



Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method)¹

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This standard has been approved for use by agencies of the Department of Defense.

1. Scope

1.1 This test method covers the determination of the heat of combustion of hydrocarbon fuels. It is designed specifically for use with aviation turbine fuels when the permissible difference between duplicate determinations is of the order of 0.2 %. It can be used for a wide range of volatile and nonvolatile materials where slightly greater differences in precision can be tolerated.

1.2 In order to attain this precision, strict adherence to all details of the procedure is essential since the error contributed by each individual measurement that affects the precision shall be kept below 0.04 %, insofar as possible.

1.3 Under normal conditions, the method is directly applicable to such fuels as gasolines, kerosines, Nos. 1 and 2 fuel oil, Nos. 1-D and 2-D diesel fuel and Nos. 0-GT, 1-GT, and 2-GT gas turbine fuels.

1.4 Through the improvement of the calorimeter controls and temperature measurements, the precision is improved over that of Test Method D 240.

1.5 The values stated in SI units are to be regarded as the standard.

1.6 *This standard does not purport to address 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.* For specific hazard statements, see Section 7, 10.6, A1.7.1 and Annex A3.

2. Referenced Documents

2.1 ASTM Standards:

- D 129 Test Method for Sulfur in Petroleum Products (General Bomb Method)²
- D 240 Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter²
- D 1018 Test Method for Hydrogen in Petroleum Fractions²

D 1193 Specification for Reagent Water³

D 1266 Test Method for Sulfur in Petroleum Products (Lamp Method)²

D 2622 Test Method for Sulfur in Petroleum Products by Wavelength Dispersive X-Ray Fluorescence Spectrometry²

D 3120 Test Method for Trace Quantities of Sulfur in Light Liquid Petroleum Hydrocarbons by Oxidative Microcoulometry²

D 3701 Test Method for Hydrogen Content of Aviation Fuels by Low Resolution Nuclear Magnetic Resonance Spectrometry⁴

D 4294 Test Method for Sulfur in Petroleum and Petroleum Products by Energy Dispersive X-ray Fluorescence Spectroscopy⁴

D 5453 Test Method for Determination of Total Sulfur in Light Hydrocarbons, Motor Fuels and Oils by Ultraviolet Fluorescence⁵

E 1 Specification for ASTM Thermometers⁶

E 144 Practice for Safe Use of Oxygen Combustion Bombs⁷

E 200 Practice for Preparation, Standardization, and Storage of Standard and Reagent Solutions for Chemical Analysis⁸

3. Terminology

3.1 Definitions:

3.1.1 *gross heat of combustion*—expressed as megajoules per kilogram. The gross heat of combustion at constant volume of a liquid or solid fuel containing only the elements carbon, hydrogen, oxygen, nitrogen, and sulfur is the quantity of heat liberated when a unit mass of the fuel is burned in oxygen in an enclosure of constant volume, the products of combustion being gaseous carbon dioxide, nitrogen, sulfur dioxide, and liquid water, with the initial temperature of the fuel and the oxygen and the final temperature of the products at 25°C.

¹ This test method is under the jurisdiction of ASTM Committee D-2 on Petroleum Products and Lubricants and is the direct responsibility of Subcommittee D02.05 on Petroleum, Coke, and Carbon Materials.

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² *Annual Book of ASTM Standards*, Vol 05.01.

³ *Annual Book of ASTM Standards*, Vol 11.01.

⁴ *Annual Book of ASTM Standards*, Vol 05.02.

⁵ *Annual Book of ASTM Standards*, Vol 05.03.

⁶ *Annual Book of ASTM Standards*, Vol 14.03.

⁷ *Annual Book of ASTM Standards*, Vol 14.04.

⁸ *Annual Book of ASTM Standards*, Vol 15.05.

Gross heat of combustion (see Note 1) is represented by the symbol Q_g .⁹

NOTE 1—Users of this test method desiring to calculate ΔH° for a pure compound should note that corrections must be applied to the value of Q_g for buoyancy of air, heat capacities of reaction components, reduction to a constant-pressure process, and deviations of the reaction from the thermodynamic standard state. In any comparison of measurements on pure compounds with those cited in these compilations⁹, the user of this test method should realize that impurities of various kinds, including water and foreign hydrocarbons may cause significant effects on the values obtained for particular samples of material.

3.1.2 *net heat of combustion*—expressed as megajoules per kilogram. The net heat of combustion at constant pressure of a liquid or a solid fuel containing only the elements carbon, hydrogen, oxygen, nitrogen, and sulfur is the quantity of heat liberated when a unit mass of the fuel is burned in oxygen at a constant pressure of 0.101 MPa (1 atm), the products of combustion being carbon dioxide, nitrogen, sulfur dioxide, and water, all in the gaseous state, with the initial temperature of the fuel and the oxygen and the final temperature of the products of combustion at 25°C. The net heat of combustion^{10,11} is represented by the symbol Q_n and is related to the gross heat of combustion by the following equation:

$$Q_n(\text{net}, 25^\circ\text{C}) = Q_g(\text{gross}, 25^\circ\text{C}) - 0.2122 \times H \quad (1)$$

where:

$Q_n(\text{net}, 25^\circ\text{C})$ = net heat of combustion at constant pressure, MJ/kg,

$Q_g(\text{gross}, 25^\circ\text{C})$ = gross heat of combustion at constant volume, MJ/kg, and

H = mass % of hydrogen in the sample.

3.1.3 *energy equivalent (effective heat capacity or water equivalent)*—the energy equivalent of the calorimeter expressed as joules per degree Celsius, J/°C.

NOTE 2—The energy equivalent may be expressed in any energy unit and any temperature unit so long as the value is used consistently throughout the calculations.

3.2 Units:

3.2.1 *Temperatures* are measured in degrees Celsius.

3.2.2 *Time* is expressed in minutes and decimal fractions thereof. It can be measured in minutes or seconds, or both.

3.2.3 *Masses* are measured in grams. No buoyancy corrections are applied except to obtain the mass of benzoic acid.

3.2.4 The energy unit of measurement employed in this test method is the joule with the heat of combustion reported in megajoules per kilogram (Note 3).

$$1 \text{ MJ/kg} = 1000 \text{ J/g} \quad (2)$$

⁹ Prosen, E. J., "Experimental Thermochemistry." F. D. Rossini, editor, Interscience Publishers, 1956, pp. 129–148. Reliable values for heats of combustion of pure compounds are given in National Bureau of Standards *Circular C-461*, "Selected Values of Properties of Hydrocarbons" (U.S. Government Printing Office, Washington, DC, 1947) and in F. D. Rossini, et al., "Selected Values of Physical and Thermodynamic Properties of Hydrocarbons and Related Compounds," Carnegie Press, Pittsburgh, PA, 1953. These compilations were prepared by F. D. Rossini, et al, as part of American Petroleum Institute Research Project 44.

¹⁰ Derivation of equations has been filed at ASTM Headquarters. Request RR: D02–1346.

¹¹ See Jessup, R. S., "Precise Measurement of Heat of Combustion with a Bomb Calorimeter," *NBS Monograph 7*, U.S. Government Printing Office.

NOTE 3—In SI the unit of heat of combustion has the dimension J/kg, but for practical use a multiple is more convenient. The MJ/kg is customarily used for the representation of heats of combustion of petroleum fuels.

3.2.5 The following relationships may be used for converting to other units:

$$1 \text{ cal (International Table calorie)} = 4.1868 \text{ J}^A$$

$$1 \text{ Btu (British thermal unit)} = 1055.06 \text{ J}$$

$$1 \text{ cal (I.T.)}/\text{g} = 0.0041868 \text{ MJ}/\text{kg}^A$$

$$1 \text{ Btu}/\text{lb} = 0.002326 \text{ MJ}/\text{kg}^A$$

^AConversion factor is exact.

4. Summary of Test Method

4.1 The heat of combustion is determined by burning a weighed sample in an oxygen-bomb calorimeter under controlled conditions. The temperature increase is measured by a temperature reading instrument which allows the precision of the method to be met. The heat of combustion is calculated from temperature observations before, during, and after combustion, with proper allowance for thermochemical and heat-transfer corrections. Either isoperibol or adiabatic calorimeters may be used.

5. Significance and Use

5.1 The heat of combustion is a measure of the energy available from a fuel. A knowledge of this value is essential when considering the thermal efficiency of equipment for producing either power or heat.

5.2 The mass heat of combustion, that is, the heat of combustion per unit mass of fuel, is measured by this procedure. Its magnitude is particularly important to weight-limited vehicles such as airplanes, surface effect vehicles, and hydrofoils as the distance such craft can travel on a given weight of fuel is a direct function of the fuel's mass heat of combustion and its density.

5.3 The volumetric heat of combustion, that is, the heat of combustion per unit volume of fuel, can be calculated by multiplying the mass heat of combustion by the density of the fuel (mass per unit volume). The volumetric heat of combustion, rather than the mass heat of combustion, is important to volume-limited craft such as automobiles and ships, as it is directly related to the distance traveled between refuelings.

6. Apparatus

6.1 *Test Room, Bomb, Calorimeter, Jacket, Thermometers, and Accessories*, as described in Annex A1.

6.2 *Semimicro Analytical Balance*, having a sensitivity of 0.01 mg as specified in 10.5.1.

6.3 *Heavy-Duty Analytical Balance*, having a sensitivity of 0.05 g as specified in 10.7.2.

7. Reagents and Materials

7.1 *Purity of Reagents*—Reagent grade chemicals shall be used in all tests. Unless otherwise indicated, it is intended that all reagents shall conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society,

where such specifications are available.¹² Other grades may be used, provided it is first ascertained that the reagent is of sufficiently high purity to permit its use without lessening the accuracy of the determination.

7.2 *Purity of Water*—Unless otherwise indicated, references to water shall be understood to mean reagent water conforming to Specification D 1193, Type IV or better.

7.3 *Benzoic Acid*¹³—The acid must be pelleted before use.

7.4 *Firing Wire*—0.127 mm (No. 36 gage) platinum wire, No. 34 B & S gage iron wire or Chromel C resistance wire, cut in 100-mm lengths.

7.5 *Methyl Red Indicator*.

7.6 *Oxygen*—Commercial oxygen produced from liquid air can be used without purification (**Warning**—Oxygen vigorously accelerates combustion. (See A3.1.)). Oxygen prepared by electrolysis of water cannot be used without purification as it can contain some hydrogen. Combustible impurities may be removed by passage over copper oxide at 500°C.

7.7 *Pressure-Sensitive Tape*—Cellophane tape 38 mm (1½ in.) wide, free of chlorine and sulfur.¹⁴

7.8 *Alkali, Standard Solutions*.

7.8.1 *Sodium Hydroxide Solution* (0.0866 *N*)—Dissolve 3.5 g of sodium hydroxide (NaOH) in water and dilute to 1 L. (**Warning**—Corrosive. Can cause severe burns or blindness. Evolution of heat produces a violent reaction or eruption upon too rapid mixture with water (see Annex A3.2.)). Standardize with potassium acid phthalate and adjust to 0.0866 *N* as described in Practice E 200, or alternative use.

7.8.2 *Sodium Carbonate Solution* (0.0725 *N*)—Dissolve 3.84 g of Na₂CO₃ in water and dilute to 1 L.

7.9 *2,2,4-Trimethylpentane*—(*isooctane*), *Standard*¹⁵ (**Warning**—Extremely flammable. Harmful if inhaled. Vapors may cause flash fire. (See Annex A3.3.)).

8. Preparation of Apparatus

8.1 *Arrangement of Apparatus*—Install the thermometers as recommended by the manufacturer of the calorimeter. Position the mercury-in-glass thermometer so that the bulb is halfway to the bottom of the bucket and locate the thermistor with its sensing element at about the midpoint of the thermometer bulb. Mount these elements so that exactly the same length is immersed each time the calorimeter is used. Install a thermistor in the water jacket with the element immersed to the same depth as in the bucket. It is helpful, but not necessary to have mercury-in-glass calorimetric thermometers in both the bucket and jacket for quick temperature observations. Thermistors can be taped to these thermometers. If the thermistors are taped to

the thermometers, it can be done in such a manner that the sensing elements are at the midpoint of the thermometer bulbs. The thermometer bulbs and temperature-sensing elements shall not touch the bomb, bucket, or water jacket.

8.2 *Calorimeter Jacket Controller and Auxiliary Equipment*—Adjust the jacket controller, valves, heater, etc., as recommended by the calorimeter manufacturer.

9. Standardization

9.1 *Energy Equivalent of the Calorimeter*—Benzoic acid shall be used as the primary standard (**Warning**—Oxygen vigorously accelerates combustion. See A3.1). Choose a sample mass so that the temperature rise is approximately equivalent to an energy change of 30 000 J. Initially determine the energy equivalent by averaging six determinations made using benzoic acid over a period of at least 3 days.

9.1.1 A relative standard deviation (RSD) of 0.1 % or less for the six determinations must be achieved. If not, continue to run until six determinations establish a value that has a RSD of 0.1 % or better. If this degree of precision cannot be achieved, review the procedure, critical measurements, mechanical operations and everything that may contribute to scatter in the results. After establishing an energy equivalent value, determine the value at frequent intervals using benzoic acid (every 1 or 2 days of testing) with the average of the last six determinations being used for the energy equivalent as long as the last six determinations have a RSD of 0.1 % or less.

9.1.2 If any part of the equipment is changed or any part of the procedure is altered, redetermine the value. Make each determination in accordance with Section 10. Determine the correction for nitric acid (HNO₃) as described in 11.3 and substitute in the following equation:

$$W = (Q_b \times m + e_1) / \Delta t \quad (3)$$

where:

W = energy equivalent of calorimeter, J/°C,

m = mass of benzoic acid, g,

Δt = corrected temperature rise, as calculated in accordance with 11.1 or 11.2, °C,

*e*₁ = correction for heat of formation of nitric acid, J, and

*Q*_b = heat of combustion of benzoic acid, J/g calculated from the certified value in kilojoules per gram mass given for NBS Standard 39i. Multiply kilojoules per gram mass by 1000 to obtain joules per gram (Note 5).

NOTE 4—2,2,4-trimethyl pentane may be used for checking the energy equivalent of the system for use with volatile fuels.

NOTE 5—Multiply the heat evolved by combustion of the standard sample by the following factor.¹⁶

$$1 + 10^{-6} [197(P - 3.04) + 42((m/V) - 3) + 30((M_w/V) - 3) - 45(t - 25)] \quad (4)$$

where:

P = initial absolute pressure of oxygen, MPa (1 atm = 0.101325 MPa) at temperature *t*,

m = mass of benzoic acid, g,

¹² *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.

¹³ Obtainable from the National Institute of Standards and Technology, Clopper and Quince Orchard Roads, Gaithersburg, MD 20899, as Standard Sample 39i.

¹⁴ Cellophane tape Scotch Brand No. 610, available from 3M Co., meets the specification requirements.

¹⁵ Obtainable from the National Institute of Standards and Technology, Clopper and Quince Roads, Gaithersburg, MD 20899, as Standard Sample No. 217b.

¹⁶ See *NBS Monograph 7*, p. 12.

M_w = mass of water placed in bomb before combustion, g,
 V = internal volume of bomb, L, and
 t = temperature to which the combustion reaction is referred, °C
 (final temperature of the calorimeter).

9.2 Heat of Combustion of Pressure-Sensitive Tape—Determine the heat of combustion of the pressure-sensitive tape in accordance with Section 10 using about 1.2 g of tape and omitting the sample. Make at least three determinations and calculate the heat of combustion as follows:

$$Q_{pst} = (\Delta t \times W - e_1)/a \quad (5)$$

where:

Q_{pst} = heat of combustion of the pressure-sensitive tape, J/g

Δt = corrected temperature rise, as calculated in accordance with 11.1 or 11.2, °C,

W = energy equivalent of the calorimeter, J/°C,

e_1 = correction for the heat of formation of HNO₃, J, and

a = mass of the pressure-sensitive tape, g.

9.2.1 Average the determinations, and redetermine the heat of combustion of the tape whenever a new roll is started.

10. Procedure

10.1 Turn on the apparatus. Make all electrical connections and open the water lines.

10.2 Before beginning, be sure that the bomb and its fittings are completely dry, inside and out.

10.3 Measure a piece of firing wire 100 mm long and attach the wire to the bomb electrodes forming a U-shaped loop.

10.4 Pipet 1.0 cm³ of water into the bomb and cover with a watch glass.

10.5 Mass of Sample:

10.5.1 Weigh the sample cup to 0.01 mg on a semimicro analytical balance. Place a piece of pressure-sensitive type (Note 6) across the top of the cup, trim around the edge with a razor blade, and seal tightly. Place a 3 by 12-mm strip of tape creased in the middle and sealed by one edge in the center of the tape disk to give a flap arrangement. Weigh the cup and tape. Remove from the balance with forceps. Fill a hypodermic syringe with the sample. The volume of sample necessary to produce a temperature rise equivalent to approximately 30 000 J can be estimated as follows:

$$V = (W \times 0.0032)/(Q \times D) \quad (6)$$

where:

V = volume of sample to be used, cm³,

W = energy equivalent of the calorimeter, J/°C,

Q = approximate heat of combustion of the sample, MJ/kg, and

D = density, g/cm³, of the sample.

or

$$V = (W \times 1.3)/(Q \times D) \quad (7)$$

where:

Q = approximate heat of combustion of the sample, Btu/lb.

NOTE 6—For relatively high-boiling samples, such as non-volatile (i.e. IBP above 180°C) kerosine-type jet fuels, it is not necessary to use tape.

10.5.2 Add the sample to the cup by inserting the tip of the needle through the tape disk at a point so that the flap of tape

will cover the puncture upon removal of the needle. Seal down the flap by pressing lightly with a metal spatula. Reweigh the cup with the tape and sample. Take care throughout the weighing and filling operation to avoid contacting the tape or cup with bare fingers. Place the cup in the curved electrode and arrange the fuse wire so that the central portion of the loop presses down on the center of the tape disk.

10.6 Bomb Assembly—Assemble the bomb and tighten the cover securely. Connect the bomb to the oxygen cylinder and slowly admit oxygen until a pressure of 3.0 MPa (30 atm) is attained. Do not purge the bomb to remove entrapped air. Disconnect the bomb from the oxygen cylinder and replace the valve cover. (**Warning**—A violent explosion may occur.) Be careful not to overcharge the bomb. If by accident, the oxygen introduced into the bomb does exceed 4.0 MPa (40 atm) **DO NOT** proceed with the combustion. A violent explosion, capable of rupturing the bomb, might occur. Detach the filling connection and exhaust the bomb in the usual manner. Discard the sample.

NOTE 7—Pressures within the range of from 2.5 to 3.55 MPa (25 to 35 atm) may be used, provided the same pressure is used for all tests, including standardization.

10.7 Calorimeter Water:

10.7.1 Adjust the temperature of the calorimeter water. The choice of the temperature to which the water is adjusted before weighing depends on a number of factors, including room temperature, the desired initial temperature of the experiment, and the relative heat capacities of the calorimeter bucket, water, and bomb. No definite rule can be given, but the operator will learn by experience how to select the proper temperature under the conditions of his particular laboratory and apparatus. The following can be used as a guide:

Isothermal method	3.0 to 3.5°C below jacket temperature
Adiabatic method	1.5 to 1.8°C below room temperature

10.7.1.1 Isoperibol Method—Adjust the temperature such that after assembly of the calorimeter bomb and bucket its temperature will be a few tenths of a degree below the desired initial temperature.

10.7.1.2 Adiabatic Method—Adjust the temperature so that the initial temperature of the determination will be as close to some fixed values as possible. Control the mean temperature of all determinations within more than ±0.5°C and the temperature rise for all determinations within ±0.3°C.

10.7.2 Weigh the calorimeter bucket to ±0.05 g on a heavy-duty analytical balance. After once establishing the dry bucket weight, it need only be checked occasionally. Fill with the desired quantity of water (2000 to 2100 g) and reweigh to 0.05 g (Note 6). The exact quantity of water is not important as long as it is enough to cover the bomb and its fittings and is the same in each determination.

NOTE 8—The change in the mass of the water in the calorimeter bucket due to evaporation after weighings will affect the energy equivalent. The effect of this loss is small and cancels if the procedure of placing the bomb in its bucket and completing the assembly of the system is carried out in the same manner and in the same length of time in the calibration experiments as in the measurement of the heat of combustion.

10.7.3 Immediately after weighing, place the bucket in position in the calorimeter jacket, carefully place the bomb in

the bucket, and complete the firing circuit. Close the calorimeter cover and lower thermometers and thermistors.

NOTE 9—The bomb should be lowered into the calorimeter without touching the water with the fingers. This can be done by using a hook on which the bomb can be hung and which can be removed after the bomb is in place in the calorimeter bucket. A hook made of a piece of brass rod about 1.6 mm ($1/16$ in.) in diameter has been found satisfactory. The hooked ends of the rod are inserted into holes on opposite sides of the screw top of the bomb and are easily removed after the bomb is in place. It is very important that all operations in the experimental procedure be carried out in an identical manner throughout for the energy equivalent and heat of combustion measurements.

10.8 Procedure for Isoperibol Method:

10.8.1 Start the stirrer motor and the controller on the jacket heater to bring the temperature of the water in the jacket to 28°C. Take time and temperature readings over a 25-min period. During this period there are three definite time intervals:

10.8.1.1 An initial period of about 6 to 9 min during which the temperature change results solely from thermal leakage and heat of stirring.

10.8.1.2 A middle period of about 12 min, at the beginning of which the charge in the bomb is fired, and during which the temperature change is due primarily to the heat liberated by the combustion reaction in the bomb and partly to thermal leakage and heat of stirring, and

10.8.1.3 A final period of 9 to 11 min during which the temperature change is again due solely to thermal leakage and heat of stirring.

10.8.2 Allow the temperature of the calorimeter water to drift up to the starting temperature and then make and record readings of the time and temperature of the initial period. During this initial period when the rate of temperature rise is constant, make observations of temperature at 1-min intervals. The starting temperature always has the same value as determined from the calibration runs.

10.8.3 When the firing temperature is reached, fire the sample by closing the firing circuit through the fuse wire in the bomb by depressing the button on the ignition unit. The pilot light should glow momentarily and the temperature should start increasing in about 15 s. If the circuit does not close, or if it remains closed, or if the temperature does not start rising, the experiment has misfired and must be discontinued. After the combustion of the sample and during the middle period when the temperature is rising rapidly, take temperature measurements at 30s intervals. After about 3 min, the rate of temperature rise will decrease so that temperature readings may be taken with more accuracy. These readings shall be continued until the rate of temperature change has been constant for at least 10 min. The readings made after the rate of temperature change has become constant constitute the final period.

NOTE 10—During the initial and final periods the thermometer should be read with the highest possible care, since the overall precision of the determination depends directly upon these temperature measurements. During the middle period, because of the very rapid rate of temperature rise, it is not possible to make readings as carefully as during the initial and final periods. This is not important because the readings of the middle period are used only for calculating the relatively small correction for thermal leakage and heat of stirring.

10.9 Procedure for Adiabatic Method:

10.9.1 Start the stirrer motor and turn on the calorimeter controller. Use the manual control switch of the controller to bring the jacket temperature in close agreement with the bucket temperature. Allow the controller to automatically control the temperature and wait 15 min for equilibrium to be attained. At this point, and at the end point also, control the temperature of the jacket to the same temperature as the bucket, or slightly (0.005°C at most) below. Make readings at 1-min intervals until three consecutive readings show no change. Fire the sample by depressing the button of the ignition unit. The pilot light should glow momentarily and the temperature should start increasing in about 15 s. (If the temperature does not start rising, the experiment has misfired and must be discontinued.) Read and record the initial resistance, estimating the value to the nearest 0.00005°C .

10.9.2 After 6 min from firing, begin reading temperature every minute. Continue until three consecutive readings show no change, or the readings decrease. Read and record the final temperature reading estimating the value to the nearest 0.0005°C .

10.10 Analysis of Bomb Contents:

10.10.1 Turn off the controller and stirrer and remove the bomb from the calorimeter. Open the needle valve and allow the gas to escape at a uniform rate such as to reduce the pressure to atmospheric in not less than 1 min. Open the bomb and examine the interior for unburned carbon. If any trace of unburned carbon is found, the experiment should be rejected. Wash the interior of the bomb including the electrodes and the sample cup with a fine jet of water and quantitatively collect the washings in a 500-cm³ Erlenmeyer flask. Use a minimum amount of wash water, preferably less than 300 cm³. Titrate the washings with standard alkali solution using methyl red indicator.

10.10.2 Determine the sulfur content of the sample to the nearest 0.02 % sulfur as described in Test Method D 129, D 1266-IP 107, D 2622, D 3120, D 4294, or D 5453 depending upon the volatility of the sample.

10.10.3 When iron or Chromel C wire is used, remove and measure the combined pieces of unburned firing wire, and subtract from the original length. Record the difference as *wire consumed*.

11. Calculation

11.1 *Temperature Rise Isoperibol Method*— Using data obtained in Section 10, plot a graph of readings of temperature versus time and calculate the corrected temperature rise, Δt , in $^{\circ}\text{C}$ as follows:

$$\Delta t = t_f - t_i - r_1(b - a) - r_2(c - b) \quad (8)$$

where:

Δt = corrected temperature rise, $^{\circ}\text{C}$,

a = time of firing,

b = time (to nearest 0.1 min) when the temperature rise reaches 63 % of total (obtained graphically or numerically),

c = time at beginning of final period in which the rate of temperature change with time has become constant,

- t_i = temperature at time of firing, °C,
 t_f = temperature at time c, °C,
 r_1 = rate at which the temperature was rising during the initial period before firing, °C, and
 r_2 = rate at which the temperature was rising during the final period, °C.

11.2 *Temperature Rise, Adiabatic Method*— Using data obtained in Section 10, calculate the temperature rise, Δt , in °C, as follows:

$$\Delta t = t_f - t_i \quad (9)$$

where:

- Δt = corrected temperature rise, °C,
 t_f = final equilibrium temperature, °C, and
 t_i = temperature at time of firing, °C.

11.3 *Thermochemical Correction* (Annex A2)—Calculate the following corrections for each test:

- e_1 = correction for the heat of formation of the HNO_3 , $J = \text{cm}^3$ of standard (0.0866 *N*) NaOH solution used in titration $\times 5$,
 e_2 = correction for the heat of formation of sulfuric acid (H_2SO_4), $J = 58.6 \times$ percentage of sulfur in sample \times mass of sample, g,
 e_3 = correction for the heat of combustion of pressure-sensitive tape, $J =$ mass of tape, g \times heat of combustion of tape J/g.
 e_4 = correction for heat of combustion of firing wire, MJ = $1.13 \times$ millimetres of iron wire consumed/ 10^6 = $0.96 \times$ millimetres of Chromel C wire consumed/ 10^6

11.4 *Gross Heat of Combustion*—Calculate the gross heat of combustion by substituting in the following equations:

$$Q_g(\text{gross } t^\circ\text{C}) = (\Delta t \times W - e_1 - e_2 - e_3 - e_4)/1000 M \quad (10)$$

$$Q_g(\text{gross, } 25^\circ\text{C}) = Q_g(\text{gross, } t^\circ\text{C}) + A(t - 25) \quad (11)$$

where:

- $Q_g(\text{gross, } t^\circ\text{C})$ = gross heat of combustion at constant volume and final temperature of the experiment, expressed as MJ/kg,
 $Q_g(\text{gross, } 25^\circ\text{C})$ = gross heat of combustion at constant volume expressed as MJ/kg,
 Δt = corrected temperature rise, °C,
 W = energy equivalent of calorimeter, J/°C
 M = mass of sample, g,
 t = final temperature of combustion, °C,
 e_1, e_2, e_3, e_4 = corrections as described in 11.3, and
 A = correction factor, MJ/kg °C to correct from final temperature of combustion to 25°C¹⁵ where values of factor A are given in Table 1.

NOTE 11—The gross heat of combustion at constant pressure may be calculated as follows:

$$Q_{gp} = Q_g + 0.006145H \quad (12)$$

TABLE 1 Values of Factor A

$Q_g(\text{Gross, } t^\circ\text{C})$	A	$Q_g(\text{Gross, } t^\circ\text{C})$	A
MJ/kg	MJ/kg·°C	MJ/kg	MJ/kg·°C
43.00	0.00157	45.75	0.00271
43.25	0.00167	46.00	0.00282
43.50	0.00178	46.25	0.00292
43.75	0.00188	46.50	0.00302
44.00	0.00199	46.75	0.00313
44.25	0.00209	47.00	0.00323
44.50	0.00219	47.25	0.00333
44.75	0.00230	47.50	0.00344
45.00	0.00240	47.75	0.00354
45.25	0.00250	48.00	0.00365
45.50	0.00261		

where:

Q_{gp} = gross heat of combustion at constant pressure, MJ/kg, and

H = hydrogen content, mass %

$Q_{btu/lb}$ = (Q , MJ/kg)/0.002326

$Q_{cal/g}$ = (Q , MJ/kg)/0.0041868

11.5 *Net Heat of Combustion*—Calculate the net heat of combustion¹⁷ as follows:

$$Q_n(\text{net, } 25^\circ\text{C}) = Q_g(Q_{g,\text{gross, } 25^\circ\text{C}}) - 0.2122 \times H \quad (13)$$

where:

$Q_n(\text{net, } 25^\circ\text{C})$ = net heat of combustion at constant pressure, MJ/kg,

$Q_g(\text{gross, } 25^\circ\text{C})$ = gross heat of combustion at constant volume, MJ/kg, and

H = mass percent of hydrogen in the sample.

When the percentage of hydrogen in the sample is not known, determine the hydrogen in accordance with Test Methods D 1018 or D 3701.

12. Report

12.1 Net heat of combustion is the quantity required in practical applications. Both gross and net heat are reported to the nearest 0.002 MJ/kg.

12.1.1 To obtain the gross or net heat of combustion in cal (I.T.)/g or Btu/lb divide by the appropriate factor given in 3.2.5 reporting to the nearest 0.5 cal/g or 1 Btu/lb.

13. Precision and Bias¹⁸

13.1 *Precision*—The precision of this test method as determined by the statistical examination of interlaboratory test results is as follows.

13.1.1 *Repeatability*—The difference between successive results obtained by the same operator with the same apparatus under constant operating conditions on identical test material

¹⁷ See NBS Monograph 7, p. 16.

¹⁸ The precision and bias values in this statement were determined in a cooperative laboratory program that follows RR: D02 – 1007. Supporting data have been filed at ASTM Headquarters and may be obtained by requesting RR: D02 – 1229.

would, in the long run, in the normal and correct operation of the test method, exceed the following values only in one case in twenty.

Method	Repeatability, MJ/kg	
	Gross	Net
1. All fuels	0.097	0.096
2. Nonvolatile	0.096	0.099
3. Volatile	0.100	0.091

13.1.2 *Reproducibility*—The difference between two single and independent results obtained by different operators working in different laboratories on identical test material would, in the long run, exceed the following values only in one case in twenty.

Method	Reproducibility, MJ/kg	
	Gross	Net
1. All fuels	0.228	0.324
2. Nonvolatile	0.239	0.234
3. Volatile	0.207	0.450

13.2 *Bias*—The bias of the procedure in this test method as determined by the statistical examination of interlaboratory test results is as follows:

Gross	Bias, MJ/kg	
	Gross	Net
0.001		0.089

ANNEXES

(Mandatory Information)

A1. APPARATUS FOR HEAT OF COMBUSTION TEST

A1.1 Test Room

A1.1.1 The room in which the calorimeter is operated must be free from drafts and not subject to sudden temperature changes. The exact temperature is not important as long as it is in the range from 23 to 26°C (74 to 78°F) and is held constant. The temperature must be constant, not only throughout the day, but from one time of the year to another. The direct rays of the sun shall not strike the calorimeter jacket, bridge, and galvanometer. Adequate facilities for lighting, heating, and ventilation should be provided. Thermostatic control of room temperature and controlled humidity are desirable.

A1.2 Oxygen Bomb

A1.2.1 The oxygen bomb shall meet the requirements specified in Practice E 144 and have an internal volume of 350 ± 50 mL. All parts shall be constructed of materials that are not affected by the combustion process or products sufficient to introduce measurable heat input or alteration of end products. If the bomb is lined with platinum or gold, all openings shall be sealed to prevent combustion products from reaching the base metal. The bomb must be designed so that all liquid combustion products can be completely recovered by washing the inner surfaces. There must be no gas leakage during a test. The bomb must be capable of withstanding a hydrostatic pressure test to a gage pressure of 20.7 MPa (3000 psi) at room temperature without stressing any part beyond its elastic limit.¹⁹ If necessary, modify the bomb such that the feet are 12 mm high to allow for better water circulation under the bomb.

A1.3 Calorimeter Bucket

A1.3.1 The calorimeter bucket shall be made of metal (preferably copper or brass) with a tarnish-resistant coating, and with all outer surfaces highly polished. Its size shall be

such that the bomb will be completely immersed in water when the calorimeter is assembled. It shall have a device for stirring the water thoroughly and at a uniform rate but with minimum heat input. Continuous stirring for 10 min shall not raise the temperature more than 0.01°C starting with identical temperatures in the calorimeter, room, and jacket. The immersed portion of the stirrer shall be coupled to the outside through a material of a low-heat conductivity.

A1.4 Jacket

A1.4.1 The calorimeter bomb, bucket, and water shall be completely enclosed within a stirred water jacket and supported so that its sides, top, and bottom are approximately 1 cm from the jacket walls. The jacket may be arranged so as to remain at a constant temperature, or with provisions for automatically adjusting the jacket temperature to equal that of the calorimeter bomb, bucket, and water for adiabatic operation. It must be constructed so that any water evaporating from the jacket will not condense on the calorimeter bucket.²⁰

A1.5 Thermometers

A1.5.1 Temperatures in the jacket and the calorimeter, respectively, shall be measured with the following thermometers:

A1.5.1.1 Etched stem, mercury-in-glass, ASTM Bomb Calorimeter Thermometers, having a range from 66 to 95°F, 19 to 35°C, 18.9 to 25.1°C, or 23.9 to 30.1°C as specified, and conforming to the requirements for Thermometer 56F, 56C, 116C, or 117C, respectively, as prescribed in Specification E 1. Each of these thermometers shall have been tested for accuracy at intervals no larger than 2.5°F or 1.5°C over the entire graduated scale. Corrections shall be calculated to 0.005°F or 0.002°C, respectively, for each test point.

¹⁹ The oxygen bomb, Parr No. 1108 or equivalent, available from Parr Instrument Co., 211 Fifty-third St., Moline, IL 61265.

²⁰ The Calorimeter Jacket, Parr No. 1261 or equivalent, available from Parr Instrument Co., meets the specification requirements.

A1.5.2 Temperature in the calorimeter shall be measured with the following thermometers:

A1.5.2.1 Platinum resistance, thermistor, or other temperature measuring devices which when used with its associated instrumentation will measure the temperature rise repeatably with a recorded resolution of 0.0001°C and a repeatability such that the precision requirements for the energy equivalent are met. Further, that these specifications are limited to the requirements that the mean temperature of all determinations not deviate by more than 0.05°C and that the temperature rise for all experiments be within $\pm 0.3^\circ\text{C}$.

A1.6 Automatic Calorimeter Microprocessor Controller

A1.6.1 In place of manually recording temperatures and calculating the energy equivalent, an automatic controller may be used. It shall be capable of storing calorimeter temperature readings taken at accurate intervals, firing the bomb and ending the experiment. The stored information along with the sample mass, nitric acid correction and sulfur content, when entered into the instrument, shall be used to calculate the desired energy equivalent or heat of combustion.

A1.7 Firing Circuit

A1.7.1 A 6 to 16-V alternating or direct current is required

for ignition purposes with an ammeter or pilot light in the circuit to indicate when current is flowing. A step-down transformer connected to a 115 V, 50/60-Hz lighting circuit or storage battery may be used²¹ (**Warning**—The ignition circuit switch shall be of the momentary contact type, normally open, except when held closed by the operator.).

A1.8 Timing Device

A1.8.1 A watch or other timing device capable of measuring time to 1 s is required for use with the isoperibol method.

A1.9 Sample Cup

A1.9.1 A low-form platinum cup, 26 mm in diameter and 11 mm deep with a spun rim.²² Base metal alloy crucibles are acceptable if after a few preliminary firings the weight does not change significantly between tests.

²¹ Ignition Unit, Parr No. 2901, available from Parr Instrument Co., meets the specification requirements.

²² Sample Cup, Parr No. 43A6, available from Parr Instrument Co., has been found satisfactory.

A2. CORRECTIONS

A2.1 Thermometer Corrections

A2.1.1 It is not necessary to apply stem corrections to the thermometers.

A2.2 Thermochemical Corrections

A2.2.1 *Heat of Formation of Nitric Acid*—A correction of 5 J is applied for each cubic centimetre of standard (0.0866 N) NaOH solution used in the acid titration. This is based on the assumption that (1) all of the acid titrated is HNO₃ and (2) the heat of formation of 0.1 N HNO₃ under the test conditions is 57.8 kJ/mole. When H₂SO₄ is also present, part of the correction for H₂SO₄ is contained in the e_1 correction, and the remainder in the e_2 correction.

A2.2.2 *Heat of Formation of Sulfuric Acid*—A correction of 5.86 kJ is applied to each gram of sulfur in the sample. This is based upon the heat of formation of 0.17 N H₂SO₄, which is + 301.4 kJ/mole. But, a correction equal to 2×57.8 kJ/mole of sulfur was applied for H₂SO₄ in the e_1 correction. Thus, the additional correction necessary is $301.4 - (2 \times 57.8) = 185.8$ kJ/mole or 5.86 kJ/g of sulfur.

A2.2.2.1 The value of 5.86 kJ/g of sulfur is based on a fuel oil containing a relatively large amount of sulfur since as the percentage of sulfur decreases, the correction decreases and

consequently a larger error can be tolerated. For this calculation 0.8 % S, 99.2 % CH₂ was taken as the empirical composition of fuel oil. If a 0.6-g sample of such a fuel oil is burned in a bomb containing 1 cm³ of water, the H₂SO₄ formed will be approximately 0.17 N.

A2.2.2.2 Using data from National Bureau of Standards *Circular No. 500*, the heat of reaction SO₂(g) + ½ O₂(g) + 651 H₂O (l) – H₂SO₄·650 H₂O (l) at constant volume and 3 MPa is – 301.4 kJ/mole.

A2.2.3 *Heat of Combustion of Fuse Wire*—When using platinum wire no correction need be applied for the heat of combustion of the wire. The electrical energy required can be neglected if the same length of wire is used in both the energy equivalent and unknown experiments. When using iron or Chromel C wire, the following heats of combustion are accepted:

Iron wire, No. 34 B & S gage	=	1.13 J/mm
Chromel C wire	=	0.96 J/mm

A2.2.4 *Heat of Combustion of Pressure-Sensitive Tape*—The correction for the heat of combustion of the tape (as determined in accordance with 9.2) assumes complete combustion of the tape.

A3. PRECAUTIONARY STATEMENTS

A3.1 Oxygen

Do not exceed the sample size limits.

Following manufacturer's commendations for filling the bomb.

Do not use oil or grease on regulators, gages, or control equipment.

Use only with equipment conditioned for oxygen service by carefully cleaning to remove oil, grease, and other combustibles.

Keep combustibles away from oxygen and eliminate ignition sources.

Keep surfaces clean to prevent ignition or explosion, or both, on contact with oxygen.

Always use a pressure regulator. Release regulator tension before opening cylinder valve.

All equipment and containers used must be suitable and recommended for oxygen service.

Never attempt to transfer oxygen from cylinder in which it is received to any other cylinder.

Do not mix gases in cylinders.

Do not drop cylinder. Make sure cylinder is secured at all times.

Keep cylinder valve closed when not in use.

Stand away from outlet when opening cylinder valve.

Keep cylinder out of sun and away from heat.

Keep cylinder from corrosive environment.

Do not use cylinder without label.

Do not use dented or damaged cylinders.

For technical use only. Do not use for inhalation purposes.

Use only in well-ventilated area.

See compressed gas association booklets G-4 and G-4.1 for details of safe practice in the use of oxygen.

A3.2 Sodium Hydroxide

Before using, secure information on procedures and protective measures for safe handling.

Do not get in eyes, on skin, on clothing.

Avoid breathing dusts or mists.

Do not take internally.

When handling, use chemical safety goggles or face shield, protective gloves, boots and clothing.

When mixing with water, add slowly to surface of solution to avoid violent spattering. In the preparation of solutions do not use hot water, limit temperature rise, with agitation, to 10°C/min or limit solution temperature to a maximum of 90°C. No single addition should cause a concentration increase greater than 5 %.

A3.3 2,2,4-Trimethylpentane

Keep away from heat, sparks, and open flame.

Keep container closed.

Use with adequate ventilation.

Avoid buildup of vapors and eliminate all sources of ignition, especially nonexplosion-proof electrical apparatus and heaters.

Avoid prolonged breathing of vapor or spray mist.

Avoid prolonged or repeated skin contact.

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