

SEMI E136-0122

TEST METHOD FOR DETERMINING THE OUTPUT POWER OF RF GENERATORS USED IN SEMICONDUCTOR PROCESSING EQUIPMENT RF POWER DELIVERY

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NOTICE: This Standard was completely rewritten in 2021.

NOTICE: Paragraphs entitled ‘NOTE:’ are not an official part of this Standard or Safety Guideline and are not intended to modify or supersede the official Standard or Safety Guideline. These have been supplied by the global technical committee to enhance the usage of the Standard or Safety Guideline.

NOTICE: The section symbol (§) is used to reference a numbered section, paragraph, or header and all subordinate paragraphs, headers, and embedded material (i.e., EXCEPTIONs, lists) therein. The paragraph symbol (§) is used to reference a particular numbered paragraph and embedded material therein. When duplicated (i.e., §§ and §§§) the symbols are used to reference more than one section or paragraph, respectively.

1 Purpose

1.1 The purpose of this Test Method is to provide an accurate method for measuring the output power of radio frequency (RF) generators used in RF power delivery systems of semiconductor processing equipment.

NOTE 1: This Test Method is referred to as a preferred method of RF power measurement for conforming to SEMI E113.

2 Scope

2.1 This Test Method specifies the testing procedures and test equipment required for determining the true RF output power (i.e., heating power) of RF generators.

2.2 This Test Method uses a calorimetric power meter, which was calibrated previously using precise low-frequency substitution techniques as a reference standard.

2.2.1 This Test Method also describes use of a transfer sensor that is calibrated using a calorimeter and a working sensor that is calibrated using the transfer sensor.

NOTICE: SEMI Standards and Safety Guidelines do not purport to address all safety issues associated with their use. It is the responsibility of the users of the documents to establish appropriate safety and health practices, and determine the applicability of regulatory or other limitations prior to use.

3 Limitations

3.1 This Test Method is meant to provide a general means of measuring the true continuous RF power in RF power delivery systems operating over a wide range of RF frequency and power. Limitations in the RF frequency and power coverage of this method are determined by the individual system components chosen.

3.2 This Test Method assumes that the transmission system characteristic impedance is constant. This assumption is derived from the fact that the calorimeter RF load will be designed to be a good match at a particular impedance. A calorimeter can only be a low-uncertainty RF load in a system in which it is a good match. It will be common for the impedance to be 50 Ω , however it is possible to envision coaxial systems designed for other impedances.

3.3 This Test Method assumes that the exciting RF power will be both continuous and of a single-frequency sinusoid. This assumption is required by the characteristics of the calorimeter RF load and some of the sensors employed. A calorimeter RF load is a broadband absorber, and will therefore respond to all incident energies, however possibly with a different effective efficiency (η_e) and reflection at different RF frequencies. It is not possible to separate the effects of different RF frequencies, so to avoid that impossibility, the spurious, harmonic, and modulation energies should be minimized. Further, some sensors employed will use diode voltage detectors that are particularly susceptible to error due to waveform distortion. In general, it is recommended to keep all off-carrier energies below -50 dBc.

Where the user chooses not to do so, careful calculations are needed, considering the sensor type and coupler characteristics, to quantify the resulting errors.

3.4 This Test Method does not address any issues related to controlling electromagnetic energy emission including RF emissions that are outside of the RF power delivery system including the RF generator under test (e.g., EMC Directive, Federal Communications Commission [FCC]). It is the responsibility of the users of this Test Method to conform to the appropriate local codes and regulations as applied to this type of equipment, some of which are covered by referenced documents.

4 Referenced Standards and Documents

4.1 SEMI Standards and Safety Guidelines

SEMI C41 — Specification and Guide for 2-Propanol

SEMI E113 — Specification for Semiconductor Processing Equipment RF Power Delivery Systems

4.2 ISOTM/IECTM Standards¹

ISO/IEC 17025 — General Requirements for the Competence of Testing and Calibration Laboratories

4.3 NIST Publications²

Special Publication 330 — The International System of Units (SI)

4.4 Other Documents

EMC Directive 2014/30/EU³ — Directive 2014/30/EU of the European Parliament and of the Council of 26 February 2014 on the Harmonisation of the Laws of the Member States Relating to Electromagnetic Compatibility

NOTICE: Unless otherwise indicated, all documents cited shall be the latest published versions.

5 Terminology

5.1 Abbreviations and Acronyms

5.1.1 *AC* — alternating current

5.1.2 *CW* — continuous wave

5.1.3 *DC* — direct current

5.1.4 *RF* — radio frequency

5.1.5 *RTD* — resistance temperature detector

5.1.6 *VNA* — vector network analyzer

5.1.7 *VSWR* — voltage standing wave ratio

5.1.8 *UUT* — unit under test

5.2 Definitions

5.2.1 *cable assembly* — the section of cable (transmission line), including the connectors, used to connect various parts of the RF power delivery system.

5.2.2 *calorimeter* — an RF power measurement instrument using differential temperature and mass flow rate to determine true heating power.

5.2.3 *effective efficiency* (η_e) — in the context of a flow calorimeter, the proportion of the RF energy dissipated in the RF load that is converted to a measurable temperature increase in the coolant.

¹ International Organization for Standardization, ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland; Telephone: +41.22.749.01.11, <http://www.iso.org>

² National Institute of Standards and Technology, 100 Bureau Drive, Stop 3460, Gaithersburg, MD 20899-3460, USA; Telephone: +1.301.975.6478, <http://www.nist.gov>

³ European Commission, Telephone: +00.800.67891011; https://ec.europa.eu/growth/sectors/electrical-engineering/emc-directive_en

5.2.4 equivalent source match — a vector quantity expressing the equivalent output reflection factor that will result in a correct power calculation when making a ratiometric comparison between a coupler-based power meter as the source and a terminating (RF load) power meter.

5.2.4.1 Discussion — The equivalent source match of a coupler-based meter is a function of the S-parameters of the coupler. Refer to Eq. 11.5 and A4 in *Radio Frequency Power Measurement*⁴. To compute an equivalent source match, vector measurement of all three coupler ports is required. For coupler-based meters that do not incorporate a connectorized coupled port, this is not possible and estimates are used instead. The most reasonable estimate of the magnitude of an equivalent source match is $|S_{22}| + (1/D)$, where D is directivity expressed as a linear ratio. Phase angle cannot be estimated.

5.2.5 flow calorimeter — a measurement system in which RF power to be measured is applied to a liquid-cooled RF load and in which the output is primarily a function of the temperature increase of the coolant.

5.2.6 harmonic frequency — the harmonic frequencies are defined as integer multiples of the fundamental RF frequency. For example, the second harmonic frequency of 13.56 MHz is 27.12 MHz.

5.2.7 RF generator — a component in the RF power delivery system used to develop RF energy.

5.2.8 RF termination — a device for terminating RF transmission systems and converting RF electrical energy into heat. RF terminations normally have values that are the same as the characteristic impedance of the transmission system.

5.2.9 RF load — another term used to describe an RF termination.

5.2.10 transfer sensor — an RF power sensor used to transfer calibration from the calorimeter to another RF power sensor. A transfer sensor is used when an input calibration is needed. A transfer sensor calibrated at its input may be calibrated using a transfer sensor calibrated by a calorimeter at its output.

5.2.11 working sensor — an RF power sensor used for testing RF generators or other RF power equipment.

5.3 Symbols

5.3.1 dB — decibel

5.3.2 dBc — decibels relative to the carrier

5.3.3 m — value of the slope of the segment

5.3.4 T — temperature

5.3.5 y — value of the y intercept of the segment

5.3.6 η_e — effective efficiency

NOTE 2: SI units (including SI-coherent derived units with special names and symbols) are not cited in this section per Appendix 3 of the SEMI Standards Procedure Manual. Information about SI is available from the National Institute for Standards and Technology (NIST) Special Publication 330 or other equivalent national authorities in countries other than the U.S.

6 Summary of Test Method

6.1 Measuring RF Generator Output Power with Flow Calorimeter — A flow calorimeter is used to convert RF energy from an RF generator output into measurable heat.

6.2 Calibrating Feed-Through Power Meter with Flow Calorimeter — The input port of a feed-through power meter (i.e., the working sensor) is calibrated from a flow calorimeter using a second feed-through power meter as a transfer sensor.

6.3 Measuring RF Generator Output Power with Feed-Through Meter — The RF power output of an RF generator at the RF generator output is measured by a working sensor connected to the RF generator output that is connected to an RF load.

⁴ Fantom, A., *Radio Frequency & Microwave Power Measurement*, 1990, Institution of Engineering and Technology (IET), London

7 Apparatus

7.1 Calorimetric Power Meter — The primary standard for RF power is a flow calorimeter. This instrument efficiently dissipates the RF electrical energy into heat, which produces an indication proportional to the temperature increase of the coolant. A flow calorimeter consists of several critical subsystems:

7.1.1 Liquid-Cooled Coaxial RF Load — It converts electrical energy into heat. Critical features are high efficiency, which is relatively independent of RF frequency and power, and low reflection. Efficiency of conversion is typically at least 0.998% and reflection S_{11} for a good RF load is typically less than 0.02 (voltage standing wave ratio [VSWR] <1.04:1). At RF frequencies higher than 200 MHz, performance may be worse in some cases.

7.1.1.1 Liquid-cooled RF loads may be designed so that electrical conductors are exposed to coolant or not. High-power RF loads are frequently designed so that the resistive element and related metallic conductors are exposed to coolant. This practice has the advantage of reducing ‘hot spots’ and can allow the resistor to be smaller with a corresponding improvement in reflection, however it also exposes the electrical components to degradation by electrolysis or plating. Particularly if calibrating using direct current (DC), this degradation should be avoided by using RF loads that do not bring coolant into contact with electrically energized parts.

7.1.2 Temperature Instruments — The primary indication output of a calorimeter is the increase in coolant temperature from the inlet of the RF load to the outlet of the RF load. Some calorimeters employ two thermometers using thermistors or resistance temperature detectors (RTDs), however the lowest-error indication is given by a thermopile made between the inlet and outlet pipes close to the RF load. A semiconductor Peltier device is an easy-to-use, commercially available thermopile.

7.1.3 Pump and Flow Control — Consistent mass flow that is repeatable from alternating current (AC) calibration to RF measurement is an important contributor to repeatability. Calorimeters can use repeatable flowmeters or positive-displacement pumps turning at a well-regulated speed to produce constant flow.

7.1.4 Coolant Temperature Management — A calorimeter will gain heat through the RF connector at a rate proportional to the difference between coolant temperature and ambient. For that reason, constant coolant-inlet temperature is critical to repeatable measurements. Controlled chillers and coolant reservoir tanks are employed to maintain stable inlet temperatures. Typically, coolant inlet temperature is maintained within 0.01°C.

7.1.5 Ambient Temperature Measurement — A calorimeter will show a power offset proportional to the difference between coolant inlet temperature and ambient. This power offset is corrected for by monitoring ambient temperature near the RF connector and applying corrections determined from test data using the calorimeter supplier’s instructions.

7.1.6 AC or DC Source — These sources supply electrical energy during calibration. Because a calorimeter reading has a very long time constant, input power shall be held stable for many minutes at a time. The important feature of a calibration supply is the stability of its output in the presence of variation in its voltage input.

7.1.7 AC or DC Power Meter — These meters accurately measure power applied to the RF load during calibration. Remote voltage sensing is required to avoid measuring power in the interconnecting wires. Use a fixture with an RF connector to supply the calibration power to the RF load and directly measure voltage at the RF load connector.

7.1.8 Control Software — To manage calibration, linearization, correction for reflection, correction for coolant properties, correction for efficiency, and to compute statistics for determining stability, a flow calorimeter standard will usually employ software, either on an internal microprocessor, on a control workstation, or both.

7.1.9 RF Interconnect Cable — It is not desirable to have any cable between the RF generator (or other unit under test [UUT]) and the calorimeter, because it is of high uncertainty to estimate cable losses at RF. When it is unavoidable to have a cable between the UUT and calorimeter, estimate the loss as accurately as possible and add to the calorimeter reading.

7.1.10 Protective Interlocks — A calorimeter installation should be furnished with interlocks to the AC/DC sources and the RF generators to prevent an inadvertent supply of energy.

7.1.10.1 A calorimeter will be damaged if energy is sourced to the RF load without adequate coolant flow. A coolant flow switch should be in the interlock system.

7.1.10.2 Testing personnel will be exposed to hazardous energy if energy is applied when cables or connectors are not connected. It is necessary to consider both engineering and administrative measures in accordance with applicable safety standards and safe work practices.

7.1.10.3 Emergency stop buttons that immediately remove all energy shall be provided at locations that are easily accessible to the testing personnel.

7.2 Feed-Through Power Sensor — An RF power-measuring device in which most of the RF power flows through from input port to output port. Sometimes it is a unitary commercial product or an RF coupler with low-power meter connected to a coupled port.

7.2.1 A feed-through power sensor shall be calibrated either at the input port or output port. The calibrations are different because of the losses in the main line of the coupler and because of the diversion of coupled RF power.

7.2.1.1 *Output Port Calibration* — When calibrated at an output port, the sensor indication is usually defined to be the RF power that would be delivered to an ideal RF load.

7.2.1.2 *Input Port Calibration* — When calibrated at an input port, the indication is usually defined to be the RF power at the reference plane of the input.

7.2.2 If a feed-through power meter is used as a transfer or working sensor without correcting for the properties of the coupler, the resulting error is highly determined by the effective directivity of the coupler. When choosing a feed-through power meter, be aware of the directivity. Common broadband couplers may have directivity as low as 20 dB, while some special-purpose couplers can have directivity approaching 50 dB. It is highly preferable to use transfer and working sensors that are calibrated to maintain accuracy over a range of RF-load impedances.

8 Reagents and Materials

8.1 Connector Cleaning Supplies — RF connectors should be cleaned every time they are mated to prevent metallic particles from contaminating the insulators and causing leaks or reflection.

8.1.1 *Solvent* — Use of 2-propanol (i.e., isopropyl alcohol or isopropanol) that meets or exceeds SEMI C41 Grade 1 is recommended for use as a connector cleaning solvent. Aggressive solvents are not recommended as they may damage insulators. Water-based cleaners or solvents containing surfactants are not recommended as their use may result in residue.

8.1.2 *Cleaning Implement* — A cotton swab with a strong handle is recommended for cleaning. Alternatively, a lint-free wipe can be used, but it can be difficult to reach into a connector with only a wipe.

9 Safety Precautions

9.1 These general precautions are not intended to replace a well-organized, local, safety policy or practices.

9.2 Work should be conducted in accordance with local safety requirements and test device supplier's recommended safety procedures.

9.3 The area immediately surrounding the test setup should be kept free and clear of unnecessary equipment and materials.

9.4 Testing personnel should ensure they have adequate lifting devices for large weights, such as long RF cables and RF generators themselves.

9.5 Interconnecting cables should be inspected prior to use to ensure they remain capable of carrying the RF power used in the test. Interconnect cables should be periodically checked during high-power testing to verify that they remain within acceptable operating temperature.

10 Calibration and Standardization

10.1 Calibrating a calorimeter at this level assumes that all of the instrumentation such as flowmeters, temperature sensors, and voltmeter for reading the thermopile, and thermopile V/°C, have been characterized, adjusted, and accepted. The calorimeter's primary output, W, is calculated from these inputs. The calculation based on inputs will contain some errors and the final calibration is intended to partially correct for those errors.

10.2 A calorimeter's response to input may not be linear with respect to RF power. Therefore, a 'linear' calibration using one or two points is not recommended. Ideally, points that closely surround the operating point(s) should be chosen and interpolated between. With enough points, linear interpolation should be sufficient. Some calorimeter control software may implement such a calibration process.

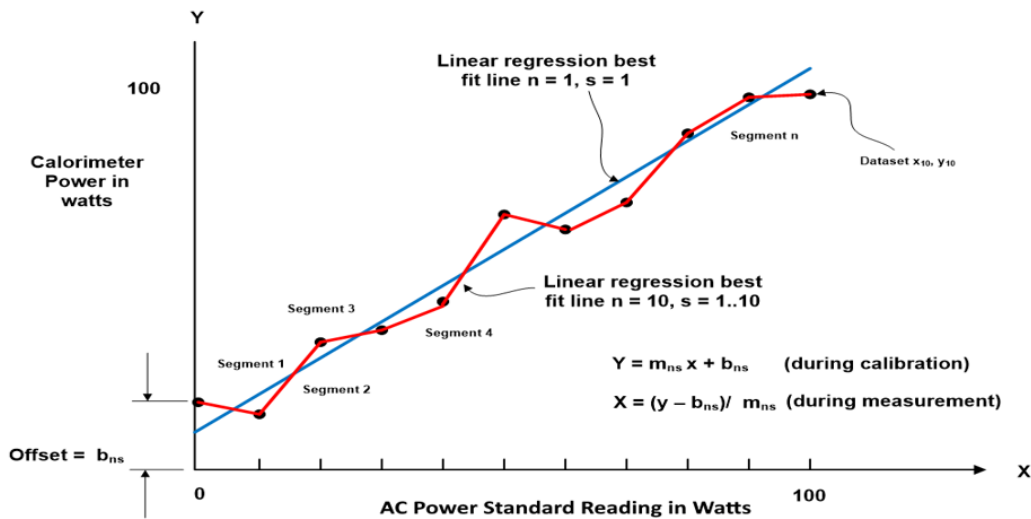


Figure 1
Piecewise Linear Calibration Concept

10.3 A calorimeter reading is dependent upon the thermal stabilization to equilibrium of the heat-transfer process, which probably includes one or more controllers (in coolant chiller[s] or a cooling control valve system). Unless studies have been undertaken to find the settling time at each RF power level and size of RF power step, it is preferable to use a statistical method to decide that any given test condition has stabilized. When this procedure calls for a determination of stabilization, use a proven time-delay or a statistical method.

NOTE 3: Statistical methods for deciding that a system is settled are discussed in Related Information 3.

10.3.1 Connections

10.3.1.1 Connect the DC power supply, the digital multimeters, and the RF load according to Figures 1 and 2.

10.3.1.2 Make the connections between the multimeters, the DC power supply, and the RF load using high-quality, low-loss cables and high-quality, corrosion-free cable terminations.

10.3.1.3 Make all of the electrical and coolant connections to the calorimeter.

10.3.2 *Stabilization* — Apply main power to the calorimeter system and allow one hour for stabilization.

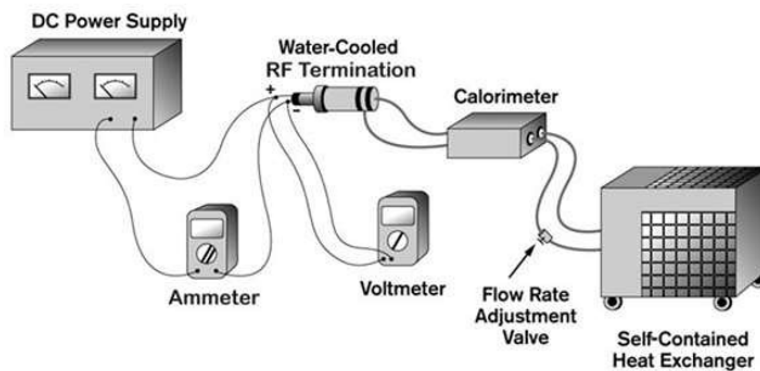


Figure 2
Calorimeter DC Calibration Configuration

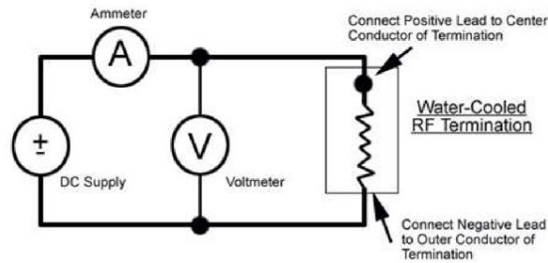


Figure 3
Calorimeter DC Calibration Connection Diagram

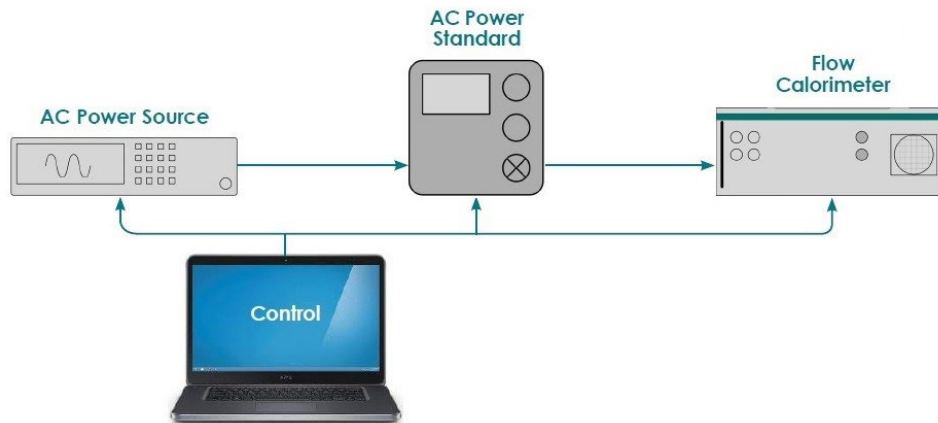


Figure 4
Calorimeter AC Calibration Arrangement

10.3.3 *Calorimeter Calibration* — Following the calorimeter warm-up, the device is ready for calibration.

10.3.3.1 Create a plan for calibration, with a list of target RF power settings.

10.3.3.2 Plan target RF power levels to be close to the RF powers at which measurements will be made. If measurements are to be made over a wide range of RF power, take nonlinearity of the calorimeter into account.

10.3.3.2.1 RF power nonlinearity of the calorimeter may be evaluated by executing a calibration plan containing additional calibration points. For example, covering the RF power range of interest with 10 or more logarithmically spaced points will reveal the general shape of the nonlinearity and provide data in support of adding or removing points. Testing with additional points will provide insight into the interpolation error inherent in making measurements between the points at which calibration data is available.

10.3.4 *RF Load Differential Temperature* — Most calorimeter systems will yield optimum performance when certain operating parameters relating to the differential temperature across the RF load and the flow rate are maintained. In most cases, a differential temperature of 2°C represents a good beginning point. The coolant flow rate may then be set to provide for this differential temperature.

10.3.4.1 The following formula may be used to arrive at the correct coolant flow rate.

$$RF\ Power = 69.32 \times T \times Flow\ Rate \quad (1)$$

where:

$RF\ Power = W$,

$T = ^\circ C$, and

$Flow\ Rate = L/min$.

10.3.4.2 Solving for *Flow Rate* yields:

$$\text{Flow Rate} = (\text{RF Power} / 69.32) / T \quad (2)$$

10.3.4.3 Choosing a *Flow Rate* for a measurement plan over a wide range of RF powers is a compromise between exceeding the recommended 2°C at the higher RF powers and losing sensitivity at the lower end.

10.3.4.4 Effective efficiency (η_e) will vary with flow rate. Analyses of η_e are time-consuming and expensive, so avoid planning to use many different flow rates. If relying on manufacturer's analysis of η_e , use only flow rates that were analyzed.

10.3.5 Calibration Steps

10.3.6 With the calorimeter operating at the appropriate flow rate, apply AC or DC power to the RF load, adjusting voltage to achieve a power as indicated by the AC power meter or the product of current times voltage on the DC instruments, that is close to the desired power chosen in the plan.

10.3.7 At each planned power level allow the power reading to stabilize.

NOTE 1: Refer to Related Information 3.

10.3.8 After the system is stabilized at an operating point, take 5 to 10 readings of the calorimeter uncalibrated power and the AC or DC instruments readings.

10.3.8.1 Take the calorimeter and instrument readings in sets, with the time elapsed to take one set to be as short as possible.

10.3.8.2 Space the sets evenly over two to five minutes.

10.3.8.3 If the calibration power is DC, compute DC power for each set. If the calibration power is AC, read the power directly from the meter.

10.3.8.4 Record the mean AC or DC power and calculate the mean of the uncalibrated calorimeter reading as a calibration data point.

10.3.9 Using the points of the AC or DC power and the uncalibrated calorimeter readings found above, find the equation for a linear segment between each set of consecutive points such that:

$$\text{Uncalibrated Calorimeter Reading} = m \times \text{AC/DC Power} + b \quad (3)$$

where m represents the value of the slope of the segment and y represents the value of the y intercept of the segment.

10.3.10 The calorimeter is now calibrated at the planned power levels and flow rate.

10.3.11 When measuring with the calorimeter, using the m and b of the segment that contains the uncalibrated calorimeter reading, the calibrated AC reading is:

$$\text{Calibrated Calorimeter Reading} = (\text{Uncalibrated Calorimeter Reading} - b) / m \quad (4)$$

11 Procedure

11.1 Measurement of Generator Output RF Power with Flow Calorimeter

11.1.1 Prepare and calibrate the flow calorimeter.

11.1.2 Document a test plan that includes:

11.1.2.1 RF power setting(s) and frequency(ies)

11.1.2.2 Stabilization criteria

11.1.2.3 Number of and spacing in time of calorimeter readings to calculate the mean

11.1.3 Connect the RF generator output to calorimeter input using a cable with losses and reflection as low as practicable.

11.1.4 Allow the calorimeter reading to stabilize without powering on the RF generator and record the stabilized 'zero' reading.