NIST HANDBOOK 150-2A

National Voluntary Laboratory Accreditation Program

Calibration Laboratories

Technical Guide for Electromagnetic DC Low Frequency Measurements

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Preface

The Calibration Laboratories Accreditation Program was developed by the National Voluntary Laboratory Accreditation Program (NVLAP) at the National Institute of Standards and Technology (NIST) as a result of interest from private industry and at the request of the National Conference of Standards Laboratories (now the NCSL International). The goal of the program is to provide a means by which calibration laboratories can be assessed for competency. This voluntary program is not designed to serve as a means of imposing specific calibration procedures or minimum uncertainties on applicant laboratories; instead, the program allows for all scientifically valid calibration schemes and requires that laboratories derive and document their measurement uncertainties.

To accomplish this goal, NVLAP employs technical experts on a contract basis, to serve as assessors in each of the following eight fields of physical metrology calibration:

- electromagnetic dc/low frequency,
- electromagnetic rf/microwave frequency,
- time and frequency,
- ionizing radiation,
- optical radiation,
- dimensional,
- mechanical, and
- thermodynamics.

NIST Handbooks 150-2A through 150-2H are technical guides for the accreditation of calibration laboratories, with each handbook corresponding to one of the eight fields of physical metrology calibration. They are intended for information and use by:

- NVLAP technical experts in assessing laboratories,
- staff of accredited laboratories,
- those laboratories seeking accreditation,
- other laboratory accreditation systems,
- users of laboratory services, and
- others needing information on the requirements and guidelines for accreditation under the NVLAP Calibration Laboratories Accreditation Program.

NOTE The Calibration Laboratories Accreditation Program has been expanded to cover chemical calibration for the providers of proficiency testing and certifiers of spectrophotometric NTRMs. (See NIST Handbooks 150-19 and 150-21.) Other NVLAP handbooks in the chemical calibration area are expected in the future.

The assessor uses NIST Handbook 150, *NVLAP Procedures and General Requirements*, and the appropriate guides (NIST Handbooks 150-2A through 150-2H) to validate that a laboratory is capable of performing calibrations within the laboratory's stated uncertainties. These technical guides and other relevant technical information support assessors in their assessments of laboratories. Along with inspecting the facilities, documentation, equipment, and personnel, the assessor can witness a calibration, have an item recalibrated, and/or examine the results of measurement assurance programs and round-robins to collect objective evidence.

NIST Handbooks 150-2A through 150-2H supplement NIST Handbook 150, which contains Title 15 of the U.S. Code of Federal Regulations (CFR) Part 285 plus all general NVLAP procedures, criteria, and policies. The criteria in NIST Handbook 150 originally encompassed the requirements of ISO/IEC Guide 25:1990 and the relevant requirements of ISO 9002 (ANSI/ASQC Q92-1987). These handbook criteria have been updated to incorporate the requirements of ISO/IEC 17025:1999. The entire series of Handbooks 150-2A through 150-2H comprises information specific to the Calibration Laboratories Program and neither adds to nor detracts from requirements contained in NIST Handbook 150.

Any questions or comments on this handbook should be submitted to the National Voluntary Laboratory Accreditation Program, National Institute of Standards and Technology, 100 Bureau Drive, Stop 2140, Gaithersburg, MD 20899-2140; phone (301) 975-4016; fax (301) 926-2884; e-mail NVLAP@nist.gov.

Acknowledgments

NIST Handbook 150-2 was first available as a draft covering all eight fields of physical metrology calibration in one volume. It has been separated into eight handbooks to allow easier updating and electronic downloading from the NVLAP web site. The preparation of these documents has been a joint effort, with input from representatives of other government agencies, laboratories, and the private sector. Acknowledgment of their efforts is in order; however, the listing of individual names is impractical. The submissions by individuals and companies offering suggestions for improvement to this document were also very welcome, as were the contributions of those who attended the public workshops.

We thank all the NIST measurement divisions for their work in writing or contributing to the individual handbooks. Listed below are those from the NIST measurement divisions who deserve special thanks for input to Handbook 150-2A:

- Mr. Norman B. Belecki (Capacitance, Inductance, AC Resistance, DC Voltage, and Inductive Voltage Dividers),
- Mr. Ronald F. Dziuba (DC Resistance),
- Mr. William L. Gans, Mr. Donald Larson, and Mr. Barry A. Bell (Fast Electrical Pulse Waveform),
- Mr. Thomas E. Lipe (AC-DC Difference),
- Dr. Martin Misakian (DC High Voltage Divider and Resistance),
- Mr. Thomas L. Nelson (Watt-Watthour Measurements),
- Mr. Nile M. Oldham (Digital Multimeters and Phase Meter Measurements), and
- Dr. James K. Olthoff (High Voltage Capacitors and High Voltage Transformers).

Additional thanks go to those who actively participated in the Technical Guide Workshop held November 1993 and to those who served as points of contact within fields of calibration. They include: Mr. Georgia L. Harris, Mr. Norman B. Belecki, Dr. Theodore D. Doiron, Mr. Robert M. Judish, Mr. Thomas C. Larason, Ms. Sally S. Bruce, and Dr. Donald B. Sullivan. A special thanks is owed to Mr. James L. Cigler for work in developing the content and format of this guide, and to Ms. Vanda White for her editorial expertise in making this a readable document.

Above all, we wish to thank Mr. Jon M. Crickenberger, the editor of the first three drafts of this document, for literally hundreds of hours of his work in creating this guide. It was he who tasked the contributors to produce the technical content, assembled the results of their efforts into a consistent format, and provided the general commentary. Without Jon's dedicated effort to this monumental task, this guide would never have been published.

NVLAP has edited the individual handbooks and made changes resulting from comments by individuals to earlier draft versions. This editing has been to a different extent for each parameter. Every effort was made to include all pertinent information relevant to an ISO/IEC 17025-derived technical guide.

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Summary

This guide presents the general technical requirements (i.e., on-site assessment and proficiency testing) of the laboratory accreditation program for calibration laboratories along with specific technical criteria and guidance applicable to electromagnetic dc/low frequency measurements. These technical guidelines are presented to indicate how the NVLAP criteria may be applied.

Any calibration laboratory (including commercial, manufacturer, university, or federal, state, or local government laboratory) engaged in calibration in electromagnetic dc/low frequency measurements listed in this handbook may apply for NVLAP accreditation. Accreditation will be granted to a laboratory that complies with the criteria for accreditation as defined in NIST Handbook 150. Accreditation does not guarantee laboratory performance – it is a finding of laboratory competence.

Fields of calibration covered: Specific calibration parameters and related stimulus and measurement devices in areas of electromagnetic dc/low frequency measurements.

Scope of accreditation:
1) Calibration parameter(s), range, and uncertainty level
2) Types of measuring and test equipment
3) Quality assurance system for measuring and test equipment.

Period of accreditation: One year, renewable annually.

On-site assessment: Visit by an assessor(s) to determine compliance with the NVLAP criteria before initial accreditation, in the first renewal year, and every two years thereafter. Preassessment and monitoring visits are conducted as required. All calibration parameters or general areas of calibration within the specific scope of accreditation requested will be assessed.

Assessors: Selected from technical experts with experience in the appropriate areas of calibration and quality systems assessment.

Proficiency testing (measurement assurance): Each laboratory is required to demonstrate its capability to successfully perform calibrations as part of on-site assessment or by documented successful completion of an approved Measurement Assurance Program (MAP) or round-robin intercomparison. Proficiency testing may be required for initial accreditation, or where other evidence of measurement assurance is not evident, and may be conducted annually thereafter. Advance notice and instructions are given before proficiency testing is scheduled.

Fees: Payments are required as listed on the NVLAP fee schedule, including the initial application fee, administrative/technical support fee, on-site assessment fee, and proficiency testing fee.

1 General information

1.1 Purpose

The purpose of this handbook is to amplify the general requirements for accreditation by NVLAP of calibration laboratories in the area of electromagnetic dc/low frequency measurements covered by the Calibration Laboratories Program. It complements and supplements the NVLAP programmatic procedures and general requirements found in NIST Handbook 150, *NVLAP Procedures and General Requirements*. The interpretive comments and additional guidelines contained in this handbook make the general NVLAP criteria specifically applicable to the Calibration Laboratories Program.

This handbook does not contain the general requirements for accreditation, which are listed in NIST Handbook 150, but rather provides guidelines for good calibration laboratory practices, which may be useful in achieving accreditation.

1.2 Organization of handbook

The handbook is organized in two sections. The first section provides additional explanations to the general procedures and requirements contained in NIST Handbook 150. The second section provides details and guidance very specific for electromagnetic dc/low frequency measurement calibration laboratories.

1.3 Description of Calibration Laboratories Accreditation Program

On May 18, 1992, as a result of the petition and public notice process, the Director of the National Institute of Standards and Technology published in the *Federal Register* a notice of intent to develop the Calibration Laboratories Accreditation Program under the procedures of the National Voluntary Laboratory Accreditation Program . On June 2, 1994, the procedures and general requirements under which NVLAP operates, Title 15, Part 285 of the U.S. Code of Federal Regulations (CFR), were revised to:

a) expand the procedures beyond testing laboratories to include accreditation of calibration laboratories,

b) update the procedures to ensure compatibility with generally accepted conformity assurance and conformity assessment concepts,

c) incorporate international changes, especially with relevant International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) documents (e.g., ISO/IEC Guides 25 (now ISO/IEC 17025:1999), 38, 43, and 58, and the ISO 9000 series), and

d) facilitate and promote acceptance of the calibration and test results between countries to avoid barriers to trade.

Calibration laboratory accreditation is offered in eight fields of physical metrology calibration covering a wide variety of parameters and includes accreditation in multifunction measuring and test equipment calibrations. Specific requirements and criteria have been established for determining laboratory qualifications for accreditation following prescribed NVLAP procedures. The criteria address quality systems, staff, facilities and equipment, test and calibration methods and procedures, manuals, records, and calibration reports.

On September 18, 1992, a public workshop was held at NIST Gaithersburg and attended by a mix of private sector and government personnel. The workshop reviewed a draft handbook, which included general requirements, as well as very specific technical requirements for dc voltage calibrations at all levels. As a result of the workshop, the draft handbook was revised to take the form of a Calibration Laboratories Program Handbook, which included the general requirements for laboratories (using ISO/IEC Guide 25 as a basis), and eight companion Technical Guides covering the specific requirements for each field of calibration offered for accreditation.

On May 18, 1993, a public workshop on the revised draft program handbook was held at NIST Boulder and attended by more than 60 industry and government personnel. Comments from this workshop, as well as responses to a survey/checklist mailing, were used to prepare the final draft of the handbook, now entitled *NVLAP Procedures and General Requirements* (NIST Handbook 150), published in March 1994. NIST Handbook 150 has since been revised to incorporate ISO/IEC 17025:1999.

A public workshop for the Calibration Laboratories Technical Guides was held at NIST Gaithersburg, on November 22 through 24, 1993. More than 60 industry and government personnel attended and provided comments on the draft version of the Technical Guide for each of eight fields of calibration. As a result, the eight Technical Guides were incorporated into a draft Handbook 150-2, *Calibration Laboratories Technical Guide*, covering the fields being offered for accreditation. [In 2000, Handbook 150-2 (draft) was divided into eight handbooks, one for each calibration area.]

The need for technical experts to serve as assessors was advertised, and the first group of assessors was selected and trained during a four-day session held from November 16 through 19, 1993, in Gaithersburg, using materials developed by NVLAP.

The Calibration Laboratories Accreditation Program officially began accepting applications when notification was given in the *Federal Register* dated May 11, 1994. Applications are accepted and processed following the procedures found in NIST Handbook 150.

1.4 References

1.4.1 The following documents are referenced in this handbook.

a) NIST Handbook 150, *NVLAP Procedures and General Requirements*; available from:

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National Institute of Standards and Technology
100 Bureau Drive, Stop 2140
Gaithersburg, MD 20899-2140

Phone: (301) 975-4016
Fax: (301) 926-2884
E-mail: nvlap@nist.gov
NVLAP Web site: http://www.nist.gov/nvlap

b) ISO/IEC/BIPM (BIPM is the Bureau International des Poids et Mesures, the International Bureau of Weights and Measures) *Guide to the Expression of Uncertainty in Measurement* (GUM), 1993.

c) ISO/IEC 17025: 1999: *General requirements for the competence of testing and calibration laboratories*.

d) ISO/IEC Guide 43: 1997, *Proficiency testing by interlaboratory comparisons, Part 1 and Part 2.*

e) ISO/IEC/BIPM *International Vocabulary of Basic and General Terms in Metrology* (VIM), 1993.

ISO documents b) through e) are available from:

Global Engineering Documents (paper copies)
Order phone: (800) 854-7179

American National Standards Institute (ANSI) (electronic copies)
Electronic Standards Store
ANSI web site: http://www.ansi.org

f) ANSI/IEEE Std. 100-1996, *IEEE Standard Dictionary of Electrical & Electronics Terms.*

g) NIST Technical Note 1297, *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results.* Available on-line at http://physics.nist.gov/Document/tn1297.pdf.

h) NCSL Recommended Practice RP-15: *Guide for Interlaboratory Comparisons*, 1999.

i) ANSI/NCSL Z540-1-1994, *Calibration Laboratories and Measuring and Test Equipment—General Requirements.*

j) NCSL Recommended Practice RP-7: *Laboratory Design*, 1993.

NCSL documents h) through j) are available from:

NCSL International
2995 Wilderness Place, Suite 107
Boulder, CO 80301-5404
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Fax: (303) 440-3384
E-mail: orders@ncsli.org
Web site: http://www.ncsli.org

k) Ehrlich, C. D. and Raspberry, S. D., "Metrological Timelines in Traceability," *J. Res. Natl. Inst. Stand. Technol.* **103**, 93 (1998).

l) Croarkin, M. C., *Measurement Assurance Programs, Part II: Development and Implementation*, NBS Special Publication 676-II (U.S. Government Printing Office, Washington, DC, 1985).

1.4.2 Additional references specific to electromagnetic dc/low frequency measurements are listed in Section 2.

1.5 Definitions

Definitions found in NIST Handbook 150 apply, but may be interpreted differently or stated differently, when necessary to amplify or clarify the meaning of specific words or phrases as they apply to specific technical criteria.

Electrical/electronic terminology is consistent with ANSI/IEEE Std. 100, *IEEE Standard Dictionary of Electrical & Electronics Terms*. Other terms with meanings specific to this document are defined below.

1.5.1 Calibration transfer: A comparison of two measurement systems or standards either directly or via a transport standard for the purpose of calibrating, or assigning values to one in terms of the other.

1.5.2 Control environment: A controlled environment provided locally to mitigate the effects of ambient conditions on the performance of a standard, by for example, a thermostatted oven as a standard cell enclosure.

1.5.3 Evaluation transfer: A comparison of the performance of two measurement systems either directly or via a transport standard for the purpose of evaluating their equivalence.

1.5.4 Josephson array: Two or more Josephson junctions in series.

1.5.5 Josephson array standard: A Josephson array and its accompanying support and measurement system (Josephson array system).

1.5.6 Josephson array system: The auxiliary apparatus including switches, cables, waveguide, instrumentation, operator, software (where applicable), and any other hardware required to operate a Josephson array properly and use it to perform measurements outside its cryostat.

1.5.7 Manufacturer's stated accuracy: Generalized statement or collection of statements describing the qualitative performance of an instrument under very broad conditions. (These statements sometimes contain such terms as "typical" or "nominal" accuracy, where accuracy is a qualitative term.) Such statements are made by the manufacturer for sales or warranty purposes, or by the user to facilitate categorizing the instrument within an inventory or making broad statements regarding its suitability for use in making a particular measurement.

Use of this terminology does not excuse the laboratory from demonstrating, through uncertainty analysis, that it has adequate measurement capability to perform the measurement needed either to assign values or corrections to standards or to verify the performance of instruments and standards it is responsible for calibrating.

1.5.8 Nominally equal: Within 5×10^{-4} of equality.

1.5.9 Proficiency testing: Determination of laboratory performance by means of comparing and evaluating calibrations or tests on the same or similar items or materials by two or more laboratories in accordance with predetermined conditions. For the NVLAP Calibration Laboratories Accreditation Program, this entails using a transport standard as a measurement artifact, sending it to applicant laboratories to be measured, and then comparing the applicant's results to those of a reference laboratory on the same artifact.

1.5.10 Situation 1: Calibration of high-accuracy standards using an intrinsic standard or system.

1.5.11 Situation 2: Calibration of secondary standards in circumstances where attainment of a four-to-one ratio between the manufacturer's stated accuracy of the secondary standard and that of the reference standard (other than an intrinsic standard or system) is made impossible by the demanding specifications of the former.

1.5.12 Situation 3: Calibration of working standards or instruments in circumstances where attainment of a four-to-one ratio between their manufacturers' stated accuracies and that of the scaling standard combined with that of the secondary or reference standard (other than an intrinsic standard or system) is made impossible by the demanding specifications of the former.

1.5.13 Situation 4: Any calibration situation where the ratio of the manufacturers' stated accuracies of the calibration workload to that of the working standard equals or exceeds four to one.

1.5.14 Standard, scaling: A ratio standard, which may be self-calibrating, used with reference or secondary standards to calibrate working standards or instruments over a large range of voltages.

1.5.15 Standard, solid-state: A complete instrument in one box that is based on a solid-state reference, is powered by the ac mains or internal batteries, and continuously produces one or more stable voltages. The solid-state reference is a semiconductor device or ensemble of devices such as a temperature-compensated Zener diode, a band-gap device, or a reference amplifier.

1.5.16 Standard, transport: A standard especially designed to be minimally affected by the rigors of transportation or by laboratory influence factors, and to have very predictable behavior over a period of time adequate for the evaluation of one measurement system in terms of another (its long-term stability may be sacrificed for ruggedness).

1.5.17 Standard, working: A multiple-valued standard, such as a precision digital voltmeter or calibrator, used for the calibration of a substantial workload; it may be calibrated in terms of scaling standards and either reference or secondary standards.

1.5.18 Traceability: Property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties. [See reference 1.4.1 e), section 6.10.]

A single measurement intercomparison is sufficient to establish uncertainty relationships only over a limited time interval (see reference 1.4.1 k)); internal measurement assurance (see reference 1.4.1 l)), using control (check) standards, is required to fully demonstrate that uncertainties remain within stated levels over time. For the purposes of demonstrating traceability for NVLAP accreditation, a laboratory must demonstrate not only that there is an unbroken chain of comparisons to national standards, but also that this chain is supported by appropriate uncertainties, measurement assurance processes, continuous standard maintenance, proper calibration procedures, and proper handling of standards. In this way, traceability is related to these other areas of calibration.

1.6 NVLAP documentation

1.6.1 Accreditation documents

Laboratories granted NVLAP accreditation are provided with two documents: Scope of Accreditation and Certificate of Accreditation.

The Scope of Accreditation lists the "Best Uncertainty" that an accredited laboratory can provide for a given range or nominal value within a given parameter of measurement. This "Best Uncertainty" is a statement of the smallest uncertainty that a laboratory has been assessed as capable of providing for that particular range or nominal value. The actual reported value of uncertainty for any particular measurement service that the accredited laboratory provides under its scope may vary depending on such contributors as the statistics of the test and uncertainties associated with the device under test.

1.6.2 Fields of calibration/parameters selection list

The Calibration Laboratories program encompasses eight fields of physical metrology calibration, with multiple parameters under each field. Each field is covered by a separate handbook (NIST Handbooks 150-2A through 150-2H). (Fields of accreditation under Chemical Calibration are covered by separate handbooks.) Depending on the extent of its calibration capabilities, a laboratory may seek accreditation to all or only selected fields and parameters within the scope of the program. The fields of calibration and their related parameters are given on the Fields of Calibration and Parameters Selection List, which is provided to a laboratory seeking accreditation as part of the NVLAP application package for the program. Additional fields of calibration and/or parameters may be added to the Calibration Laboratories program upon request of customer laboratories and/or if decided by NVLAP to be in the best interest of the Calibration Laboratories program.

The laboratory is requested to indicate on the Fields of Calibration/Parameters Selection List the parameter(s) for which accreditation is desired, along with appropriate ranges and uncertainties. There is also provision for an applicant laboratory to request accreditation for parameters not currently listed on the Selection List, or for accreditation of the quality system employed for assuring Measurement and Test Equipment (M & TE) used in support of product certification. Request for accreditation of quality assurance systems for M & TE will be treated as a separate field of calibration for the purpose of setting appropriate fees. Once a laboratory meets all the requirements for accreditation for the Fields of Calibration/Parameters Selection List, this information will become the basis for the Scope of Accreditation document.

1.6.3 Checklists

Checklists enable assessors to document the assessment of the laboratory against the NVLAP requirements found in NIST Handbook 150. The NVLAP Calibration Laboratories Accreditation Program incorporates the NVLAP General Operations Checklist. The questions are applicable to evaluating a laboratory's ability to operate a calibration program, and address factors such as the laboratory's organization, management, and quality system in addition to its calibration competency.

The NVLAP General Operations Checklist is numbered to correspond to the requirements in NIST Handbook 150. Comment sheets are used by the assessor to explain deficiencies noted on the checklist. Additionally, the assessor may use the sheets to make comments on aspects of the laboratory's performance other than deficiencies.

1.7 Assessing and evaluating a laboratory

1.7.1 On-site assessment

1.7.1.1 The NVLAP lead assessor will schedule with the laboratory the date for on-site evaluation, and will request the quality manual and documented quality and calibration procedures in advance of the visit to reduce time spent at the laboratory; such materials will be returned by the assessor. NVLAP and the assessor will protect the confidentiality of the materials and information provided. The laboratory should be prepared to conduct routine calibrations, have equipment in good working order, and be ready for examination according to the guidance contained in this handbook, the requirements identified in NIST Handbook 150, and the laboratory's quality manual. The assessor will need time and work space to complete assessment documentation while at the laboratory, and will discuss these needs at the opening meeting of the on-site assessment.

1.7.1.2 NVLAP technical assessors are provided with the NVLAP General Operations Checklist to help ensure the completeness, objectivity, and uniformity of the on-site assessment.

1.7.1.3 When accreditation has been requested for a considerable number of fields of calibration and parameters, the assessment may range from observing calibrations in progress, requiring repeat measurements on completed calibrations, to listening to laboratory staff describe the calibration process. The depth into which the assessor performs the assessment depends on the number of fields of calibration and associated parameters for which accreditation is requested and the time required to perform a given calibration.

1.7.1.4 The assessor, or the assessment team, does the following during a typical on-site assessment:

a) Conducts an entry briefing with the laboratory manager to explain the purpose of the on-site visit and to discuss the schedule for the day(s). At the discretion of the laboratory manager, other staff may attend the briefing.

b) Reviews quality system manual, equipment and maintenance records, record-keeping procedures, laboratory calibration reports, and personnel competency records. At least one laboratory staff member must be available to answer questions; however, the assessor may wish to review the documents alone. The assessor(s) does not usually ask to take any laboratory documents with him/her, and previously supplied documents will be returned.

c) Physically examines equipment and facilities, observes the demonstration of selected procedures by appropriate personnel assigned to perform calibrations, and interviews the personnel. The demonstrations must include preparation for calibration of devices, and the setup and use of measuring and test equipment, standards and systems.

d) Holds an exit briefing with the laboratory manager and staff to discuss the assessment findings. Deficiencies are discussed and resolutions may be mutually agreed upon. Items that must be addressed before accreditation can be granted are emphasized, and outstanding deficiencies require response to NVLAP within 30 days. Items that have been corrected during the on-site and any recommendations are specially noted.

e) Completes an On-site Assessment Report, as part of the exit briefing, summarizing the findings. The assessor(s) attaches copies of the completed checklists to this report during the exit briefing. The report is signed by the lead assessor and the laboratory's Authorized Representative to acknowledge the discussion. This signature does not necessarily indicate agreement; challenge(s) may be made through NVLAP. A copy is given to the representative for retention. All observations made by the NVLAP assessor are held in the strictest confidence.

1.7.2 Proficiency testing

1.7.2.1 Background

Once the quality system review and on-site assessment steps have been satisfactorily completed, it is necessary to gather another set of data points to aid in deciding whether or not the applicant laboratory is competent to perform calibrations within the fields of interest to the uncertainties claimed. In the eight fields of calibration covered by Handbooks 150-2A through 150-2H, there are approximately 85 parameters of interest. Under most parameters there are several subsets, referred to as ranges. For example, in the electromagnetic dc/low frequency field, the dc resistance parameter can range from 0.001 Ω up to the terraohm (1 x 10^{12} Ω) level in decade values. When considering all possible ranges, there are thousands of areas in which proficiency testing can be conducted. NVLAP reserves the right to test by sampling in any area; hence, applicant laboratories must be prepared, with reasonable notice, to demonstrate proficiency in any of a number of parameters.

1.7.2.2 Proficiency testing vs. measurement assurance

There is an important difference between proficiency testing and measurement assurance. The objective of proficiency testing is to determine through a measurement process that the laboratory's measurement results compare favorably with the measurement results of the audit laboratory (NIST or one designated by NVLAP), taking into account the relative uncertainties assigned by both the applicant and audit laboratories. The objective of proficiency testing is not to determine and certify the total uncertainty of the applicant laboratory, as is done in a Measurement Assurance Program (MAP) with NIST, but to verify (through the assessment process) that the uncertainty claimed by the applicant laboratory is reasonable, and then use the claimed uncertainty to test that the measurement result obtained through the proficiency test is acceptable.

It is neither the intention nor the mission of NVLAP to conduct MAPs or to otherwise provide traceability for laboratories. Laboratories obtain these services from the NIST measurement divisions. NVLAP assesses the implementation, application, and documentation of MAPs by laboratories. NVLAP accreditation encourages the use of MAPs by the calibration laboratory community, and MAP results produce objective evidence that NVLAP assessors look for as part of the assessment process.

1.7.2.3 Requirements

NVLAP's proficiency testing program uses a sampling approach. All applicant laboratories are required to complete an annual proficiency test in one parameter under each field of calibration for which it has applied to be accredited. For the purposes of the NVLAP Calibration Laboratories Accreditation Program, the results of the proficiency test are considered as objective evidence, along with the on-site visit, of a laboratory's ability to perform competent calibrations. Proficiency testing is conducted annually using different parameters in each field; however, those laboratories accredited in only one parameter within a field are retested in the same parameter.

1.7.2.4 Uncertainty determination

The applicant laboratory is required to perform a measurement or series of measurements on an artifact using the same calibration method, apparatus, and personnel that it uses to calibrate its customers' equipment. The laboratory must be able to identify and quantify all sources of uncertainty that affect the measurement. The laboratory should attach an overall uncertainty to the measurement by combining all uncertainty contributions, in their type A and type B components, in the root-sum-squared method as described in the *Guide to the Expression of Uncertainty in Measurement* (see reference 1.4.1 b)). The confidence limit used should be k = 2, which is equivalent to a 95 % confidence probability.

1.7.2.5 Pass/fail criteria

The performance of the proficiency test is judged by calculating the error of the measurement, normalized with respect to the uncertainty of the measurement, using the following equation:

$$E_{normal} = \left| (Value_{lab} - Value_{ref}) / (Uncertainty_{ref}^2 + Uncertainty_{lab}^2)^{1/2} \right|$$

where

E_{normal} = normalized error of the applicant laboratory
$Value_{lab}$ = the value as measured by the applicant laboratory
$Value_{ref}$ = the value as measured by the reference laboratory
$Uncertainty_{ref}$ = the uncertainty of the reference laboratory
$Uncertainty_{lab}$ = the uncertainty of the applicant laboratory

To pass the proficiency test, the applicant laboratory must have a value for E_{normal} less than 1 (i.e., $E_{normal} < 1$). The results may be plotted graphically, with lines representing the limits of uncertainty of the measurements. The anonymity of each applicant laboratory will always be preserved.

1.7.2.6 Scheduling and handling

Proficiency testing is scheduled by NVLAP-designated reference laboratories. These sites are NIST laboratories or NVLAP-accredited laboratories that have been found to have the ability to perform the required proficiency tests to an uncertainty level appropriate for the laboratories they evaluate. The proficiency test is scheduled independently and not to correspond with the on-site visit. Applicant laboratories are notified in advance as to the approximate arrival time of the measurement artifact. Instructions for performing the test, reporting the results, communicating with the reference laboratory, and shipping are included along with the artifact as part of the proficiency test package. Applicant laboratories are instructed to perform all required measurements within a reasonable time and are told where to ship the artifacts once the testing has been completed.

1.7.2.7 Notification of results

NVLAP notifies each laboratory of its own results in a proficiency test. If a laboratory has been evaluated prior to the completion of the proficiency test, the status of that laboratory's accreditation is contingent upon successful completion of proficiency testing. The laboratory's accreditation status may be changed to reflect a partial accreditation, or may be completely suspended pending demonstration of the laboratory's ability to successfully complete the proficiency test at a later date.

1.7.3 Traceability

1.7.3.1 Establishing traceability

Laboratories must establish an unbroken chain of comparisons leading to the appropriate international or national standard, such that the uncertainties of the comparisons support the level of uncertainty that the laboratory gives to its customers. Generally speaking, the uncertainties of the comparisons increase as they move from a higher (international or national level) to a lower level standard. This uncertainty chain is the evidence of traceability and must be documented accordingly. Traceability does not simply mean having standards calibrated at the national laboratory, but must consider how a measurement, with its corresponding uncertainty, is transferred from the national level to the calibration laboratory's customers.

1.7.3.2 Considerations in determining traceability

Without some type of measurement assurance process, one cannot be reasonably certain that the comparisons have been transferred properly to the laboratory's customers. The measurement process itself must be verified to be in control over time. Therefore, traceability is not a static concept that, once established, may be ignored; it is dynamic. Process control exercised in each calibration provides the assurance that a valid transfer of the international or national standard has taken place. This assurance may be accomplished through the use of tools such as check standards and control charts. Also, the laboratory's primary standards must be maintained in such a way as to verify their integrity. Examples of this may be

1) having more than one primary standard to use for intercomparisons,
2) monitoring the primary standard with a check or working standard (looking for changes), and
3) verifying a primary standard on a well-characterized measurement/calibration system.

Using scientifically sound measurement procedures to transfer the primary standard value to the working level and the customer's item is essential to establishing traceability. If the procedure itself yields the wrong result, there is no way the laboratory can perform a calibration traceable to the international or national standard. Handling the laboratory's standards affects the measurement process, and therefore the ability to transfer the standard's value to the customer. Examples of handling problems are

1) dirty or improperly cleaned standards,
2) maintaining standards in an improper environment,
3) not maintaining custody and security, and
4) improper handling of standards during the measurement process.

1.7.3.3 Relationship to existing standards

The above discussion illustrates how traceability is dependent on many aspects of the measurement process and therefore must be considered in all phases of calibration. It is not just coincidental that the factors addressed above are main topics of concern in ISO/IEC 17025:1999.

1.7.4 Uncertainty

NVLAP recognizes the methodology for determining uncertainty as described in the *Guide to the Expression of Uncertainty in Measurement*, published by ISO. To be NVLAP-accredited, a laboratory must document the derivation of the uncertainties that it reports to its customers. These uncertainties will appear on the scope issued to each accredited laboratory to an accuracy appropriate to the standards, procedures, and measuring devices used.

2 Criteria for accreditation

2.1 Introduction

2.1.1 Applicant laboratories are assessed using the requirements in NIST Handbook 150, *NVLAP Procedures and General Requirements*. This guide, NIST Handbook 150-2A, was developed from a NIST measurement laboratory perspective and provides examples and guidelines, not requirements, to assessors and interested calibration laboratories on good laboratory practices and recommended standards. Therefore, the guide language reflects this philosophy through the use of "shoulds" instead of "shalls" (along with other less prescriptive language) when describing criteria. The requirements presented here are not absolute since specific requirements depend on the measurement uncertainty for which an applicant laboratory wishes to be accredited. This is a business decision for each laboratory and beyond the scope of NVLAP. Simply stated, to be accredited, an applicant laboratory must have a quality system and be able to prove (and document) that it is capable of doing what it says it does (i.e., correctly calibrate to a stated uncertainty) within the framework of NIST Handbook 150. Accreditation will be granted, and therefore may be referenced in calibration reports, etc., only for those specific parameters, ranges and uncertainties using calibration methods and procedures for which a laboratory has been evaluated. Calibrations performed by a laboratory using methods and procedures not considered appropriate for the level of measurements being made, and which have not been evaluated by the accreditation process, are outside the scope of accreditation and may not be referenced as "accredited" calibrations on calibration reports, etc.

2.1.2 Sections 2.2 through 2.15 provide specific interpretations of the NIST Handbook 150 criteria for electromagnetic dc/low frequency measurement calibration laboratories. This guide is dynamic in that new parameters may be added and existing criteria updated and improved.

2.2 Areas of commonality among all dc/low frequency parameters

2.2.1 Background

A given laboratory in the electromagnetic dc/low frequency area of calibration can rely on one or more of a number of different standards types, depending upon the nature of the calibrations to be performed, the calibration volume, and the levels of measurement uncertainty required. The laboratory's standards may have values assigned as the result of calibrations, MAP services, or measurements involving intrinsic standards. At all except the highest accuracy levels, standards or instrumentation are available whose performance exceeds the demands for accuracy of the calibration process by such a large margin that only minimal quality assurance techniques are required to ensure the adequacy of the standard. At the highest accuracy levels, instrumentation is specified to be so close in performance to the standards themselves that considerable effort is required to ensure both that the standards are behaving properly and that the instrumentation used to compare the standards with the units being calibrated has adequate uncertainty, resolution, and precision for the task.

2.2.2 Scope

2.2.2.1 This section contains specific technical criteria in accordance with which a laboratory should demonstrate that it operates, if it is to be recognized as competent to carry out electromagnetic dc/low frequency calibrations.

2.2.2.2 This section may also be used as a guide by calibration laboratories in the development and implementation of their quality systems.

2.2.2.3 To cover the complexity of the calibration process in going from the highest to the lowest accuracies, this section will treat four distinct types of calibration situations:

a) **Situation 1:** Calibration of high-accuracy standards using an intrinsic reference standard or system.

b) **Situation 2:** Calibration of secondary standards in circumstances where attainment of a four-to-one ratio between the manufacturer's stated accuracy of the secondary standard and that of the reference standard (other than an intrinsic standard or system) is made impossible by the demanding specifications of the secondary standard.

c) **Situation 3:** The similar situation where working standards or instrumentation are being calibrated.

d) **Situation 4:** The situation where a four-to-one ratio or higher is readily attainable.

2.2.2.4 In laboratories where calibrations of the highest accuracies are performed, all four types may exist; in laboratories where instruments of only modest accuracy are calibrated, only the last is likely to be encountered. It should be noted that each of these situations requires skills and knowledge different from the others, and, therefore, demonstrated competence in one may not be sufficient to guarantee adequate performance in the others.

2.2.3 Quality system

2.2.3.1 Items specified in this section are minimum recommendations for accreditation for the applications noted, and evidence pertaining to each should be available for review.

2.2.3.2 Situation 1 (Intrinsic standard or system as a standard)

a) General recommendations for monitoring measurement quality include:

1) Either/or:

a. Direct intrinsic standard or system-to-intrinsic standard or system comparison with NIST or another accredited laboratory under conditions set forth in Situation 1 under Measurement Traceability and Calibration

b. Indirect system-to-system comparisons using appropriate transport standards (reduced uncertainty).

2) Calibration history of device used to measure differences between intrinsic standard or system and unknown values.

3) Calibration history of the intrinsic standard or system components (for example, the time base of the reference frequency counter in a Josephson voltage array system).

4) Evidence of system to check periodically on system precision and stability (for example, leakage currents, ground loops, thermal emf's, step integrity, trapped magnetic flux, noise, and microwave power impinging on a Josephson voltage array).

5) Laboratory environmental monitoring.

b) When an intrinsic standard or system is used for calibration of working standards (for example, zener voltage standards calibrated with Josephson voltage array), additional recommendations include:

   1) Control charts on appropriate check standard(s).

   2) Data analysis on workload.

c) When an intrinsic standard or system is used for the calibration of working standards requiring a secondary transfer of measurements (for example, calibration of standard cells and solid-state standards at 1.02 V using a Josephson voltage array), additional recommendations include:

   1) Control charts on secondary check standards (saturated standard cell bank used as check standard).

   2) Data analysis on workload and transfer standard (zener voltage standard in the example).

d) When an intrinsic standard or system is used for the calibration of test equipment (for example, digital voltmeters and calibrators up to 10 V), additional recommendations include:

   1) Control charts on test equipment and transfer standard used as check standards.

   2) Data analysis on workload.

2.2.3.3 Situation 2 (Calibrations of secondary standards at accuracies where four-to-one manufacturer's stated accuracy ratios cannot be met or exceeded)

General recommendations for monitoring measurement quality include:

a) An active process for maintaining check standards on a regular basis.

b) Redundant measurements for statistical control of precision.

c) A system for checking independence from operator effects.

2.2.3.4 Situation 3 (Calibrations of working standards or instruments at accuracies where four-to-one manufacturer's stated accuracy ratios cannot be met or exceeded)

General recommendations for monitoring measurement quality include:

a) Single value check standards.

b) Evaluation of scaling processes.

c) Like-item check standards.

d) A system for checking independence from operator effects.

2.2.3.5 Situation 4 (Calibrations at accuracies where four-to-one manufacturer's stated accuracy ratios are met or exceeded)

General recommendations for monitoring measurement quality include:

a) A history of the standard.

b) A system to ensure the integrity the of standard (mechanism for ensuring no significant loss of accuracy due to transport, if applicable).

c) A system for checking independence from operator effects.

2.2.4 Personnel

2.2.4.1 Those with technical responsibility for electromagnetic dc/low frequency calibrations should have one or more of the following:

a) Formal statistics training including concepts of randomness; understanding of results of t-tests, F-tests, and linear regression; rudiments of experimental design; and error analysis.

b) Ready access to a statistician specializing in experimental data analysis.

c) A permanent, trained quality-assurance specialist on the staff.

2.2.4.2 The laboratory should provide training in elementary statistics to all personnel engaged in data reduction for Situations 1, 2, and 3. Technicians making measurements need a good understanding of basic electrical principles and those factors which influence measurements and measurement results.

2.2.4.3 The intrinsic standard or system operator should be trained on a NIST intrinsic standard or system or one in an accredited laboratory, with 3 or 4 days of hands-on experience, and should have expertise in electronics, cryogenics (if appropriate), and computer usage. Professional support should include someone with strong physics background and experimental skills.

2.2.4.4 Personnel responsible for calibrations of secondary and working standards and instruments of the highest accuracy should have good experimental skills and understand low-level measurements, including factors affecting measurement sensitivity and accuracy.

2.2.4.5 In addition to the provisions listed above under secondary and working standards, personnel responsible for calibration of lower level standards and test equipment should understand the metrological, chemical, and thermal properties of the items under test and their interaction with circuits and instrumentation.

2.2.5 Accommodation and environmental conditions

2.2.5.1 Environment

The environment (acoustic noise, dust, lighting, relative humidity, temperature, and vibration) of the calibration laboratory should be controlled according to applicable provisions of NCSL Recommended Practice RP-7, with the exception that relative humidity should have a maximum value of 55 % (see 1.4.1 j)). Temperature and relative humidity should be recorded on a continuous or sampled basis; records of abnormal conditions (as a minimum) should be retained for a period to be determined by the laboratory, but no less than one year.

2.2.5.2 Electrical power

The quality of electric mains supplying power for instrumentation should be in compliance with applicable provisions of NCSL Recommended Practice RP-7; or alternatively, these provisions may be met through the use of uninterruptible power supplies.

2.2.5.3 Grounds

For circumstances outlined above, a dc instrumentation ground is required. This ground should meet or exceed the specifications given in NCSL Recommended Practice RP-7.

2.2.5.4 Electromagnetic interference

Electrical and magnetic fields should be controlled to be in compliance with the provisions of NCSL Recommended Practice RP-7.

2.2.6 Measurement traceability

2.2.6.1 Situation 1

a) For circumstances requiring measurement uncertainties approaching that of NIST, an evaluation transfer employing a portable intrinsic standard or system to compare the system's measurements with those of the system used at NIST for the U.S. representation or to another, similar intrinsic standard whose use has been accredited should be made:

1) Prior to initial accreditation;

2) Upon the change of personnel responsible for the operation of the system;

3) Following any significant change in the system structure; and

4) Immediately following any measurement problem revealed by check standard data and not proven to be a problem inherent to the check standard(s).

b) For circumstances requiring measurement uncertainties in a range sufficiently above the NIST uncertainty, evaluation transfers using well-characterized transportable transfer standards to compare the system's measurements with those of the NIST system used for the U.S. representation, or another, similar intrinsic standard whose use has been accredited, may be used.

2.2.6.2 Situation 2

a) Traceability should be established for the reference standard through the use of a carefully evaluated transport standard to be calibrated at NIST or at an accredited laboratory having an intrinsic standard or system as a reference standard. Except under extraordinary conditions, the reference standard should not be removed from the laboratory and should be maintained continuously at operational environmental conditions to sustain traceability.

b) Calibration transfers should be made at least annually for the first 5 years of use of the reference standard or until a sufficient history of data can be accumulated to support the use of a longer interval between transfers.

c) After an appropriate data history is accumulated, a statistical model of the behavior of the reference standard should be developed and used to assign its values and their uncertainties. This model is to be verified on a regular basis via calibration transfers and by rigorous analysis of the behavior of the reference standard, the transport standard, and the check standards from both statistical and metrological points of view. This process, with a regular re-evaluation of all components of measurement uncertainty involved, should constitute traceability for this situation.

2.2.6.3 Situation 3

a) Provisions of Situation 2 are applicable.

b) Additionally, provisions for scaling to the limits of parameters covered from those provided by the reference or secondary standard should be subjected to the same types of calibration and statistical control with the exception that scaling techniques or standards may be verified by self-comparison or "boot-strap" techniques, where appropriate, in lieu of extra-laboratory calibrations. The use of such techniques should be rigorously and formally analyzed and the analyses documented.

2.2.6.4 Situation 4

The reference standards should be calibrated on a regular basis at NIST or by any accredited calibration laboratory with capability adequate to sustain the uncertainties required of them.

2.2.7 Test and calibration methods and method validation

2.2.7.1 The measurement methods that are used should eliminate or take into account the following effects at a level of precision sufficient to comply with the requirements of the calibration: thermal emf's; leakage currents; electrostatic interference; electromagnetic interference; instrument offsets; and short-term temperature, relative humidity, and air pressure fluctuations.

2.2.7.2 There are essentially three approaches to calibration under Situations 2 through 4, depending on the level of uncertainty to which the metrologist is working. These approaches are independent of the physical or parametric characteristics of the test item(s). The three approaches are:

a) Direct intercomparison of standard(s) and unknown(s).

b) Measurement of unknown(s) on a system characterized against standard(s).

c) Measurement of unknown(s) using standard(s) with smaller uncertainties (four-to-one rule of thumb).

2.2.7.3 This section describes each approach and provides guidance concerning the expression of the resulting total uncertainty. The aim is to provide insight into the process by which an assessor can determine whether or not the approach is valid for any given application, and then to assess whether or not the stated uncertainty and its associated traceability have been satisfactorily achieved.

a) Direct intercomparison

   1) Some typical measurement parameters using this approach include: capacitance (using ac bridges), voltage (using direct opposition), and resistance (using current comparator bridges). In this process, the unknown is measured either directly or indirectly (using correction factors) with respect to the known value of the standard(s). The degree to which the standard is actually known, along with transfer uncertainties arising from the act of measurement, determines the uncertainty in measurement of the unknown. This technique is prevalent in higher echelon laboratories such as

those obtaining values for their standards from NIST, and usually results in the achievement of a total measurement uncertainty relatively close to that which NIST reports on its certificate as total NIST uncertainty. This is due to the fact that the performing laboratory goes to great lengths to quantify Type A (evaluated by statistical methods) and Type B (evaluated by other means) uncertainties through a rigorous program of statistical process control (SPC) involving much data gathering and reduction. The comparator is maintained in control through the use of control charts which are analyzed continuously as part of the measurement process (experiment).

2) Critical to determining the suitability of this process is the understanding of the measurement scheme (multiple standards versus multiple unknowns, the ability of the measurement design to identify or eliminate measurement effects such as reversal error, left-right effect, etc.), and the statistical techniques employed (Student t and F testing, standard deviation computation, coverage factor used, etc.).

3) It is important to state again that the process remains unchanged regardless of the parameter(s) being measured, and the assessor should have a clear understanding of the quantification of Type A and B uncertainties as they are combined into total uncertainty for the purpose of reporting. In all cases, the policy and procedures of the ISO *Guide to the Expression of Uncertainty in Measurement* will be complied with. Finally, the total uncertainty will be specified using a coverage factor of two on the report of calibration.

4) An example of the quantification and enumeration of an uncertainty budget for this type of measurement is shown as Example H.1, End-gage calibration, at Annex H of the ISO *Guide to the Expression of Uncertainty in Measurement.*

b) Unknowns measured on a characterized system

1) In this technique, a measurement system is characterized by a systematic analysis of the results which it produces when used to measure a standard or group of standards. In some cases, where it is determined that there are short term systematic errors present, these are often "calibrated" or adjusted out so that the system reads correctly when a standard is measured. One should be careful to ensure that the systematic error is quantifiable both in magnitude and direction. In many cases, such as with vector quantities (magnitude and phase) found in many ac measurements, the magnitude (real plus imaginary components) of the offset may not be subtracted arithmetically. In those cases, the system is verified to read within an uncertainty band before the system is certified to be capable of reading the unknown to the desired uncertainty.

2) Having standardized the measurement system, the unknown(s) are measured taking enough redundant measurements to develop an estimate of system randomness which is added as a Type B component to the uncertainty band appropriate to the measurement system.

3) These systems are usually comprised of several stimulus and measurement components which, though all candidates for individual calibration, usually are not maintained on a periodic recall schedule for calibration. If the system is documented properly, it should be readily apparent to the assessor that the individual items in fact do not require individual calibration as long as the system is maintained in measurement process control through the use of reference and check standards and appropriate control chart analysis and corrective action. If this is the case, the appropriate components should be identified as not requiring periodic calibration, and that they are verified upon performance of the system standardization process.

4) As in the first case, all levels of management should be committed to the chosen method of standardization and uncertainty determination as clearly specified in the quality manual. It should be explainable to the assessor, and all control charts and other supporting measurement data should be readily available for on-site assessment.

c) Test accuracy ratio or test uncertainty ratio methods

1) In this process, an unknown used to make measurements of relatively large specified uncertainty, referred to as the "tolerance," is verified to perform within that tolerance by comparison with a standard or standards capable of much smaller measurement uncertainty compared to the tolerance (at least 1/4 the tolerance of the unknown). The probability of incorrectly measuring the unknown without correcting for the uncertainty component of the standard, as being either within tolerance when it is in fact not, or out of tolerance when it is actually within, is very low (unlikely) when the standard(s) is at least four times less uncertain than the tolerance of the unknown. This is referred to as a test accuracy ratio (TAR) of four-to-one; even better is a TAR of ten-to-one in terms of safety in reporting the measured value of the unknown without applying any corrections for the uncertainty of the standard(s).

   Using a test uncertainty ratio (TUR), the uncertainty of the measurement must be 4 times better (or more) than the measurement uncertainty of the instrument being calibrated.

2) Some examples of this type of testing are calibrations of high uncertainty working standards (1 % to 10 % as opposed to 0.1 % or 4×10^{-6}, etc.) such as power setting attenuators, multifunction meters, calibrators (some are more accurate than others), etc. The assessor should be made fully aware of the measurement requirement by statements in the quality manual. In addition, valid test procedures should contain, or be accompanied by, easily understood matrices showing the relative uncertainties of the measurement of the device under test and the specified accuracy of stimulus or measurement devices (test and measuring equipment) used.

3) In assessing competence in this field of calibration, particular attention should be given to the calibration status of measuring and test equipment (M & TE) being used, documentation and approval of calibration procedures, technical qualifications and training of the metrologist(s) and documentation of test results. It is impossible to verify to the assessor's complete satisfaction every possible combination of measurement parameters (e.g., voltage vs. frequency vs. voltage range vs. frequency range, etc.) that exist for all the different types of devices that may be encountered in a typical calibration laboratory. It is important that the assessor become convinced that the measurement philosophy as dictated by the quality manual is well established throughout the laboratory under evaluation, so that by sampling a representative number of calibration stations, confidence in the competency of the total operation is achieved.

2.2.8 Unique areas of concern

The following sections (2.3 through 2.15) cover each of the metrology disciplines that comprise the electromagnetic dc/low frequency area, and provide specific guidance for assessors and laboratories.

2.3 Direct voltage

2.3.1 References

a) EN 45001: *General criteria for the operation of testing laboratories* (1989).

b) NCSL Recommended Intrinsic/Derived Standards Practice RISP-1: *Josephson Voltage Standard* (1993).

c) Morrison, R., *Grounding and Shielding Techniques in Instrumentation*, John Wiley & Sons, New York, 1967.

d) Bertone, G. A., et al, "Elimination of the Anomalous Humidity Effect in Precision Capacitance Based Transducers," *IEEE Trans. Instrum. Meas.*, **40**, (6), pp. 897-901, Dec. 1991.

e) Braudaway, D. W., "Standards Laboratory Environments," *Sandia Report*, Sand90-1962 UCC90.

f) Field, B. F., "Solid-State Voltage Standard Performance and Design Guidelines," *NBS Tech. Note 1239*, September 1987.

g) Field, B. F., "Solid-State DC Voltage Standard Calibrations," *NBS Special Publication 250-28*, 1988.

h) Field, B. F., "Standard Cell Calibrations," *NBS Special Publication 250-24*, 1987.

2.3.2 Equipment

2.3.2.1 Table 1 gives an indication of the standards available to support dc voltage calibration processes and their best accuracy, range of use, and general application. A number of such standards types may be used in a single calibration system to support a variety of dc voltage accuracy levels.

2.3.2.2 Because of the large range of voltages covered by typical voltmeters, measurement systems based on Josephson arrays, standard cells, or solid-state standards must make complementary use of accurate means of scaling in order to provide full calibration support. Scaling techniques in general need not be traceable to national standards; on the other hand, to use them properly demands a high degree of knowledge and skill on the part of the laboratory staff, especially for measurements at the highest accuracies. These techniques are not generally useful to sustain a production calibration process directly because of the time consumed in their execution. They are universally used for the calibration of a working standard—a precision dc calibrator or digital voltmeter—which is then used to calibrate a large workload. The frequency of reverification of this working standard depends on the accuracy demands of the calibration workload and the performance with time of the working standard itself.

Table 1.
Examples of standards, uncertainties, ranges, and applications for dc voltage calibration processes.

Name	Best Specified Uncertainty, Value	Range	Application
Josephson array system	$<0.1 \times 10^{-6}$ at 1 V $<0.01 \times 10^{-6}$ at 10 V	200μV to 2.5 V for 1 V array; 200 μV to 11 V for 10 V array	Primary (intrinsic) standard for calibration of highest-accuracy artifacts (solid-state standards, standard cells), and linearity of precision digital voltmeters and calibrators.
Saturated standard cell	$<0.5 \times 10^{-6}$ at 1.02 V	1.02 V	Reference standard for calibration of other cells, solid-state standards, and instruments (at one point).
Solid-state standard	$<0.5 \times 10^{-6}$ at 10 V	1 V to 10 V (one to four fixed voltage values)	Calibration of calibrators and meters; transport standards for intercomparison of banks of standards (cells or solid-state standards); intermediary and check standards for Josephson array systems.
Calibrator	2×10^{-6} at 10 V	0.1 V to 1 kV	Calibration of large populations of digital meters, either automatically or manually.
Digital voltmeter (or multimeter)	4×10^{-6} at 10 V	10 mV to 1 kV	Calibration of less accurate DVM's or accurate sources; calibration of thermometers, other sensors.
Unsaturated standard cell	5×10^{-5} at 1.02 V	1.02 V	Calibration of low-accuracy meters; reference for classical potentiometers.

2.3.2.3 Saturated standard cells are extremely sensitive to temperature level and temperature changes. For measurements of the lowest uncertainties, temperature level effects should be compensated by converting the measured emf of the standards to that at a nominal temperature using the Wolff International Temperature Formula,

$$E(\theta) = E(20) - 40.6 \times 10^{-6} (\theta - 20) - 0.95 \times 10^{-6} (\theta - 20)^2 + 0.01 \times 10^{-6} (\theta - 20)^3$$

where E is the emf of a saturated standard cell and θ is the temperature in degrees Celsius, provided that the level change being compensated does not exceed 0.05 °C. This serves to eliminate or greatly reduce the effects of short-term temperature changes and allows the laboratory to better determine and control the behavior of the reference and check standards.

2.3.2.4 Because of the small reaction rates and large time constants of the chemical processes inside a standard cell, the cell's emf and its short-term stability are functions of the temperature history of the cell for the past 60 days or longer. Accordingly, means should be provided to maintain the temperature constant within 0.005 °C on a continuous basis to ensure against deterioration of the cell's performance for any measurements with required uncertainties of $\pm 1 \times 10^{-6}$ or better.

2.3.2.5 Auxiliary equipment

a) The auxiliary equipment used with a Josephson array voltage standard should at a minimum be comprised of equipment with performance equivalent to the items described in NCSL RISP-1, Chapters D and E (see 2.3.1 b)).

b) Table 2 indicates reference standards commonly used for the calibration of 10 V standards. Auxiliary equipment for use with a 10 V standard based on solid-state voltage standards for calibration of like-valued standards includes the following items. A calibrated meter or potentiometer and null detector with a minimum uncertainty and resolution at the $\pm 1 \times 10^{-4}$ level, capable of discriminating 0.1 µV and having a precision of ±0.08 µV or better should be used to measure the differences between the emf's of standards and references. A means of monitoring the temperature of the reference device(s) at the 0.1 °C level is required.

c) Table 3 indicates reference standards commonly used for the calibration of 1.02 V standards. Auxiliary equipment for use with a 1.02 V standard based on saturated standard cells for the calibration of like-valued standards includes the following items. A calibrated meter or potentiometer and null detector with a minimum uncertainty and resolution at the $\pm 5 \times 10^{-5}$ level, capable of discriminating 0.05 µV and having a precision of ±0.05 µV or better should be used to measure the differences between the emf's of standards and references for calibrations at accuracy levels of $\pm 2 \times 10^{-6}$ or better. For lower accuracies these requirements are relaxed, but instruments capable of discriminating at least 0.1 µV should be used. A means of monitoring the temperature of the standard cells at the mK level of resolution and stability is required.

d) Examples of typical auxiliary equipment for use with either 10 V or 1.02 V standards to perform calibrations throughout the range of voltages covered by the unit being calibrated, e.g., scaling or ratio standards, are given in Table 4.

e) Auxiliary equipment for use with instrumentation standards for calibrating a workload comprised of instruments for measuring or supplying the range of voltages covered by this document includes:

  1) For the case where both the reference and the item under calibration are voltmeters, a source capable of supplying dc voltages throughout the calibration range with a one-hour short-term stability at a level such that its effect on the calibration is at a minimum 10 % of the uncertainty sought.

  2) For the case where the reference is a calibrator and the item being calibrated is a voltage source such as another calibrator, the laboratory should either use a voltmeter or potentiometer with sufficient accuracy that the uncertainty of the measurement of the difference between the voltage of the reference and the nominally equal voltage of the unit being calibrated is less than 10 % of the accuracy requirement of the calibration, or a voltmeter or potentiometer whose linearity and stability are such that the uncertainty of the comparison of the voltage from the reference and a nominally equal voltage from the unit being calibrated does not exceed 10 % of the uncertainty requirement of the calibration.

Table 2. Reference standards commonly used for the calibration of 10 V standards.

Best Uncertainty	Minimum Standards Required	Remarks
$\leq 0.1 \times 10^{-6}$	10 V Josephson array standard	A Josephson array standard should be a system that includes one or more check standards at the 10 V level.
$\pm 0.5 \times 10^{-6}$	Four solid-state standards having individual control environments; or Two standards each comprised of three or more solid-state reference units, each set contained in an individual control environment; or Two groups of four each saturated standard cells, each group being contained in a separate oven, and an adequate, verifiable self-calibrating means of scaling to 10 V from 1.02 V	Only the 10 V outputs of the solid-state standards should be used. The solid-state device, amplifiers, ratio resistors, and other temperature-sensitive components upon which the stability of a solid-state standard is based should be contained in a oven having provision for monitoring the stability of its temperature with adequate precision to ensure proper performance of the standard. The "control environment" also includes the power supplies for the above. Provision should also be made for battery back-up power in the event of a failure of the power mains. The saturated standard cell groups should each be contained in an oven capable of controlling the temperature of the group to be constant within 0.002 K over a working day and within 0.01 K over a one-month period. The temperature should be capable of being monitored at the 0.001 K level of precision. These groups should not be used as a reference standard for a period of two months following a loss of temperature control in the absence of evidence that emf recovery is complete. This evidence should include measurements comparing the cell emf's with those of stable sources not subjected to the same or similar environmental perturbations. Neither group should be removed from the laboratory for purposes of calibration or traceability to support calibrations at uncertainty levels of $\pm 1 \times 10^{-6}$ or better; traceability should be achieved with the use of a transport standard of adequate performance to support the required measurements.

Table 2. (cont.) Reference standards commonly used for the calibration of 10 V standards.

Best Uncertainty	Minimum Standards Required	Remarks
$\pm 2 \times 10^{-6}$	Three solid-state standards each in individual control environments; or One set of three or more solid-state standards; or A dc voltage calibrator; or One group of at least four saturated standard cells in an oven and an adequate, verifiable self-calibrating means of scaling to 10 V from 1.02 V; or A digital voltmeter	The above requirements apply. The calibrator should be adequately specified and should be supported by the use of check standards for uncertainties better than $\pm 12 \times 10^{-6}$. The voltmeter should be adequately specified and should be supported by the use of check standards for uncertainties better than $\pm 12 \times 10^{-6}$.
$\pm 40 \times 10^{-6}$	Three solid-state standards packaged individually, used at 10 V; or One set of three or more solid-state standards, used at 10 V; or One group of at least four saturated standard cells in an oven and an adequate, calibrated means of scaling to 10 V from 1.02 V	Neither ovens for controlling the temperature of critical components nor back-up battery power is required for the use of solid-state standards. Oven stability requirements for saturated standard cells are relaxed to ± 0.05 K, for both short- and long-term requirements.

Table 3. Reference standards commonly used for the calibration of 1.02 V standards.

Best Uncertainty	Minimum Standards Required	Remarks
$\leq \pm 0.1 \times 10^{-6}$	A Josephson array	A Josephson array standard should be a system that includes one or more check standards at the 1.02 V level.
$\pm 0.3 \times 10^{-6}$	Two groups of four each saturated standard cells, each group being contained in a separate oven	The saturated standard cell groups should each be contained in an oven capable of controlling the temperature of the group to be constant within 0.002 K over a working day and within 0.01 K over a one-month period. The temperature should be capable of being monitored at the 0.001 K level of precision. These groups should not be used as a reference standard for a period of two months following a loss of temperature control in the absence of evidence that emf recovery is complete. This evidence should include measurements comparing the cell emf's with those of stable sources not subjected to the same or similar environmental perturbations. Neither group should be removed from the laboratory for purposes of calibration or traceability to support calibrations at uncertainty levels of $\pm 1 \times 10^{-6}$ or better; traceability should be achieved with the use of a transport standard of adequate performance to support the required measurements.
$\pm 1 \times 10^{-6}$	Two groups of four each saturated standard cells, each group being contained in a separate oven	One of the groups may be used as a transportable standard for traceability purposes. Standard cell oven performance requirements are relaxed to ±0.01 K for one-day performance and to ±0.02 K for one month.

Table 3. (cont.) Reference standards commonly used for the calibration of 1.02 V standards.

Best Uncertainty	Minimum Standards Required	Remarks
$\pm 1 \times 10^{-6}$	Four solid-state standards having individual control environments and an adequate, verifiable self-calibrating means of scaling from 10 V to 1.02 V; or Two standards, each comprised of three or more solid-state reference units, each set contained in an individual control environment and an adequate, verifiable self-calibrating means of scaling from 10 V to 1.02 V	Only the 10 V outputs of the solid-state standards should be used. The solid-state device, amplifiers, ratio resistors, and other temperature-sensitive components upon which the stability of the standard is based should be contained in a oven having provision for monitoring the stability of its temperature with adequate precision to ensure proper performance of the standard. The "control environment" also includes the power supplies for the above. Provision should also be made for battery back-up power in the event of a failure of the power mains.
$\pm 4 \times 10^{-6}$	One group of at least four saturated standard cells in an oven; or Three solid-state standards, each in individual control environments; or One set of three or more solid-state standards in a control environment	The 1.02 V outputs of the solid-state standards may be used in lieu of an external scaling arrangement.
$\pm 7 \times 10^{-6}$	A dc voltage calibrator; or a digital multimeter	These instruments should be used in conjunction with appropriate check standards for calibrations of instruments of $\pm 15 \times 10^{-6}$ uncertainty or better.

Table 3. (cont.) Reference standards commonly used for the calibration of 1.02 V standards.

Best Uncertainty	Minimum Standards Required	Remarks
$\pm 160 \times 10^{-6}$	Three solid-state standards packaged individually; or One set of three or more solid-state standards; or One group of at least four saturated standard cells in an oven	The 1.02 V outputs of the solid-state standards may be used in lieu of an external scaling arrangement. Neither ovens for controlling the temperature of critical components nor back-up battery power is required for the use of solid-state standards. Oven requirements for saturated standard cells are relaxed to ±0.05 K, for both short- and long-term requirements.
$\pm 250 \times 10^{-6}$	One group of at least three unsaturated standard cells	Unsaturated cells are not in ovens. They should not be used as references during the three days immediately following a loss of laboratory environmental control. Current draw permanently reduces the emf's of unsaturated cells; intercomparisons among the group should be made prior to any calibration at uncertainty levels of $\pm 100 \times 10^{-6}$ or better.

Table 4. Scaling standards.

Type	Ratio(s)	Range	Min. Specified Ratio Uncertainty	Remarks
Binary resistive divider	0 to 1 continuous in 10^{-8} steps	0 to 20 V	$\pm 0.03 \times 10^{-6}$ (of input)	Used for within-range linearity calibrations; must be used with a device with larger ratios to calibrate an instrument completely.
Direct current comparator potentiometer	10^{-7} to 1 continuous in 10^{-8} steps	0 to 10 V	$\pm 0.03 \times 10^{-6}$ (of input)	See above.
Hamon devices	10 : 1 100 : 1	0 to 3 V (10 : 1) 0 to 10 V (100 : 1)	$\pm 0.5 \times 10^{-6}$ (10 : 1) $\pm 0.01 \times 10^{-6}$ (100 : 1)	Precision resistors networks configurable in series, series/parallel, or parallel with high accuracy; for calibration of other ratio devices, self-calibrating.
Hamon-based reference divider	10 : 1 100 : 1	0 to 100 V 0 to 1000 V	$\pm 0.2 \times 10^{-6}$ $\pm 0.5 \times 10^{-6}$	Instrument; used directly for range calibrations of calibrators and voltmeters, self-calibrating.
Kelvin-Varley divider	0 to 1 continuous in 10^{-7} steps	0 to 750 V	$\pm 0.1 \times 10^{-6}$ of input voltage	Used both for in-range linearity calibrations and range-to-range measurements; may be self-calibrating.
Resistance transfer standard	i : 1 where $1 \leq i \leq 12$	0 to 2300 V depending on resistance	$\pm (1 \times 10^{-6} + 1\ \mu\Omega)$	Based on Hamon scaling; used for calibration of fixed-ratio dividers; may be used directly or with a Kelvin-Varley divider for workload measurements.
Voltbox (Volt Ratio Standard)	i : 1.5 where i is multiples of 1,2,3,5	0 to 1200 V	$\pm 10 \times 10^{-6}$	Series resistive divider with fixed ratios chosen to be additive.

2.4 Capacitance - low frequency

2.4.1 Scope

This section gives specific technical criteria for measurements of capacitance in the frequency range from 50 Hz to 20 kHz.

2.4.2 References

a) Hague, Bernard, *Alternating Current Bridge Methods*, sixth ed., London, Pitman & Sons, 1971.

b) Harris, Forest K., *Electrical Measurements*, New York, John Wiley & Sons, Inc., 1952.

c) Kibble, B. P., and Rayner, G. H., *Coaxial AC Bridges*, Bristol, Adam Hilger, Ltd., 1984.

d) Cutkosky, R. D., "Techniques for Comparing Four Terminal-Pair Admittance Standards," *J. Res. Nat. Bur. Stand. C.*, **74C**, (3 & 4), pp. 63-78, July-Dec. 1970.

e) Shields, J. Q., "Absolute Measurement of Loss Angle Using a Toroidal Cross Capacitor," *IEEE Trans. Instr. Meas.*, **IM-27**, (4), pp. 464-466, Dec. 1978.

f) Jones, R. N., "A Technique for Extrapolating the 1 KC Values of Secondary Standard Capacitors to Higher Frequencies," *NBS Tech. Note 210*, Nov. 1963.

g) Various manufacturers' catalogs and specification sheets, particularly from ESI, GENRAD, Hewlett-Packard, and QuadTech.

h) Chang, Y. M., "NIST Measurement Assurance Program for Capacitance Standards at 1 KHz," *Nat. Inst. Of Stand. and Tech. (U.S.), Tech. Note 1417*, 19 pg., Mar. 1996.

i) Waltrip, B. C. and Oldham, N. M., "Digital Impedance Bridge," *IEEE Trans. Instru. Meas.*, **44**, (2), pp. 436-439, Apr. 1995.

j) Chang, Y. M. and Tillett, S. B., "NIST Calibration Service for Capacitance Standards at Low Frequencies," *Nat. Inst. Of Stand. and Tech. (U.S.), Spec. Pub. 250-47*, 77 pg., Apr. 1998.

k) Koffman, A. D., Waltrip, B. C., Oldham, N. M., and Avramov-Zamurovic, "Capacitance and Dissipation Factor Measurements from 1 KHz to 10 MHz," *1998 Nat'l. Conf. Stds. Labs. Workshop & Symposium (NCSL)*, Jul. 19-23, 1998, Albuquerque, NM, pp. 63-68, Jul. 1998.

2.4.3 Assuring the quality of test and calibration results

2.4.3.1 The laboratory should have controls based on artifact capacitors (check standards) at each level normally measured or calibrated, regardless of whether the calibration is a comparison of an unknown capacitor with a standard capacitor or is the result of deriving capacitance from other impedance standards, unless the instrumentation used for the measurement or calibration has an uncertainty one-fourth or smaller than the required measurement uncertainty. The check standards should be at least at the level of quality of the best items being calibrated, and preferably at a higher level of quality. The statistical results of these controls should indicate a process precision comfortably smaller than the Type A uncertainty so that the variability of the measuring system can be distinguished from that of the item being calibrated.

2.4.3.2 Environmental aspects of the laboratory capable of affecting the measurement uncertainty should be monitored on a continuous basis, and measurements relevant to a calibration should not be made within three days following a significant environmental disturbance.

2.4.4 Accommodation and environmental conditions

2.4.4.1 The temperature of the standard capacitors being used and/or calibrated should be controlled at such a level that the changes of capacitance resulting from temperature changes during the measurement process do not contribute in excess of 10 % of the stated (or required) measurement uncertainty. Approximate temperature coefficients of various types of capacitance standards are given below:

Dielectric	Approximate Temperature Coefficient (microfarad/farad/K)	Remarks
Fused silica	12 ± 2	
Dry nitrogen (Sealed)	2 ± 2	Suffers from temperature hysteresis
Air	10 to 20	Loss and capacitance affected by humidity
Mica	35 ± 10	

2.4.4.2 The bottom three types of capacitors are subject to temperature hysteresis at some level; i.e., large changes in temperature create non-restorable changes in capacitance. These effects are generally not serious in air and mica capacitors because of their limited accuracies but can be serious in nitrogen-dielectric capacitors. Therefore, the latter should be protected from large changes in ambient temperature by being kept in temperature-lagged enclosures such as the foam boxes in which they are supplied. Extreme care should be taken in transporting them.

2.4.4.3 Typical nitrogen-dielectric standard capacitors have a support structure that becomes a cantilever when the capacitor is placed on its side. Gravity may then cause significant dimensional changes in the capacitor's structure which can affect its capacitance. Because of the nature of the design, there is no equivalent force to restore its prior dimensions when the capacitor is again upright. Such standards should always be stored, carried, and used in an upright position.

2.4.4.4 A significant minority of this type of capacitor is sensitive to physical disturbances, either shock or vibration. The existing empirical data shows that changes as large as 20×10^{-6} can result from relatively small shocks under controlled conditions; changes on the order of 200×10^{-6} or more have been seen between calibrations and are presumed to be the result of shock and vibration that occurred during shipment.

2.4.5 Equipment

2.4.5.1 Capacitance measurements and calibrations may be made referenced to standard capacitors or to other impedance standards, or combinations of impedance standards. In any case, the standards that are used should have values with sufficiently low uncertainty to support the uncertainties of the measurements or calibrations being carried out. The standards should have been calibrated at each frequency at which they are used. If this cannot be done, the laboratory should provide the analysis from which the capacitance values are obtained and the documentation of the uncertainty of such values.

2.4.5.2 The laboratory should maintain standards covering each level of capacitance calibrated or measured, or have a calibrated system for scaling to cover the entire range of values calibrated from a few standards (since one standard is insufficient to check the scaling capability).

2.4.5.3 Standard capacitors are most commonly of two- or three-terminal design whereas newer instruments (LCR meters, for example) are designed to make four-terminal or four-pair-terminal measurements. The laboratory should have jigs to be used for the calibration of such instruments or for their use in making two- and three-terminal measurements. These jigs should be analyzed and the results of the analyses used to correct for lead and shielding effects when making these types of measurements. These analyses should be available for review.

2.4.5.4 At the present time, dissipation factor calibrations are not available at NIST for high-accuracy standards. The *de facto* standard for this is the General Radio - GENRAD - QuadTech - ESI nitrogen dielectric parallel-plate capacitance standard whose dissipation factor is taken to be 0 ± 10^{-6}. Dissipation factor measurements should be carefully checked.

2.4.6 Test and calibration methods and method validation

Calibration procedures for standard capacitors should show the background method for deriving capacitance from other impedance standards unless the calibration is a comparison of two or more capacitors. In the latter case, the type of measurement technique that is used should be clearly described, including shielding, grounding and other considerations.

2.4.7 Handling of test and calibration items

2.4.7.1 Standard capacitors of the nitrogen-dielectric, parallel-plate type should be protected from large temperature excursions and physical shock and vibration. See 2.4.4 above.

2.4.7.2 Standard capacitors having fused-silica dielectric are extremely stable, but should be kept in an environment controlled to within 0.01 K of a nominal fixed temperature to reach their potential accuracy level.

2.4.8 Reporting the results

2.4.8.1 In addition to the requirements of ISO/IEC 17025, certificates or reports of calibration or verification should include:

a) The value(s) of measured capacitance,

b) The frequency at which the measurements are made,

c) The ambient temperature at the time of the measurement, and

d) (Optionally) the dissipation factor or loss.

2.4.8.2 The certificate or report should also clearly state whether the result is of a two-terminal, three-terminal, four-terminal, or four-pair terminal measurement.

2.4.8.3 If the measurement type does not match the terminal type of the calibrated item, a description of the jig or fixture used to modify the terminals should be given, unless the calibrations are at such a frequency and uncertainty level that the results are not affected by the use of the jig, in which case this should be clearly stated.

2.4.8.4 The description should include both the physical and electrical characteristics of the jig.

2.5 Inductive voltage dividers (decade transformer dividers) - low frequency

2.5.1 Scope

This section describes specific technical criteria for calibrations and use of inductive voltage dividers (IVDs) in the audio-frequency range.

2.5.2 References

a) Fink, Donald G. and Beaty, H. Wayne (eds.), *Standard Handbook for Electrical Engineers*, Thirteenth Ed., New York, McGraw Hill, 1993.

b) Lisle, R. V., and Zapf, T. L., "Comparison Calibration of Inductive Voltage Dividers," *ISA Transactions*, **3**, (3), July 1964.

c) Sze, W. C., Dunn, A. F., and Zapf, T. L., "An International Comparison of Inductive Voltage Divider Calibrations at 400 and 1000 Hz," *IEEE Trans. Instr. Meas.*, **IM-14**, (3), pp. 124-131, Sept. 1965.

d) Sze, W. C., "Comparator for Calibration of Inductive Voltage Dividers from 1 to 10 kHz," *ISA Transactions*, **6**, (4), pp. 263-267, 1967.

e) Deacon, T. A., and Hill, J. J., "Two-Stage Inductive Voltage Dividers," *IEEE Proc.*, 115:272, 1968.

f) Sze, W. C., "An Injection Method for the Calibration of Inductive Voltage Dividers," *J. Res. Nat. Bur. Stand. C.*, **72C**, pp. 49-50, Jan.-Mar. 1968.

g) Homan, D. N., and Zapf, T. L., "Two Stage, Guarded Inductive Voltage Divider for Use at 100 kHz," *ISA Transactions*, **9**, (3), pp. 201-209, 1970.

h) Various manufacturers' catalogs and specification sheets, particularly from Dytronics, ESI, Gertsch, and Tegam.

2.5.3 Assuring the quality of test and calibration results

For the calibration of IVDs, a second divider should be employed as a check standard and backup. While IVDs are extremely stable, a second IVD with a known calibration history permits identifying and correcting problems with the injection circuit used to balance the bridge formed by the standard and unknown dividers.

2.5.4 Accommodation and environmental conditions

Inductive voltage dividers should be protected against the influence of ac magnetic fields and should never be excited by direct current.

2.5.5 Equipment

Inductive voltage divider calibrations may be made relative to other inductive voltage dividers, specially designed transformers, resistive voltage dividers (at low frequencies), or capacitive voltage dividers. IVD's may be used as ratio arm pairs in impedance calibration bridges; therefore, these criteria may be required for assessment of calibrations of capacitance or inductance standards.

2.5.6 Test and calibration methods and method validation

2.5.6.1 IVD corrections and uncertainties are typically expressed in terms of proportional parts of the input rather than the ratio. This has to be taken into account when the divider is used to provide a ratio which has to meet uncertainty specifications expressed in ratios or voltages.

2.5.6.2 Calibration and use procedures for inductive voltage dividers should take into account the possible effects of loading on the ratios of the divider.

2.5.6.3 Procedures should provide for means of identifying and correcting magnetization of the cores of the inductive voltage divider.

2.5.6.4 Procedures should take into account the fact that the ratios associated with the dial settings of single-stage dividers (especially for the three most significant dials) are not additive. The ratio associated with any given setting of a dial depends on the settings of the less significant dials. Accordingly, one should increase the uncertainty of the divider ratio when more than one dial has a non-zero setting. Most IVDs manufactured in the U.S. are of single stage construction. Two-stage dividers are characterized by having two sets of input terminals.

2.5.6.5 Procedures should call for strict observance of the input voltage restrictions of the dividers; these are normally given as a fraction of the frequency of the applied signal.

2.5.7 Handling of test and calibration items

Inductive voltage dividers and transformers have no special handling requirements beyond those in the General Requirements for DC and Low Frequency Measurements and Calibrations.

2.5.8 Reporting the results

2.5.8.1 In addition to the reporting requirements of ISO/IEC 17025, certificates or reports of calibration of inductive voltage dividers should include:

a) Corrections or errors for both in-phase and quadrature components of ratio, and

b) The input voltage and frequency.

2.5.8.2 Multiple measurements should be made of at least a sampling of the settings having quadrature values of unusually high value, with some index of the range of their values reported as an indicator of the condition of the divider's switches.

2.6 Inductance - low frequency

2.6.1 Scope

This section describes specific technical criteria for calibrations of self- and mutual-inductance air-core standards and iron-core inductors in the frequency range from 50 Hz to 20 kHz.

2.6.2 References

a) Hague, Bernard, *Alternating Current Bridge Methods*, sixth ed., London, Pitman & Sons, 1971.

b) Fink, Donald G. and Beaty, H. Wayne (eds.), *Standard Handbook for Electrical Engineers*, Thirteenth Ed., New York, McGraw Hill, 1993.

c) Zapf, Thomas L., "Calibration of Inductance Standards in the Maxwell-Wien Bridge Circuit," *J. Res. Nat. Bur. Stand. C.*, **65C**, pp.183-188, Sept. 1961.

d) Homan, D. N., "Some Techniques for Measuring Small Mutual Inductances," *J. Res. Nat. Bur. Stand. C.*, **70C**, pp.221-226, 1966.

e) Dunn, Andrew F. and Tsao, Hoi, "Ratio Comparisons of Impedance Standards," *IEEE Trans. Instr. Meas.*, **IM-18**, pp. 276-283, Dec. 1969.

f) Hanke, R. and Dröge, K., "Calculated Frequency Characteristic of GR1482 Inductance Standards Between 100 Hz and 100 kHz," *IEEE Trans. Instr. Meas.*, **40**, pp. 893-896, Dec. 1991.

g) Recommended Practice RP-52.1, *Recommended Environments for Standards Laboratories*, Instrument Society of America, Research Triangle Park, NC, 1975.

h) Various manufacturers' catalogs and specification sheets, particularly from ESI, GENRAD, Hewlett-Packard, and QuadTech.

2.6.3 Assuring the quality of test and calibration results

2.6.3.1 The laboratory should have controls based on artifact inductors (check standards) at nominal values for each range of inductance normally measured or calibrated, regardless of whether the calibration is a comparison of an unknown inductor with a standard inductor or is the result of deriving inductance from other impedance standards, unless the instrumentation used for the measurement or calibration has an uncertainty one-fourth or less than the required measurement uncertainty. The check standards should be at least at the level of quality of the best items being calibrated, and preferably at a higher level of quality. The statistical results of these controls should indicate a process precision comfortably smaller than the Type A uncertainty so that the variability of the measuring system can be distinguished from that of the item being calibrated.

2.6.3.2 Environmental aspects of the laboratory capable of affecting the measurement uncertainty should be monitored on a continuous basis, and inductance measurements relevant to a calibration should not be made within 24 hours following a significant environmental disturbance.

2.6.4 Accommodation and environmental conditions

2.6.4.1 The temperature of the standard inductors being used and/or calibrated should be controlled at such a level that the changes of inductance resulting from temperature changes during the measurement process do not contribute in excess of 10 % of the stated (or required) measurement uncertainty. (Note: the temperature coefficient of inductance is of the order of 30×10^{-6} / K.)

2.6.4.2 For the calibration or measurement of standard inductors at the highest accuracy, a stand should be provided such that the standard is more than 50 cm from the nearest magnetic material while it is being measured.

2.6.5 Equipment

2.6.5.1 Inductance measurements and calibrations may be made referenced to standard inductors or to other impedance standards, or to combinations of impedance standards. In any case, the standards used should have inductance values of sufficiently low uncertainty to support the uncertainties of the measurements or calibrations being carried out. The standards should have been calibrated at each frequency at which they are used. If this cannot be done, the laboratory should provide the analysis from which the inductance values are obtained and the documentation of the uncertainty of such values.

2.6.5.2 The laboratory should maintain standards covering each level of inductance calibrated or measured, or have a calibrated system for scaling to cover the entire range of values calibrated from a few standards. (One standard is insufficient to check the scaling capability.)

2.6.5.3 Standard inductors are most commonly of two- or three-terminal design whereas newer instruments (LCR – inductance (L), capacitance (C), resistance (R) – meters, for example) are designed to make four-terminal or four-terminal-pair measurements. The laboratory should use jigs for calibrating such instruments or for making two-terminal measurements. These jigs should be analyzed and the results of the analyses used to correct for lead and shielding effects when making these types of measurements. These analyses should be available for review.

2.6.5.4 The inductance of iron-core inductors is current dependent. The laboratory should have adequate instrumentation to control, measure, and report the current level used in such measurements.

2.6.6 Test and calibration methods and method validation

2.6.6.1 Calibration procedures for inductors should show the background method for deriving inductance from other impedance standards unless the calibration is a comparison of two or more inductances. In the latter case, the type of measurement technique used should be clearly described, including shielding, grounding and other considerations.

2.6.6.2 Calibration procedures and methods for mutual inductance should show the principle of measurement and the derivation of equations used to obtain the mutual inductance from the measured values of inductance.

2.6.6.3 Calibration procedures for iron-core inductors should include techniques for measuring the current in the inductor being measured.

2.6.7 Handling of test and calibration items

Typical inductance standards are relatively robust and therefore do not require special handling.

2.6.8 Reporting the results

2.6.8.1 In addition to the reporting requirements of ISO/IEC 17025, certificates or reports of calibration or verification should include:

a) The value(s) of inductance measured,

b) The frequency at which the measurements are made,

c) The ambient temperature at the time of the measurement, and

d) (Optionally) the equivalent series resistance.

2.6.8.2 The certificate or report should also clearly state whether the result is of a two-terminal, three-terminal, four-terminal, or four-terminal-pair measurement.

2.6.8.3 If the measurement type does not match the terminal type of the calibrated item, a description of the jig or fixture used to modify the terminals should be given, unless the calibrations are at such a frequency and uncertainty level that the results are not affected by the use of the jig, in which case this should be clearly stated.

2.6.8.4 The description should include both the physical and electrical characteristics of the jig.

2.6.8.5 If the inductor is of a iron-core type, the current level used during the calibration should also be stated.

2.6.8.6 If the inductor is a mutual inductor, the mutual inductance should be given.

2.6.8.7 The report may optionally contain the equivalent series resistance, a value for the storage factor Q, or the resonance frequency of the inductor.

2.7 Fast electrical pulse waveforms

2.7.1 Scope

This section contains specific technical criteria that a laboratory should follow if it is to be recognized as competent to carry out fast electrical pulse waveform calibrations. These calibrations include those for pulse parameters, pulse time delay, and impulse spectrum amplitude.

2.7.2 References

a) IEC Publications 469-1 and 469-2, *Pulse techniques and apparatus, Part 1: Pulse terms and definitions; Part 2: Pulse measurement and analysis, general considerations.* IEC, Geneva, Switzerland, 1974.

b) IEEE Std. 181-2000, *IEEE standard on transitions, pulses, and related waveforms*, IEEE, New York, July 2003.

c) IEEE Std. 376, *IEEE standard for measurement of impulse strength and impulse bandwidth*, 1975, IEEE, New York, 1975.

d) "Time domain automatic network analyzer for measurement of rf and microwave components," *Nat. Bur. Stand. (U.S.) Tech. Note 672*, Sept. 1975.

e) "Spectrum amplitude - Definition, generation and measurement," *Nat. Bur. Stand. (U.S.) Tech. Note 699*, Oct. 1977.

f) "Deconvolution of time domain waveforms in the presence of noise," *Nat. Bur. Stand. (U.S.) Tech. Note 1047*, Oct. 1981.

g) "Impulse generator spectrum amplitude measurement techniques," *IEEE Trans. Instrum. and Meas.*, **IM-25**, (4), Dec. 1976.

h) "The measurement and deconvolution of time jitter in equivalent-time waveform samplers," *IEEE Trans. Instrum. and Meas.*, **IM-32**, (1), Mar. 1983.

i) Gans, W. L., "Dynamic calibration of waveform recorders and oscilloscopes using pulse standards," *IEEE Trans. Instrum. and Meas.*, **IM-39**, (6), Dec. 1990.

j) Deyst, J. P., Paulter, N. G., Jr., Daboczi, T., Stenbakken, G. N., Souders, T. M., "A fast-pulse oscilloscope calibration system,Instrumentation and Measurement," *IEEE Trans. Instrum. and Meas.*, **IM-47**, (5), pp. 1037-1041, Oct. 1998.

k) Souders, T. M., Andrews, J., Caravone, A., Deyst, J. P., Duff, C., and Naboicheck, S., "A pulse measurement intercomparison," *IEEE Trans. Instrum. and Meas.*, **IM-47**, (5), pp. 1031-1036, Oct. 1998.

l) Paulter, N. G., and Larson, D. R., "Pulse Parameter Uncertainty Analysis," *Metrologia*, **59**, pp. 143-155, 2002.

2.7.3 Statistical process control

The laboratory should possess and periodically calibrate at least one control standard for pulse parameters, at least one control standard for pulse time delay, and at least one control standard for impulse spectrum amplitude.

2.7.4 Accommodation and environmental conditions

All fast electrical pulse waveform calibrations should be performed under the following environmental conditions:

a) Laboratory ambient temperature nominally 23 °C,

b) Laboratory ambient relative humidity between 30 % and 50 %, and

c) Test system line voltage within ± 3 % of nominal with less than 1 % total harmonic distortion (THD).

2.7.5 Equipment

2.7.5.1 All fast electrical pulse waveform calibrations should be performed on a system which consists, at the least, of a computer-controlled equivalent-time sampler. In addition, adequate standards should be used periodically to calibrate the system's time base delay, gain, and linearity; voltage axis offset, gain, and linearity; and sampler dynamic response.

2.7.5.2 Because these calibration systems are still in a state of rapid change, unresolved questions concerning calibration equipment may be directed to the appropriate NIST personnel.

2.7.6 Test and calibration methods and method validation

2.7.6.1 The methods utilized for all fast electrical pulse waveform calibrations should adhere as closely as possible to those described in the references.

2.7.6.2 Because these calibration methods are still in a state of rapid change, unresolved questions concerning calibration methodology may be directed to the appropriate NIST personnel.

2.7.7 Reporting the results

2.7.7.1 In addition to the reporting requirements of ISO/IEC 17025, the calibration report should include:

a) The laboratory ambient temperature, with tolerances if applicable,

b) Relative humidity, with tolerances if applicable, and

c) Line voltage, with tolerances if applicable.

2.7.7.2 The calibration report should include a plot of all significant pulse waveforms with the dimensions and scale factors for both time and voltage axes clearly labeled.

2.8 Dc resistance

2.8.1 Scope

This section describes specific technical criteria for the calibration of dc resistors.

2.8.2 References

a) Dziuba, R. F., Boynton, P. B., Elmquist, R. E., Jarrett, D. G., Moore, T. P., and Neal, J. D.,"NIST Measurement Service for DC Standard Resistors," *Natl. Inst. Stand. & Tech., Tech. Note 1298*, 65 pages (U.S. Government Printing Office, Washington, DC, November 1992).

b) Elmquist, R. E., Wood, B. N., Jaeger, K., "Quantized Hall Resistance Recommended Intrinsic-Derived Standards Practice," *National Conference of Standards Laboratories*, Boulder, CO, Aug. 1997.

c) Elmquist, R. E., and Dziuba, R. F.,"Loading effects in resistance scaling," *IEEE Trans. Instr. Meas.* **46,** (2), pp. 322-324, Apr. 1997.

d) Jarrett, D. G., "Automated guarded bridge for calibration of multimegohm standards resistors from 10 MΩ to 1 TΩ," *IEEE Trans. Instr. Meas.* **46,** (2) pp. 325-328, Apr. 1997.

e) Boynton, P. B., Sims, J. E., and Dziuba, R. F., "NIST Measurement Assurance Program for Standard Resistors," *Natl. Inst. Stand. & Tech., Tech. Note 2434*, 53 pages, Nov. 1997.

f) Jarrett, D. G., "Evaluation of guarded high-resistance Hamon transfer standards," *IEEE Trans. Instr. Meas.* **48,** (2), pp. 324-328, Apr. 1999.

g) Dziuba, R. F., and Kile, L. L., "An automated guarded bridge system for the comparison of 10 kΩ standard resistors," *IEEE Trans. Instr. Meas.*, **48,** (3), pp. 673-677, June 1999.

h) Jarrett, D. G., Marshall, J. A., Marshall, T. A., and Dziuba, R. F., "Design and evaluation of a low thermal electromotive force guarded scanner for resistance measurements," *Rev. Sci. Instr.* (Am. Inst. Phys.) **70,** (6), pp. 2866-2871, June 1999.

i) Delahaye, F., Witt, T. J., Elmquist, R. E., and Dzuiba, R. F., "Comparison of Quantum Hall Effect Resistance Standards of the NIST and the BIPM," *Metrologia*, **37,** pp. 173-176, 2000.

2.8.3 Accommodation and environmental conditions

2.8.3.1 The temperature of a standard resistor should be controlled at a level such that changes of resistance of the standard resistor resulting from temperature changes during the measurement process contribute 10 % or less to the measurement uncertainty.

2.8.3.2 The relative humidity in the laboratory should not exceed 45 %.

2.8.3.3 The barometric pressure in the laboratory should be monitored when measuring pressure-sensitive standard resistors (e.g., Thomas-type 1 Ω) with measurement uncertainties of 0.5×10^{-6} or less.

2.8.4 Equipment

2.8.4.1 The laboratory should maintain a local unit of resistance (traceable to the quantum Hall effect) with three or more standard resistors, one of which may be used as a check standard during the measurement process.

2.8.4.2 The laboratory should have the capability to scale from its local unit of resistance to other resistance levels that will encompass its range of calibration services. At these other resistance levels, the laboratory should maintain one or more standard resistors, one of which is used as a check standard during the measurement process.

2.8.5 Test and calibration methods and method validation

2.8.5.1 An indication of the temperature of the resistor under test should be recorded during the measurement run.

2.8.5.2 The barometric pressure should be recorded when measuring pressure sensitive resistors with measurement uncertainties of 0.5×10^{-6} or less. If the resistor is immersed in a liquid, the depth of immersion should also be measured and recorded in order to determine the additional pressure effect on the resistor.

2.8.5.3 For voltage-sensitive resistors (e.g., film type), the test voltage applied across the test resistor should be recorded.

2.8.5.4 For high-current resistors (shunts), the test current applied to the resistor should be recorded.

2.8.5.5 A check standard should be used during each measurement run.

2.8.6 Assuring the quality of test and calibration results

For each measurement run, the laboratory should examine the difference between the check standard and its predicted value based on previous history to determine whether the measurement system is operating under statistical control. In addition, the standard deviation of a measurement run and the previous history of the test resistor (if available) should be examined to determine the quality of the measured value.

2.8.7 Reporting the results

The calibration certificate/report issued by a laboratory should contain the following:

a) Resistor temperature,

b) Effective pressure, if applicable,

c) Relative humidity, if applicable,

d) Test voltage, if applicable, and

e) Test current, if applicable.

2.9 Ac-dc difference - thermal voltage converters

2.9.1 Scope

2.9.1.1 This section contains specific technical criteria that a laboratory should meet in order to demonstrate competence in performing calibrations of thermal voltage converters (TVCs). These instruments include:

a) Coaxial thermal voltage converters,

b) Battery-powered multirange thermal voltage converters, and

c) Mains-powered multirange thermal voltage converters.

2.9.1.2 This section covers a voltage range of 0.5 V to 1000 V, and a frequency range of 5 Hz to 1 MHz. It may be of general use outside this parameter range, but the reader should seek specific guidance for measurements conducted beyond these ranges.

2.9.2 References

a) NCSL Recommended Practice RP-11: Reports and Certificates of Calibration, 1991.

b) ISA RP52.1, Recommended Environments for Standards Laboratories, Instrument Society of America, 1975.

c) SAND90-1962, Standards Laboratories Environments.

d) Kinard, J. R. and Lipe, T. E., "Recharacterization of thermal voltage converters after thermoelement replacement," *IEEE Trans. Instrum. Meas.*, **38**, pp. 351-356.

e) Kinard, J. R, Hastings, J. R., Lipe, T. E., and Childers, C. B., "AC-DC Difference Calibrations," *Natl. Inst. Stand. & Tech., Spec. Publ. 250-27*, 308 pages, May 1989.

f) Lipe, T. E., "A re-evaluation of the NIST low-frequency standards for ac-dc difference in the voltage range of 0.6 V - 100 V," *IEEE Trans. Instru. Meas.*, **45**, (6), pp. 913-917, Dec. 1996.

2.9.3 Assuring the quality of test and calibration results

2.9.3.1 Sources of error or variability for the calibration should be monitored by the calibration of the subsystems involved in the calibration. These subsystems may include the voltage source(s) used in the calibration system, the detectors (voltmeters, for example) used to measure the output emf of the TVCs, and any auxiliary instruments (voltmeters, frequency counters, temperature sensors) used to monitor the functions of the system. In addition, check standards should be used to ensure that the calibration system is in statistical control. The laboratory should maintain some form of statistical process control in accordance with the uncertainty levels of the calibration; the lower the uncertainty of the calibration, the more stringent the controls required to ensure that the process is under statistical control. In general, if a laboratory is attempting to maintain uncertainties of less than four times the uncertainty quoted by NIST for a similar measurement, some sort of statistical process control is required. The frequency and thoroughness of check standards measurements should be commensurate with calibration uncertainty levels.

2.9.3.2 The laboratory should have control standards which adequately span the voltage and frequency ranges normally calibrated by the facility. Historical records of intercomparisons between control artifacts and between control artifacts and calibration standards should be kept, and all new data acquired from these intercomparisons compared to the historical record to ensure that the process is in statistical control. For thermal voltage converters, checks between control artifacts and calibration standards should be performed at least once per year, assuming that the devices are not damaged in any way.

2.9.3.3 Should a thermoelement be damaged, or fail and be replaced, the laboratory should assign the ac-dc difference values of the new TVC in accordance with the uncertainties quoted by the laboratory. For quoted uncertainties comparable to the standard NIST uncertainties, the TVC should be intercompared to existing standards at appropriate voltages and frequencies to determine the ac-dc differences of the repaired TVC. For quoted uncertainties up to about four times the NIST uncertainties, a thermoelement replacement algorithm (**2.8.2 d)**) may be employed to calculate the new corrections, with spot checks at one or two points to confirm the results of the calculations. For larger uncertainties, a thermoelement may in general be replaced without affecting the ac-dc difference. It is also worth noting that the ac-dc difference of a thermal voltage converter depends upon the characteristics of the thermoelement only at low voltages; at high voltage, the resistor makes the overwhelming contribution to the ac-dc difference and its uncertainty.

2.9.4 Accommodation and environmental conditions

2.9.4.1 Thermal voltage converters are generally tolerant of gradual temperature changes; nevertheless, the temperature of the calibration area should comply with ISA RP52.1 or Sandia Report SAND90-1962. This requires a nominal temperature of 23 °C. In addition, the time derivative of the temperature should be as small as possible, less than 0.5 °C per hour. In general, fluctuations in temperature may cause thermal expansion of the resistors in a TVC. This affects high-voltage TVC ranges, where the change in capacitance between the resistor and the overall structure may lead to changes in the ac-dc difference, particularly at frequencies of 50 kHz and above.

2.9.4.2 The relative humidity in the calibration area should comply with the requirements listed in ISA RP52.1 or Sandia Report SAND90-1962. These requirements include a nominal relative humidity of 20 %-55 %. The time derivative of the relative humidity in the calibration area should be kept small – less than 2 % per hour. Changes in relative humidity may cause changes in the characteristics of high-voltage wire-wound resistors in some TVCs, which may lead to variations in the ac-dc differences of the TVC.

2.9.4.3 Reasonable care should be taken to avoid mechanical shock to TVCs. Excessive mechanical shock may alter the geometry of the internal structure of a TVC, which in turn may lead to variations in ac-dc difference, particularly at high frequencies. In addition, TVCs that have been damaged by shock may show intermittent contact problems and pose a safety hazard if the shell of the TVC comes in contact with any high-voltage structures.

2.9.4.4 Electrical power supplied to the calibration system should conform to the guidelines in ISA RP52.1 for voltage regulation. An uninterruptible power system or line conditioner may be required to achieve these standards.

2.9.4.5 Thermal voltage converters are generally immune to electromagnetic interference; however, instruments that are operated under ac line power may be susceptible to noise along ground leads and are more likely to be affected by EMI. These considerations are addressed in ISA RP52.1.

2.9.5 Equipment

2.9.5.1 The laboratory should have the equipment necessary to intercompare both working and reference standards.

2.9.5.2 The ac and dc voltage source(s) should be in calibration when measurements of TVCs are performed. Instruments for detecting the thermoelement output (voltmeters, for example) should also be in calibration.

2.9.5.3 Instruments (voltmeters, temperature probes, counters, oscilloscopes, etc.) for monitoring the ambient temperature of the calibration area and for monitoring the ac and dc voltage and frequency supplied to the TVCs during a calibration should be functional and within specifications.

2.9.5.4 If possible, multiple TVCs should be available for use as reference or check standards. In addition to making intercomparisons of similar voltage ranges possible, multiple TVCs offer redundancy in the event of a failure of a TVC, or when a TVC is being calibrated by an external laboratory.

2.9.5.5 If the calibration is controlled by and calibration data reduction performed by automated means (that is, by computer), the hardware and software should be thoroughly checked to ensure that the data derived by this system is accurate, and that the system itself does not introduce any bias into the measurements. In addition, software should have consistency checks to ensure that over-ranging the TVCs by accidentally entering an incorrect voltage does not occur, or that program loops do not increment the applied voltage beyond the range of the TVCs.

2.9.6 Handling of test and calibration items

2.9.6.1 Thermal voltage converters should be stored and handled in such a way as to minimize the potential for structural or electrical damage.

2.9.6.2 Instruments operating from batteries should be checked to ensure that the batteries appropriate to the measurement are sound enough to enable the instrument to perform as required.

2.9.6.3 The output of ac and dc calibrators may be lethal. The laboratory should be aware of this danger and take steps to avoid situations where contact with exposed high-voltage points may occur. This is particularly relevant for ac power amplifiers, which can deliver up to 160 mA and which may have only rudimentary protection.

2.9.6.4 When voltages greater than 120 V are present in the calibration area, the laboratory should display an obvious warning to that effect. In addition, the TVCs may be isolated from the world by a box or covering, which makes contact with the voltage difficult. Such isolation will also be beneficial for temperature control.

2.9.7 Test and calibration methods and method validation

2.9.7.1 The laboratory should maintain documentation describing the calibration system, software, and procedures, as well as documentation concerning the determination of the uncertainty assigned to calibrations and procedures for performing check standard measurements.

2.9.7.2 If a variety of instruments are calibrated at the laboratory, the laboratory should maintain documentation concerning testing methodology (connections, grounding, etc.) to supplement the user's manuals of the instruments.

2.9.7.3 All ac-dc difference calibration results should by computed using the formula

$$\delta = (Q_{ac} - Q_{dc}) / Q_{dc}$$

where δ is the (uncorrected) ac-dc difference of the UUT, Q_{ac} is the difference between the outputs of the standard TVC and UUT with ac applied, and Q_{dc} the difference between the outputs of the standard TVC and UUT for the average of both polarities of dc voltage that produces the same output from the TVC as that produced by Q_{ac}. This convention states that the ac-dc difference is positive when more than the nominal ac voltage is required to match the average of the polarities of the dc reference voltage.

2.9.7.4 The polarity of the dc voltage should be reversed either by an isolated switch or by internal switching in the dc source. **The dc voltage should *never* be reversed by connecting the shell of the input connector to high voltage.** Not only is this a dangerous safety hazard, but this practice may also result in thermoelement bead failure.

2.9.7.5 All measurements of ac-dc difference should be performed using the voltage sequence: ac, dc+, dc-, ac, dc-, dc+, ac or dc+, ac, dc-, ac, dc+. In either case, the average of both positive and negative polarities of applied dc voltage should be used to account for dc reversal error in the thermoelement. If no dc reversal is done, the uncertainty of the measurement should be expanded appropriately.

2.9.7.6 All measurements should be made at equal time intervals after switching from ac to dc or dc to ac, or when reversing the dc voltage. This effectively cancels out any linear drift in the TVCs. Waiting until the TVC output stabilizes (at possibly very different time intervals) introduces error from drift in the TVCs.

2.9.7.7 The time required to switch voltages or polarities should be minimized so as to minimize the cooling of the TVCs while no signal is applied. A waiting period may be required for the TVCs to stabilize after switching, but this waiting period should be equal for every occurrence of switching. This time period may vary according to applied voltage and switch dead time. In addition, any safety delays built into voltage sources should either be disabled or accounted for in the waiting period.

2.9.7.8 All leads connecting the voltage source(s) to the TVCs should be as short as possible to minimize capacitance in the leads. Any structures (adapters, for example) required to connect the TVCs to the voltage leads should also be as short as possible.

2.9.7.9 A suitable warmup period should be observed in order for the TVCs to stabilize after the application of voltage. For higher voltage ranges, quite a long warmup time may be necessary.

2.9.7.10 For coaxial single-range TVCs, the outer shell of the input connector should be grounded through one (and only one) of the voltage sources.

2.9.7.11 For multirange TVCs that are powered by a battery pack, the outer shell of the input connector should be grounded through one of the voltage sources. For some instruments, this requires that the shell of the uhf-type input connector be grounded, but the dc ground stud left floating. For other instruments, the outer shell of the Type N input connector should be grounded.

2.9.7.12 Grounding schemes for instruments calibrated under ac line power vary with the calibration system. In general, the ground should be made at the ground terminal of the instrument, and the supplies in the calibration system should be floated. The laboratory should be aware of the potential for common-mode signals entering the instrument and should take steps to minimize such signals.

2.9.7.13 During a calibration, the ac supply and dc supply should be matched to within 50 μV/V to ensure that any ac-dc difference arising from source mismatch will be negligible. Records of the voltage adjustment are useful in monitoring the performance of the sources.

2.9.7.14 The ambient temperature should be recorded at some point in the calibration procedure.

2.9.8 Records

2.9.8.1 All measurements should be recorded, either manually or by automated means. Corrections which are applied manually should be checked against a master correction table to ensure accuracy. Information concerning the unit under test (UUT), standard TVC, voltage ranges of the test and standard TVCs, applied voltage, and the raw data, correction and final number at a given frequency should be recorded. In addition, the ambient temperature of the calibration area should be recorded.

2.9.8.2 Information concerning check standards or range-to-range intercomparisons should be recorded and maintained for the life of the check standard or calibration artifact.

2.9.8.3 Calibration information on individual TVCs should be maintained as long as practicable, but for at least 3 years.

2.9.9 Reporting the results

2.9.9.1 All content of reports or certificates of calibration should conform to NCSL Recommended Practice RP-11 as well as ISO/IEC 17025.

2.9.9.2 The uncertainty should be derived from a detailed analysis of the measurement system, which may include some or all of the following:

a) Type B uncertainties in thermal voltage converters:

   1) Uncertainty in calibration of primary standards or reference artifacts, including uncertainty quoted from calibration of these standards by a higher-echelon laboratory,

   2) Uncertainty in range-to-range intercomparisons between reference and working standards or in voltage of frequency build-up measurements between adjacent voltage or frequency ranges,

   3) Effect of short-term drift in the TVCs,

   4) Effect of long-term stability of the TVCs, and

   5) Effect of dc reversal error in TVCs, if not measured directly.

b) Type B uncertainties in measurement system:

   1) Uncertainty in voltage output from ac and dc voltage source(s),

   2) Uncertainty in applied frequency,

   3) Uncertainty in detector performance (stability, linearity, etc.), and

   4) Effects of grounding on various types of TVCs.

c) Type A (statistical) uncertainties.

d) Environmental considerations.

2.9.9.3 The method of calibration, particularly the connection scheme used, should be included in the calibration report or certificate.

2.10 High voltage capacitors

2.10.1 Scope

This section contains specific technical criteria that a laboratory should meet if it is to be recognized as competent to carry out high-voltage capacitor calibrations.

2.10.2 References

a) Anderson, W. E., "A Calibration Service for Voltage Transformers and High-Voltage Capacitors," NBS Special Publication 250-33, 1988.

b) Harris, F. K., *Electrical Measurements*, John Wiley & Sons, New York, 1966.

2.10.3 Assuring the quality of test and calibration results

The laboratory should have standard capacitors for use as check standards.

2.10.4 Accommodation and environmental conditions

2.10.4.1 Temperature variations should be less than 1 °C during the actual testing period.

2.10.4.2 Appropriate methods for determining changes in check standard values with temperature should be used.

2.10.5 Equipment

2.10.5.1 The laboratory should have the equipment needed to generate and measure voltages over the range of rated voltages and frequencies specified for the capacitors to be calibrated.

2.10.5.2 The laboratory should have the equipment needed to measure the capacitance and dissipation factors angle of a high-voltage capacitor.

2.10.5.3 The uncertainties of all check standards and calibration techniques should be documented.

2.10.6 Test and calibration methods and method validation

High-voltage capacitors may be calibrated by either direct or comparative methods.

2.10.7 Handling of test and calibration items

Check standards should be handled with care in order to avoid changes in the calibration.

2.10.8 Reporting the results

Calibration reports should specify:

a) The calibration technique used,

b) The temperature at the time of the test,

c) The voltage frequency,

d) Uncertainties of the measurements, and

e) The test results, including the capacitance and dissipation factor.

2.11 High-voltage transformers

2.11.1 Scope

This section contains specific technical criteria that a laboratory should meet if it is to be recognized as competent to carry out high-voltage transformer calibrations.

2.11.2 References

a) Anderson, W. E., "A Calibration Service for Voltage Transformers and High-Voltage Capacitors," *NBS Special Publication 250-33*, 1988.

b) ANSI/IEEE C57.13-1978, *IEEE Standard Requirements for Instrument Transformers*, American National Standards Institute.

c) Harris, F. K., *Electrical Measurements*, John Wiley & Sons, New York, 1966.

2.11.3 Assuring the quality of test and calibration results

The laboratory should have check standards, such as standard capacitors, voltage transformers, and/or voltage sources, appropriate for the calibration method used.

2.11.4 Accommodation and environmental conditions

2.11.4.1 Temperature variations should be less than 1 °C during the actual testing period.

2.11.4.2 Appropriate methods for determining changes in check standard values with temperature should be used.

2.11.5 Equipment

2.11.5.1 The laboratory should have the equipment needed to generate and measure voltages over the range of primary voltages and frequencies required by the transformers to be calibrated.

2.11.5.2 The laboratory should have the equipment needed to measure the ratio correction factor and phase angle of a voltage transformer, including a range of secondary burdens appropriate for the transformers being calibrated.

2.11.5.3 The uncertainties of all check standards and calibration techniques should be documented.

2.11.6 Test and calibration methods and method validation

Voltage transformers may be calibrated by either direct or comparative methods.

2.11.7 Handling of test and calibration items

Check standards should be handled with care in order to avoid changes in the calibration.

2.11.8 Reporting the results

Calibration reports should specify:

a) The calibration technique used,

b) The temperature at the time of the test,

c) The voltage frequency,

d) Uncertainties of the measurements, and

e) The test results, including the ratio correction factor and the phase angle of the transformer.

2.12 Digital multimeters and multifunction calibrators

2.12.1 Scope

This section contains specific technical criteria that a laboratory should meet to be competent to calibrate digital multimeters (DMMs) and multifunction calibrators on all functions.

2.12.2 References

a) Oldham, N. M., and Parker, M. E., "NIST Multifunction Calibration System," *NIST Special Publication 250-46*, February 1998.

b) Oldham, N. M., Parker, M. E., Young, A. M., and Smith, A. G., "A High Accuracy 10 Hz - 1 MHz Automatic AC Voltage Calibration System," IMTC/87 Conference Proceedings, IEEE Instrumentation/Measurement Technical Conference, April 27-29, 1987, Boston, MA, digest published in *IEEE Trans. Instrum. Meas.*, **IM-36**, (4), pp. 279-281, Dec. 1987.

2.12.3 Equipment

The laboratory should have a calibration system capable of calibrating all of the ranges of the test DMMs and calibrators normally used by the laboratory. The system may consist of calibrated artifact standards such as dc voltage references, resistors, voltage dividers, thermal voltage and current converters, suitable for calibrating the reference and DMMs and calibrators. Alternatively, the reference DMMs and/or calibrators may be directly calibrated by an accredited laboratory.

The test instruments should be connected and programmed according to documented procedures.

2.12.4 Assuring the quality of test and calibration methods

The laboratory should periodically calibrate at least one control DMM over the range normally used by the laboratory to calibrate test DMMs.

2.12.5 Accommodation and environmental conditions

2.12.5.1 Calibrations should be performed under the following conditions:

a) Ambient temperature of (23 ±1) °C.

b) Ambient relative humidity between 30 % and 50 %.

c) Mains voltage within ±10 % of nominal, with less than 3 % THD.

2.12.5.2 These requirements may be relaxed to the point that their combined influence will not exceed 25 % of the error budget.

2.12.6 Reporting the results

The calibration report should denote the following:

a) Test parameters (function, amplitude [range and applied], and frequency),

b) DMM correction,

c) Test uncertainty and description of how the uncertainty was calculated,

d) Ambient (or instrument) temperature and humidity with tolerances, and

e) Brief description of the standard used to perform the calibration.

2.13 Watt/watthour meters

2.13.1 Scope

This section contains specific technical criteria that a laboratory should meet to be competent to calibrate power frequency wattmeters (WMs) and watthour meters (WHMs).

2.13.2 References

a) "Code for Electricity Metering," ANSI C-12.

b) Ramboz, J. D., and McAuliff, R. C., "A Calibration Service for Wattmeters and Watthour Meters," *NBS Tech Note 1179*, July 1983.

c) Oldham, N. M., Laug, O. B., Waltrip, B. C., and Palm, R. H.,"The NIST Digitally Synthesized Power Calibration Source," *NIST Tech Note 1281*, Aug. 1990.

2.13.3 Equipment

The laboratory should have the necessary power/energy calibrator to calibrate all of the ranges of the test WMs and WHMs. This calibrator should be calibrated to an uncertainty smaller (by a factor of 2 or more) than the desired test WM/WHM uncertainty. The test WM/WHM should be connected to the calibrator in accordance with the calibrator or test WM/WHM specifications.

2.13.4 Assuring the quality of test and calibration results

The laboratory should periodically calibrate at least one control WM/WHM over the range normally used by the laboratory to calibrate test WM/WHMs.

2.13.5 Accommodation and environmental conditions

2.13.5.1 Calibrations should be performed under the following conditions:

a) Ambient temperature of (23 ± 1) °C.

b) Ambient relative humidity between 30 % and 50 %.

c) Mains voltage within ±10 % of nominal, with less than 3 % THD.

2.13.5.2 These requirements may be relaxed to the point that their combined influence will not exceed 25 % of the error budget.

2.13.6 Reporting the results

The calibration report should denote the following:

a) Test parameters (function, amplitude [range and applied], and frequency),

b) WM/WHM correction,

c) Test uncertainty and description of how the uncertainty was calculated,

d) Ambient (or instrument) temperature and humidity with tolerances, and

e) Brief description of the standard used to perform the calibration.

2.14 Phase meters

2.14.1 Scope

This section contains specific technical criteria that a laboratory should meet to be deemed competent to calibrate digital phase meters (DPM) with voltage and/or current inputs.

2.14.2 References

Turgel, R. S., "NBS 50 kHz Phase Angle Calibration Standard," *NBS Tech Note 1220*, 1986.

2.14.3 Equipment

The laboratory should have a phase angle calibrator capable of calibrating all of the ranges of the test DPMs. This calibrator should be calibrated to an uncertainty smaller (by a factor of 2 or more) than the desired DPM uncertainty. The test DPM should be connected to the calibrator in accordance with the calibrator or test DPM specifications.

2.14.4 Assuring the quality of test and calibration results

The laboratory should periodically calibrate at least one control DPM over the range normally used by the laboratory to calibrate test DPMs.

2.14.5 Accommodation and environmental conditions

2.14.5.1 Calibrations should be performed under the following conditions:

a) Ambient temperature of (23 ± 1) °C.

b) Ambient relative humidity between 30 % and 50 %.

c) Mains voltage within ±10 % of nominal, with less than 3 % THD.

2.14.5.2 These requirements may be relaxed to the point that their combined influence will not exceed 25 % of the error budget.

2.14.6 Reporting the results

The calibration report should denote the following:

a) Test parameters (signal amplitudes [range and applied], and frequency),

b) DPM correction,

c) Test uncertainty and description of how the uncertainty was calculated,

d) Ambient (or instrument) temperature and humidity with tolerances, and

e) Brief description of the standard used to perform the calibration.

2.15 Dc high voltage dividers and dc high voltage resistors

2.15.1 Scope

This section contains specific technical requirements in accordance with which a laboratory should demonstrate that it operates, if it is to be recognized as competent to carry out calibrations of dc high voltage dividers and dc high voltage resistors.

2.15.2 References

a) ISA RP52.1, Recommended Environments for Standards Laboratories, Instrument Society of America, 1975.

b) Misakian, M., "High Voltage Divider and Resistor Calibrations," *NBS Technical Note 1215*, National Institute of Standards and Technology (formerly National Bureau of Standards), July 1985.

c) Park, J. H., "Special Shielded Resistor for High-Voltage DC Measurements," *J. Res. NBS*, **66C**, pp. 19-24, 1962.

d) Wenner, F., "Methods, Apparatus, and Procedures for Comparison of Precision Standard Resistors," *J. Res. NBS*, **25**, pp. 229-294, 1940.

2.15.3 Assuring the quality of test and calibration results

2.15.3.1 Components of the calibration apparatus, e.g., high voltage and low voltage resistors, should be calibrated periodically at intervals depending in part on the stability of the components. The uncertainties associated with the component values should be commensurate with the uncertainty levels claimed when high voltage dividers and resistors are calibrated with the apparatus. Records should be maintained of component values to identify trends and instabilities.

2.15.3.2 The laboratory should have one or more check standards that can be used to verify the satisfactory performance of the calibration apparatus over its operational range of voltages, ratios and resistance values. Provision should be made for evaluation of the check standard. This evaluation should be made periodically at intervals dependent in part on the stability of the check standard. Evaluations should be performed at least yearly. Records of calibration apparatus performance and check standard performance should be maintained to identify trends and instabilities.

2.15.4 Accommodation and environmental conditions

2.15.4.1 Excessive vibration in the calibration room should be avoided. If an obvious source of vibration exists, precautions should be taken to prevent adverse effects on the calibration apparatus and on the laboratory's measurements.

2.15.4.2 All high voltage should be confined within grounded or properly insulated enclosures. Instrument cabinets containing high voltage should have safety interlocks on access doors. If confinement is impossible, exposed high voltage should be enclosed with safety fences with working interlocks. Entrance into the high voltage area should be impossible (except by deliberate breach of the enclosure) without tripping one or more interlocks.

2.15.4.3 "DANGER HIGH VOLTAGE" signs should be on display on all entrances to high voltage areas. A warning light, preferably flashing, should indicate when the voltage is on. In all cases where there is direct access from the outside hallway to the high voltage area, there should be a warning light, a "DANGER HIGH VOLTAGE" sign, a safety interlock, and a locked door.

2.15.4.4 Before touching a high voltage circuit or leaving it unattended, it should be de-energized and grounded. When possible, the grounding stick should be left on the high voltage terminal until the circuit is re-energized. Grounding sticks should be available near entrances to high voltage areas. Automatic grounding systems, or systems that employ audible warning signals to remind personnel to ground the high voltage equipment, are encouraged.

2.15.4.5 Circuit breakers, disconnects, or contacts used to energize a high voltage source should be left open whenever the supply is not used. Laboratories should always be left in such a configuration that at least two switches should be used to energize the high voltage circuits. Whenever possible, a "return-to-zero-before-energizing" interlock should be incorporated into the high voltage supply.

2.15.4.6 Two people should be present when high voltage is on. Exceptions to this rule are permitted when:

a) There are no exposed high voltages. This means that all high voltage conductors are inside grounded or insulated enclosures and are inaccessible to the operator when the high voltage circuit is energized.

b) There are exposed high voltages, but doors or openings that allow the operator to reach the high voltage conductors have interlocks that not only disconnect the high voltage power source, but also discharge the stored energy in the high voltage circuit to ground.

2.15.4.7 The temperature should be maintained at (23 ± 1.5) °C and sufficiently stable so that the calibration apparatus and unit under test are in thermal equilibrium with the ambient temperature. The relative humidity should be constant for the duration of the calibration and remain below 50 % so that leakage currents over critical insulating surfaces are negligible.

2.15.5 Equipment

2.15.5.1 The laboratory should have sufficient standard resistors, both high voltage and low voltage, for its calibration apparatus, with values necessary to determine the ratio and resistance values calibrated by the laboratory. Periodic checks, e.g., quarterly, of the calibration apparatus should be made using appropriate check standards.

2.15.5.2 The laboratory should have means for generating high dc voltages over the voltage range of interest in a safe manner.

2.15.5.3 The laboratory should have temperature and humidity measuring capabilities suitable to the calibration procedure.

2.15.5.4 The laboratory should have equipment needed to make auxiliary measurements on components of the calibration system and for comparative measurements (e.g., precision voltmeter for comparative voltage measurements).

2.15.5.5 A laboratory that certifies high voltage dividers and/or high voltage resistors should demonstrate a (two-sided) measurement uncertainty that does not exceed 33 % of the specified uncertainty.

2.15.5.6 The laboratory should have equipment needed to make ratio and resistance measurements under high voltage conditions.

2.15.5.7 Voltages applied to the unit under test should be known within ±2 %.

2.15.5.8 The high voltage power supply should be stable to the extent necessary to meet the uncertainty requirements of the calibration.

2.15.5.9 The total uncertainty associated with the resistors used in the calibration process, taking into account heating effects, voltage coefficients, lead and contact resistances, leakage currents, and corona should be no larger than 30 % of the uncertainty quoted in reports issued by the laboratory.

2.15.6 Handling of test and calibration items

2.15.6.1 Precautions should be taken to avoid exposing components of the calibration apparatus or check standard to mechanical shock or vibration.

2.15.6.2 High voltage dividers and resistors should be protected from moisture, mechanical shock and vibration during handling in the laboratory. Provision should be made for similar protection during shipment of the device to and from the laboratory (responsibility for this provision rests primarily with the sender of the device).

2.15.7 Test and calibration methods and method validation

2.15.7.1 The laboratory should have a manual outlining procedures to be followed for each type of calibration.

2.15.7.2 Ratios and resistance values may be determined using bridge techniques or by direct comparison methods. The schedule of applied high voltage as a function of time should be agreed to by the laboratory and the owner of the device under test.

2.15.8 Records

2.15.8.1 All measurements should be recorded. If the calibration results are recorded by hand, the work sheets should show the measurement data, corrections, equation used for calculating the divider ratio or resistance, and final answers. The components used in the calibration apparatus, temperature, relative humidity, unit under test, operator, date, and other pertinent information for the calibration should be included.

2.15.8.2 Information relating to the procedures, equipment, results, and personnel involved for a particular calibration should be maintained for a minimum of five years.

2.15.8.3 Records associated with components of the calibration apparatus or check standard should be kept during the lifetime of the components or check standard.

2.15.9 Reporting the results

2.15.9.1 All content of certificates or reports of calibration should conform to the guidelines of NCSL Recommended Practice RP-11, as well as the requirements of ISO/IEC 17025.

2.15.9.2 All certificates or reports should contain an uncertainty statement which is scientifically determined from measurement data and which agrees with the laboratory's stated definition.

2.15.9.3 The uncertainty should be derived from a model of the measurement system that includes (as applicable) the uncertainties associated with:

a) Resistors in calibration apparatus,

b) Lead and contact resistances,

c) Sensitivity of detector(s) (e.g., voltmeter or null indicator),

d) Heating effects of components,

e) Corona,

f) Leakage currents over critical insulating surfaces, and

g) Voltage coefficients.

2.15.9.4 The uncertainty should be computed according to the ISO *Guide to the Expression of Uncertainty in Measurement* or another well-documented method.

2.15.9.5 The calibration report should indicate:

a) The ratio and/or resistance values as a function of time and dc high voltage, and

b) Ambient temperature and relative humidity at the time of the measurements.

2.15.9.6 Voltage dividers and resistors that are out of tolerance need not be reported.