Designation: F3268 – 18a

Standard Guide for *in vitro* Degradation Testing of Absorbable Metals[1]

This standard is issued under the fixed designation F3268; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 The purpose of this standard is to outline appropriate experimental approaches for conducting an initial evaluation of the *in vitro* degradation properties of a device or test sample fabricated from an absorbable metal or alloy.

1.2 The described experimental approaches are intended to control the corrosion test environment through standardization of conditions and utilization of physiologically relevant electrolyte fluids. Evaluation of a standardized degradation control material is also incorporated to facilitate comparison and normalization of results across laboratories.

1.3 The obtained test results may be used to screen materials and/or constructs prior to evaluation of a more refined fabricated device. The described tests may also be utilized to define a device's performance threshold prior to more extensive *in vitro* performance evaluations (e.g. fatigue testing) or *in vivo* evaluations.

1.4 This standard is considered to be applicable to all absorbable metals, including magnesium, iron, and zinc-based metals and alloys.

1.5 The described tests are not considered to be representative of *in vivo* conditions and could potentially provide a more rapid or slower degradation rate than an absorbable metal's actual *in vivo* corrosion rate. The herein described test methods are to be used for material comparison purposes only and are not to act as either a predictor or substitute for evaluation of the *in vivo* degradation properties of a device.

1.6 This standard only provides guidance regarding the *in vitro* degradation of absorbable metals and does not address any aspect regarding either *in vivo* or biocompatibility evaluations.

1.7 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.8 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

B943 Specification for Zinc and Tin Alloy Wire Used in Thermal Spraying for Electronic Applications

B954 Test Method for Analysis of Magnesium and Magnesium Alloys by Atomic Emission Spectrometry

E2375 Practice for Ultrasonic Testing of Wrought Products

F1854 Test Method for Stereological Evaluation of Porous Coatings on Medical Implants

F2129 Test Method for Conducting Cyclic Potentiodynamic Polarization Measurements to Determine the Corrosion Susceptibility of Small Implant Devices

F2739 Guide for Quantifying Cell Viability and Related Attributes within Biomaterial Scaffolds

F3160 Guide for Metallurgical Characterization of Absorbable Metallic Materials for Medical Implants

G1 Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens

G3 Practice for Conventions Applicable to Electrochemical Measurements in Corrosion Testing

G4 Guide for Conducting Corrosion Tests in Field Applications

G16 Guide for Applying Statistics to Analysis of Corrosion Data

G31 Guide for Laboratory Immersion Corrosion Testing of Metals

G46 Guide for Examination and Evaluation of Pitting Corrosion

G59 Test Method for Conducting Potentiodynamic Polarization Resistance Measurements

G102 Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements

[1] This guide is under the jurisdiction of ASTM Committee F04 on Medical and Surgical Materials and Devices and is the direct responsibility of Subcommittee F04.15 on Material Test Methods.

Current edition approved Oct. 1, 2018. Published November 2018. Originally approved in 2018. Last previous edition approved in 2018 as F3268–18. DOI: 10.1520/F3268-18A.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

G106 Practice for Verification of Algorithm and Equipment for Electrochemical Impedance Measurements
G215 Guide for Electrode Potential Measurement
2.2 *DIN Standards:*[3]
DIN 50918 Elektrochemische Korrosionsuntersuchungen. Deutsche Normen. Berlin: Beuth Verlag; 1978. p. 1-6
2.3 *ISO Standards:*[4]
ISO 10993-15 Biological evaluation of medical devices Part 15: Identification and quantification of degradation products from metals and alloys
ISO 13485 Medical devices – Quality management systems – Requirements for regulatory purposes

3. Terminology

3.1 *Definitions:*

3.1.1 *absorbable, adj—in the body*, referring to an initially distinct foreign material or substance that either directly or through intended degradation can be excreted, metabolized or assimilated by cells and/or tissue.

3.1.2 *surface roughness, R_A, n*—the arithmetic average deviation of the surface profile from the centerline, normally reported in micrometers.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *degradation, n*—the breakdown of a metallic test material or metallic device principally due to corrosion in an electrolyte solution relevant to physiologic conditions.

3.2.2 *degradation control material, n*—multiple batches of a defined metallic compositon with sufficiently uniform corrosion properties to verify an experimental setup and to compare relative intra-laboratory and/or inter-laboratory corrosion rates.

4. Summary of Guide

4.1 Guidance is given on *in vitro* evaluation of the corrosion/degradation properties of absorbable metal materials and devices fabricated from absorbable metals. Considerations specific to the application of corrosion testing methods to absorbable metal materials are outlined for both immersion and electrochemical methods.

4.1.1 Electrolyte composition is a critical factor in corrosion experiments. Several electrolytes are commonly used to mimic *in vivo* conditions. Electrolyte selection may also take into consideration the alloy being tested.

4.1.2 Control of the experimental conditions (i.e., temperature, pH and fluid movement around the test piece(s)) can markedly affect the corrosion rates and experimental outcomes. Controlling and documenting these factors are important with regard to generating consistent, reproducible results. Experimental conditions may be altered, depending on the intent of the experiment.

4.1.3 The surrounding atmosphere may interact with the electrolyte solution (liquid-gas interface), depending on electrolyte composition, particularly if the electrolyte contains a carbonate buffer or if oxygen in the electrolyte is consumed during the corrosion process, as with iron-based alloys. Measurement and control of the atmospheric composition may be important, depending on the specific circumstances of the experiment.

4.1.4 Measurements of corrosion may include weight loss of the sample, accumulation of corrosion products in the experiment, generation of H_2 gas, and changes to physical and mechanical properties.

4.2 Electrochemical methods, Polarization Resistance, and Electrochemical Impedance Spectroscopy also can be used to measure relative corrosion rates and generate additional insight into the corrosion process. The electrolyte used in these methods may not be relevant to *in vivo* conditions and may not mimic the process *in vivo*. It is important to fully document relevant experimental conditions (e.g. electrolyte composition, current, current density and atmosphere), so that their impact on the test results can be understood.

4.3 Use of a degradation control material to monitor the consistency of the experimental system is recommended, but not mandatory. See Annex A1 for details.

5. Significance and Use

5.1 This standard provides an itemization of potential *in vitro* test methods to evaluate the degradation of absorbable metals. The provided approach defers to the user of this standard to pick most appropriate method(s) based on the specific requirements of the intended application. However, a minimum of at least two different corrosion evaluation methods is considered necessary for basic profiling of the material or device, with additional methods potentially needed for an adequate characterization. However, in some instances there may be only one method that correlates to *in vivo* degradation results.

5.2 It is recognized that not all test methods will be meaningful for every situation. In addition, some methods carry different potential than others regarding their relative approximation to the *in vivo* conditions within which actual use is to occur. As a result, some discussion and ranking of the relevance of the described methods is provided by this guidance.

5.3 It should be noted that degradation of absorbable metals is not linear. Thus, precautions should be taken that evaluations of the degradation profile of a metal or metal device are appropriately adapted to reflect the varying stages and rates of degradation. Relevant factors can include the amount or percentage (%) of tissue coverage of the implanted device and the metabolic rate of surrounding tissue, which is not necessarily accompanied by a high perfusion rate.

5.4 It is recognized that *in vivo* environments will impart specialized considerations that can directly affect the corrosion rate, even when compared with other *in vivo* locations. Thus, a basic understanding of the biochemistry and physiology of the specific targeted implant location (e.g. hard tissue; soft tissue; high, low or zero perfusion areas/tissue; high, low or zero loading environments) is needed to optimize *in vitro* and *in vivo* evaluations.

[3] Available from Deutsches Institut für Normung e.V.(DIN), Am DIN-Platz, Burggrafenstrasse 6, 10787 Berlin, Germany, http://www.din.de.

[4] Available from International Organization for Standardization (ISO), ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, http://www.iso.org.

5.5 Within the evaluation of absorbable metals, rate uniformity is considered to be the principle concern and design goal. The recognized primary value for the herein described *in vitro* testing under static (i.e. not dynamic) conditions is to monitor and screen materials and/or devices for their corrosion consistency. Such an evaluation may provide a practical understanding of the uniformity of the device prior to any subsequent *in vivo* testing - where device consistency is considered to be critical for optimizing the quality of the obtained observations.

5.6 Once a suitable level of device corrosion consistency has been established (either directly or historically), static and/or dynamic fatigue testing can then be undertaken, if needed, to further enhance the understanding of the corrosion process within the context of the device's overall design and its intended application/use.

5.7 Depending on the intended application, appropriate levels of implant loading may range from minimal to severe. Thus, this standard does NOT directly address the appropriate level of loading of absorbable metallic devices, guidance for which may be found in documents specific to the intended implant application and the design requirements for the product.

5.8 This standard does NOT directly address dynamic fatigue testing of absorbable metallic devices.

6. Material/Metallurgical Characterization

6.1 A full understanding of the compositional and morphological features of the material or device to be tested is needed prior to conducting any *in vitro* degradation evaluation. Lack of control of critical material features (e.g. elemental composition, contamination, grain size, etc.) may lead to inconsistent results both *in vitro* and/or *in vivo*. Characterization of the test material should be undertaken in accordance with ASTM F3160.

6.2 Depending on the goals of the experiment, selected mechanical tests may be repeated at various intervals during the corrosion experiment. In most cases, it would be appropriate to retire mechanically tested samples.

7. General Testing Conditions

7.1 The intention of the following listing of general considerations is to provide a fundamental overview of the critical factors involved with generating consistent *in vitro* corrosion characterization results.

7.2 *Fluid Composition:*

7.2.1 For all *in vitro* test systems, fluid composition is a critical factor that requires both control and disclosure. Additionally, pH (which can be influenced by degradation product composition and generation rate), fluid flow, and solution buffer capacity are significant variables that can affect an absorbable metal's corrosion rate. While it is desirable to maintain an *in vitro* pH at a level that is representative of the *in vivo* condition, it is important to note that the composition of a buffer's anions can significantly affect the corrosion rate. Critical electrolytes and biomolecules that are known to directly affect the corrosion rate of Mg alloys include phosphate, carbonate, chloride, calcium, serum proteins, and lipids [see references **(1-7)**]. As a result, solutions with a physiologically relevant combination of electrolytes should be used.

NOTE 1—If the intention of the experiment is to provide an *in vitro* approximation to an *in vivo* system, the use of a well-controlled, simpler electrolyte system that has been correlated to *in vivo* data may be preferable to a more complex, less stable system.

7.2.2 Numerous formulations exist for simulated body fluids (SBFs) or buffering solutions that are intended to mimic the *in vivo* condition. Hank's Solution, which is phosphate-based and designed to buffer in a normal atmosphere, provides an approximation of the electrolyte composition found in the body. However, while it does provide a reasonable approximation of inorganic moieties, it does NOT provide the body's buffer capacity (as enhanced through carbonate equilibria[5]) or the presence of a myriad of organic molecules – many of which, particularly proteins, can be expected to adsorb to the implant surface and further affect the degradation rate. Table 1 defines the main ions in several common SBF solutions.

7.2.3 Additional factors to consider in electrolyte solutions are the levels of dissolved O_2 and CO_2, which, depending on a particular metal's composition and corrosion mechanism, can significantly affect the degradation rate. The reduced or zero level of bicarbonate within Hank's Solution limits its ability to interact with a CO_2 atmosphere, resulting in a limitation to its buffering capacity. Conversely, biological salt solutions that are bicarbonate-based and thereby interact with a CO_2 atmosphere are Earles and possibly Krebs Ringers. However, these balanced salts and culture media are designed to buffer at either 5 or 10% CO_2, depending on the amount of bicarbonate included. This concern is also true for complete medium (e.g. Dulbecco's Modified Eagle's Medium (DMEM), Minimum Essential Media (MEM), Roswell Park Memorial Institute Medium 1640 (RPMI 1640), etc.) that introduce additional constituents, such as amino acids, chemicals, and proteins, which can impact corrosion rates. Thus it can be surmised that such buffered electrolyte solutions can only approximate the actual corrosion occurring *in vivo* and may need adjustment during the degradation process to meet the requirements of the intended evaluation. Buffering capacity can affect results.

NOTE 2—The actual *in vivo* concentration of O_2 and CO_2 may not be known. However, maintaining control of O_2 and CO_2 in the *in vitro*

[5] Hank's Balanced Salt Solution can be purchased at various concentrations of calcium, magnesium and bicarbonate. Bicarbonate buffering is typically 4.2 mmol/L which is lower than other Salt Solutions.

TABLE 1 Composition of SBF Test Solutions[A]

Ion mmol/L	Solution				Extra-Cellular Fluid
	Tyrode's	Hanks'	Ringer's	Isotonic	
Na^+	149	141	147	154	142
K^+	2.7	5.4	4	—	5
Ca^{2+}	1.8	1.3	3	—	2.5
Mg^{2+}	1.0	0.74	0	—	1.5
Cl^-	145	145	157	154	103+

[A] Table obtained from: Corrosion Mechanisms of Metallic Biomaterials, Barbosa, M. (Table 3, p. 239); in *Biomaterials Degradation – Fundamental Aspects and Related Clinical Phenomena*, Ed. Mario Barbosa, pp. 227-239+ (1991).

experiment enhances experimental reproducibility.

7.2.4 In summary, the composition of electrolytes and atmospheres should be tailored to approximate the expected conditions in the intended clinical application, to the extent that they are known. As a result, full composition of the electrolyte solution and overlying atmosphere shall be included in the report along with relevant details regarding their replenishment rate.

7.2.5 For an overview discussion regarding environmental factors for absorbable metals, see Section 1.3.2 of Y.F. Zheng et al. Materials Science and Engineering R 77 (2014) 1-34 **(8)**.

7.3 *Fluid Flow:*

7.3.1 An additional factor for consideration is the level of fluid flow, which can affect both the rate of chemical exchange and the adhesion of degradation products. It has been recognized that flow-induced shear stress can significantly accelerate degradation of Mg (see reference **(8)**). Thus, fluid flow should be considered as a potentially critical factor when assessing a material's or device's degradation rate. However, due to the presence of both tissue and proteins, it should be noted that the impact of fluid flow under *in vivo* conditions may not be as pronounced as is found in *in vitro* models (see articles by Wittchow **(11)** and Bowen **(12)**].

7.3.2 While an active flow environment may not be needed when preliminarily screening materials, a physiologically relevant fluid flow that resembles the targeted application is highly recommended when attempting an approximation of *in vivo* performance. For example, the flow-induced shear stress on a newly deployed coronary stent may be very different from that of an absorbable screw placed into tibial bone. Additionally, an initial perfusion rate may change over time (e.g. from 10 to 2 relative units), which could then potentially alter the related rate of degradation. Also, the additional influence of normal cell and protein coverage and any drugs (e.g. anti-proliferatives) or other biological factors that may affect cell coverage and/or perfusion at the corrosion interface also requires consideration.

7.3.3 Flow induced through use of a shaker table may (or may not) be adequate to be representative of the *in vivo* condition.

7.4 *Atmospheric Composition:*

7.4.1 Since atmospheric composition can significantly influence the electrolyte solution (see prior discussion under fluid composition), a definable and, if needed, controlled (can be ambient) atmosphere should be maintained for all test methods, including during materials screening. Any selected atmosphere should be reflective of the intent of the experiment and the material's specific degradation considerations. An atmosphere for maintenance of pH through CO_2 / bicarbonate buffering may be chosen. For experiments meant to approximate *in vivo* conditions, appropriate considerations would result in an atmosphere that is compositionally relevant to both the implant's intended application as well as to the particular metal's projected corrosion chemistry once it is placed *in vivo*. Selected atmospheric compositions may also be reflective of the projected gaseous exchange rate within the *in vivo* environment of the intended clinical application. For example, both the ambient concentration and exchange rate of dissolved gasses can be expected to differ between lung, arterial and intramuscular implantation applications.

7.5 *Temperature:*

7.5.1 Solution temperature is a critical part of any corrosion environment (even when used in screening tests), in that elevated temperatures will typically increase reaction rates as well as introduce the potential for other chemical reactions. As a result, (37 ±1 °C) shall be used for all principle corrosion test conditions, where achievable, regardless of any recommendations/requirements described within a cited reference method. If ± 1 °C is not achievable in a particular experimental setup, the temperature shall be maintained within the minimum practical limits to maintain experimental consistency and reproducibility. Such a universally recognized *in vivo* temperature is considered to broadly represent the physiological condition and thereby provide the most broadly applicable scientific value. However, testing at other temperatures may also be included to determine differences in reaction mechanisms and rates. An additional alternate evaluation temperature may be especially useful if the temperature at the intended implant application and/or the temperature in a particular animal model differs significantly from (37 ± 1 °C).

7.6 *Utilization of a Degradation Control Material:*

7.6.1 In any corrosion evaluation, the experimental rate observed for a degradation control material may be included, both in the test and in the generated report. Such an evaluation of the corrosion rate of a degradation control material allows for continued monitoring of the consistency of a specific corrosion test system. Once included and tested, the experimentally obtained results can be utilized to demonstrate the repeatability of the specific test system while simultaneously providing a comparative control that allows for a normalized assessment of results across different test laboratories.

7.6.2 In some cases, it may be desirable to use a material already in use for the same or similar product as a control material, particularly if relative differences are of interest. A material for which the experimenter(s) have corrosion performance data may be advantageous in some experimental situations.

NOTE 3—**Caution:** Some alloys may not be sufficiently consistent from heat to heat to provide reproducible degradation results. It is up to the user to verify the suitability of a material as a degradation control material.

7.6.3 Guidance and further discussion regarding the appropriate specification and manufacturing of a degradation control material may be found in Annex A1.

7.6.4 Guidance regarding the appropriate utilization of a degradation control material within an experimental environment may be found in Annex A2.

7.7 In summary, flow conditions along with electrolytes, atmospheres, temperature and any other conditions relevant to the experiment should be tailored to approximate the expected conditions in the intended clinical application. As a result, full composition of the electrolyte solution and overlying atmosphere shall be reported along with relevant details regarding flow.

8. Initial Sample Characterization and Preparation

8.1 Sample dimensions will be dictated primarily by the limitations of the selected test method. However, the utilized size and description shall be reported in sufficient detail, including surface area and/or other features that may affect the results, so that its dimensions and features can be both easily understood and readily reproduced by others wishing to repeat the evaluation. Thus, information that will allow ready determination of a sample's external dimensions and overall volume shall be reported. Additionally, if the evaluated structure is porous, a description of the porosity and the relative size and interconnectivity of the pores also should be reported so as to allow a full understanding of the material's or device's electrolyte-accessible surface-to-volume ratio. ASTM F1854 contains methods useful for evaluating surface porosity.

8.1.1 Sufficient information about the sample shall be reported such that all pertinent references may be followed, e.g. ASTM G31 recommends a minimum electrolyte volume to sample surface area, for which the sample surface should be known within the limits specified in the reference.

9. Immersion Corrosion Evaluation

9.1 The intent of an immersion corrosion evaluation is to understand the rate of degradation when an implant or material is exposed (at rest) to a corrosive environment. As described previously, an approximation of the *in vivo* flow environment should be provided if it carries potential for clinical relevance.

9.2 Specific methods that guide the observation of passive corrosion in absorbable metal implants are:

9.2.1 NACE TM0169/ASTM G31 – Laboratory Immersion Corrosion Testing of Metals.

9.2.2 Also worthy of consideration are evaluation approaches contained within ASTM G1, ASTM G4, ASTM G46, and ASTM G102. ISO 10993-15 addresses methods for passive and polarization corrosion testing.

9.2.3 Guide G16 provides statistical methods appropriate to corrosion data, including regression methods for the analysis of longitudinal data. The methods may be applied to corrosion rates and/or changes in mechanical or other properties.

9.3 *Test Solution:*

9.3.1 Preparation and documentation of electrolyte solutions is necessary so that it can be accurately reproduced over multiple test setups, allowing for comparable results across testing regimes and laboratories. ASTM G31 gives guidance on electrolyte compositions and documentation.

9.3.2 Small changes in electrolyte composition during the test period, by either depletion of electrolyte components or the addition of corrosion products to the electrolyte during the test period, may affect corrosion rates, giving skewed or erroneous results [ASTM G31]. The ratio of electrolyte solution to surface area of the test piece can impact the degree to which the electrolyte solution may change during the test. ASTM G31 gives guidance for the ratio of solution volumes to test piece surface area which should be considered during experimental design. Corrosion rates for magnesium-based alloys and other group I and group II metals are affected by changes in electrolyte pH **(8)**. Starting pH is more easily controlled than pH fluctuations during the course of an experiment. The closer the initial pH is set to the target value, (i.e., within plus or minus 0.1 pH units), the longer the corrosion experiment may stay within predefined limits. If there is justification for a different pH specification for a particular experimental application, it should take precedence.

NOTE 4—**Caution:** The use of 2-(4-(2-hydroxyethyl)-1-pipeazinyl) ethanesulfonic acid (HEPES) buffer may negatively affect the corrosion rates of magnesium alloys **(8)**.

9.3.3 Corrosion rates for iron-based alloys are affected by the oxygen content of the electrolyte. It may be necessary to control oxygen saturation to achieve consistent results [ASTM G31], **(8, 9)**.

NOTE 5—Bioreactors are well suited to adequately control corrosion conditions, with the potential to simultaneously expose the corroding implant to hard and/or soft tissues See ASTM F2739 for additional details on bioreactors and their potential use.

9.4 *Mass Loss*—Loss of sample mass can be used as a basic measure of corrosion.

9.4.1 Corrosion products should be removed from the sample as completely as possible prior to weighing a post-corrosion test sample. ASTM G1 and ASTM G31 give guidance on removing corrosion products from test articles prior to weighing.

NOTE 6—Chromic acid is carcinogenic and, in some jurisdictions, may be restricted by local regulation.

9.4.2 Weighing accuracy of the post-corrosion sample should be equivalent to the accuracy of the initial sample weight and sufficiently accurate to assess weight loss.

9.4.3 ASTM G1 and ASTM G31 provide formulas for converting mass loss to corrosion rate for flat prismatic geometries.

9.5 *Measurement of Corrosion Products*—The quantitative evaluation of corrosion products -m may be used as a measure of corrosion if the reactions are well understood.

9.5.1 *Hydrogen Gas Evolution*—For magnesium metals and alloys with relatively short longevities, hydrogen (H_2) gas evolution can also be considered as a means for determining the corrosion rate or be used to confirm other measures of corrosion rate.

9.5.1.1 This method/approach is applicable when the majority of the alloy evolves hydrogen during the corrosion process (e.g. magnesium and group I and II metals) **(16)**.

9.5.1.2 The collected hydrogen volume can be converted to moles after correcting for non-standard temperature, pressure, and the partial (vapor) pressure of electrolyte solution **(16)**.

9.5.1.3 For experiments not taken to complete dissolution, corrosion rate may be calculated using the following equation:[6]

$$P_H = 2.279 V_H \quad (1)$$

where:

V_H = volume (ml) / surface area (cm^2) / days, and
P_H = mm/year.

9.5.1.4 Slow or low-volume evolution may require special sensors or may not be practical or possible to detect.

[6] Shi, Atrens. *Corrosion Science*. 53 (2011) 226-246.

9.5.2 *Metal Ion Release*—Monitoring of the accumulation of metal ions within the electrolyte solution provides an indication of the corrosion release.

9.5.3 Measurement of corrosion products provides additional fundamental information about the degradation/corrosion process **(16)**.

9.5.3.1 Precipitates produced during the corrosion process must be completely isolated for a quantitative evaluation of the corrosion process. Precipitates may often be filtered for complete removal from the electrolyte.

9.5.3.2 Precipitates produced during the evaluation may be completely dissolved by adding strong acid (HCl or H_2SO_4) prior to analyzing the solution content **(16)**. Some components of a sample (e.g. marker materials) may not completely dissolve. The extent of dissolution shall be verified.

9.5.3.3 The use of acid-washed glass containers may prevent corrosion products from adhering to the glass surfaces of the vessel. Alternatively, they may be dissolved with strong acids **(16)**.

9.5.3.4 The addition of corrosion products to the electrolyte may affect ongoing corrosion rates [ASTM G31], **(16)**. An understanding of the effect of corrosion products on the corrosion rates may improve the experimental design.

9.5.3.5 The electrolyte may need to be monitored for both addition of corrosion product and depletion of essential electrolyte components [ASTM G31].

9.5.3.6 A change of more than 10% in electrolyte composition may be adjusted by adding additional electrolyte [ASTM G31].

10. Electrochemical Corrosion Evaluation

10.1 Corrosion, in general, is an electrochemical process that requires both an anode and a cathode, as well as an ionic path through the electrolyte. Corrosion is also highly pH-dependent, so its monitoring is an essential component of any electrochemical evaluation. Typical electrochemical methods applicable to absorbable metals include polarization resistance, Tafel extrapolation, and electrochemical impedance spectroscopy (EIS).

10.2 *Polarization Resistance*—Electrochemical corrosion evaluations typically begin with this test, which is conducted by monitoring the corrosion potential Ecorr (also known as electrochemical corrosion potential, free corrosion potential, and open-circuit potential) of an electrolyte-immersed corroding sample versus a standard calomel electrode for a specified period of time. The sample is typically polarized at ± 10 mV each side of the Open Circuit potential, recording the induced current between the working and counter electrodes. The resistance to corrosion is measured as the slope of the potential-versus-current curve.

10.3 *Potentiodynamic Polarization (also known as DC Polarization)*—This test refers to a technique wherein the potential of an electrode with respect to a reference electrode is varied at a selected rate by application of a current through the electrolyte. The test is typically applied after a definable rest potential has been achieved. The result are anodic and cathodic polarization plots, which depicts the relationship between the change in potential (E) and the logarithm of the current density (log i) from polarization from the open-circuit potential in the anodic and cathodic directions. Many specific corrosion details can be derived from these plots, the scope of which can be found in the following methods, which also include means for the polarization resistance determination of E_{corr}:

10.3.1 ASTM F2129 – Standard Test Method for Conducting Cyclic Potentiodynamic Polarization Measurements to Determine the Corrosion Susceptibility of Small Implant Devices

10.3.2 ASTM G59 – Standard Test Method for Conducting Potentiodynamic Polarization Resistance Measurements

10.3.3 DIN 50918 – Elektrochemische Korrosionsuntersuchungen. Deutsche Normen. Berlin: Beuth Verlag; 1978. p. 1-6.

10.3.4 ISO 10993-15 – Biological evaluation of medical devices Part 15: Identification and quantification of degradation products from metals and alloys

10.3.5 The oxygen-poor environment utilized with electrochemical evaluations may yield results not reflective of results achieved in an *in vivo* environment, particularly with iron-based alloys.

10.3.6 Corrosion rates calculated for magnesium alloys may be underestimated because of the Negative Difference Effect (NDE) which causes hydrogen evolution to increase at potentials more positive than Ecorr instead of decreasing and thus diverging from Tafel kinetics **(15)**.

10.4 *Electrochemical Impedance Spectroscopy (also known as Dielectric Spectroscopy or Impedance Spectroscopy)*—This approach measures the dielectric properties of a medium as a function of frequency. It is based on the interaction of an external field with the electric dipole moment of the sample, often expressed by permittivity. The technique measures the impedance of a system over a range of frequencies, and therefore the frequency response of the system, including energy storage and dissipation properties, with the data expressed graphically in a Bode or Nyquist plot. The obtained values may be related to the corrosion rate when the measurement is made at the corrosion potential. Electrochemical impedance methods for determining the polarization resistance of biodegradable metal are:

10.4.1 ASTM G106 – Standard Practice for Verification of Algorithm and Equipment for Electrochemical Impedance Measurements

10.4.2 ASTM G3 – Standard Practice for Conventions Applicable to Electrochemical Measurements in Corrosion Testing

10.4.3 Another electrochemical test methods include both ASTM G59 and ASTM G102, the latter of which may be useful for its calculation methods.

10.5 *Specific Precautions for Electrochemical Evaluations:*

10.5.1 *Electrolyte*—Regardless of the test method utilized, the electrolyte solution and thermal test conditions described in this standard shall be substituted for the solutions described in the respective cited standards. The composition and volume of electrolyte shall be provided in the report either through specification or direct inclusion.

10.5.2 *Sample*—The size and surface area of the test and degradation control sample(s) shall be provided in the report.