



Standard Test Method for Analysis of Stainless and Alloy Steels by X-ray Fluorescence Spectrometry¹

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1. Scope

1.1 This test method² covers the analysis of stainless and alloy steels by wavelength dispersive X-ray Fluorescence Spectrometry for the determination of the following elements:

| Element | Range % |
|------------|---------------|
| Chromium | 2.0 to 25.0 |
| Cobalt | 0.03 to 0.40 |
| Copper | 0.05 to 3.50 |
| Manganese | 0.3 to 5.0 |
| Molybdenum | 0.15 to 3.5 |
| Nickel | 0.20 to 35.0 |
| Niobium | 0.05 to 1.3 |
| Phosphorus | 0.01 to 0.03 |
| Silicon | 0.05 to 0.20 |
| Sulfur | 0.02 to 0.30 |
| Titanium | 0.002 to 0.04 |
| Vanadium | 0.03 to 0.25 |

NOTE 1—Unless exceptions are noted, concentration ranges can be extended by the use of suitable reference materials.

1.2 *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 precautionary statements are given in Section 10.

2. Referenced Documents

2.1 ASTM Standards:

- E 135 Terminology Relating to Analytical Chemistry for Metals, Ores, and Related Materials³
- E 305 Practice for Establishing and Controlling Spectrochemical Analytical Curves³
- E 691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method⁴
- E 1361 Guide for Correction of Interelement Effects in X-ray Spectrometric Analysis³

¹ This test method is under the jurisdiction of ASTM Committee E01 on Analytical Chemistry for Metals, Ores and Related Materials and is the direct responsibility of Subcommittee E01.01 on Iron, Steel, and Ferroalloys.

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² Supporting data for this test method as determined by cooperative testing have been filed at ASTM International Headquarters as RR: E-1-1032.

³ *Annual Book of ASTM Standards*, Vol 03.05.

⁴ *Annual Book of ASTM Standards*, Vol 14.02.

- E 1601 Practice for Conducting an Interlaboratory Study to Evaluate the Performance of an Analytical Method³
- E 1622 Practice for Correction of Spectral Line Overlap in Wavelength-Dispersive X-ray Spectrometry³
- E 1806 Practice for Sampling Steel and Iron for Determination of Chemical Composition⁵

3. Terminology

3.1 For definitions of terms used in this test method, refer to Terminology E 135.

4. Summary of Test Method

4.1 The test specimen is finished to a clean, uniform surface and then irradiated with an X-ray beam of high energy. The secondary X-rays produced are dispersed by means of crystals and the intensities are measured by suitable detectors at selected wavelengths. The outputs of the detectors in voltage pulses are counted. Radiation measurements are made based on the time required to reach a fixed number of counts, or on the total counts obtained for a fixed time (generally expressed in counts per unit time). Concentrations of the elements are determined by relating the measured radiation of unknown specimens to analytical curves prepared with suitable reference materials. A fixed-channel, polychromator system or a sequential, monochromator can be used for measurement of the elements.

5. Significance and Use

5.1 This procedure is suitable for manufacturing control and for verifying that the product meets specifications. It provides rapid, multi-element determinations with sufficient accuracy to assure product quality. The analytical performance data included may be used as a benchmark to determine if similar X-ray spectrometers provide equivalent precision and accuracy, or if the performance of a particular spectrometer has changed.

6. Interferences

6.1 Interelement effects or matrix effects exist for some of the elements listed. Mathematical correction may be used to solve for these elements. Various mathematical correction

⁵ *Annual Book of ASTM Standards*, Vol 03.06.

procedures are commonly utilized. See Guides E 1361 and E 1622. Any of these procedures that achieves analytical accuracy equivalent to that provided by this test method is acceptable.

7. Apparatus

7.1 Specimen Preparation Equipment:

7.1.1 *Surface Grinder or Sander With Abrasive Belts or Disks, or Lathe*, capable of providing a flat, uniform surface on the reference materials and test specimens. Aluminum oxide and zirconium oxide belts and discs with a grit size of between 60 and 180 have been found suitable.

7.2 Excitation Source:

7.2.1 *X-ray Tube Power Supply*, providing a constant potential or rectified power of sufficient energy to produce secondary radiation of the specimen for the elements specified. The generator may be equipped with a line voltage regulator and current stabilizer.

7.2.2 *X-ray Tubes*, with targets of various high-purity elements that are capable of continuous operation at required potentials and currents and that will excite the elements to be determined.

7.3 *Spectrometer*, designed for X-ray emission analysis and equipped with specimen holders and a specimen chamber. The chamber shall contain a specimen spinner, and must be equipped for vacuum or helium-flushed operation for the determination of elements of atomic number 20 (calcium) or lower.

7.3.1 *Analyzing Crystals*, flat or curved crystals with optimized capability for the diffraction of the wavelengths of interest. The use of synthetic multilayer structures can be found in state-of-the-art equipment.

7.3.2 *Collimators or Slits*, for controlling the divergence of the characteristic X rays. Use per the equipment manufacturer's recommendations.

7.3.3 *Detectors*, sealed or gas-flow proportional type, scintillation counters or equivalent.

7.3.4 *Vacuum System*, providing for the determination of elements whose radiation is absorbed by air (for example, silicon, phosphorus, and sulfur). The system shall consist of a vacuum pump, gage, and electrical controls to provide automatic pump down of the optical path, and maintain a controlled pressure, usually 13 Pa (100 :m Hg) or less, controlled to $\sqrt{3}$ Pa ($\sqrt{20}$:m Hg). A helium-flushed system is an alternative to a vacuum system.

7.4 *Measuring System*, consisting of electronic circuits capable of amplifying and integrating pulses received from the detectors. For some measurements, a pulse height selector in conjunction with the detectors may be required to provide more accurate measurements. The system shall be equipped with an appropriate device.

8. Reagents and Materials

8.1 *Detector Gas (P-10)*, consisting of a mixture of 90 % argon and 10 % methane, for use with gas-flow proportional counters only.

9. Reference Materials

9.1 *Certified Reference Materials* are available from national and international sources.

9.2 *Reference Materials* with matrices similar to that of the test specimen and containing varying amounts of the elements to be determined may be used provided they have been analyzed in accordance with ASTM standard methods or similar procedures established by the certifying body. These reference materials shall be homogeneous and free of voids and porosity.

9.3 The reference materials shall cover the concentration ranges of the elements being sought. A minimum of three reference materials shall be used for each element. A greater number of calibrants may be required if the analyst chooses to perform mathematical corrections for interelement effects. See Guide E 1361.

10. Hazards

10.1 OSHA Standards for ionizing radiation⁶ shall be observed at all X-ray emission spectrometer installations. It is also recommended that operating and maintenance personnel follow the guidelines of safe operating procedures given in current handbooks and publications from National Institute of Standards and Technology⁷ and the U.S. Government Printing Office⁸, or similar handbooks on radiation safety.

10.2 X-ray equipment shall be used only under the guidance and supervision of a responsible, qualified person.

10.3 *Monitoring Devices*, either film badges or dosimeters⁹ may be worn by all operating and maintenance personnel. Safety regulations shall conform to applicable local, state, and federal regulations.

11. Preparation of Reference Materials and Test Specimens

11.1 The analyst must choose a measurement area or diameter from the options built into the spectrometer. All test specimens and reference materials must have a flat surface of greater diameter than the chosen viewed area.

11.2 Prepare the reference materials and test specimens to provide a clean, flat uniform surface to be exposed to the X-ray beam. One surface of a reference material may be designated by the producer as the certified surface. The same surface preparation medium shall be used for all reference materials and test specimens.

11.3 Refinish the surface of the reference materials and test specimens as needed to eliminate oxidation.

⁶ *Federal Register*, Vol 36, No. 105, May 1971, Section 1910.96 or of latest issue of Subpart G, available from Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20025; or *National Bureau of Standards Handbook III*, ANSI N43.2-1971.

⁷ Available from Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20025.

⁸ Available from U.S. Department of Health, Education, and Welfare, Rockville, MD 20850.

⁹ Available from Seimens Gammasonics, Inc., 2000 Nuclear Drive, Des Plaines, IL 60018.

12. Preparation of Apparatus

12.1 Prepare and operate the spectrometer in accordance with the manufacturer's instructions.

NOTE 2—It is not within the scope of this test method to prescribe minute details relative to the preparation of the apparatus. For a description and specific details concerning the operation of a particular spectrometer, refer to the manufacturer's manual.

12.1.1 *Start-up*—Turn on the power supply and electronic circuits and allow sufficient time for instrument warm-up prior to taking measurements.

12.2 *Tube Power Supply*—The power supply conditions should be set according to the manufacturers recommendations.

12.2.1 The voltage and current established as optimum for the X-ray tube power supply in an individual laboratory shall be reproduced for subsequent measurements.

12.3 *Proportional Counter Gas Flow*—When a gas-flow proportional counter is used, adjust the flow of the P-10 gas in accordance with the equipment manufacturer's instructions. When changing P-10 tanks, the detectors should be adequately flushed with detector gas before the instrument is used. After changing P-10 tanks, check pulse height selector according to the manufacturer's instructions.

12.4 *Measurement Conditions*—The K-L_{2,3}(K α) lines for each element are used. When using a scanning (sequential) spectrometer, locations shall be calibrated according to the manufacturer's guidelines.

12.4.1 *Crystals and Detectors*—The following crystals and detectors are used for the elements indicated:

| Element | Crystal | Detector |
|------------|-----------|------------|
| Chromium | L1, L2 | SP, Sc, FP |
| Cobalt | L1, L2 | SP, Sc, FP |
| Copper | L1, L2 | SP, Sc, FP |
| Manganese | L1, L2 | SP, Sc, FP |
| Molybdenum | L1, L2 | Sc |
| Nickel | L1, L2 | SP, Sc, FP |
| Niobium | L1, L2 | Sc |
| Phosphorus | Ge | FP, SP |
| Silicon | PET, InSb | Fb, SP |
| Sulfur | Ge | FP, SP |
| Titanium | L1, L2 | SP, Sc, FP |
| Vanadium | L1, L2 | SP, Sc, FP |

L1 = LiF(200),
 L2 = LiF(220),
 SP = Sealed Proportional,
 Sc = Scintillation, and
 FP = Flow Proportional.

12.4.2 *Counting Time*—Collect a sufficient number of counts so that the precision of the analysis will not be affected by the variation in the counting statistics. A minimum of 10 000 counts is required for one percent precision of the counting statistics, 40 000 for one-half percent.

13. Calibration and Standardization

13.1 *Calibration (Preparation of Analytical Curves)*—Using the conditions given in Section 12, measure a series of reference materials that cover the required concentration ranges. Use at least three reference materials for each element. Prepare an analytical curve for each element being determined (refer to Practice E 305). For information on correction of interelement effects in X-ray Spectrometric Analysis refer to Guide E 1361. Information on correction of spectral line

overlap in wavelength dispersive X-ray spectrometry can be found in Practice E 1622.

13.2 *Standardization (Analytical Curve Adjustment)*—Using a control reference material, check the calibration of the X-ray spectrometer at a frequency consistent with SPC practice or when the detector gas or major components have been changed. If the calibration check indicates that the spectrometer has drifted, make appropriate adjustments according to the instructions in the manufacturer's manual. Refer to Practice E 305 for frequency of verification of standardization.

14. Procedure

14.1 *Specimen Loading*—Place the reference materials and test specimens in the appropriate specimen holding container. If the spectrometer is equipped with an automated loading device, repeatability may be improved by loading and unloading all specimens from the same holder. The container shall have a suitable opening to achieve the required precision in an acceptable amount of time. The holder must be equipped to keep the specimen from moving inside the holder.

14.2 *Excitation*—Expose the specimen to primary X radiation in accordance with Section 12.

14.3 *Radiation Measurements*—Obtain and record the counting rate measurement for each element. Either fixed count or fixed time modes may be used. Obtain at least the predetermined minimum counts for all specimens.

14.4 *Spectral Interferences*—Some X-ray spectrometers will not completely resolve radiation from several metal combinations (for example, molybdenum and sulfur; molybdenum and phosphorus; and iron and cobalt). Therefore, care must be exercised in the interpretation of intensities when both elements are present. Mathematical calculations must be used to correct for the interferences.

14.5 *Replicate Measurements*—Make a single measurement on each test specimen. The performance of an X-ray spectrometer is not improved significantly by making multiple measurements on the same surface of the specimen. Confidence in the accuracy of analysis will improve by making multiple measurements on freshly prepared surfaces of the same specimen.

15. Calculation of Results

15.1 Using the radiation measurements for the test specimen and the appropriate analytical curves, determine the concentration of the various elements.

15.1.1 If mathematical calculations must be made to correct the concentrations for interelement effects, any one of a number of correction procedures may be employed. Refer to the equipment manufacturer's manual for the recommended procedure for the instrument being used. See Guide E 1361.

16. Precision and Bias

16.1 *Precision*—An acceptable number of laboratories tested this method in accordance with Practice E 691. Precision data, including repeatability (precision within laboratories), *r*, and reproducibility (precision between laboratories), *R*, are provided in Tables 1-12.

16.2 *Bias (Accuracy)*—Bias data calculated in accordance with Practice E 1060 are included in Table 13.

TABLE 1 Statistical Information for Chromium

| Test Material | No. of Labs | % Chromium | Min SD (s_M , E 1601) | Reproducibility SD (s_R , E 1601) | Reproducibility Index (R, E 1601) | R_{rel} % |
|---------------|-------------|------------|-----------------------------|---|--------------------------------------|-------------|
| 1 | 6 | 17.818 | 0.05258 | 0.06684 | 0.306 | 1.7 |
| 2 | 6 | 15.627 | 0.04638 | 0.05578 | 0.237 | 1.5 |
| 3 | 6 | 23.906 | 0.06581 | 0.08487 | 0.933 | 3.9 |
| 4 | 6 | 24.011 | 0.09029 | 0.10822 | 0.640 | 2.7 |
| 5 | 6 | 18.146 | 0.04525 | 0.05693 | 0.333 | 1.8 |
| 6 | 6 | 2.058 | 0.00819 | 0.01047 | 0.254 | 12.3 |
| 7 | 6 | 17.240 | 0.05008 | 0.06307 | 0.247 | 1.4 |
| 8 | 6 | 17.664 | 0.03935 | 0.04879 | 0.435 | 2.5 |
| 9 | 6 | 19.952 | 0.06473 | 0.07789 | 0.769 | 3.9 |
| 10 | 6 | 21.191 | 0.08769 | 0.10222 | 0.293 | 1.4 |
| 11 | 6 | 19.018 | 0.05731 | 0.06784 | 0.688 | 3.6 |

TABLE 2 Statistical Information for Copper

| Test Material | No. of Labs | % Copper | Min SD (s_M , E 1601) | Reproducibility SD (s_R , E 1601) | Reproducibility Index (R, E 1601) | R_{rel} % |
|---------------|-------------|----------|-----------------------------|---|--------------------------------------|-------------|
| 1 | 6 | 0.104 | 0.0012 | 0.001572 | 0.013 | 12.9 |
| 2 | 6 | 0.160 | 0.0012 | 0.001564 | 0.024 | 14.8 |
| 3 | 5 | 0.054 | 0.0013 | 0.001682 | 0.011 | 21.0 |
| 4 | 6 | 0.584 | 0.0034 | 0.004222 | 0.035 | 6.0 |
| 5 | 5 | 0.023 | 0.0013 | 0.001634 | 0.015 | 65.1 |
| 6 | 6 | 0.441 | 0.0017 | 0.002206 | 0.062 | 14.0 |
| 7 | 6 | 0.370 | 0.0021 | 0.002723 | 0.016 | 4.3 |
| 8 | 6 | 0.311 | 0.0026 | 0.003222 | 0.016 | 5.1 |
| 9 | 6 | 3.249 | 0.0197 | 0.023712 | 0.166 | 5.1 |
| 10 | 6 | 0.075 | 0.0010 | 0.001252 | 0.016 | 5.1 |
| 11 | 6 | 0.132 | 0.0011 | 0.0011 | 0.023 | 17.3 |

17. Keywords

17.1 spectrometric analysis; stainless steels; X-ray emission

TABLE 3 Statistical Information for Cobalt

| Test Material | No. of Labs | % Cobalt | Min SD ($s_{M, E 1601}$) | Reproducibility SD ($s_{R, E 1601}$) | Reproducibility Index (R, E 1601) | R_{rel} % |
|---------------|-------------|----------|-------------------------------|---|--------------------------------------|-------------|
| 1 | 7 | 0.233 | 0.0027 | 0.00335 | 0.028 | 12.2 |
| 2 | 6 | 0.047 | 0.0013 | 0.001616 | 0.049 | 103.0 |
| 3 | 5 | 0.029 | 0.0015 | 0.001879 | 0.009 | 32.7 |
| 4 | 6 | 0.292 | 0.0030 | 0.003668 | 0.072 | 24.5 |
| 5 | 6 | 0.024 | 0.0015 | 0.001828 | 0.006 | 25.8 |
| 6 | 6 | 0.018 | 0.0022 | 0.002598 | 0.022 | 122.6 |
| 7 | 7 | 0.156 | 0.0026 | 0.003287 | 0.021 | 13.2 |
| 8 | 7 | 0.222 | 0.0015 | 0.001982 | 0.013 | 6.0 |
| 9 | 6 | 0.402 | 0.0020 | 0.00254 | 0.106 | 26.5 |
| 10 | 6 | 0.032 | 0.0017 | 0.002034 | 0.019 | 60.0 |
| 11 | 5 | 0.019 | 0.0012 | 0.001469 | 0.007 | 37.6 |

TABLE 4 Statistical Information for Manganese

| Test Material | No. of Labs | % Manganese | Min SD ($s_{M, E 1601}$) | Reproducibility SD ($s_{R, E 1601}$) | Reproducibility Index (R, E 1601) | R_{rel} % |
|---------------|-------------|-------------|-------------------------------|---|--------------------------------------|-------------|
| 1 | 7 | 0.9656 | 0.0080 | 0.0286 | 0.0800 | 8.28 |
| 2 | 7 | 0.4243 | 0.0035 | 0.0331 | 0.0926 | 21.82 |
| 3 | 7 | 0.3143 | 0.0109 | 0.0495 | 0.1387 | 44.12 |
| 4 | 7 | 1.6587 | 0.0078 | 0.0488 | 0.1367 | 8.24 |
| 5 | 7 | 0.7637 | 0.0049 | 0.0263 | 0.0735 | 9.63 |
| 6 | 7 | 1.4665 | 0.0052 | 0.0840 | 0.2352 | 16.04 |
| 7 | 7 | 1.7348 | 0.0110 | 0.0572 | 0.1601 | 9.23 |
| 8 | 7 | 1.6327 | 0.0100 | 0.0392 | 0.1099 | 6.73 |
| 9 | 7 | 0.4430 | 0.0039 | 0.0350 | 0.0980 | 22.11 |
| 10 | 7 | 4.9410 | 0.0174 | 0.1570 | 0.4396 | 8.90 |
| 11 | 7 | 0.9595 | 0.0054 | 0.0338 | 0.0946 | 9.86 |

TABLE 5 Statistical Information for Molybdenum

| Test Material | No. of Labs | % Molybdenum | Min SD ($s_{M, E 1601}$) | Reproducibility SD ($s_{R, E 1601}$) | Reproducibility Index (R, E 1601) | R_{rel} % |
|---------------|-------------|--------------|-------------------------------|---|--------------------------------------|-------------|
| 1 | 7 | 0.433 | 0.0016 | 0.001986 | 0.008 | 1.9 |
| 2 | 7 | 0.166 | 0.0020 | 0.002473 | 0.013 | 8.1 |
| 3 | 5 | 0.016 | 0.0014 | 0.001468 | 0.009 | 54.9 |
| 4 | 7 | 0.464 | 0.0078 | 0.008461 | 0.026 | 5.7 |
| 5 | 5 | 0.005 | 0.0014 | 0.001495 | 0.011 | 235.6 |
| 6 | 7 | 3.085 | 0.0060 | 0.007455 | 0.090 | 2.9 |
| 7 | 7 | 0.566 | 0.0029 | 0.003452 | 0.028 | 4.9 |
| 8 | 7 | 0.333 | 0.0043 | 0.005506 | 0.009 | 2.8 |
| 9 | 7 | 2.066 | 0.0070 | 0.008213 | 0.170 | 8.2 |
| 10 | 7 | 2.205 | 0.0070 | 0.008213 | 0.096 | 4.4 |
| 11 | 7 | 2.637 | 0.0065 | 0.008128 | 0.192 | 7.3 |

TABLE 6 Statistical Information for Nickel

| Test Material | No. of Labs | % Nickel | Min SD ($s_{M, E 1601}$) | Reproducibility SD ($s_{R, E 1601}$) | Reproducibility Index (R, E 1601) | R_{rel} % |
|---------------|-------------|----------|-------------------------------|---|--------------------------------------|-------------|
| 1 | 7 | 10.938 | 0.03123 | 0.04002 | 0.210 | 1.9 |
| 2 | 7 | 2.110 | 0.01039 | 0.01334 | 0.210 | 10.0 |
| 3 | 6 | 0.284 | 0.00382 | 0.00508 | 0.056 | 19.5 |
| 4 | 7 | 21.175 | 0.06064 | 0.07502 | 0.453 | 2.1 |
| 5 | 7 | 9.231 | 0.04841 | 0.05806 | 0.219 | 2.4 |
| 6 | 7 | 18.582 | 0.07075 | 0.08675 | 1.623 | 8.7 |
| 7 | 7 | 8.156 | 0.02684 | 0.03339 | 0.172 | 2.1 |
| 8 | 7 | 10.053 | 0.0392 | 0.04989 | 0.187 | 1.9 |
| 9 | 7 | 34.113 | 0.11373 | 0.13766 | 0.467 | 1.4 |
| 10 | 7 | 13.247 | 0.06444 | 0.0779 | 0.863 | 6.5 |
| 11 | 6 | 3.31 | 0.0152 | 0.0609 | 0.1704 | 5.2 |

TABLE 7 Statistical Information for Niobium

| Test Material | No. of Labs | % Niobium | Min SD (s_{M1} , E 1601) | Reproducibility SD (s_{R1} , E 1601) | Reproducibility Index (R, E 1601) | R_{rel} % |
|---------------|-------------|-----------|--------------------------------|--|--------------------------------------|-------------|
| 1 | 7 | 0.194 | 0.0008 | 0.001022 | 0.025 | 12.7 |
| 2 | 6 | 0.015 | 0.0003 | 0.000405 | 0.016 | 106.2 |
| 3 | 5 | 0.007 | 0.0002 | 0.000317 | 0.015 | 203.5 |
| 4 | 7 | 0.072 | 0.0004 | 0.000536 | 0.020 | 27.7 |
| 5 | 7 | 0.943 | 0.0048 | 0.00582 | 0.094 | 10.0 |
| 6 | 7 | 1.151 | 0.0032 | 0.004043 | 0.206 | 17.9 |
| 7 | 7 | 0.016 | 0.0003 | 0.000357 | 0.017 | 104.1 |
| 8 | 6 | 0.015 | 0.0004 | 0.000400 | 0.015 | 98.8 |
| 9 | 7 | 0.483 | 0.0010 | 0.0010 | 0.087 | 18.1 |
| 10 | 7 | 0.213 | 0.0008 | 0.0008 | 0.031 | 14.3 |
| 11 | 7 | 0.067 | 0.0003 | 0.0003 | 0.016 | 23.9 |

TABLE 8 Statistical Information for Phosphorus

| Test Material | No. of Labs | % Phosphorus | Min SD (s_{M1} , E 1601) | Reproducibility SD (s_{R1} , E 1601) | Reproducibility Index (R, E 1601) | R_{rel} % |
|---------------|-------------|--------------|--------------------------------|--|--------------------------------------|-------------|
| 1 | 7 | 0.020 | 0.008 | 0.000967 | 0.003 | 14.7 |
| 2 | 7 | 0.023 | 0.0012 | 0.001359 | 0.004 | 17.0 |
| 3 | 7 | 0.016 | 0.0008 | 0.000913 | 0.003 | 17.5 |
| 4 | 7 | 0.027 | 0.0029 | 0.003078 | 0.008 | 30.1 |
| 5 | 7 | 0.020 | 0.0011 | 0.001291 | 0.004 | 21.3 |
| 6 | 7 | 0.011 | 0.0028 | 0.003007 | 0.012 | 108.3 |
| 7 | 7 | 0.028 | 0.0013 | 0.001537 | 0.005 | 16.3 |
| 8 | 7 | 0.021 | 0.0010 | 0.001129 | 0.004 | 18.9 |
| 9 | 7 | 0.017 | 0.0010 | 0.001284 | 0.008 | 47.4 |
| 10 | 7 | 0.026 | 0.0045 | 0.004624 | 0.013 | 48.6 |
| 11 | 6 | 0.025 | 0.0017 | 0.001598 | 0.005 | 19.7 |

TABLE 9 Statistical Information for Silicon

| Test Material | No. of Labs | % Silicon | Min SD (s_{M1} , E 1601) | Reproducibility SD (s_{R1} , E 1601) | Reproducibility Index (R, E 1601) | R_{rel} % |
|---------------|-------------|-----------|--------------------------------|--|--------------------------------------|-------------|
| 1 | 7 | 0.825 | 0.0110 | 0.013934 | 0.065 | 7.9 |
| 2 | 7 | 0.552 | 0.0076 | 0.009823 | 0.063 | 11.4 |
| 3 | 7 | 0.598 | 0.0089 | 0.010898 | 0.071 | 11.9 |
| 4 | 7 | 1.679 | 0.0159 | 0.019746 | 0.080 | 4.8 |
| 5 | 7 | 0.502 | 0.0085 | 0.011178 | 0.058 | 11.6 |
| 6 | 7 | 1.788 | 0.0167 | 0.020035 | 0.170 | 9.5 |
| 7 | 7 | 0.575 | 0.0179 | 0.020622 | 0.056 | 9.7 |
| 8 | 7 | 0.395 | 0.0070 | 0.008612 | 0.057 | 14.6 |
| 9 | 7 | 0.256 | 0.0070 | 0.008622 | 0.074 | 29.0 |
| 10 | 7 | 0.321 | 0.0065 | 0.007876 | 0.061 | 18.8 |
| 11 | 7 | 0.321 | 0.0092 | 0.011595 | 0.061 | 18.8 |

TABLE 10 Statistical Information for Sulfur

| Test Material | No. of Labs | % Sulfur | Min SD (s_{M1} , E 1601) | Reproducibility SD (s_{R1} , E 1601) | Reproducibility Index (R, E 1601) | R_{rel} % |
|---------------|-------------|----------|--------------------------------|--|--------------------------------------|-------------|
| 1 | 5 | 0.0086 | 0.0016 | 0.0020 | 0.0058 | 64.22 |
| 2 | 5 | 0.0039 | 0.0014 | 0.0025 | 0.0071 | 180.79 |
| 3 | 5 | 0.0169 | 0.0031 | 0.0039 | 0.0109 | 64.86 |
| 4 | 5 | 0.0241 | 0.0017 | 0.0020 | 0.0055 | 23.00 |
| 5 | 5 | 0.0198 | 0.0010 | 0.0020 | 0.0057 | 28.91 |
| 6 | 5 | 0.0225 | 0.0017 | 0.0067 | 0.0187 | 82.84 |
| 7 | 5 | 0.2494 | 0.0044 | 0.0208 | 0.0583 | 23.39 |
| 8 | 5 | 0.0041 | 0.0018 | 0.0023 | 0.0065 | 156.32 |
| 9 | 5 | 0.0024 | 0.0009 | 0.0027 | 0.0076 | 316.47 |
| 10 | 5 | 0.0041 | 0.0019 | 0.0023 | 0.0065 | 157.16 |
| 11 | 5 | 0.0185 | 0.0020 | 0.0043 | 0.0121 | 65.58 |

TABLE 11 Statistical Information for Titanium

| Test Material | No. of Labs | % Titanium | Min SD (s_M , E 1601) | Reproducibility SD (s_R , E 1601) | Reproducibility Index (R, E 1601) | R_{rel} % |
|---------------|-------------|------------|-----------------------------|---|--------------------------------------|-------------|
| 1 | 7 | 0.0091 | 0.0012 | 0.0053 | 0.0150 | 163.92 |
| 2 | 3 | 0.0008 | 0.0004 | 0.0012 | 0.0034 | 413.75 |
| 3 | 3 | 0.0008 | 0.0004 | 0.0013 | 0.0036 | 415.93 |
| 4 | 7 | 0.0489 | 0.0010 | 0.0040 | 0.0112 | 22.93 |
| 5 | 6 | 0.0014 | 0.0010 | 0.0013 | 0.0037 | 270.24 |
| 6 | 6 | 0.0073 | 0.0093 | 0.0101 | 0.0284 | 384.64 |
| 7 | 6 | 0.0007 | 0.0003 | 0.0007 | 0.0019 | 276.07 |
| 8 | 7 | 0.4355 | 0.0025 | 0.0136 | 0.0383 | 8.78 |
| 9 | 7 | 0.0015 | 0.0004 | 0.0011 | 0.0030 | 193.63 |
| 10 | 7 | 0.0021 | 0.0002 | 0.0011 | 0.0030 | 139.99 |
| 11 | 6 | 0.956 | 0.0198 | 0.0136 | 0.0662 | 69.22 |

TABLE 12 Statistical Information for Vanadium

| Test Material | No. of Labs | % Vanadium | Min SD (s_M , E 1601) | Reproducibility SD (s_R , E 1601) | Reproducibility Index (R, E 1601) | R_{rel} % |
|---------------|-------------|------------|-----------------------------|---|--------------------------------------|-------------|
| 1 | 7 | 0.028 | 0.0016 | 0.001844 | 0.016 | 55.7 |
| 2 | 7 | 0.057 | 0.0017 | 0.00085 | 0.015 | 26.3 |
| 3 | 7 | 0.091 | 0.0013 | 0.001633 | 0.016 | 17.3 |
| 4 | 7 | 0.091 | 0.0010 | 0.001334 | 0.013 | 140.0 |
| 5 | 7 | 0.015 | 0.0007 | 0.000828 | 0.003 | 19.2 |
| 6 | 7 | 0.077 | 0.0010 | 0.001217 | 0.019 | 24.9 |
| 7 | 7 | 0.071 | 0.0008 | 0.001036 | 0.012 | 16.7 |
| 8 | 7 | 0.137 | 0.0014 | 0.001828 | 0.025 | 18.2 |
| 9 | 7 | 0.062 | 0.0011 | 0.001436 | 0.013 | 21.3 |
| 10 | 7 | 0.231 | 0.0024 | 0.003079 | 0.014 | 6.1 |
| 11 | 6 | 0.024 | 0.0008 | 0.00983 | 0.010 | 43.9 |

TABLE 13 Bias Information

| Element | Assumed True Value, % | Average Spectrometer Value, % | Number of Laboratories | Deviation from Assumed True Value |
|------------|-----------------------|-------------------------------|------------------------|-----------------------------------|
| Chromium | 17.81 | 17.82 | 6 | 0.01 |
| | 15.64 | 15.63 | 6 | -0.01 |
| | 24.14 | 23.91 | 6 | -0.23 |
| | 23.98 | 24.01 | 6 | 0.03 |
| | 18.09 | 18.15 | 6 | 0.06 |
| | 2.06 | 2.06 | 6 | 0.00 |
| | 17.21 | 17.24 | 6 | 0.03 |
| | 17.68 | 17.66 | 6 | -0.02 |
| | 19.81 | 19.95 | 6 | 0.14 |
| | 21.17 | 21.19 | 6 | 0.02 |
| | 18.90 | 19.01 | 6 | 0.11 |
| Copper | 0.104 | 0.102 | 6 | -0.002 |
| | 0.162 | 0.160 | 6 | -0.002 |
| | 0.58 | 0.58 | 6 | 0.00 |
| | 0.44 | 0.44 | 6 | 0.00 |
| | 0.36 | 0.37 | 6 | 0.01 |
| | 0.30 | 0.31 | 6 | 0.01 |
| | 3.26 | 3.25 | 6 | -0.01 |
| | 0.075 | 0.075 | 6 | 0.00 |
| | 0.14 | 0.13 | 6 | -0.01 |
| Cobalt | 0.22 | 0.23 | 7 | 0.01 |
| | 0.31 | 0.29 | 6 | -0.02 |
| | 0.16 | 0.16 | 7 | 0.00 |
| | 0.23 | 0.22 | 7 | -0.01 |
| | 0.41 | 0.40 | 6 | -0.01 |
| | 0.034 | 0.032 | 6 | -0.002 |
| Manganese | 0.96 | 0.97 | 7 | 0.01 |
| | 0.42 | 0.42 | 7 | 0.00 |
| | 0.315 | 0.314 | 7 | -0.001 |
| | 1.66 | 1.66 | 7 | 0.00 |
| | 0.788 | 0.764 | 7 | -0.024 |
| | 1.50 | 1.47 | 7 | -0.03 |
| | 1.68 | 1.74 | 7 | 0.06 |
| | 1.63 | 1.63 | 7 | 0.00 |
| | 0.46 | 0.44 | 7 | -0.02 |
| | 5.09 | 4.94 | 7 | -0.15 |
| | 0.99 | 0.96 | 7 | -0.03 |
| Molybdenum | 0.164 | 0.166 | 7 | 0.002 |
| | 0.46 | 0.46 | 7 | 0.00 |
| | 3.15 | 3.08 | 7 | -0.07 |
| | 0.55 | 0.57 | 7 | 0.02 |
| | 0.33 | 0.33 | 7 | 0.00 |
| | 2.10 | 2.07 | 7 | -0.03 |
| | 2.19 | 2.20 | 7 | 0.01 |
| | 2.59 | 2.64 | 7 | 0.05 |
| | Nickel | 10.88 | 10.94 | 7 |
| 2.16 | | 2.11 | 7 | -0.05 |
| 0.29 | | 0.28 | 7 | -0.01 |
| 21.16 | | 21.18 | 7 | 0.02 |
| 9.21 | | 9.21 | 7 | 0.00 |
| 18.2 | | 18.6 | 7 | 0.4 |
| 8.14 | | 8.16 | 7 | 0.02 |
| 10.01 | | 10.05 | 7 | 0.04 |
| 34.1 | | 34.1 | 7 | 0.0 |
| 13.10 | | 13.25 | 7 | 0.15 |
| 3.31 | | 3.30 | 7 | -0.01 |
| Niobium | (.16) | 0.194 | 7 | |
| | 0.050 | 0.072 | 7 | 0.022 |
| | 0.99 | 0.94 | 7 | -0.05 |
| | 1.22 | 1.15 | 7 | -0.07 |
| | 0.01 | 0.02 | 7 | 0.01 |
| | 0.51 | 0.48 | 7 | -0.03 |
| | 0.22 | 0.21 | 7 | -0.01 |
| | 0.07 | 0.07 | 7 | 0.00 |
| Phosphorus | 0.021 | 0.021 | 7 | 0.000 |
| | 0.026 | 0.023 | 7 | -0.003 |

TABLE 13 *Continued*

| Element | Assumed True Value, % | Average Spectrometer Value, % | Number of Laboratories | Deviation from Assumed True Value |
|----------|-----------------------|-------------------------------|------------------------|-----------------------------------|
| | 0.018 | 0.016 | 7 | -0.002 |
| | 0.029 | 0.027 | 7 | -0.002 |
| | 0.018 | 0.020 | 7 | 0.002 |
| | 0.011 | 0.011 | 7 | 0.000 |
| | 0.030 | 0.028 | 7 | -0.002 |
| | 0.022 | 0.021 | 7 | -0.001 |
| | 0.018 | 0.017 | 7 | -0.001 |
| | 0.028 | 0.026 | 7 | -0.002 |
| | 0.027 | 0.025 | 7 | -0.002 |
| Silicon | 0.80 | 0.82 | 7 | 0.02 |
| | 0.545 | 0.552 | 7 | 0.007 |
| | 0.58 | 0.60 | 7 | 0.02 |
| | 1.66 | 1.68 | 7 | 0.02 |
| | 0.52 | 0.50 | 7 | -0.02 |
| | 1.80 | 1.79 | 7 | -0.01 |
| | 0.58 | 0.58 | 7 | 0.00 |
| | 0.40 | 0.48 | 7 | 0.08 |
| | 0.24 | 0.21 | 7 | -0.03 |
| | 0.32 | 0.32 | 7 | 0.00 |
| | 0.067 | 0.067 | 7 | 0.000 |
| Sulfur | 0.0064 | 0.0086 | 5 | 0.0022 |
| | 0.001 | 0.004 | 5 | 0.003 |
| | 0.015 | 0.017 | 5 | 0.002 |
| | 0.024 | 0.024 | 5 | 0.000 |
| | 0.019 | 0.020 | 5 | 0.001 |
| | 0.025 | 0.022 | 5 | -0.003 |
| | 0.309 | 0.249 | 5 | -0.060 |
| | 0.0018 | 0.0041 | 5 | 0.0023 |
| | 0.002 | 0.002 | 5 | 0.000 |
| | 0.003 | 0.004 | 5 | 0.001 |
| | 0.026 | 0.018 | 5 | -0.008 |
| Titanium | (.01) | 0.0091 | 7 | |
| | 0.050 | 0.049 | 7 | -0.001 |
| | 0.45 | 0.44 | 7 | -0.01 |
| | 0.002 | 0.002 | 7 | 0.000 |
| | 0.002 | 0.002 | 7 | 0.000 |
| | 0.11 | 0.10 | 7 | -0.01 |
| Vanadium | 0.030 | 0.028 | 7 | 0.002 |
| | 0.056 | 0.057 | 7 | 0.001 |
| | 0.08 | 0.09 | 7 | 0.01 |
| | 0.09 | 0.09 | 7 | 0.00 |
| | 0.07 | 0.07 | 7 | 0.00 |
| | 0.13 | 0.14 | 7 | 0.01 |
| | 0.059 | 0.062 | 7 | 0.003 |
| | 0.23 | 0.23 | 7 | 0.00 |

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