistical design," "testing strategy," "state estimation," etc. The basic features of a systematic approach to the improvement of measurement reliability are:

1. Development of a system model,
2. Use of the model to identify the measurements needed, and
3. Over-specification to test sensor and model accuracy.

The development of the system model can range from a straightforward task to a research project. In the lowest-order example, an electric circuit consisting of passive components can be modeled using available circuit theory. In fact, extremely sophisticated circuit models of land-based power systems are available and are being used for system design and operation. An area of present research interest is the combination of nonlinear processes with linear circuit models. The complexity of the proposed space power systems makes it likely that very advanced modeling efforts will be required.

Having developed the system model, the next conceptual step is the identification of the measurement systems which are needed. This identification requires that the physics and chemistry of failure be known, so that precursors to failure can be identified. It should be emphasized that, in this context, failure means more than lack of operation of a single component. It means that a component, or a group of components, operates in such a manner that the system as a whole fails to meet its specified objective. For example, the high-voltage power supply used with a free-electron laser could operate properly but, because of an error in the control circuit, the output voltage could be ten percent below the specified level. In terms of the performance of the laser, the failure of the device to operate at all and the generation of too small a voltage are equally disastrous failures. The system model allows the analysis of the efficacy of various measurements and measurement systems in the identification of existing or incipient failure modes. This analysis permits the prudent determination of the minimum number of measurement systems which will be required.

Some level of over-specification is required to provide for self-calibration of the measurement system and to verify that the system model is providing an adequate prediction of system performance. Both of these features are necessary in a system with an expected ten-year-unattended life. Nearly all of the measurement systems are expected to exhibit drift and need recalibration. Secondly, component aging may cause the system behavior to change and this change could well be detected as a deviation between the model predictions and the system response. In order to make prudent decisions about system operation, one must have the ability to separate sensor failure from system failure.

This approach to measurement reliability cannot be added after the system is constructed. The measurement approach must be designed, built, and tested hand-in-hand with the space-based system which it will monitor.

Computer models of power systems are presently only in embryonic stages as compared to what would be required for SDI applications. Significant research in methods of system modeling, in the determination of optimum sensor arrangements, and in component characterization would obviously need to be performed before the capabilities discussed above are possible.

5. SUMMARY

Many measurements which are presently not possible will be required to operate anticipated SDI power and weapon systems. The following are points which represent the main findings and conclusions of this study concerning the most critical metrology shortcomings and the most promising areas of metrology research:

- No adequate method exists for measuring high voltages and currents under space-platform conditions. Magneto- and electro-optical measurements appear promising for space applications.

- Improved accuracy in power measurements at high frequencies are necessary for waste-heat management.

- Intrinsic standards and measurement techniques (such as CARS, NQR thermometry, and Josephson junctions) should be developed for long-term measurement calibrations. The development of reliable calibration standards is critical to the long-term control of complex space systems.

- High-temperature, radiation-hardened sensors need to be developed for practically all parameters. Specifically the development of semiconductor devices to survive the anticipated environment on a space nuclear power platform is essential.

- Improved dynamic-pressure sensors and the corresponding standards for calibration need to be developed.
- Radiation sensors which can survive high temperatures ($T > 2000\,\mathrm{K}$) and temperature sensors which can survive high radiation fluxes are required.
- Electron and ion beam diagnostic devices need to be improved to be suitable for SDI applications.
- All sensors, support electronics, standards, and control systems must be characterized under all conditions anticipated during long-term space deployment.
- Most importantly, long-term calibration and reliability of sensors must be addressed either by means of improved hardware or by improved software for internal control and calibration.

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8. APPENDIX

8.1 SDI Metrology Assessment Data Base

The content of this Appendix is the data base which was created to organize the information obtained about SDI space power measurement requirements. The data presented here are organized alphabetically by SDI program and then by parameter. The top of each data sheet details the SDI measurement requirement with appropriate comments. The next two sections on the page discuss the two most probable measurement techniques with an assessment of their suitability. A blank entry means that either the information is undetermined or was unavailable to us at the time of publication. The contents of the Appendix is listed below:

Electromagnetic Launcher (EML) Program 41

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SDI REQUIREMENTS -

Program: EML **Parameter:** ACCELERATION

Application: IN-BORE PROJECTILE ACCELERATION

Range: 1000 to 2000 km/s^2 **Uncertainty:**

Reason for Measurement: Characterize bore design, analyze acceleration efficiency, and determine force on the projectile.

Other Requirements:

Comments: Necessary for development of smart projectiles that can withstand the force of acceleration, and also useful for analysis of energy dispersion during a shot.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Derivative of in-bore velocity profile.

Present Range: **Present Uncertainty:**

Assessment: Limited by the in-bore velocity measurements.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Force sensor on projectile

Present Range: **Present Uncertainty:**

Assessment: Still in early development. There are telemetry problems with retrieving the data. Size of projectiles currently used is a limitation.

Comments: This method has been used previously on artillery shell tests.

SDI REQUIREMENTS -

Program: EML **Parameter:** B-FIELD

Application: MEASURE MAGNETIC FIELDS IN AND AROUND EML

Range: up to 10 Tesla **Uncertainty:**

Reason for Measurement: Characterize the operation of the launcher.

Other Requirements: Fields are rapidly varying, up to 10^9 Tesla/s. A time profile of the magnetic fields is desirable.

Comments: Difficult to measure the magnetic field in the bore during an actual shot. The magnetic fields around the launcher must be characterized to determine the effect on surrounding electronics and on human personnel.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Hall Probe

Present Range: > 10 Tesla **Present Uncertainty:** 0.1%

Assessment: Adequate for some measurements. Very orientation sensitive. Presently not suitable for in-bore measurements. The frequency response may be questionable.

Comments: Long-term stabilities 0.1% to 1%. Could be too expensive for large-scale field mapping around the EML.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Single-turn pick-up coils

Present Range: > 10 Tesla **Present Uncertainty:** 1%

Assessment: Limited accuracy. May be useful for field mapping. Calibration is a problem. Must integrate signal.

Comments: Not suitable for dc fields. 1% uncertainty is only under controlled situations. This is a relatively inexpensive technique.

SDI REQUIREMENTS -

Program: EML **Parameter:** CURRENT

Application: CURRENT PULSE MEASUREMENT

Range: 1 to 1.5 MA **Uncertainty:** 1% to 0.1%

Reason for Measurement: Monitor power source. Control projectile velocity.

Other Requirements: Pulse varies in length from milliseconds to seconds. Large, fast-changing magnetic fields are present. The amplitude-versus-time profile must be characterized.

Comments: Amplitudes of up to 4 MA may eventually be used. Ground- based measurement uncertainties should be 1% for developmental purposes. Uncertainties of 0.1% may eventually be required for targeting purposes in space-based applications.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Rogowski Coils

Present Range: greater than 4 MA **Present Uncertainty:** ~10%

Assessment: Useful for characterizing rise-and-fall portions of the current pulse. Difficult to use for DC portion of pulse since integration of signal is required.

Comments: Stated accuracy is for present use measuring long, high-magnitude pulses. For fast changing current pulses (ms) accuracies on the order of 1–2% are possible.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Magneto-optical Current Sensor

Present Range: greater than 4MA **Present Uncertainty:** 1%

Assessment: Appears promising. More suitable for long current pulse than Rogowski coil since no integration is required. Signal is electrically isolated from the pulsed current system.

Comments: 1% uncertainty is claimed by groups measuring 100 μs, 1 MA pulses in fusion machines. 1.5% uncertainties quoted for 60-Hz utility measurements. Need to characterize long term performance.

SDI REQUIREMENTS -

Program: EML **Parameter:** FLOW

Application: COOLANT FLOW

Range: 26 to 33 kg/s **Uncertainty:**

Reason for Measurement: Monitor cooling system.

Other Requirements: Must operate in fast-changing magnetic fields.

Comments: Most likely coolant is H_2. The absolute magnitude of the flow rate is not a critical measurement.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Monitor pump speed.

Present Range: **Present Uncertainty:**

Assessment: Adequate.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Turbine meters

Present Range: **Present Uncertainty:** 1%

Assessment: May not be appropriate for very large volume flows.

Comments: Uses magnetic pick-up to obtain signal.

SDI REQUIREMENTS -

Program: EML **Parameter:** PRESSURE

Application: MEASURE INTERNAL BORE PRESSURE

Range: **Uncertainty:**

Reason for Measurement: Monitor activity in the bore.

Other Requirements: Measurement must be made in varying B-fields. The sensor may not protrude into the bore and must withstand the corrosive plasma from the vaporization of the armature.

Comments: A time profile of the dynamic pressure in the bore would be ideal.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Piezo-electric pressure transducers

Present Range: 100,000 psi **Present Uncertainty:**

Assessment: Large magnetic-field changes induce voltages on the sensor leads. The frequency response is adequate. Absolute calibration of dynamic pressure sensors is presently quite unreliable.

Comments: Must be positioned inside bore or on projectile. Frequency response is approximately 50 kHz

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: EML **Parameter:** STRAIN

Application: BORE STRAIN

Range: **Uncertainty:**

Reason for Measurement: Monitor forces on the bore.

Other Requirements: Measurement made in high, rapidly-changing magnetic field.

Comments: This measurement needs to be made in order to determine the projected lifetime of an EML bore.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: EML **Parameter:** TEMPERATURE

Application: COOLANT TEMPERATURE

Range: 20 to 300 K **Uncertainty:**

Reason for Measurement: Monitor power dissipation in EML.

Other Requirements: Must withstand the corrosive nature of the coolants. Must operate in rapidly-changing magnetic fields.

Comments: H_2 is most likely coolant. It is not anticipated that this will need to be an extremely accurate measurement.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Thermocouples

Present Range: up to 2000 K **Present Uncertainty:** 0.1%

Assessment: Possible calibration difficulties over long time periods. The magnetic fields may interfere with the small voltage signals from the thermocouples.

Comments: The stated 0.1% uncertainly is under very controlled conditions.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Thermistors

Present Range: 55 to 1150 K **Present Uncertainty:** 1 to 3%

Assessment: Suitable for temperatures above 55 K.

Comments: Long lifetime (> 10 years).

SDI REQUIREMENTS -

Program: EML **Parameter:** VELOCITY

Application: PROJECTILE EXIT VELOCITY

Range: 5 to 10 km/s **Uncertainty:** 0.5%

Reason for Measurement: Necessary to properly target the projectile.

Other Requirements: The measurement technique must allow for more than one shot.

Comments: The exit velocity needs to be controlled to within 0.5% to achieve mid-course intercept. Therefore it should be measurable to better than 0.5%.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Break wires

Present Range: **Present Uncertainty:**

Assessment: Inappropriate for multi-shot and space-deployment applications.

Comments: Technique measures the time between breaking wires spaced a known distance apart.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: LIDAR

Present Range: **Present Uncertainty:**

Assessment: Still developmental. Optics geometry is difficult for multishot situations.

Comments: Residual plasma from the vaporization of the armature and the presence of a pressure shock wave preceding the projectile interfer with the laser beam.

SDI METROLOGY ASSESSMENT

SDI REQUIREMENTS -

Program: EML **Parameter:** VELOCITY

Application: IN-BORE VELOCITY

Range: 0 to 10 km/s **Uncertainty:**

Reason for Measurement: To determine the behavior of the projectile in the bore and to aid in targeting.

Other Requirements: Need a velocity-versus-time (or position) profile in order to analyze the acceleration characteristics of the EML.

Comments: Multiple-shot situations make this measurement more difficult.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Break wires

Present Range: **Present Uncertainty:**

Assessment: Only suitable for single shot. Difficult to get high spatial resolution for a velocity-versus-time profile.

Comments: Measures time between equally spaced breaking wires.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: LIDAR

Present Range: **Present Uncertainty:**

Assessment: Still developmental. Optics geometry is difficult to design for multiple-shot experiments.

Comments: Residual plasma from vaporization of the armature and the presence of a pressure shock wave preceding the projectile interfere with the laser beam.

SDI REQUIREMENTS -

Program: EML **Parameter:** VOLTAGE

Application: MUZZLE VOLTAGE

Range: 0 to 10 kV **Uncertainty:** 1%

Reason for Measurement: Monitor power consumption and conversion efficiency.

Other Requirements: Measurement made in rapidly changing magnetic fields. A voltage-versus-time profile is needed.

Comments: Signal bandwidth is ~10 kHz.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Digital transient recorder

Present Range: 1 kV **Present Uncertainty:** 0.1%

Assessment: Large induced voltages in the contact leads limit the accuracy of this method.

Comments: An appropriate voltage divider must be used to scale voltages down to measurable levels. This voltage divider must operate in large, fast-changing external magnetic fields.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Pockels Cell

Present Range: **Present Uncertainty:** 5%

Assessment: Crystals are stress sensitive. Still developmental. Improved accuracy is required to meet required uncertainties. The cell is anticipated to be insensitive to the magnetic fields.

Comments: One advantage of this technique is that the sensor signals are electrically isolated from the measured voltage.

SDI REQUIREMENTS -

Program: EML **Parameter:** VOLTAGE

Application: BREECH VOLTAGE

Range: 0 to 10 kV **Uncertainty:** 1%

Reason for Measurement: Monitor power consumption and energy conversion efficiency.

Other Requirements: Measurement must be made in changing magnetic fields. The signal is time varying on a millisecond time scale.

Comments: A voltage-versus-time profile is needed. The required bandwidth is ~10 kHz.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Digital Transient recorders

Present Range: 1 kV **Present Uncertainty:** 0.1%

Assessment: Large induced voltages due to time-varying magnetic fields limit the accuracy of this technique.

Comments: An appropriate voltage divider will need to be used which can operate in large-magnitude, time-varying magnetic fields.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Pockels Cell

Present Range: **Present Uncertainty:** 5%

Assessment: Cells are stress sensitive. Improved accuracy is required to meet required uncertainties. Still developmental. The sensor is anticipated to be insensitive to the magnetic fields.

Comments: The sensor output is electrically isolated from the measured voltage signal.

SDI REQUIREMENTS -

Program: ENVIRONMENTAL **Parameter:** PRESSURE

Application: RESIDUAL GAS PRESSURE SURROUNDING SPACECRAFT

Range: 10^{-4} to 10^{-10} torr **Uncertainty:**

Reason for Measurement: Background pressure affects sensors. Also to to monitor for leaks and decomposition of materials.

Other Requirements: Need to identify species as well as absolute pressure. Pressures may change drastically in less than a second.

Comments: High background pressures may be produced by effluents from the power systems.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Ion gauges and cold-cathode gauges

Present Range: **Present Uncertainty:** 10%

Assessment: Only measures pressure. Does not identify species. Uncertainties may vary by as much as 50% over time. Uncertainties increase if the composition of the background gas is unknown.

Comments: Limited lifetime due to degradation of filaments and cathodes in in space environments. Use of a cold-cathode gauge for a 1 week space experiment resulted in substantial corrosion of the cathode.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Residual-gas analyzer

Present Range: **Present Uncertainty:**

Assessment: Calibration is difficult. More complex than an ion gauge, but it does supply information about the composition of the background gas. Long-term stability and operation is questionable

Comments: Uncertainties may vary by as much as 100% over time as conditions vary.

SDI REQUIREMENTS -

Program: FEL **Parameter:** B-FIELD

Application: MEASURE MAGNETIC FIELD INSIDE THE WIGGLER

Range: 0.3 to 0.5 Tesla **Uncertainty:** 0.5%

Reason for Measurement: Characterize the FEL.

Other Requirements:

Comments: The wiggler is the device which generates the magnetic field which causes the electrons in the beam to oscillate and radiate coherently. The wiggler can be constructed from either electro- or permanent magnets. The field is constant in time, but is spatially non-uniform.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Hall Probe

Present Range: **Present Uncertainty:** 0.1%

Assessment: Presently a long and tedious measurement. The wiggler system must be disconnected for the measurement. The Hall probe is probably adequate if the long-term drift is sufficiently small.

Comments: It will be necessary to perform this measurement a number of times throughout the lifetime of the laser if permanent magnets are used.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: FEL **Parameter:** B-FIELD

Application: MEASURE B-FIELD IN TURNING MAGNETS OF LINAC

Range: near 1 Tesla **Uncertainty:** 0.001%

Reason for Measurement: To analyze the electron beam characteristics and to measure the electron beam energy.

Other Requirements:

Comments: The field must be characterized to 0.001% in order to accurately measure the electron beam energy.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Nuclear Magnetic Resonance (NMR)

Present Range: **Present Uncertainty:** < 1 ppm

Assessment: Slow process. Works primarily on uniform fields.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Hall probe

Present Range: **Present Uncertainty:** 0.01%

Assessment: Not sufficiently accurate to map the most uniform field areas of the magnets.

Comments: Must be used for the more non-uniform regions (e.g., near the edges of the magnets.)

SDI REQUIREMENTS -

Program: FEL **Parameter:** BEAM

Application: POSITION OF ELECTRON BEAM IN ACCELERATOR

Range: **Uncertainty:** 100 μm

Reason for Measurement: Beam control

Other Requirements:

Comments: This is a critical measurement for control of the accelerator. The beam must be centered for optimum laser operation.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Screen

Present Range: **Present Uncertainty:** 100 μm

Assessment: Adequate for development. Not suitable for deployment since the screen intercepts the beam and the screen has a limited lifetime.

Comments: Cherenkov radiation from the beam striking a screen is monitored to determine the beam position. The screen is inserted and then removed after the measurement.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Split wall monitor (SWM)

Present Range: **Present Uncertainty:**

Assessment: Still conceptual. It would be non-interceptive and therefore suitable for deployment situations.

Comments: SWM measures the voltage drop across a resistive beam pipe with many symmetric pieces. The beam is positioned such that the signal generated by each axial portion of the SWM is equal.

SDI REQUIREMENTS -

Program: FEL **Parameter:** BEAM

Application: ELECTRON BEAM SPATIAL PROFILE

Range: **Uncertainty:**

Reason for Measurement: Monitor beam characteristics.

Other Requirements: Should be non-interceptive.

Comments: Possible non-interceptive technique is the multi-pole (split) wall-current monitor. It may be useful for obtaining xy multiple moments about a mean position. The technology has yet to be developed.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Screen

Present Range: **Present Uncertainty:**

Assessment: Suitable for development, but beam interception makes this method unacceptable for deployment. Also, the screen is quite fragile and has a limited lifetime.

Comments: The screen intercepts the beam and emits Cherenkov radiation which is detected. This method provides only relative measurements. Absolute calibration is extremely difficult.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Moving-wire probes

Present Range: **Present Uncertainty:** 1 μm

Assessment: Appears adequate since the wire perturbs the beam only slightly. Present lifetimes are estimated to exceed 20000 cycles.

Comments: Consists of a carbon filament, 1 μm thick. Measures electron scattering from the filament as it moves through the beam.

SDI REQUIREMENTS -

Program: FEL

Parameter: BEAM

Application: ELECTRON BEAM CURRENT

Range: 700 A peak

Uncertainty:

Reason for Measurement: Beam control

Other Requirements: A current-versus-time profile is needed with better than 1 ps time resolution

Comments: Currents average 1 ampere over a 10 μs pulse packet. Each pulse package is divided into micropulses of 10 to 20 ps in length with peak currents of ~700 A.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Wall-current monitor

Present Range:

Present Uncertainty:

Assessment: Present uncertainty and calibration techniques are uncertain. Time resolution is on the order of a few ps and would need to be improved. This technique is non-interceptive.

Comments: Measures the voltage drop across a piece of resistive beam pipe through which the electron beam passes.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Screen with a streak camera

Present Range:

Present Uncertainty:

Assessment: Time resolution is better than 2 ps, but absolute accuracy is uncertain. The screen intercepts the beam and the quartz screen is very fragile, making this technique unsuitable for space.

Comments: The streak camera measures Cherenkov radiation from the electron beam striking the screen. The radiation intensity is proportional to the current, but is almost impossible to normalize absolutely.

SDI REQUIREMENTS -

Program: FEL **Parameter:** BEAM

Application: ELECTRON BEAM EMITTANCE

Range: **Uncertainty:**

Reason for Measurement: To determine beam loss and accelerator efficiency.

Other Requirements:

Comments: Less emittance implies less beam loss and greater efficiency.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Pepper Pot with Screen

Present Range: **Present Uncertainty:**

Assessment: Suitable for development stages. Interception of the beam makes it unsuitable for deployment purposes. Applicable only for electrons with energies below 1 MeV.

Comments: Emittance is determined from the beam pattern measured on a screen from the beam passing through the pepper pot.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Angular Dispersion of Optical Transition Radiation (OTR)

Present Range: **Present Uncertainty:**

Assessment: The technique is interceptive, and is appropriate only for electrons with energies greater than 100 MeV.

Comments: The depth of the valley between OTR lobes generated by an electron beam striking a dielectric or metallic surface is a direct measure of the angular spread of an electron beam.

SDI REQUIREMENTS -

Program: FEL **Parameter:** BEAM

Application: ELECTRON BEAM ENERGY

Range: **Uncertainty:** 0.1%

Reason for Measurement: To monitor the accelerator performance.

Other Requirements:

Comments: An absolute measurement may not be critical. However, 0.1% stability and reproducibility is essential for long-term accelerator operation.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Monitor Emission from a Magnetic Wiggler

Present Range: **Present Uncertainty:** 0.1%

Assessment: Appears suitable. Long-term stability of optical sensors would need to be characterized.

Comments: The frequency of light emitted from a well-characterized magnetic wiggler is measured. This is directly related to the electron-beam energy.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Magnetic-field deflection

Present Range: **Present Uncertainty:** 0.01%

Assessment: Highly accurate if the magnetic field is well defined. Presently used in ground-based facilities.

Comments:

SDI REQUIREMENTS -

Program: FEL **Parameter:** BEAM

Application: ELECTRON BEAM PULSE LENGTH

Range: 3 to 20 ps **Uncertainty:** < 1 ps

Reason for Measurement: To monitor the energy spread of the electron beam.

Other Requirements:

Comments: This measurement is complementary to the measurement of the beam current. The lower the energy spread of the beam, the higher the operating efficiency of the FEL.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Screen with streak camera

Present Range: **Present Uncertainty:** 2 ps

Assessment: This is determined from the current-versus-time profile. More accuracy is required. Additionally, the screen is interceptive.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: FEL **Parameter:** BEAM

Application: PHASE BETWEEN BEAM BUNCHING AND RF ACCELERATOR

Range: **Uncertainty:** 0.1 degree

Reason for Measurement: To monitor the efficiency of the accelerator.

Other Requirements:

Comments: An absolute measurement of the phase may not be essential. The relative phase may be adjusted for maximum beam output and then must remain constant.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Balance mixer

Present Range: **Present Uncertainty:** 0.1 degree

Assessment: Suitable.

Comments: Presently used on ground-based FEL test facilities.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: FEL **Parameter:** CURRENT

Application: KLYSTRON CURRENT

Range: 100 A **Uncertainty:**

Reason for Measurement: To monitor klystron operation.

Other Requirements:

Comments: Some klystrons are pulsed, others run continuously.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Rogowski coil

Present Range: **Present Uncertainty:** 1%

Assessment: Probably suitable. Long-term operation must be characterized

Comments: Commonly used on ground-based systems.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: FEL **Parameter:** FREQUENCY

Application: KLYSTRON VOLTAGE FREQUENCY

Range: 1–3 GHz **Uncertainty:**

Reason for Measurement: To monitor klystron operation.

Other Requirements:

Comments: A well-defined frequency is critical. The rf frequency must match the bunching frequency of the electron beam.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Spectrum analyzer

Present Range: **Present Uncertainty:**

Assessment: Suitable, depending upon long-term reliability.

Comments: Allows the determination of the frequency spectrum if more than a single frequency or harmonic is present. Used on ground-based FEL test systems.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Frequency counter

Present Range: **Present Uncertainty:** 0.0001 ppm

Assessment: Suitable.

Comments: Ground-based standard may be telemetered to the platform.

SDI REQUIREMENTS -

Program: FEL **Parameter:** LENGTH

Application: MIRROR POSITIONS IN WIGGLER

Range: up to 10 m **Uncertainty:** $< 1\mu m$

Reason for Measurement: To aid in the start-up operations of the FEL.

Other Requirements:

Comments: The position needs to be accurate in order for the laser to lase at the correct wavelength.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Laser-interferometric techniques

Present Range: **Present Uncertainty:** 0.1 ppm

Assessment: Accuracy is adequate, but this would not be a trivial measurement at the present time.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: FEL

Parameter: OPTICAL

Application: LASER FREQUENCY

Range: 10^{15} to 10^{13} Hz

Uncertainty:

Reason for Measurement: To monitor the laser operation.

Other Requirements:

Comments: One of the two most critical of absolute measurements that must be made on the FEL. Bandwidths are on the order of 0.001% of the primary frequency. The frequencies listed above correspond to wavelengths of 0.2 to 10 μm.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Wavemeter

Present Range:

Present Uncertainty: 0.001 ppm

Assessment: Intrinsically calibrated.

Comments: Presently used on ground-based FEL systems.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Frequency-counting methods

Present Range:

Present Uncertainty: 0.0001 ppm

Assessment: Extremely difficult (if not impossible) to measure to within ± one Hz. Otherwise OK.

Comments:

SDI REQUIREMENTS -

Program: FEL **Parameter:** OPTICAL

Application: LASER POWER

Range: 80 Watts (average) **Uncertainty:** 5%

Reason for Measurement: To monitor laser operation.

Other Requirements:

Comments: The second most critical absolute measurement to be made on the FEL. Present FEL's are on the order of 1 watt cw. The power range given above is at 1.6 μm. The FEL being constructed at NIST is anticipated to run at 10 to 100 watts cw.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Pyroelectric detector

Present Range: **Present Uncertainty:** 1%

Assessment: Used on ground-based FEL systems. Long-term operation must be evaluated, as well as the ability to scale up to large peak power levels.

Comments: Change in temperature affects the electrical polarization of the material thus changing an electrical output. Time resolution is 10 ps. Remote electrical calibration may be possible.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Calorimeter

Present Range: **Present Uncertainty:** 1–5%

Assessment: Present techniques are suitable for ground-based applications (up to and including the megawatt regime), however, these techniques are not easily transferable to space applications.

Comments: Requires accurate temperature sensors.

SDI REQUIREMENTS -

Program: FEL **Parameter:** POWER

Application: KLYSTRON RF POWER

Range: **Uncertainty:** 1%

Reason for Measurement: To monitor klystron operation and provide information for waste-heat management.

Other Requirements:

Comments: 1% uncertainty necessary to monitor waste heat in space-based situations. 10% is sufficient for ground-based applications.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Water load

Present Range: **Present Uncertainty:** 10%

Assessment: Would require improved uncertainties for space use along with precise temperature control and monitoring. Probably unsuitable for space-based measurements. Adequate for ground applications.

Comments: Presently used in ground-based facilities. Measures the change in the temperature of a water load to determine the total power input.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Directional couplers

Present Range: **Present Uncertainty:** 5%

Assessment: Suitability for space measurements needs to be determined and uncertainty needs to be improved. Probably adequate for all ground-based applications.

Comments: Detects power flowing in the wave guide. Presently used on most ground-based systems.

SDI REQUIREMENTS -

Program: FEL **Parameter:** PRESSURE

Application: INTERNAL ACCELERATOR PRESSURE

Range: 10^{-7} to 10^{-9} torr **Uncertainty:** 5%

Reason for Measurement: Excess pressure degrades the electron beam.

Other Requirements:

Comments: This pressure will need to be maintained using vacuum pumps, even in space applications, due to the background pressure surrounding the spacecraft. One could determine an approximate pressure by monitoring the ion current in an ion pump.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Ion gauge

Present Range: **Present Uncertainty:** 10 %

Assessment: Limited lifetime and fragility makes the ion gauge unsuitable for space deployment. It is suitable for ground-based applications.

Comments: Uncertainty varies with conditions.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Cold-cathode gauge

Present Range: **Present Uncertainty:** 10%

Assessment: The cathode corrodes under spacecraft environment. However, the gauge is otherwise sufficiently rugged for space applications. Uncertainties and long-term calibration would need to be improved.

Comments: Tests on spacecraft have shown severe corrosion of the cathode after one week of exposure to the space environment surrounding the spacecraft. New cathodes are being developed for long-term use.

SDI REQUIREMENTS -

Program: FEL **Parameter:** TEMPERATURE

Application: RF CAVITY TEMPERATURE

Range: 10 to 100 °C **Uncertainty:** < 0.1 °C

Reason for Measurement: The temperature affects the resonant frequency.

Other Requirements:

Comments: The absolute temperature need not be known, but the relative temperature must be constant and reproducible to better than 0.1 °C. Most systems use a feedback system to control the temperature.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Thermocouple

Present Range: **Present Uncertainty:** 0.1%

Assessment: It would be state-of-the-art calibration to hold a thermocouple uncertainty to less than 0.1% at less than 100 °C. May be suitable for coarse temperature control.

Comments: One would need to be concerned with rf interference on the thermocouple leads.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Monitor phase of rf signal inside cavity

Present Range: **Present Uncertainty:** < 0.1 °C

Assessment: Extremely accurate, but is suitable only when the temperature is close to the required value.

Comments:

SDI REQUIREMENTS -

Program: FEL **Parameter:** VIBRATION

Application: VIBRATION OF MIRRORS

Range: 0.5 to 5 μm **Uncertainty:** $< 1\mu$m

Reason for Measurement: To troubleshoot laser inoperation.

Other Requirements:

Comments: Previous problems with other FEL's have been thought to be caused by 5 μm vibrations of the mirrors.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Laser-interferometric techniques

Present Range: **Present Uncertainty:** $< 1\mu$m

Assessment: Still developmental. Suitability will probably depend upon the frequency range of the vibrations.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: FEL **Parameter:** VOLTAGE

Application: KLYSTRON RF VOLTAGE

Range: 135 kV **Uncertainty:** 0.1%

Reason for Measurement: To aid in electron beam control.

Other Requirements: RF frequency is up to 3 GHz.

Comments: Absolute accuracy is unnecessary, but stability (0.1%) is essential. The absolute voltage is adjusted to produce best accelerator output. For space-based operation 0.1% measured uncertainty may be required to permit fast start-up procedures.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Measure fields in rf cavity

Present Range: **Present Uncertainty:** 5%

Assessment: Accuracy needs improvement. No high voltage rf calibration techniques presently exist. Shielding effects at high-voltage levels may affect the calibration by as much as 50%.

Comments: Basically an electrode inside the cavity which produces a signal proportional to the E-field which is related to the voltage. Presently used in ground-based systems.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: FEL **Parameter:** VOLTAGE

Application: ELECTRON GUN ACCELERATION VOLTAGE

Range: 8 to 100 kV dc **Uncertainty:** 0.1%

Reason for Measurement: To monitor electron source operation.

Other Requirements:

Comments: Absolute measurement is not essential for ground-based applications, but the voltage must be stable and reproducible to within 0.1%. For space-based applications, where remote, fast-start procedures must be possible, an absolute measurement of this voltage with 0.1% uncertainty may be necessary.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Voltage divider

Present Range: > 100 kV **Present Uncertainty:** 0.1%

Assessment: Long-term operation characteristics of HVDC dividers is unknown. Space environment and temperature effects are unknown. Dividers with 0.1% uncertainty are large.

Comments: High-magnitude film resistors could be used to minimize size and current drain. However, these may be more susceptible to long-term damage due to radiation, space debris, etc.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Pockels cell

Present Range: > 100 kV **Present Uncertainty:** 5%

Assessment: Still developmental. Accuracy would need improvement. The cells tend to be temperature and stress dependent and their long-term performance in space environments would need to be determined.

Comments:

SDI REQUIREMENTS -

Program: FEL **Parameter:** VOLTAGE

Application: SOURCE GRID PULSE VOLTAGE

Range: 300 V **Uncertainty:** 0.1%

Reason for Measurement: To monitor the electron source operation.

Other Requirements: This is a pulsed voltage.

Comments: Stability and reproducibility are critical, but absolute magnitude determination may not be essential.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Oscilloscope

Present Range: **Present Uncertainty:** 0.1%

Assessment: Long-term operation needs to be assessed.

Comments: Accuracy depends upon bandwidth of signal. Presently used on ground-based systems.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Transient digitizers

Present Range: **Present Uncertainty:** 0.01% to 0.1%

Assessment: Long-term operation needs to be assessed.

Comments: Uncertainty depends upon the bandwidth of the signal. This technique could possibly provide a measurement with uncertainties of 0.1% over the long-term (under controlled conditions).

SDI REQUIREMENTS -

Program: GAS GENERATOR **Parameter:** FLOW

Application: FUEL FLOW RATES

Range: ~30 kg/s **Uncertainty:**

Reason for Measurement: To monitor the operation of the generator.

Other Requirements:

Comments: Anticipated requirements are presently exceeded by the requirements of the F1 rocket and the space shuttle. The gas generator is considered a proven technology with few unsolved metrology questions.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: GAS GENERATOR **Parameter:** PRESSURE

Application: FUEL PRESSURE

Range: 0 to 1000 psi **Uncertainty:**

Reason for Measurement: To monitor gas generator performance.

Other Requirements:

Comments: These pressures are similar to those used in present-day rocket engines.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Mechanical pressure gauges

Present Range: **Present Uncertainty:**

Assessment:

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: GAS GENERATOR **Parameter:** TEMPERATURE

Application: OUTLET TEMPERATURE

Range: 840 to 1230 °C **Uncertainty:**

Reason for Measurement: Monitor operation.

Other Requirements:

Comments: Similar temperature range as for present-day rockets.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Thermistor

Present Range: Up to 1000 °C **Present Uncertainty:** 1 to 3%

Assessment: Temperature range may need to be extended.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: HPG

Parameter: B FIELD

Application: HPG MAGNETIC FIELD

Range: 4.5 to 6 Tesla

Uncertainty:

Reason for Measurement: To monitor operation of the HPG.

Other Requirements:

Comments:

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Hall Probe

Present Range: > 6 Tesla

Present Uncertainty: 0.1%

Assessment: Appears adequate.

Comments: 0.1% is uncertainty under controlled conditions. Long-term drift is $\sim$1%.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range:

Present Uncertainty:

Assessment:

Comments:

SDI REQUIREMENTS -

Program: HPG **Parameter:** CURRENT

Application: OUTPUT CURRENT

Range: 1 to 2 MA **Uncertainty:**

Reason for Measurement: To monitor the performance of the HPG.

Other Requirements: Pulse width is 4 to 12 ms for pulsed operation.

Comments: Repetition rate of pulses is expected to be between 4 and 10 Hz for EML operation.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Rogowski Coil

Present Range: **Present Uncertainty:** 1%

Assessment: May be satisfactory, depending on uncertainty requirements of the load. Long-term performance of the coil would need to be determined.

Comments: Presently used on many ground-based test facilities.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: HPG **Parameter:** CURRENT

Application: MAGNETIC FIELD CURRENT

Range: 0.8 to 1.1 kA **Uncertainty:**

Reason for Measurement: To monitor the operation of the HPG.

Other Requirements: The sensor must operate near fairly high (4–6 Tesla) magnetic fields.

Comments:

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Current Shunt

Present Range: **Present Uncertainty:** 10 ppm

Assessment: A shunt could be a fairly large device depending upon the required uncertainty. Effects of long-term exposures to space environment need to be assessed.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Hall Probe

Present Range: **Present Uncertainty:** 1%

Assessment: May be appropriate depending upon accuracy requirements.

Comments: Magneto-optic devices may also be appropriate.

SDI REQUIREMENTS -

Program: HPG **Parameter:** FLOW

Application: COOLANT FLOW RATE

Range: 5.2 to 28 kg/s **Uncertainty:**

Reason for Measurement: To monitor the HPG cooling system

Other Requirements: Coolants will be either liquid hydrogen or possibly liquid ammonia.

Comments: 5.2 kg/s for liquid hydrogen. 28 kg/s for liquid ammonia. This is not considered to be a highly critical measurement.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Turbine flow meter

Present Range: 10^3 l/s **Present Uncertainty:** 1%

Assessment: Suitable for cryogenic and corrosive liquids. May not be suitable for very large flow volumes.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: HPG **Parameter:** FREQUENCY

Application: ROTATIONAL FREQUENCY OF FLYWHEEL

Range: 14 to 18 krpm **Uncertainty:**

Reason for Measurement: To monitor HPG operation and to control net torque on the space platform.

Other Requirements:

Comments: Each shot of an EML will change the rotational frequency by 100 to 200 rpm and the shot repetition rate will be between 4 and 10 Hz for EML applications. Rotational frequencies will need to be controlled in space-based applications in order to minimize rotational forces on the platform.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Frequency counter

Present Range: **Present Uncertainty:** 0.0001 ppm

Assessment: Suitable. May be remotely calibrated.

Comments: A method of producing an electrical frequency signal proportional to the rotational frequency must be determined which exhibits long-life.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: HPG **Parameter:** PRESSURE

Application: COOLANT PRESSURE

Range: 500 to 1000 psi **Uncertainty:**

Reason for Measurement: To monitor the HPG coolant system and to detect leakage.

Other Requirements: Coolants will most likely be liquid hydrogen or liquid ammonia.

Comments:

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Mechanical Sensors

Present Range: **Present Uncertainty:** 200 ppm

Assessment: Suitable sensor will depend upon the coolant and upon the required dynamic response times.

Comments: Long-term calibration and lifetime are uncertain for any mechanical sensor without testing.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI METROLOGY ASSESSMENT

SDI REQUIREMENTS -

Program: HPG **Parameter:** TEMPERATURE

Application: ROTOR TEMPERATURE

Range: 50 to 520 K **Uncertainty:**

Reason for Measurement: To monitor HPG performance and to predict imminent rotor failure.

Other Requirements: Would preferably be a non-contact technique.

Comments:

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Eddy-current thermometry

Present Range: **Present Uncertainty:**

Assessment: Useful for non-contact temperature measurements of metals. Very difficult to calibrate at present. Still developmental in that systems for most present uses are custom designed for each task.

Comments: Because calibration of these devices is so difficult, the uncertainty of the technique is presently not well defined.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI METROLOGY ASSESSMENT

SDI REQUIREMENTS -

Program: HPG **Parameter:** VOLTAGE

Application: OUTPUT VOLTAGE

Range: 50 to 200 V **Uncertainty:**

Reason for Measurement: To monitor HPG operation.

Other Requirements: Output pulses are 4 to 12 ms in width for pulsed mode. HPG's may also be operated continuously. The sensor may have to operate near fairly large magnetic fields.

Comments: Transients larger than 200 V may be be present depending on the load. The repetition rate for pulsed operation is expected to be between 4 and 10 Hz for EML applications.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Analog-to-Digital Converter

Present Range: < 1000 V **Present Uncertainty:** 0.001% to 0.1%

Assessment: Probably suitable depending upon accuracy requirements.

Comments: Long-term drift should be investigated. The bandwidth is low enough such that accurate measurements should be possible.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI METROLOGY ASSESSMENT

SDI REQUIREMENTS -

Program: HPG

Parameter: VOLTAGE

Application: MAGNETIC FIELD INPUT VOLTAGE

Range: 260 VAC

Uncertainty:

Reason for Measurement: To monitor field-coil operation.

Other Requirements:

Comments: Not considered to be a critical measurement.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: AC digital voltmeter

Present Range: < 1000 VAC

Present Uncertainty: 10 ppm

Assessment: Proven technology.

Comments: Long-term operation should be characterized.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range:

Present Uncertainty:

Assessment:

Comments:

SDI REQUIREMENTS -

Program: HV ALTERNATOR **Parameter:** CURRENT

Application: OUTPUT CURRENT

Range: up to 1 kA **Uncertainty:**

Reason for Measurement: To monitor alternator operation.

Other Requirements: The frequency range is anticipated to be 400 Hz to 5 kHz.

Comments:

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: AC Resistor and Digital Voltmeter

Present Range: **Present Uncertainty:** 100 ppm

Assessment: Shunt could be large at 1 kA depending upon desired accuracy. Long-term operation needs to be characterized.

Comments: Uncertainty increases if the current signal is non-sinusoidal.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Current Transformer

Present Range: > 1000 A **Present Uncertainty:** .01%

Assessment: Suitable. Limited calibration presently available at frequencies other than 60 Hz.

Comments:

SDI METROLOGY ASSESSMENT

SDI REQUIREMENTS -

Program: HV ALTERNATOR **Parameter:** FREQUENCY

Application: VOLTAGE FREQUENCY

Range: 400 Hz to 5 kHz **Uncertainty:**

Reason for Measurement: To monitor alternator operation.

Other Requirements:

Comments: Not considered a critical measurement.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Frequency counter

Present Range: **Present Uncertainty:** 0.0001 ppm

Assessment: Suitable, assuming waveform is constant.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: HV ALTERNATOR **Parameter:** FREQUENCY

Application: ROTATIONAL FREQUENCY OF ALTERNATOR

Range: 6000 rpm **Uncertainty:**

Reason for Measurement: To monitor alternator operation.

Other Requirements:

Comments: Alternator rotational frequency will need to be closely controlled to minimize the net forces on the space platform.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Frequency counter

Present Range: **Present Uncertainty:** 0.0001 ppm

Assessment: Suitable.

Comments: A method of producing an electrical signal proportional to the rotational frequency must be determined which will have a long lifetime.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI METROLOGY ASSESSMENT

SDI REQUIREMENTS -

Program: HV ALTERNATOR **Parameter:** VOLTAGE

Application: OUTPUT VOLTAGE FROM ALTERNATOR

Range: 10–85 kV **Uncertainty:**

Reason for Measurement: Monitor alternator

Other Requirements: The voltage is ac, and the frequency range is 400 Hz to 5kHz.

Comments: This measurement is critical for evaluating the power-conditioning circuitry.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Capacitance Divider

Present Range: > 100 kV ac **Present Uncertainty:** 0.1%

Assessment: A relatively large device. Presently, calibration standards only exist at 60 Hz.

Comments: Long-term performance would need to be investigated.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: MMW **Parameter:** FLOW

Application: Coolant Flow Rate

Range: up to 2000 kg/s **Uncertainty:**

Reason for Measurement: To monitor reactor cooling system.

Other Requirements: Sensor must withstand reactor radiation and the corrosive nature of the coolants.

Comments: Coolant may be gas or liquid. This is probably not a critical measurement.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Measure turbine pump speed

Present Range: **Present Uncertainty:**

Assessment: Suitable, but only for gas phase coolants.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Pressure drop across the core of the reactor

Present Range: **Present Uncertainty:**

Assessment: Possibly suitable. The possible dynamic range is limited (~2 orders of magnitude). This technique is dependent upon an accurate coolant pressure measurement.

Comments:

SDI METROLOGY ASSESSMENT

SDI REQUIREMENTS -

Program: MMW **Parameter:** POSITION

Application: CONTROL ROD POSITION

Range: **Uncertainty:**

Reason for Measurement: To monitor the reactor status.

Other Requirements:

Comments: Obviously, required for safety reasons and to allow appropriate control during start-up procedures.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Stepper motors/actuators

Present Range: **Present Uncertainty:**

Assessment: Special designs to withstand high-temperature and radiation environments should be adequate.

Comments: These have already been designed for the SP-100 program, although they will be rated at lower temperatures than may be required for MMW program.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: MMW **Parameter:** PRESSURE

Application: COOLANT PRESSURE

Range: Up to 7.6 MPa **Uncertainty:** variable

Reason for Measurement: To monitor the cooling system performance.

Other Requirements: Sensor must withstand reactor radiation and the corrosive nature of coolants.

Comments: For H_2 coolant, the pressure may vary from 10 kPa to 7.6 MPa. For lithium, the pressure may vary from low to 0.241 MPa. The measurements are dynamic on the scale of seconds. The Rankin cycle reactor design requires higher accuracy than the other designs being considered.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Mechanical sensors (diaphragms, bellows, etc.)

Present Range: **Present Uncertainty:** 200 ppm

Assessment: Limited dynamic range and relatively slow response. Susceptible to corrosion from coolants. The uncertainty will be higher than 200 ppm for dynamic measurements.

Comments: The 200 ppm uncertainty quoted above is under steady-state conditions. The severe environments anticipated for this application need to be dealt with individually.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Silicon Strain-gauge elements

Present Range: **Present Uncertainty:**

Assessment: Questionable response time and longevity.

Comments: Presently used for ground-based nuclear reactors.

SDI REQUIREMENTS -

Program: MMW **Parameter:** PRESSURE

Application: INTERIOR REACTOR PRESSURE

Range: 0.241–8 MPa **Uncertainty:**

Reason for Measurement: To monitor reactor and cooling system performance.

Other Requirements: Must survive in a highly radioactive and high-temperature environment.

Comments: 3–8 MPa is for gas cooled systems, 0.241 MPa for liquid lithium cooled systems. This is not considered a critical measurement, and be adequately monitored by the coolant-pressure measurements.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Indirect

Present Range: **Present Uncertainty:**

Assessment: Probably adequate.

Comments: For gas coolants, the pressure can be determined by temperature and flow measurements. For liquid coolants, the reactor pressure is the same as the coolant pressure.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: CARS

Present Range: **Present Uncertainty:**

Assessment: Significant development is still required. Allows for ps response times and for remote sensing, which is desirable in harsh environments.

Comments: This is presently a very complex technique with a significant amount of support electronics.

SDI REQUIREMENTS -

Program: MMW **Parameter:** PURITY

Application: CONTAMINATION OF COOLANTS

Range: ppm **Uncertainty:**

Reason for Measurement: To monitor corrosion in the cooling system.

Other Requirements: Must sample from corrosive, high-temperature liquids.

Comments: Most important for closed systems using liquid lithium as a coolant.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Gas Chromatography

Present Range: ppm detection **Present Uncertainty:**

Assessment: Questionable for long-term unmonitored service. May be inappropriate for lithium coolants, and would need to be of a rugged design.

Comments: Currently used in ground-based nuclear reactors.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: MMW **Parameter:** RADIATION

Application: HIGH-NEUTRON FLUX INSIDE OR NEAR REACTOR

Range: $< 10^{16}$ neutron/cm^2-s **Uncertainty:** 1 to 2%

Reason for Measurement: Monitor reactor power, and device dosage.

Other Requirements: Must withstand high temperatures. Should be measured both inside and outside the reactor in order to achieve a reliable power density mapping.

Comments: Detectors inside the reactor indicate power density distributions, detectors on the exterior of the reactor indicate average power. Total dosage and real time dosage measurements are also required. No detectors can presently operate at temperatures > 2000 K.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Ion Chambers

Present Range: **Present Uncertainty:** 3–5%

Assessment: Limited to 300 °F. Probably not adequate unless positioned in a temperature controlled location.

Comments: No neutron detectors currently can survive temperatures greater than 2000 K.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Fission Chambers

Present Range: $< 10^{16}$ neutron/cm^2-s **Present Uncertainty:** 3–5%

Assessment: Limited to 1100 °C. Long-term stability under high-temperature, high-flux conditions would need to be determined.

Comments: Ceramic materials could extend the temperature range of these devices.

SDI REQUIREMENTS -

Program: MMW **Parameter:** RADIATION

Application: REACTOR RADIATION (GAMMA, ETC.)

Range: 10^7 to 10^8 Rad **Uncertainty:**

Reason for Measurement: Monitor reactor performance, and dosage.

Other Requirements: Must survive in high-temperature, high-radiation environments.

Comments: Also useful as an alternate method of obtaining total power measurements.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Ion chambers.

Present Range: **Present Uncertainty:** 3-5%

Assessment: Cannot withstand high temperatures.

Comments: Currently used in ground-based nuclear reactors.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: MMW **Parameter:** RADIATION

Application: LOW NEUTRON FLUX

Range: **Uncertainty:**

Reason for Measurement: To monitor reactor start-up conditions.

Other Requirements: Must withstand high neutron flux and high temperatures of full-scale operation.

Comments: Sensors both inside and outside of reactor chamber would be advantageous. Presently, no detector can survive the high neutron-flux conditions of full-power operation and maintain its low flux calibration over low-flux ranges. This measurement is particularly important for fast-start reactors.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Ion Chambers

Present Range: **Present Uncertainty:**

Assessment: Limited to 300 °F.

Comments: No present neutron detectors are designed to operate at temperatures exceeding 2000 °C.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Fission Chambers

Present Range: **Present Uncertainty:**

Assessment: Limited to 1100 °C. The calibration stability after periods of high flux would need to be improved.

Comments: The use of ceramic materials could extend the useful temperature range of this device.

SDI REQUIREMENTS -

Program: MMW **Parameter:** RADIOACTIVITY

Application: COOLANT RADIOACTIVITY

Range: **Uncertainty:**

Reason for Measurement: To monitor for fuel cell leakage.

Other Requirements: Must operate with high-temperature, corrosive liquids.

Comments: Of more importance for liquid cooled reactors which are anticipated to run for long periods of time.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Gamma Spectrometers (Ge/Li detectors)

Present Range: **Present Uncertainty:**

Assessment: Would need to be designed to withstand forces of lift-off for uses in space deployment.

Comments: Presently used in ground-based nuclear reactors.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: MMW **Parameter:** TEMPERATURE

Application: REACTOR COOLANT TEMPERATURE

Range: 250 K TO 2500 K **Uncertainty:** 1 to 10%

Reason for Measurement: Monitor reactor performance.

Other Requirements: The sensor must withstand radiation from the reactor and the corrosive nature of the coolants.

Comments: Two types of coolants are being considered, H_2 and liquid lithium. The 250–2500 K range is for H_2, and the freezing to 1550 K range is for lithium. Measurements are dynamic on the time scale of seconds. The required accuracy depends upon the operating parameters of the reactor.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Thermocouples (Tungsten-Rhenium)

Present Range: up to 2200 °C **Present Uncertainty:**

Assessment: May be suitable, but the transmutation problem must be solved. Super-pure element thermocouples will be necessary. The corrosion problem must also be addressed.

Comments: The lifetime is dependent on neutron fluence (10^{19} n/cm^2 is the limit). High radiation causes transmutation of the elements in the thermocouples which produces measurement drift over time.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Optical temperature measurements

Present Range: $>$ 2000 °C **Present Uncertainty:** 1%

Assessment: May exhibit drift problems in high-temperature, high-radiation environments.

Comments: Still a developing technology. Commercial units are becoming available but have not been characterized for long-term space use. 1% uncertainty listed above is quoted at 2000 °C.

SDI REQUIREMENTS -

Program: MMW **Parameter:** TEMPERATURE

Application: INTERIOR REACTOR TEMPERATURE

Range: 1300 K to 2765 K **Uncertainty:** variable

Reason for Measurement: To monitor for hot spots inside the reactor core.

Other Requirements: Must survive in a highly radioactive environment.

Comments: The same problems exist here as for the coolant temperature measurement, except the radiation requirements are more severe. This is a critical measurement for safety purposes. The desired accuracy depends strongly upon the reactor design.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Thermocouples

Present Range: 2200 °C **Present Uncertainty:**

Assessment: High-radiation environment causes element transmutation and temperature drift.

Comments: Higher purity thermocouples may solve this problem. New alloys may increase the present temperature limits.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Optical thermometry

Present Range: > 2000 K **Present Uncertainty:**

Assessment: Still a developing technology. Long-term operation in a radioactive environment needs to be characterized.

Comments:

SDI REQUIREMENTS -

Program: MMW **Parameter:** TEMPERATURE

Application: PLATFORM TEMPERATURE

Range: 400 K to 600 K **Uncertainty:** 0.1% to 1.0%

Reason for Measurement: To monitor waste heat management and provide a reference temperature for thermocouples.

Other Requirements: This must be an absolute temperature measurement.

Comments: This measurement may be made in a shielded location, away from the harsh environment of the reactor.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Thermocouples

Present Range: > 1200 °C **Present Uncertainty:** 0.1%

Assessment: Requires a temperature standard for an absolute measurement since a thermocouple measures a temperature difference.

Comments: A thermocouple is not a likely choice since this is necessarily an absolute measurement and a thermocouple is by nature a relative sensor.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Nuclear Quadrupole Resonance Thermometry

Present Range: > 600 K **Present Uncertainty:** ±1 mK

Assessment: Still experimental. It is a desirable technique since it measures an intrinsic property of a solid and therefore is self-calibrating.

Comments: New research on the use of different crystals would need to be initiated since current work uses $KClO_3$ which has a low melting point. The technique is presently quite complex.

SDI METROLOGY ASSESSMENT

SDI REQUIREMENTS -

Program: MMW **Parameter:** VIBRATION

Application: REACTOR AND VALVE VIBRATION

Range: **Uncertainty:**

Reason for Measurement: To Identify loose parts, and to monitor flow valves.

Other Requirements: Must operate in radioactive and high-temperature environments.

Comments: Not considered to be critical inside the reactor. More critical inside turbines and generators.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Transducers

Present Range: **Present Uncertainty:**

Assessment: Probably suitable since this is not an absolute measurement.

Comments: Used in ground-based nuclear reactors to monitor for noise and vibration.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: MMW **Parameter:** VOLTAGE

Application: OUTPUT VOLTAGE

Range: 10 to 20 kV ac **Uncertainty:** 5%

Reason for Measurement: For power system control.

Other Requirements: Frequency is 20 kHz to 100 kHz.

Comments: During initial start-up (i.e. up to 25% of full power) the output voltage must be regulated to 25%. After that, 5% regulation is required. The frequency should be regulated to 2% at all times.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Voltage transformer

Present Range: > 100 kV ac **Present Uncertainty:**

Assessment: No calibration services presently exist for this measurement. The apparatus may be quite bulky, and long-term performance is undetermined.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Electro-optic techniques

Present Range: **Present Uncertainty:** ~5%

Assessment: Long-term operation is uncharacterized. The apparatus should be fairly compact.

Comments: The effect of temperature and radiation on the optical cells would need to be determined.

SDI REQUIREMENTS -

Program: MMW **Parameter:** VOLUME

Application: TOTAL COOLANT VOLUME

Range: **Uncertainty:**

Reason for Measurement: To monitor for leaks.

Other Requirements:

Comments:

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Measure pressure in the reservoir

Present Range: **Present Uncertainty:**

Assessment:

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: NPB **Parameter:** BEAM

Application: BEAM TRANSPORT CURRENT

Range: 1 to 100 mA **Uncertainty:** 1%

Reason for Measurement: To monitor beam conditions.

Other Requirements: A time profile is needed to determine the beam characteristics and to monitor the performance of the accelerator.

Comments: An average current value is also required to tune the accelerator for optimum operation.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Current-sensing toroid

Present Range: **Present Uncertainty:** 1%

Assessment: Currently in use at ground-based NPB facilities. Appears satisfactory for present uses.

Comments: The voltage signal induced on a resistive toroid through which the beam passes is measured and calibrated with the beam current.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Microstrip probes

Present Range: **Present Uncertainty:** 10%

Assessment: Accuracy needs to be improved.

Comments: Microstrip probes detect the traveling electric and magnetic fields produced by the charged particle beam.

SDI REQUIREMENTS -

Program: NPB **Parameter:** BEAM

Application: ION BEAM POSITION IN ACCELERATOR

Range: 100 μm **Uncertainty:** 50 μm

Reason for Measurement: For beam focusing and control.

Other Requirements:

Comments: This is a critical measurement for optimum accelerator operation.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Symmetrically-spaced microstrip probes

Present Range: **Present Uncertainty:** 50 μm

Assessment: Suitable.

Comments: Microstrip probes detect the magnetic and electric fields produced by the charged particle beam. Position is varied until output from symmetrically placed sensors are equal.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: NPB **Parameter:** BEAM

Application: PHASE BETWEEN BEAM PULSES AND RF VOLTAGE

Range: **Uncertainty:** 1%

Reason for Measurement: To monitor the efficiency of the accelerator.

Other Requirements:

Comments: An absolute measurement is not required. Phase is adjusted to produce maximum beam current and acceleration efficiency. Once phase is set, it then must remain constant.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Phase-lock loop amplifier

Present Range: **Present Uncertainty:** 0.5 degrees

Assessment: Suitable.

Comments: Phase is determined by comparison of outputs from beam sensors and rf voltage sensors.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: NPB **Parameter:** BEAM

Application: ION BEAM ENERGY

Range: ~100 MeV **Uncertainty:** 100 ppm

Reason for Measurement: For beam control.

Other Requirements:

Comments: Determination of the kinetic energy of the NEUTRAL beam leaving the NPB apparatus is essential. The energy of the neutral beam will have to be determined by calculations using the kinetic energy of the ion beam before neutralization.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Time-of-flight

Present Range: **Present Uncertainty:** variable

Assessment: May be suitable depending on the frequency of the pulses in the NPB. Not sufficiently accurate at very high frequency.

Comments: Uses sequential microstrip probes to measure the time for an ion packet to travel a known distance.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Electrostatic analyzer

Present Range: **Present Uncertainty:**

Assessment: Suitable for final determination of the ion beam kinetic energy. Not appropriate for beam energy measurements inside the accelerator.

Comments:

SDI REQUIREMENTS -

Program: NPB **Parameter:** BEAM

Application: PARTICLE BEAM BUNCH LENGTH

Range: A few degrees **Uncertainty:**

Reason for Measurement: Determination of momentum spread of the ion beam.

Other Requirements:

Comments: Important for monitoring the efficiency of the rf accelerator.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Microstrip probe

Present Range: **Present Uncertainty:**

Assessment: An extremely difficult measurement. This technique would require signal digitizing rates of 500 GHz. This is, at present, not possible.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: NPB **Parameter:** BEAM

Application: BEAM PROFILE (CROSS SECTION)

Range: **Uncertainty:** 10%

Reason for Measurement: To monitor the charged particle beam characteristics.

Other Requirements:

Comments: Also useful to monitor the ion source conditions.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Flying-wire scanner

Present Range: **Present Uncertainty:** 10%

Assessment: May be suitable for deployment. The technique slightly interferes with the ion beam and has a limited lifespan.

Comments: The wire passes through the beam at 10–20 m/s while measuring the impinging current. This provides a current profile in one dimension.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Viewing screen

Present Range: **Present Uncertainty:** 10%

Assessment: Suitable for development. Provides a current profile in two dimensions, but is not suitable for deployment since it intercepts the beam.

Comments: The beam impinges on a phosphor screen and the image is recorded. The lifetime of the screen is determined by the peak beam intensity. If a gas is used, then technique is non-interceptive.

SDI METROLOGY ASSESSMENT

SDI REQUIREMENTS -

Program: NPB **Parameter:** BEAM

Application: BEAM LOSS MONITOR

Range: **Uncertainty:**

Reason for Measurement: To determine the loss of ion beam intensity due to dispersion.

Other Requirements:

Comments: Obviously, the less beam loss there is, the more efficiently the accelerator is operating. Also, large amounts of dispersion can cause damage to the accelerator elements.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Ion chamber

Present Range: **Present Uncertainty:** 3–5%

Assessment: Suitable, if the lifetime and long-term calibration are adequate.

Comments: The ion chamber detects radiation due to portions of the ion beam striking a surface.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: NPB **Parameter:** BEAM

Application: BEAM EMITTANCE

Range: **Uncertainty:**

Reason for Measurement: To monitor beam loss.

Other Requirements:

Comments: The less emittance, the less beam loss, and the more efficiently the accelerator operates.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Slit and collector emittance scanner

Present Range: **Present Uncertainty:**

Assessment: The detector intercepts the beam, therefore not suitable for deployment. Suitable only for ions with energy less than 10 MeV.

Comments: The detector intercepts the beam and measures the angle of divergence of the ions in the beam.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: FMIT program

Present Range: **Present Uncertainty:**

Assessment: Non-interceptive. Suitable for ions with energy up to 2 MeV.

Comments: The ion beam intercepts a gas and the resulting radiation is monitored.

SDI REQUIREMENTS -

Program: NPB **Parameter:** CURRENT

Application: ION SOURCE ARC CURRENT

Range: 100 to 150 A **Uncertainty:**

Reason for Measurement: To monitor the ion source conditions.

Other Requirements:

Comments:

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Current shunt

Present Range: 1 kA **Present Uncertainty:** 10 ppm

Assessment: Is as accurate as the accuracy of the voltmeter and shunt resistor used. Long-term operation needs to be characterized.

Comments: For large currents, shunts become large.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Hall Probes

Present Range: **Present Uncertainty:** 1%

Assessment: Probably suitable.

Comments: Measures the field proportional to a current.

SDI REQUIREMENTS -

Program: NPB **Parameter:** CURRENT

Application: KLYSTRON CURRENT

Range: 12 A **Uncertainty:**

Reason for Measurement: To monitor klystron operation.

Other Requirements:

Comments: Not considered a critical measurement. An absolute magnitude measurement is not essential.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Rogowski coil

Present Range: **Present Uncertainty:**

Assessment: Satisfactory if the lifetime and long-term operating characteristics are adequate.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: NPB **Parameter:** FREQUENCY

Application: KLYSTRON RF FREQUENCY

Range: 1 to 3 GHz **Uncertainty:** 0.1 %

Reason for Measurement: For beam control and to determine accelerator efficiency.

Other Requirements:

Comments: An absolute measurement is not critical. The frequency must be the same as the beam bunching frequency.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Frequency counter

Present Range: **Present Uncertainty:** 0.0001 ppm

Assessment: Suitable

Comments: Earth-based telemetry can provide reference frequency.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Spectrum analyzer

Present Range: **Present Uncertainty:**

Assessment:

Comments: Allows analysis of the frequency spectrum if more than one frequency is present.

SDI REQUIREMENTS -

Program: NPB **Parameter:** POWER

Application: KLYSTRON RF POWER MEASUREMENT

Range: 1 MW **Uncertainty:** 1% to 10%

Reason for Measurement: For power management.

Other Requirements:

Comments: No high-power calibration program presently exists at NIST. The present program operates in the 1 mW power range at 1 to 2% uncertainty. 1% uncertainty will be required for space-based applications, 10% uncertainties are required for ground-based systems.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Water load

Present Range: **Present Uncertainty:** 10%

Assessment: Requires accurate temperature monitoring. Suitable for ground-based applications, but not for space deployment.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Directional Couplers

Present Range: **Present Uncertainty:** 5%

Assessment: Suitable for low accuracy requirements. Uncertainty needs to be improved for space deployment.

Comments: These devices exhibit little or no temperature effects.

SDI REQUIREMENTS -

Program: NPB **Parameter:** TEMPERATURE

Application: SOURCE TEMPERATURE

Range: 470 K **Uncertainty:**

Reason for Measurement: To monitor ion source conditions.

Other Requirements:

Comments: Requires precise control. Ground-based systems monitor the source output as a measure of the temperature via feedback circuitry.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Thermocouple

Present Range: **Present Uncertainty:** .1%

Assessment: Must be protected from radiation, otherwise probably suitable for coarse temperature measurements.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI METROLOGY ASSESSMENT

SDI REQUIREMENTS -

Program: NPB **Parameter:** VOLTAGE

Application: ION SOURCE ARC VOLTAGE

Range: 110 to 140 V dc **Uncertainty:** 0.1 %

Reason for Measurement: To monitor source conditions.

Other Requirements:

Comments: The voltage must be regulated to 0.1%. An absolute measurement of 1–2% is adequate since the voltage is varied to produce the optimum source output.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Digital voltmeter

Present Range: < 1000 V dc **Present Uncertainty:** 10 ppm

Assessment: Appears suitable. Long term space environment effects would need to be assessed.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: NPB **Parameter:** VOLTAGE

Application: EXTRACTION VOLTAGE

Range: 10 to 20 kV dc **Uncertainty:**

Reason for Measurement: For beam control.

Other Requirements:

Comments: Absolute accuracy is not required. but stability is essential.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Resistive voltage divider

Present Range: > 100 kV **Present Uncertainty:** 0.1%

Assessment: Long-term operation properties of high-voltage dividers is unknown. Behavior at elevated temperatures is uncertain. High-accuracy dividers tend to be large.

Comments: Film resistors (rather than wire-wound) should be used to minimize current requirements, but these may be susceptible to surface damage and leakage in high precision applications.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Pockels Cell (electro-optics measurement)

Present Range: > 100 kV dc **Present Uncertainty:** 5%

Assessment: Still developmental. Uncertainties would need to be improved. Cells tend to be temperature and stress sensitive.

Comments:

SDI REQUIREMENTS -

Program: NPB **Parameter:** VOLTAGE

Application: BEAM TRANSPORT VOLTAGE

Range: 80 to 120 kV dc **Uncertainty:** 0.1 %

Reason for Measurement: To monitor accelerator performance.

Other Requirements:

Comments: Stability is essential for reliable accelerator operation. For space-based operation, 0.1% measurement uncertainties may be required. For ground-based systems, less stringent uncertainties are required.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Resistive voltage divider

Present Range: > 100 kV **Present Uncertainty:** 0.1 %

Assessment: Long-term operation parameters and elevated-temperature performance are uncertain. High-accuracy devices tend to be large.

Comments: Film resistors (rather than precision wire-wound) should be used to minimize the current requirements of the divider. However, these resistors may be more susceptible to damage in space applications.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Pockels Cell

Present Range: > 100 kV **Present Uncertainty:** 5%

Assessment: Still developmental. Uncertainties would need to be improved. The optical cells tend to be temperature and stress sensitive.

Comments:

SDI REQUIREMENTS -

Program: NPB **Parameter:** VOLTAGE

Application: BEAM STEERING VOLTAGE

Range: 1 kV dc **Uncertainty:** 5 ppm

Reason for Measurement: For beam control.

Other Requirements:

Comments: 5 ppm regulation and stability is essential. For space-based applications 5 ppm uncertainties may also be required. Less stringent uncertainty requirements exist for ground-based facilities.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Digital voltmeter

Present Range: **Present Uncertainty:** 10 ppm

Assessment: Specially built voltmeters with special external calibration standards could meet these requirements under laboratory conditions.

Comments: For 10 years, 100 ppm is about the best that could be done with no supplemental calibration. Operation in a harsh environment would make the uncertainties larger.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: NPB **Parameter:** VOLTAGE

Application: KLYSTRON VOLTAGE

Range: 80 to 250 kV **Uncertainty:** 0.5%

Reason for Measurement: For beam control.

Other Requirements: Voltage is at RF frequencies (up to 3 GHz)

Comments: The absolute magnitude is not critical, however, 0.5% stability and regulation are essential.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Measure E-fields inside a cavity

Present Range: **Present Uncertainty:** 5%

Assessment: Accuracy needs substantial improvement.

Comments: An electrode inside the cavity detects the RF field magnitude which is proportional to the voltage. At high-field levels, uncertainties can increase to as much as 50%.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: SP-100 **Parameter:** FLOW

Application: COOLANT FLOW RATE

Range: 9.6 to 9.9 kg/s **Uncertainty:**

Reason for Measurement: To monitor pumps and the thaw process.

Other Requirements: Flow meters must survive frozen lithium and give indication of thaw status. Also the sensor must be unaffected by corrosive liquids.

Comments: The actual flow rate will probably not be measured on space-deployed systems. However, a flow indicator will be included to monitor the thawing of the coolant during initial start-up procedures.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Electro-magnetic flow meters

Present Range: **Present Uncertainty:**

Assessment: Non-intrusive. May be used because of conductive nature of the lithium. Long-term operation is presently uncharacterized.

Comments: Presently only planned for ground-based testing.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: SP-100 **Parameter:** POSITION

Application: CONTROL ROD POSITION

Range: **Uncertainty:**

Reason for Measurement: To control the reactor power and to monitor start and stop procedures.

Other Requirements: Actuators and sensors must survive in a harsh environment. Also, the actual position must be determinable at any time for safety reasons.

Comments: The devices must survive temperatures of 150 K to 700 K, 1.5×10^8 Rads Gamma, and 2×10^{15} neutrons/cm^2.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: High-temperature resolver-type position sensors

Present Range: **Present Uncertainty:**

Assessment: Designed specifically for this purpose. Should be suitable.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: SP-100 **Parameter:** PRESSURE

Application: COOLANT PRESSURE

Range: 40 psia **Uncertainty:**

Reason for Measurement: To monitor for over-pressure and for leakage.

Other Requirements:

Comments: Pressure drop through primary loop is 4.2 kPa; Pressure drop through secondary loop is 11.2 kPa; Pressure drop through reactor is 16.48 kPa; Pressure drop through heat rejector is 19.52 kPa.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Undetermined at this time.

Present Range: **Present Uncertainty:**

Assessment:

Comments: It has not been decided if an actual pressure measurement will be made (i.e. with a transducer) or if pressure switches will be used as pressure limiters.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: SP-100 **Parameter:** PRESSURE

Application: INTERIOR REACTOR PRESSURE

Range: 40 psia **Uncertainty:**

Reason for Measurement: To monitor for overpressure.

Other Requirements:

Comments:

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: To be determined by coolant pressure measurements.

Present Range: **Present Uncertainty:**

Assessment:

Comments: No plans presently exist to measure this directly. The coolant system has been adequately modeled such that the pressure inside the reactor can be derived from the coolant pressure.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: SP-100 **Parameter:** PURITY

Application: CONTAMINATION OF COOLANTS

Range: **Uncertainty:**

Reason for Measurement: To monitor for corrosion of cooling system.

Other Requirements: Must withstand high temperatures and corrosive coolants.

Comments:

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: No plans presently exist to measure this parameter.

Present Range: **Present Uncertainty:**

Assessment:

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: SP-100 **Parameter:** RADIATION

Application: NEUTRON FLUX INSIDE OR NEAR THE REACTOR

Range: 10^{16} neutrons/cm^2 fluence **Uncertainty:**

Reason for Measurement: To monitor reactor conditions and start-up procedures.

Other Requirements: Must survive high temperatures.

Comments: Fluences will be $< 10^{13}$ neutrons/cm^2 within a 4.5 meter diameter user plane. All fluences assume 7.3 years of full operation.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Undetermined at this time.

Present Range: **Present Uncertainty:**

Assessment:

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI METROLOGY ASSESSMENT

SDI REQUIREMENTS -

Program: SP-100 **Parameter:** RADIATION

Application: REACTOR RADIATION (GAMMA)

Range: 2.7×10^8 Rad. **Uncertainty:**

Reason for Measurement: To monitor reactor operation, and human exposure (if necessary).

Other Requirements:

Comments: Gamma fluences will be $< 5 \times 10^5$ Rad at a 4.5 meter diameter user plane. All fluences assume 7.3 years of operation.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: No measurements currently planned.

Present Range: **Present Uncertainty:**

Assessment:

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: SP-100 **Parameter:** RADIOACTIVITY

Application: COOLANT RADIOACTIVITY

Range: **Uncertainty:**

Reason for Measurement: To monitor for broken fuel elements.

Other Requirements: Must withstand high temperatures and corrosive coolants.

Comments:

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: No plans to monitor this parameter.

Present Range: **Present Uncertainty:**

Assessment:

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: SP-100 **Parameter:** TEMPERATURE

Application: REACTOR COOLANT TEMPERATURE

Range: up to 1369 K **Uncertainty:** 2% or 10 K

Reason for Measurement: To monitor reactor operation.

Other Requirements: Long-term stability in high-temperature, radioactive, corrosive environments is required.

Comments: The temperature drop through the heat exchanger is 47 K. The secondary loop temperature is 846 K (maximum). No thermal power calculation will be performed during routine operation.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Thermocouples (Tungsten/Rhenium)

Present Range: 2760 °C **Present Uncertainty:** variable

Assessment: Need to eliminate long-term, high-temperature drift and drift due to radioactive exposure.

Comments: Requires a cold reference temperature. Thermocouples will be placed on the outside of coolant pipes in areas shielded from reactor radiation.

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Johnson Noise Thermometer (JNT)

Present Range: > 1000 °C **Present Uncertainty:** 0.5%

Assessment: Sufficiently accurate with long time constants.

Comments: Will require a method of calibrating the support electronics. It is undecided at this time if the JNT will be used for absolute or relative measurements.

SDI REQUIREMENTS -

Program: SP-100 **Parameter:** TEMPERATURE

Application: INTERIOR REACTOR TEMPERATURE

Range: > 1300 K **Uncertainty:**

Reason for Measurement: To monitor reactor operation and thermal power.

Other Requirements: Must survive high temperatures and high radiation.

Comments: Also may be used to monitor for hot spots.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Thermocouples placed behind reactor shield.

Present Range: **Present Uncertainty:**

Assessment: The shield will protect the thermocouples from the most intense levels of radiation. However, the difficulties mentioned for the coolant temperature measurements apply here as well.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: SP-100 **Parameter:** TEMPERATURE

Application: PLATFORM TEMPERATURE (REFERENCE TEMPERATURE)

Range: 400–600 K **Uncertainty:** 1–2%

Reason for Measurement: Required for reference and calibration.

Other Requirements: No long-term drift.

Comments: All other temperature measurements will depend upon this measurement.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Thermistor

Present Range: **Present Uncertainty:** 1–3%

Assessment: Probably adequate in a controlled environment. Thermistors are stable to within 3% for long-term use.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: TURBINES **Parameter:** FREQUENCY

Application: TURBINE ROTATION FREQUENCY

Range: 6 to 20 krpm **Uncertainty:**

Reason for Measurement: To monitor turbine operation.

Other Requirements: Very similar requirements as for terrestrial turbines.

Comments: The rotation must be monitored closely in order to minimize the net rotational forces on the space platform.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Frequency counter

Present Range: **Present Uncertainty:** 0.0001 ppm

Assessment: Suitable.

Comments: Method of producing electrical signals proportional to the rotation frequency must be determined.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: TURBINES **Parameter:** PRESSURE

Application: TURBINE INLET PRESSURE

Range: 1.2 to 6.9 MPa **Uncertainty:**

Reason for Measurement: To monitor turbine operation.

Other Requirements: Pressure may vary from 0 to peak value in seconds. Gas may be at high temperature and also radioactive.

Comments: Pressure values given here are for MMW applications.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Mechanical sensors (pistons gauges, etc.)

Present Range: **Present Uncertainty:** 200 ppm

Assessment:

Comments: 200 ppm uncertainty is for steady state conditions. Severe environments need individual attention. Most sensors would require improved response times.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI REQUIREMENTS -

Program: TURBINES **Parameter:** PRESSURE

Application: TURBINE OUTLET PRESSURE

Range: 0.12 to 0.5 MPa **Uncertainty:**

Reason for Measurement: To monitor turbine operation.

Other Requirements: Pressure may vary from minimum to maximum in seconds. Gas may be at high temperature and also radioactive.

Comments: Pressure values are for MMW applications.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Mechanical Sensors

Present Range: **Present Uncertainty:** 200 ppm

Assessment:

Comments: Same as for inlet pressure measurements.

OTHER POSSIBLE MEASUREMENT METHOD -

Method:

Present Range: **Present Uncertainty:**

Assessment:

Comments:

SDI METROLOGY ASSESSMENT

SDI REQUIREMENTS -

Program: TURBINES **Parameter:** TEMPERATURE

Application: TURBINE INLET TEMPERATURE

Range: 800 to 1450 K **Uncertainty:**

Reason for Measurement: To monitor turbine operation.

Other Requirements: Temperatures may vary from minimum to maximum in seconds. The gas may be radioactive.

Comments. Temperature values are for MMW operation.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Thermocouples

Present Range: **Present Uncertainty:** 0.1%

Assessment: Response time is questionable as is long-term operation characteristics.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Optical-fiber radiation thermometry

Present Range: **Present Uncertainty:** 1%

Assessment: The response time is sufficiently short that this technique should be able to follow the temperature-versus-time profile. Long-term performance has not been characterized.

Comments:

SDI REQUIREMENTS -

Program: TURBINES **Parameter:** TEMPERATURE

Application: TURBINE OUTLET TEMPERATURE

Range: 580 to 1150 K **Uncertainty:**

Reason for Measurement: To monitor turbine operation.

Other Requirements: Temperatures may vary from minimum to maximum in seconds. The gas may be radioactive.

Comments: Given temperature range is for MMW applications.

ANTICIPATED MEASUREMENT TECHNIQUE -

Method: Thermocouples

Present Range: **Present Uncertainty:** 0.1%

Assessment: Response time is questionable as is long-term operation characteristics.

Comments:

OTHER POSSIBLE MEASUREMENT METHOD -

Method: Optical-fiber radiation thermometry

Present Range: **Present Uncertainty:** 0.1%

Assessment: Fast response time allows the acquisition of the temperature-versus-time profile. However, the long-term performance of these sensors has not yet been characterized.

Comments:

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

A survey has been performed to determine the measurement requirements of space power related parameters for anticipated SDI systems. These requirements have been compared to present state-of-the-art metrology capabilities as represented by the calibration capabilities of the National Institute of Standards and Technology. Metrology areas where present state-of-the-art capabilities are inadequate to meet SDI requirements are discussed, and areas of metrology-related research which appear promising to meet these needs are examined. Particular attention is paid to the difficulties of long-term, unattended sensor calibrations and long-term measurement reliability.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

calibration; measurements; metrology; reliability; sensors; space power; Strategic Defense Initiative

13. AVAILABILITY

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