



Designation: D5865 – 13

Standard Test Method for Gross Calorific Value of Coal and Coke¹

This standard is issued under the fixed designation D5865; 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 This test method pertains to the determination of the gross calorific value of coal and coke by either an isoperibol or adiabatic bomb calorimeter.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *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 and health practices and determine the applicability of regulatory limitations prior to use.* Specific hazard statements are given in Section 8.

2. Referenced Documents

2.1 *ASTM Standards:*²

D121 Terminology of Coal and Coke

D346 Practice for Collection and Preparation of Coke Samples for Laboratory Analysis

D388 Classification of Coals by Rank

D1193 Specification for Reagent Water

D2013 Practice for Preparing Coal Samples for Analysis

D3173 Test Method for Moisture in the Analysis Sample of Coal and Coke

D3177 Test Methods for Total Sulfur in the Analysis Sample of Coal and Coke (Withdrawn 2012)³

D3180 Practice for Calculating Coal and Coke Analyses from As-Determined to Different Bases

D4239 Test Method for Sulfur in the Analysis Sample of Coal and Coke Using High-Temperature Tube Furnace Combustion

¹ This test method is under the jurisdiction of ASTM Committee D05 on Coal and Coke and is the direct responsibility of Subcommittee D05.21 on Methods of Analysis.

Current edition approved Oct. 1, 2013. Published October 2013. Originally approved in 1995. Last previous edition approved in 2012 as D5865 – 12. DOI: 10.1520/D5865-13.

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.

³ The last approved version of this historical standard is referenced on www.astm.org.

D7582 Test Methods for Proximate Analysis of Coal and Coke by Macro Thermogravimetric Analysis

E144 Practice for Safe Use of Oxygen Combustion Vessels

E178 Practice for Dealing With Outlying Observations

E882 Guide for Accountability and Quality Control in the Chemical Analysis Laboratory

E2251 Specification for Liquid-in-Glass ASTM Thermometers with Low-Hazard Precision Liquids

3. Terminology

3.1 For additional definitions of terms used in this test method, refer to Terminology D121.

3.2 *Definitions:*

3.2.1 *adiabatic calorimeter*—a calorimeter that operates in the adiabatic mode and may or may not use a microprocessor. The initial temperature before initiating the combustion and the final temperatures are recorded by the operator or the microprocessor.

3.2.2 *automated calorimeter*—a calorimeter which has a microprocessor that takes the thermometric readings and calculates the Calibration Value and the Heat of Combustion Values.

3.2.3 *British thermal unit [Btu]*—is the amount of heat required to raise the temperature of one pound - mass [lbm] of liquid water at one atmosphere pressure one degree Fahrenheit at a stated temperature. The results of combustion calorimetric tests of fuels for steam power plants may be expressed in terms of the 1956 International Steam Table calorie (I.T. cal) which is defined by the relation, 1 I.T. cal = 4.1868 J. The Btu used in modern steam tables is defined by the means of the relation, 1 I.T. cal / g = 1.8 I.T. Btu / lb. Thus, 1 I.T. Btu / lb = 2.326 J / g.

3.2.4 *calorific value*—the heat produced by combustion of a unit quantity of a substance under specified conditions.

3.2.5 *calorimeter*—a device for measuring calorific value consisting of a bomb, its contents, a vessel for holding the bomb, temperature measuring devices, ignition leads, water, stirrer, and a jacket maintained at specified temperature conditions.

3.2.6 *gross calorific value (gross heat of combustion at constant volume), Q_v (gross)*—the heat produced by complete combustion of a substance at constant volume with all water formed condensed to a liquid.

*A Summary of Changes section appears at the end of this standard

3.2.7 *heat of formation*—the change in heat content resulting from the formation of 1 mole of a substance from its elements at constant pressure.

3.2.8 *isoperibol calorimeter*—a calorimeter that operates in the isoperibol mode and uses a microprocessor to record the initial and final temperatures and make the appropriate heat leak corrections during the temperature rise. It determines when the calorimeter is in equilibrium and ignites the sample and determines when the calorimeter has reached equilibrium after ignition.

3.2.9 *net calorific value (net heat of combustion at constant pressure), Q_p (net)*—the heat produced by combustion of a substance at a constant pressure of 0.1 MPa (1 atm), with any water formed remaining as vapor.

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 *corrected temperature rise*—the calorimeter temperature change caused by the process that occurs inside the bomb corrected for various effects.

3.3.2 *heat capacity*—the energy required to raise the temperature of the calorimeter one arbitrary unit.

3.3.2.1 *Discussion*—The heat capacity can also be referred to as the energy equivalent or water equivalent of the calorimeter.

4. Summary of Test Method

4.1 The heat capacity of the calorimeter is determined by burning a specified mass of benzoic acid in oxygen. A comparable amount of the analysis sample is burned under the same conditions in the calorimeter. The calorific value of the analysis sample is computed by multiplying the corrected temperature rise, adjusted for extraneous heat effects, by the heat capacity and dividing by the mass of the sample.

4.2 Oxidation of coal after sampling can result in a reduction of calorific value. In particular, lignite and sub-bituminous rank coal samples may experience greater oxidation effects than samples of higher rank coals. Unnecessary exposure of the samples to the air for the time of sampling or delay in analysis shall be avoided. (See X2.1.)

5. Significance and Use

5.1 The gross calorific value can be used to compute the total calorific content of the quantity of coal or coke represented by the sample for payment purposes.

5.2 The gross calorific value can be used for computing the calorific value versus sulfur content to determine whether the coal meets regulatory requirements for industrial fuels.

5.3 The gross calorific value can be used to evaluate the effectiveness of beneficiation processes.

5.4 The gross calorific value can be required to classify coals according to Classification D388.

6. Apparatus and Facilities

6.1 *Test Area*—An area free from drafts, shielded from direct sunlight and other radiation sources. Thermostatic control of room temperature and controlled relative humidity are desirable.

6.2 *Combustion Bomb*—Constructed of materials that are not affected by the combustion process or the products formed to introduce measurable heat input or alteration of end products. The bomb shall be designed so that all liquid combustion products can be completely recovered by washing the inner surfaces. There shall be no gas leakage. The bomb shall be capable of withstanding a hydrostatic pressure test to 20 MPa (3000 psig) at room temperature without stressing any part beyond its specified elastic limit.

6.3 *Balance*—A laboratory balance capable of weighing the analysis sample to the nearest 0.0001 g. The balance shall be checked weekly, at a minimum, for accuracy.

6.4 *Calorimeter Vessel*—Made of metal with a tarnish-resistant coating, with all outer surfaces highly polished. Its size shall be such that the bomb is completely immersed in water during a determination. A stirrer shall be provided for uniform mixing of the water. The immersed portion of the stirrer shall be accessible to the outside through a coupler of low thermal conductivity. The stirrer speed shall remain constant to minimize any temperature variations due to stirring. Continuous stirring for 10 min shall not raise the calorimeter temperature more than 0.01°C when starting with identical temperatures in the calorimeter, test area and jacket. For calorimeters having a bucket it can be a separate component or integral component of the bomb. The vessel shall be of such construction that the environment of the calorimeter's entire outer boundaries can be maintained at a uniform temperature.

6.5 *Jacket*—A container with the inner perimeter maintained at constant temperature $\pm 0.1^\circ\text{C}$ (isoperibol) or at the same temperature $\pm 0.1^\circ\text{C}$ as the calorimeter vessel (adiabatic) during the test. To minimize convection, the sides, top and bottom of the calorimeter vessel shall not be more than 10 mm from the inner surface of the jacket. Mechanical supports for the calorimeter vessel shall be of low thermal conductivity.

6.6 *Thermometers:*

6.6.1 *Platinum resistance or thermistor thermometers*—shall be capable of measuring to the nearest 0.0001°C. These types of thermometers consist of two major subsystems. The first and most obvious is the temperature sensing probe itself. The second and equally important aspect is the measurement subsystem. For both subsystems, the relationship between the thermometer resistance and temperature shall be well characterized. The absolute temperature shall be known to $\pm 0.1^\circ\text{C}$ at the temperature of the calorimetric measurement.

6.6.2 Assessing the valid working range of the calorimeter, as outlined in 10.9, is sufficient to demonstrate that all important aspects of the calorimeter functionality, including the thermometry, are in good working order. The traceability of the heat of combustion measurement is governed by the traceability of the heat of combustion of the benzoic acid calibrant in addition to meeting the aforementioned criteria.

6.6.3 *Liquid-in-Glass Thermometers*—Conforming to the requirements for thermometers S56C, S116C, or S117C as prescribed in Specification E2251.

6.6.3.1 *Thermometer Accessories*—A magnifier is required for reading liquid-in-glass thermometers to one tenth of the smallest scale division. The magnifier shall have a lens and holder designed so as to minimize errors as a result of parallax.

6.7 *Sample Holder*—An open crucible of platinum, quartz, or base metal alloy. Before use in the calorimeter, heat treat base metal crucibles for a minimum of 4 h at 500°C to ensure the crucible surface is completely oxidized. Base metal alloy crucibles are acceptable, if after three preliminary firings, the weight does not change by more than 0.0001 g.

6.8 *Ignition Fuse*—Ignition fuse of 100-mm length and 0.16-mm (No. 34 B&S gauge) diameter or smaller. Nickel-chromium alloy (Chromel C) alloy, cotton thread, or iron wire are acceptable. Platinum or palladium wire, 0.10-mm diameter (No. 38 B&S gauge), can be used provided constant ignition energy is supplied. Use the same type and length (or mass) of ignition fuse for calorific value determinations as used for standardization.

6.9 *Ignition Circuit*—A 6- to 30-V alternating or direct current is required for ignition purposes. A step-down transformer connected to an alternating current circuit, capacitors, or batteries can be used. For manually operated calorimeters, the ignition circuit switch shall be of the momentary double-contact type, normally open except when held closed by the operator. An ammeter or pilot light can be used in the circuit to indicate when current is flowing.

6.10 *Controller*—For automated calorimeters, capable of charging the bomb; filling the calorimeter vessel; firing the ignition circuit; recording calorimeter temperatures before, during, and after the test; recording the balance weights; and carrying out all necessary corrections and calculations.

6.11 *Crucible Liner*—Quartz fiber or alundum for lining the crucible to promote complete combustion of samples that do not burn completely during the determination of the calorific value.⁴

7. Reagents

7.1 *Reagent Water*—Conforming to conductivity requirements for Type II of Specification **D1193** for preparation of reagents and washing of the bomb interior.

7.2 *Purity of Reagents*—Use reagent grade chemicals conforming to the specification of the Committee on Analytical Reagents of the American Chemical Society in all tests.⁵

7.3 *Benzoic Acid—Standard (C₆H₅COOH)*—Pellets made from benzoic acid available from the National Institute of Standards and Technology (NIST) or benzoic acid calibrated against NIST standard material. The calorific value of benzoic acid, for use in the calibration calculations, shall be traceable to a recognized certificate value.

⁴ Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:D05-1025.

⁵ *Reagent Chemicals, American Chemical Society Specifications*, American Chemical Society, Washington, DC. For suggestions on the testing of reagents not listed by the American Chemical Society, see *Analar Standards for Laboratory Chemicals*, BDH Ltd., Poole, Dorset, U.K., and the *United States Pharmacopeia and National Formulary*, U.S. Pharmacopeial Convention, Inc. (USPC), Rockville, MD.

7.4 *Oxygen*—Manufactured from liquid air, guaranteed to be greater than 99.5 % pure, and free of combustible matter. Oxygen made by the electrolytic process contains small amounts of hydrogen rendering it unfit unless purified by passage over copper oxide at 500°C.

7.5 *Titration Indicator*—Methyl orange, methyl red, or methyl purple for indicating the end point when titrating the acid formed during combustion. The same indicator shall be used for both calibration and calorific value determinations.

7.6 *Standard Solution*—Sodium carbonate (Na₂CO₃) or other suitable standard solution. A convenient standard solution may be prepared as follows. Dissolve 3.706 g of sodium carbonate, dried for 24 h at 105°C, in water and dilute to 1 L. The resulting concentration (0.0699 N) assumes the energy of formation of HNO₃ under bomb conditions is -59.7 kJ/mol (-14.3 kcal/mole) (see **X1.1**). One milliliter of this solution is equivalent to 4.2 J (1.0 cal) in the acid titration. Alternatively, 1.0 ml of a 0.1000 N base solution is equivalent to 6.0 J (1.4 cal) in the acid titration. In general, one milliliter of an arbitrary standard titrant solution is equivalent to its concentration (equivalents / liter or normality [N]) times 59.7 J (14.3 cal).

8. Hazards

8.1 The following precautions are recommended for safe calorimeter operation. Additional precautions are noted in Practice **E144**. Also consult the calorimeter equipment manufacturer's installation and operating instructions before using the calorimeter.

8.1.1 The mass of sample and any combustion aid as well as the pressure of the oxygen admitted to the bomb shall not exceed the bomb manufacturer's specifications.

8.1.2 Inspect the bomb parts carefully after each use. Replace cracked or significantly worn parts. Replace O-rings and valve seats in accordance with manufacturer's instruction. For more details, consult the manufacturer.

8.1.3 Equip the oxygen supply cylinder with an approved type of safety device, such as a relief valve, in addition to the needle valve and pressure gauge used in regulating the oxygen feed to the bomb. Valves, gauges, and gaskets shall meet industry safety codes. Suitable reducing valves and adapters for 3- to 4-MPa (300- to 500-psig) discharge pressure can be obtained from commercial sources of compressed gas equipment. Check the pressure gauge annually for accuracy or after any accidental over pressures that reach maximum gauge pressure.

8.1.4 During ignition of a sample, the operator shall not extend any portion of the body over the calorimeter.

8.1.5 Do not fire the bomb if the bomb has been dropped or turned over after loading.

8.1.6 Do not fire the bomb if there is evidence of gas leakage when the bomb is submerged in the calorimeter vessel.

8.1.7 For manually operated calorimeters, the ignition switch shall be depressed only long enough to fire the charge.

9. Sample

9.1 The analysis sample is the material pulverized to pass 250- μ m (No. 60) sieve, prepared in accordance with either Practice **D346** for coke or Method **D2013** for coal.

10. Determination of the Heat Capacity of the Calorimeter

10.1 *Sample*—Weigh 0.8 to 1.2 g of benzoic acid into a sample holder. Record sample weight to the nearest 0.0001 g.

10.2 Preparation of Bomb:

10.2.1 Rinse the bomb with water to wet internal seals and surface areas of the bomb or precondition the calorimeter according to the manufacturer's instructions. Add 1.0 mL of water to the bomb before assembly.

10.2.2 Connect a measured fuse in accordance with manufacturer's guidelines.

10.2.3 Assemble the bomb. Admit oxygen to the bomb to a consistent pressure of between 2 and 3 MPa (20 and 30 atm). The same pressure is used for each heat capacity run. Control oxygen flow to the bomb so as not to blow material from the sample holder. If the pressure exceeds the specified pressure, detach the filling connection and exhaust the bomb. Discard the sample.

10.3 Preparation of Calorimeter:

10.3.1 Fill the calorimeter vessel with water at a temperature not more than 2°C below room temperature and place the assembled bomb in the calorimeter. Check that no oxygen bubbles are leaking from the bomb. If there is evidence of leakage, remove and exhaust the bomb. Discard the sample.

10.3.2 The mass of water used for each test run shall be $M \pm 0.5$ g where M is a fixed mass of water. Devices used to supply the required mass of water on a volumetric basis shall be adjusted when necessary to compensate for change in the density of water with temperature.

10.3.3 With the calorimeter vessel positioned in the jacket start the stirrers.

10.4 Temperature Observations Automated Calorimeters:

10.4.1 *Stabilization*—The calorimeter vessel's temperature shall remain stable over a period of 30 s before firing. The stability shall be $\pm 0.001^\circ\text{C}$ for an adiabatic calorimeters and $\pm 0.001^\circ\text{C/s}$ or less for an isoperibol calorimeter.

10.4.2 *Extrapolation Method*—Fire the charge, record the temperature rise. The test can be terminated when the observed thermal curve matches a thermal curve which allows extrapolation to a final temperature with a maximum uncertainty of $\pm 0.002^\circ\text{C}$.

10.4.3 *Full Development Method*—Fire the charge and record the temperature rise until the temperature has stabilized for a period of 30 s in accordance with the stability requirements specified in 10.4.1.

10.5 Temperature Observations Manual Calorimeters:

10.5.1 When using ASTM Thermometers S56C, estimate all readings to the nearest 0.002°C. When using ASTM Thermometers S116C, or S117C, estimate readings to 0.001°C and 25- Ω resistance thermometer readings to the nearest 0.0001 Ω . Tap or vibrate liquid-in-glass thermometers just before reading to avoid errors caused by liquid sticking to the walls of the capillary.

10.5.2 Allow 5 min for the temperature of the calorimeter vessel to stabilize. Adjust the jacket temperature to match the calorimeter vessel temperature within 0.01°C and maintain for 3 min.

10.5.3 Fire the charge. Record the time as a and the temperature as t_a .

10.5.4 For adiabatic calorimeters adjust the jacket temperature to match that of the calorimeter vessel temperature during the period of the rise. Keep the two temperatures as equal as possible during the period of rapid rise. Adjust to within 0.01°C when approaching the final stabilization temperature. Record subsequent readings at intervals no greater than 1 min until three successive readings do not differ by more than $\pm 0.001^\circ\text{C}$. Record the first reading after the rate of change has stabilized as the final temperature t_c and the time of this reading as c . For isoperibol calorimeters, when approaching the final stabilization temperature, record readings until three successive readings do not differ by more than 0.001°C per min. Record the first reading after the rate of change has stabilized as the final temperature as t_c and the time of this reading as c .

10.5.5 *Bomb depressurization*—When the thermochemical corrections will be made by titration, the depressurization and subsequent rinse collection shall be done in a manner ensuring at least 80% recovery of the acidic combustion products. An effective measure of the recovery is offered by the recovery factor described in the following section.⁶ Depressurization at a rate such that the operation is not less than one minute provides effective recovery and does not require validation. There are no special requirements related to the bomb depressurization if the calculated nitric acid procedure is used.

10.5.5.1 Determine the recovery factor from the slope of the straight line resulting from the regression analysis of the titration results (mg of sulfur vs. meq) using three or more samples with at least two different sulfur concentrations that span the range of sulfur values typically encountered in the laboratory. One equivalent of sulfuric acid (1000 meq) is formed from 16.03 grams of sulfur. A plot of sulfur (mg) vs. milliequivalents (meq) of titrant used to neutralize the bomb rinsings has a theoretical slope of 16.03. The milliequivalents of titrant is the product of milliliters of base used and its concentration (normality). The mass of sulfur in the sample in milligrams is the product of the sulfur concentration in weight percent in the analysis sample, the sample mass and ten. A slope of 16 implies 100% recovery. Increasing values are indicative of diminished recovery. For example, a value of 20 indicates 80% recovery ($16.03 \times 100 / 20 = 80\%$).

10.5.6 After depressurization, open the bomb and examine the bomb interior carefully for signs of unburned material or sooty deposits. Discard the test result if either is observed.

10.6 Thermochemical Corrections (see Appendix X1):

10.6.1 *Acid Correction (see X1.1)*—One may use either the titration (10.6.1.1) or calculated titration (10.6.1.2) procedure for coal and coke samples.

10.6.1.1 *Titration Method*—Wash the interior of the bomb with distilled water containing the titration indicator (see 7.5) until the washings are free of acid and combine with the rinse of the capsule. Titrate the washings with the standard solutions (see 7.6) using a titration indicator, or a pH or millivolt meter.

⁶ Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:D05-1028, "Interlaboratory Study for the Use of Calculated Nitric Acid Correction."

The product of the volume of titrant used in milliliters, the concentration of the standard solution (normality) and 59.7 J (14.3 cal) shall be taken as $e1$.

10.6.1.2 *Calculated Nitric Acid Method*—For test samples that contain no nitrogen, the nitric acid formed in the bomb during the combustion process is derived from the nitrogen in the air that occupies the bomb prior to pressurizing it with oxygen. The quantity of nitric acid formed is a function of the volume of the bomb, the oxygen filling pressure and the quantity of energy released in the bomb during a test. For a given bomb and filling pressure, the relationship between the amount of nitric acid formed and the energy released can be determined using the following procedure. The calorimeter should be tested using one-gram pellets of benzoic acid when the bomb volume is nominally 340 milliliters. If the bomb volume differs significantly from 340 ml, the sample weight used should be adjusted as required in order to comply with the bomb manufacturer’s safe operating guidelines. Tests should be run in duplicate. Determine the nitric acid correction by titrating the bomb washings as outlined in 10.6.1.1. Divide the correction obtained ($e1$) by the amount of energy released in the bomb for the corresponding test. The energy contribution from the ignition fuse ($e2$) is usually small (<1% of the total energy released) and may be ignored. The average value of this ratio is used to establish a factor (NAF) that allows the nitric acid correction to be determined for any arbitrary energy release.

$$e1 = (NAF) * \text{energy released for the test} \quad (1)$$

Example:

The nitric acid correction for a 340-ml oxygen bomb is found to be 41.9 J (10.0 calories) when the released energy corresponds to that liberated by one gram of benzoic acid, 26.45 kJ (6318 calories). The ratio of these quantities is 1.58 J per 1000 joules of released energy or 1.58 calories per 1000 calories of released energy. The nitric acid correction for any calorimetric test can then be expressed as follows:

$$e1 = 1.58 * \text{energy released for the test (kJ or kcal)} \quad (2)$$

For a given calorimeter, the energy released in the bomb during a test for the purposes of calculating the nitric acid correction ($e1$) may be expressed as the product of the temperature rise for the test and the effective calorimeter heat capacity or calorimeter calibration factor.⁶

$$e1 = (1.58/1000) * E * t \quad (3)$$

The calculated nitric acid method can be applied to samples containing up to 2% nitrogen without introducing a significant error in the resulting heat of combustion value.

10.6.2 *Fuse Correction (see X1.3)*—Determine the fuse correction using one of the two alternatives:

10.6.2.1 Measure the combined pieces of unburned ignition fuse and subtract from the original length to determine the fuse consumed in firing according to Eq 4.

$$e2 = K_f * l \quad (4)$$

where:

- $e2$ = the correction for the heat of combustion of the firing fuse,
- l = the length of fuse consumed during combustion,

- K_f = 0.96 J/mm (0.23 cal/mm) for No. 34 B&S gauge Chromel C,
- K_f = 1.13 J/mm (0.27 cal/mm) for No. 34 B&S gauge iron wire, and
- K_f = 0.00 J/mm for platinum or palladium wire provided the ignition energy is constant.

or;

10.6.2.2 Weigh the combined pieces of unburned fuse and subtract from the original weight to determine the weight in milligrams of the fuse consumed in firing (m). Remove any ball of oxidized metal from the ends before weighing.

$$e2 = K_m * m \quad (5)$$

where:

- $e2$ = the correction for the heat of combustion of the firing fuse,
- m = the weight in mg of fuse consumed during combustion,
- K_m = 5.9 J/mg (1.4 cal/mg) for No. 34 B&S gauge Chromel C,
- K_m = 7.5 J/mg (1.8 cal/mg) for No. 34 B&S gauge iron wire, and
- K_m = 0.00 J/mg for platinum or palladium wire provided the ignition energy is constant.

When cotton thread is used, employ the correction in J recommended by the instrument manufacturer.

10.7 *Calculation of the Corrected Temperature Rise*—Compute the corrected temperature rise, t , as follows:

$$t = t_c - t_a + C_e + C_r \quad (6)$$

where:

- t = corrected temperature rise, °C;
- t_a = initial temperature reading at time of firing;
- t_c = final temperature reading;
- C_e = thermometer, emergent stem correction (see Eq A1.6 or Eq A1.8);
- C_r = radiation correction (see Eq A1.1 or Eq A1.2).

10.7.1 The temperature rise in isoperibol calorimeters require a radiation correction.

10.8 *Calculation of the Heat Capacity*—Calculate the heat capacity (E) of the calorimeter using the following equation:

$$E = [(H_c * m) + e1 + e2] / t \quad (7)$$

where:

- E = the calorimeter heat capacity, J/°C;
- H_c = heat of combustion of benzoic acid, as stated in the certificate, J/g;
- m = mass of benzoic acid, g;
- $e1$ = acid correction from 10.6.1 from either the titration method (10.6.1.1) or the calculated titration (10.6.1.2);
- $e2$ = fuse correction from 10.6.2, J; and
- t = corrected temperature rise from 10.7, °C.

10.8.1 Using the procedures described in 10.1 – 10.8 complete a total of ten acceptable test runs. An individual test shall be rejected only if there is evidence of incomplete combustion.

10.8.2 The precision of ten acceptable calibration test runs shall have a relative standard deviation (RSD) no greater than 0.17%. If after considering the possibility of outliers using criteria established in Practice E178, this limit is not met, one should review operation of the calorimeter for any assignable cause. Operating deficiencies should be corrected before performing additional calibration measurements as required. Table 1 provides an example summary of a series of calibration tests. The formulas used to arrive at the mean value and relative standard deviation are independent of the units used for the calibration measurements.

10.9 *Valid Working Range for the Calibration of the Calorimeter:*

10.9.1 It is a generally accepted principle of reliable analysis that instruments should be calibrated over the full range of measurement and that measurements be restricted to the range calibrated. It is not good practice to report extrapolated data obtained outside the range of calibration. The range of reliable calibration can be considered as the range of reliable measurement and vice versa.

10.9.2 It should be possible to vary the amount of benzoic acid calibrant by at least $\pm 25\%$ without observing a significant trend in the values obtained for the effective heat capacity or instrument calibration factor. The working limits for the instrument calibration shall be determined and defined in terms of the corrected temperature rise. All subsequent measurements shall be kept within these limits.

10.9.3 A convenient way to check a previously calibrated instrument is to use benzoic acid as an unknown. The mean value for the heat of combustion from duplicate runs using 0.7 g and 1.3 g sample masses, respectively, should be within ± 56 J/g or ± 24 Btu / lb of the accepted heat of combustion value.

10.9.4 For any given instrument, examination of the applicable range of the instrument calibration should be carried out when the instrument is new, moved to a different location or subject to major repair.

11. Calibration Verification

11.1 The calorimeter calibration shall be checked on a regular basis. Renewed determination of the heat capacity is required whenever significant alterations have been made to the instrument or to the test conditions. The optimum frequency for checking the heat capacity or instrument calibration will depend on the stability of the measurement system and the risk involved when the system departs from statistical control. Since all data obtained during the period last-known-in-control to first-known-out-of-control are suspect, such intervals may need to be minimized.

11.1.1 There are several empirical approaches to deciding on how frequently the instrument calibration should be checked. The experience of the laboratory may indicate the expected frequency of occurrence of trouble, in which case reference sample measurements, at least three in number, should be equally spaced within such an interval. Another approach is the "length of run" concept. In this, recognizable breaks in the production (of data) process are identified which could cause significant changes in precision or bias. Such breaks could include change of work shift; rest periods; change, modification, or adjustment of apparatus; use of new calibration standards; significantly long down-times; use of a new lot of reagents. At least three reference samples should be measured during any of these periods when the periods are considered to be potentially significant.

11.1.2 Periodic checks of the instrument calibration are a risk-reducing procedure. However, if it involves more than ten percent of a laboratory's measurement effort, either the quality control process may need improvement or too much effort is being exerted in this direction. If less than five percent of effort is devoted to such measurements, the laboratory may be taking too high a risk of producing unacceptable data, or may not even know the quality of the data it is producing. The above statements are made with a laboratory making a significant number of high-quality routine measurements in mind. If a laboratory's program involves occasional or one-of-a-kind

TABLE 1 Calibration Measurements

Run Number	Column A	Column B
	Heat Capacity J/C	Difference from Average Squared
1	10258	20
2	10249	20
3	10270	272
4	10254	0
5	10245	72
6	10249	20
7	10241	156
8	10266	156
9	10258	20
10	10245	72
Sum	102535	811
Average	10254	Sum Column A /10
Variance (s ²)	90	Sum Column B /9
Standard Deviation(s)	9	Sqrt (Variance)
Relative Standard Deviation (RSD)	0.09%	s/Average * 100