
**Fine ceramics (advanced ceramics,
advanced technical ceramics) —
Measurement of Seebeck coefficient
and electrical conductivity of bulk-
type thermoelectric materials at room
and high temperatures**

*Céramiques techniques — Mesurage du coefficient de Seebeck et de
la conductivité électrique de matériaux thermoélectriques en vrac à
température ambiante et à haute température*



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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 206, *Fine ceramics*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Fine ceramics (advanced ceramics, advanced technical ceramics) — Measurement of Seebeck coefficient and electrical conductivity of bulk-type thermoelectric materials at room and high temperatures

1 Scope

This document specifies the measurement methods for the electronic transport properties of bulk-type thermoelectric materials at room and elevated temperatures. The measurement methods cover the simultaneous determination of Seebeck coefficient and electrical conductivity of bulk-type thermoelectric materials in a temperature range from 300 K to 1 200 K. The measurement methods are applicable to bulk-type thermoelectric materials used for power generation, energy harvesting, cooling and heating, among other things.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

ISO 23331, *Fine ceramics (advanced ceramics, advanced technical ceramics) — Test method for total electrical conductivity of conductive fine ceramics*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1

thermoelectric figure of merit

zT

dimensionless factor representing the thermoelectric conversion efficiency of a given material

3.2

thermoelectric power factor

$S^2\sigma$

characteristic value of a thermoelectric material given by the product of the square of Seebeck coefficient (S) and electrical conductivity (σ)

Note 1 to entry: The units of the thermoelectric power factor are watts per metre per square kelvin (W/mK²).

3.3 Seebeck coefficient

S

intrinsic property which describes the induced voltage (thermal electromotive force, E) from a given temperature difference (ΔT) in a material

Note 1 to entry: The units of the Seebeck coefficient are microvolts per kelvin ($\mu\text{V/K}$).

3.4 electrical conductivity

σ

ability of a material to allow the transport of electric charges

Note 1 to entry: The units of electrical conductivity are Siemens per centimetre (S/cm).

4 Principle

This document is for simultaneously measuring the Seebeck coefficient and the electrical conductivity of bulk-type thermoelectric materials using one measurement system. The off-axis four-terminal method can be used to simultaneously measure the Seebeck coefficient and the electrical conductivity of bulk-type thermoelectric material using one measurement system. As shown in [Figure 1](#), the specimen is set between two metal blocks in the heating zone and two thermocouple probes separately contact the surface of the specimen. The measurement of the Seebeck coefficient of a bulk-type thermoelectric material is necessary to measure the temperature difference between two positions (point H and point C) on a specimen and the voltage across the two same positions ([Figure 1](#)). Seebeck coefficient can be calculated by following [Formula \(1\)](#):

$$S = E / \Delta T \quad (1)$$

where

E is the induced thermoelectric voltage (thermal electromotive force) between the point H and point C of the specimen;

ΔT is the temperature difference between the point H and point C ($= T_H - T_C$).

For Seebeck coefficient measurement, measured temperature is the average temperature of the hot- and cold-side thermocouple probes.

By using the measuring system illustrated in [Figure 2](#), electrical conductivity is also measured based on the four-terminal method. This method is conducted by placing four probes. Constant current is applied through the two outmost probes, causing a measurable voltage drop, V , between the two inner probes. The electrical resistance, R , is calculated using Ohm's law following [Formula \(2\)](#):

$$R = V / I \quad (2)$$

where

V is the voltage;

I is the current.

The resistivity, ρ , is be calculated following [Formula \(3\)](#):

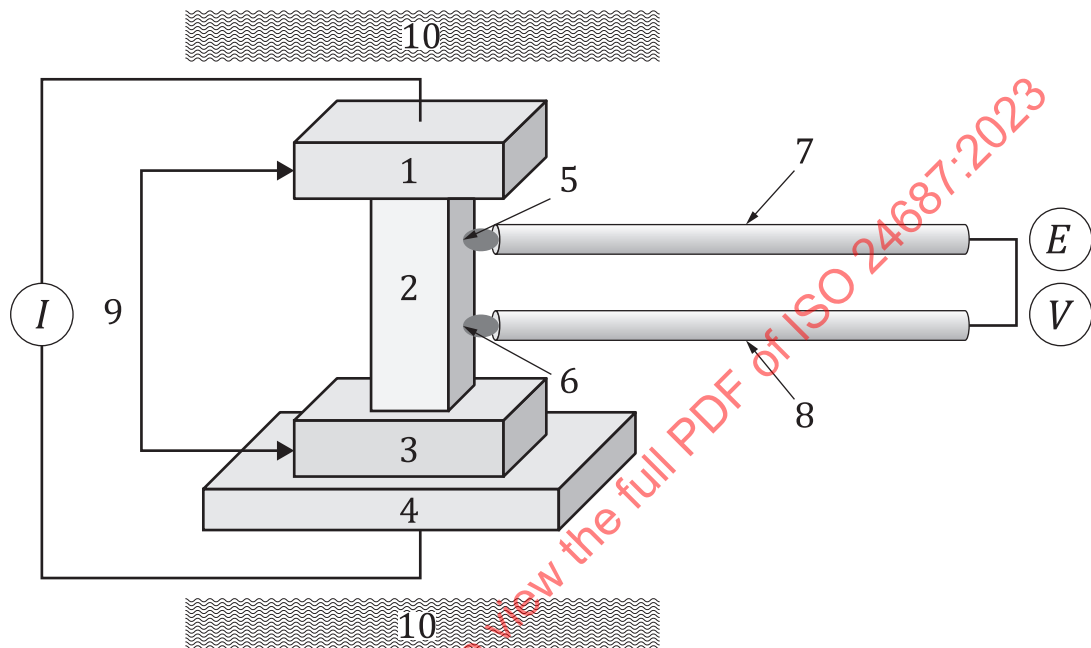
$$\rho = RA / l \quad (3)$$

where

A is the cross-sectional area of the specimen;

l is the separation between the two inner probes.

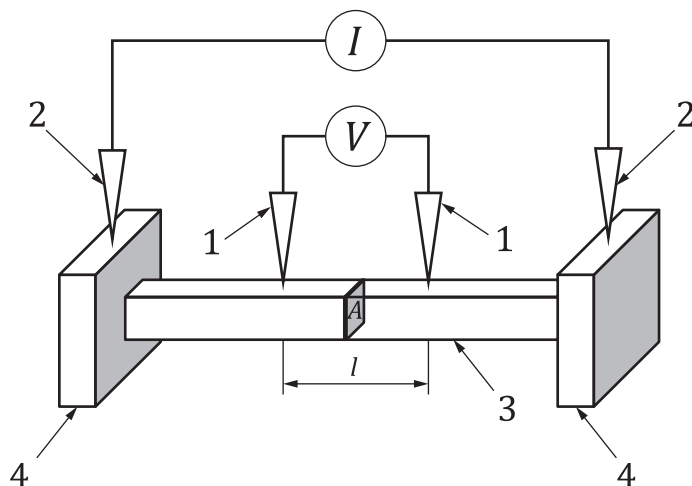
The electrical conductivity is the reciprocal of the resistivity. For electrical conductivity measurement, measured temperature is the actual temperature of the specimen, which generally can be measured by furnace temperature.



Key

- | | |
|--|---------------------------------------|
| 1 upper metal block | 2 specimen |
| 3 lower metal block | 4 heater |
| 5 point C | 6 point H |
| 7 upper thermocouple probe (cold side) | 8 lower thermocouple probe (hot side) |
| 9 current electrode | 10 heating furnace |

Figure 1 — Schematic diagram of off-axis four-terminal method for simultaneous measurement of Seebeck coefficient and electrical conductivity

**Key**

- | | | | |
|---|--------------|---|--------------|
| 1 | inner probes | 2 | outer probes |
| 3 | specimen | 4 | electrodes |

Figure 2 — Schematic diagram of four-terminal method to measure the electrical resistivity

The results of an interlaboratory test are given in [Annex A](#).

5 Significance and use

This document gives guidance for simultaneously measuring the high-accuracy and low-error Seebeck coefficient and electrical conductivity of thermoelectric materials. Therefore, this standard is intended to be used for the development, characterization and quality control of thermoelectric materials, data acquisition for high-efficiency thermoelectric system design, etc.

Thermoelectric materials show Seebeck effect, Peltier effect and Thomson effect. The Seebeck effect is the direct conversion of heat into electricity. The conversion efficiency of a thermoelectric material is determined by the dimensionless thermoelectric figure of merit, zT , calculated following [Formula \(4\)](#):

$$zT = S^2 \sigma T / \kappa \quad (4)$$

where

- S is the Seebeck coefficient;
- σ is the electrical conductivity;
- κ is the thermal conductivity;
- T is the absolute temperature.

Thermoelectric materials show a trade-off relation between Seebeck coefficient and electrical conductivity according to carrier concentration. Therefore, the accuracy of the power factor, $S^2 \sigma$, where S is the Seebeck coefficient and σ is the electrical conductivity, can be improved through simultaneous measurement of Seebeck coefficient and electrical conductivity in one run.

6 Apparatus

6.1 Current source, accurate to $\pm 0,5 \%$ on ranges of -1 A to $+1 \text{ A}$ used in the measurement.

6.2 Electronic voltmeter, at least capable of measuring potential differences from 10^{-7} V to 0,05 V with a resolution below 10^{-7} V.

6.3 Conducting metal blocks.

The contact surface of conducting metal blocks shall be sufficiently large compared to a measurement specimen. A specimen shall be placed between two conducting metal blocks, such as platinum or tungsten. One end of the specimen is heated while the other acts as a heat sink, dispersing heat, thus cooling that side. In addition, the conducting metal blocks play a role as the electrodes for applying the current when measuring the electrical conductivity.

NOTE Pt or Pt – Pd alloy is the best electrode material due to high measuring temperatures.

6.4 Thermocouple probes.

The diameter of thermocouple probes shall be 0,5 mm or less to obtain reproducible Seebeck coefficient value. Thermocouples should have a resolution of at least 0,01 K or better. Thermocouple probes integrating electrical probes for measuring the voltage and thermal probes for measuring the temperature should be designed for working from 300 K to 1 200 K. Thermocouple probes should be checked periodically as their output may drift with usage or contamination.

NOTE In some equipment, the voltage can be measured only with thermocouple wires without additional electrical probes.

6.5 Test chamber.

The test chamber shall be capable of heating both the specimen and the conducting metal blocks up to at least 1 200 K as well as maintaining the test temperature within ± 1 K during the test, by which vacuum environment shall be available for test requirement. The test chamber should be evacuated below 3 Pa and can be backfilled with a variety of gases such as helium, argon, nitrogen and oxygen or a mixture of these. Low-pressure helium can be used to improve the thermal contact between the probe and the sample. However, low pressure may affect the measured Seebeck coefficient. Determination of optimum pressure of backfilled gas is required by Seebeck coefficient measurement according to gas pressure for the same sample to be measured. For the measurement of oxides, oxygen partial pressure should be controlled and monitored to avoid the reduction or oxidation of the samples.

6.6 Dimension-measuring device, such as a Vernier-calliper or other devices used for measuring the dimensions of the specimen, accurate to at least 0,01 mm in accordance with ISO 3611.

6.7 Apparatus and equipment, checked periodically through measuring a certified reference material or a reference material to ensure if they are working properly (see [Annex B](#)).

7 Sampling

7.1 Shape and dimension of specimen

The preferred shape of the specimen should be rectangular bar to ensure stable contacts with thermocouple probes. The area of contact between the specimen and electrode is important, especially to measure the Seebeck coefficient since this relates to heat transfer. The point of contact between the specimen and the electrode is difficult to ensure the reliability of Seebeck coefficient measurement. The two end sides of the specimen in contact with the metal blocks shall be parallel. The parallelism tolerance of two end sides should be 0,01 mm or less. To secure the contact area between the specimen and the electrode, surface roughness, R_a , of 10 μm or less is required. [Figure 3](#) gives the recommended dimensions of a rectangular bar-type specimen.

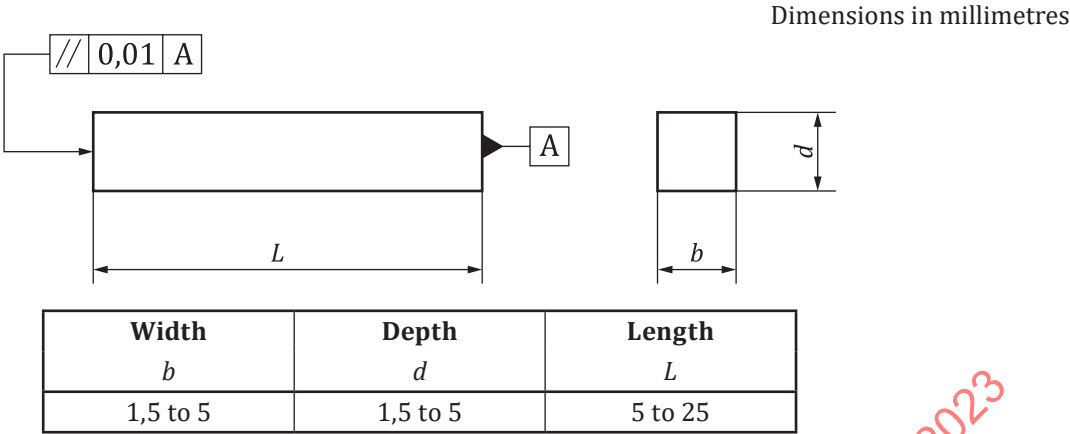


Figure 3 — Recommended dimensions for a rectangular specimen

The cylindrical specimen can also be used. In this case, two thermocouple probes shall make stable contacts on the surface of the specimen.

7.2 Pre-treatment

The surfaces of the specimen shall be ground and polished to ensure they are flat and acquire stable contact with conducting metal blocks and thermocouple probes.

7.3 Storage

Specimens shall be stored separately and not allowed to impact or scratch each other.

7.4 Number of specimens

Three or more test pieces should be measured for the purpose of giving an overall estimation of Seebeck coefficient and electrical conductivity.

8 Procedure

8.1 Dimension measurement of specimen

Measure the width, depth and length of a specimen with a resolution of 0,01 mm. If the specimen is cylindrical, measure the diameter and length of the specimen.

8.2 Placement of specimen

Place the specimen between two conducting metal blocks so that the specimen does not rock or shift during the measurement. Thermocouple probes with lateral spring are then placed on the specimen, as shown in [Figure 1](#).

When connecting the thermocouple probes to the surface of the specimen, measure the accurate distance between two thermocouple probes (l in [Figure 1](#)) to within 5 % of the distance.

NOTE 1 Thermocouple probes mounted in a spring assembly can be moved in and out to achieve the desired pressure.

NOTE 2 The spacing between two thermocouple probes can be adjustable, depending on the length of specimen.

8.3 Evacuating and purging the chamber

For measurement at high temperature in a vacuum environment, make the chamber reach a vacuum of at least 3 Pa.

For measurement at high temperature in an inert gas environment, the test chamber should be backfilled with a variety of inert gas such as helium, argon, nitrogen or oxygen, or a mixture of these, after purging the chamber several times.

8.4 Measurement of electrical conductivity

- As shown in [Figure 1](#), the specimen is placed between two conducting metal blocks.
- Heat the specimen placed between metal blocks in the test chamber to the desired test temperature and maintain this temperature.
- For measurement of electrical resistivity, the effect of Peltier-induced voltage should be excluded. Before measuring, the linearity of I-V plot should be checked. This confirms the steady-state to improve the accuracy of the electrical resistivity measurement.
- Measure the electrical conductivity using the four-terminal method according to the provisions of ISO 23331. Constant current, I , is applied to the specimen through the conducting metal blocks and voltage drop, V , is measured on the thermocouple probes as shown in [Figure 1](#). The voltage drop across the sample should be measured within a second after applying the dc current to remove a parasitic thermoelectric offset-voltage caused by the Peltier effect. When the electrical contact between the test specimen and the probes is stable, the voltage shall be proportional to changes in the applied current.

8.5 Measurement of Seebeck coefficient

- After measurement of electrical conductivity, heat one metal block to create a temperature gradient in the specimen.
- For measurement of Seebeck coefficient, thermal contact between the specimen and the thermocouple should be confirmed. Before measuring, the linearity of temperature-dependent voltage should be checked. This process enables the accuracy of the Seebeck coefficient measurement to be improved.
- At each measuring temperature, generate at least five temperature gradients within the sample. These gradients are to be kept in the range of 0 K – 10 K.
- For each gradient, measure the temperature difference ($\Delta T = T_H - T_C$) between the thermocouple probes and simultaneously measure the corresponding induced thermoelectric voltage, E .
- Plot the measured values of E as a function of the measured values of ΔT and check for linearity.

9 Calculation

9.1 Seebeck coefficient

Relative Seebeck coefficient, S_M , can be calculated by following [Formula \(5\)](#):

$$S_M = \frac{E}{(T_H - T_C)} = \{S_C T_C - S_H T_H + S(T_H - T_C)\} / (T_H - T_C) \quad (5)$$

where

S_M is the relative Seebeck coefficient ($\mu\text{V/K}$);

- E is the induced thermoelectric voltage (μV);
- S_C is the absolute Seebeck coefficient of the electrical probe integrated in the TC thermocouple probe ($\mu\text{V/K}$);
- S_H is the absolute Seebeck coefficient of the electrical probe integrated in the TH thermocouple probe ($\mu\text{V/K}$);
- T_H is the temperature at the contact point between the specimen and the hot thermocouple probe (point H) (K);
- T_C is the temperature at the contact point between the specimen and the cold thermocouple probe (point C) (K);
- S is the absolute Seebeck coefficient of the specimen ($\mu\text{V/K}$).

Thus, S can be calculated by following [Formula \(6\)](#):

$$S = S_M + \frac{S_H T_H - S_C T_C}{(T_H - T_C)} \quad (6)$$

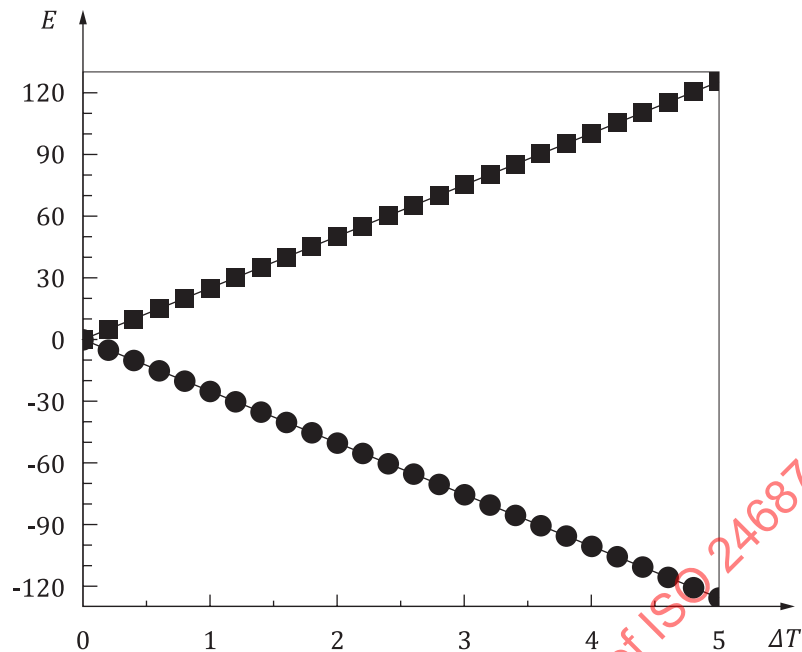
The temperature dependent absolute Seebeck coefficient of a reference material such as Pt (see [Table 1](#)) shall be determined through separate measurement based on Thomson effect to obtain the values of S_H and S_C . Seebeck coefficient of Pt can be estimated by $-2,63 - 0,014\,5T$ at temperatures above 600 K.

Table 1 — Seebeck coefficient values of Pt at various temperatures

Temperature K	Seebeck coefficient $\mu\text{V/K}$
300	-5,28
500	-9,89
700	-13,31
900	-16,39
1 100	-19,29

NOTE In some equipment, the values of Seebeck coefficient already corrected for the contribution of the probes are provided.

The Seebeck coefficient of the material at a given temperature is determined using the slope of the voltage versus temperature difference when the voltage response to the temperature gradient is linear, as shown in [Figure 4](#).

**Key**

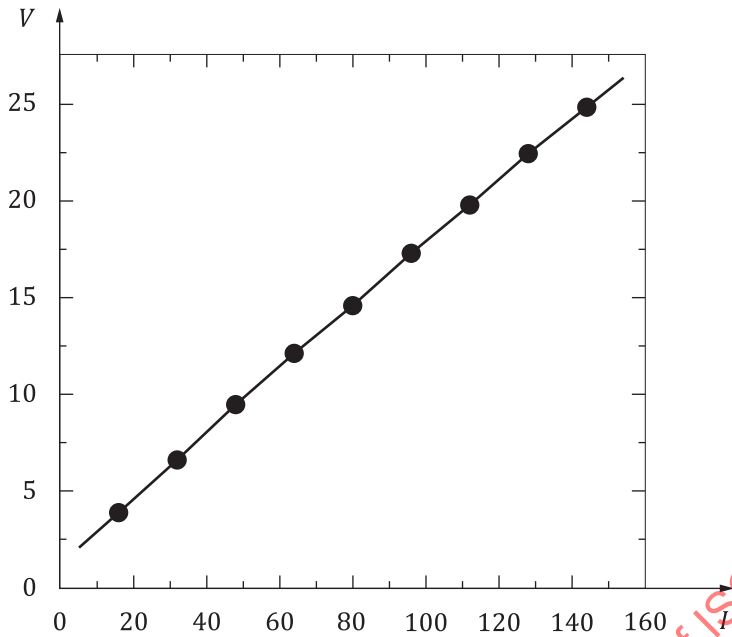
- ΔT temperature difference (K)
- E induced voltage (μV/K)
- data for p-type materials
- data for n-type materials

Figure 4 — Example of the induced voltage with respect to the difference in temperature

9.2 Electrical conductivity

Electrical conductivity values should be calculated according to the provisions of ISO 23331.

The electrical conductivity of the material at a given temperature is determined using the slope of the voltage versus the current when the voltage response to the current gradient is linear, as shown in [Figure 5](#).



Key
I current (mA)
V voltage (μV)

Figure 5 — Example of *I-V* plot for measurement of electrical conductivity

10 Expression of results

10.1 Seebeck coefficient and electrical conductivity

Report the Seebeck coefficient and electrical conductivity of the specimen at various temperatures as shown in Table 2. Seebeck coefficient and electrical conductivity should be reported with four significant digits.

Table 2 — Seebeck coefficient and electrical conductivity at various temperatures

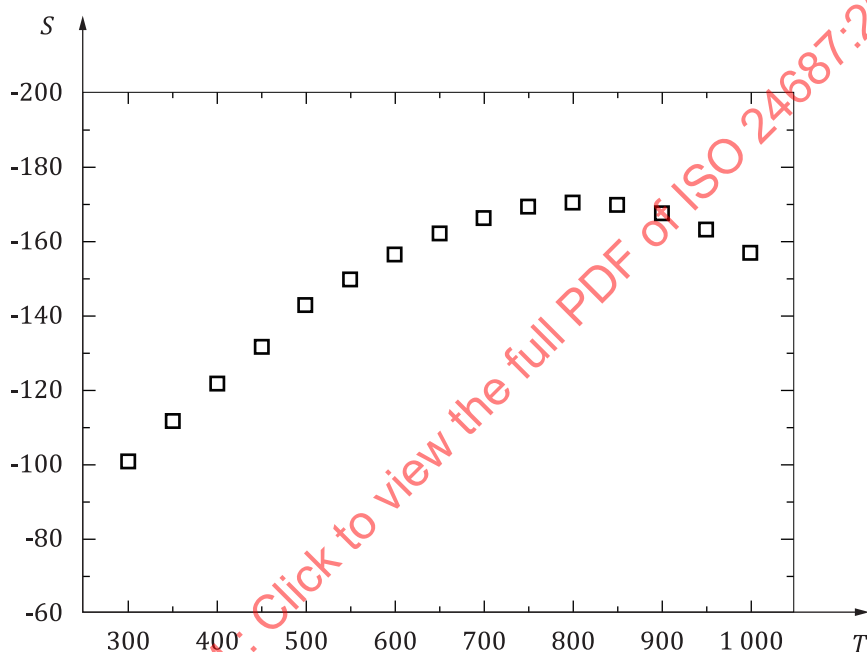
Temperature <i>T</i> K	Seebeck coefficient <i>S</i> μV/K	Electrical conductivity <i>σ</i> S/cm
300	−100,8	2 708
350	−111,6	2 567
400	−121,9	2 430
450	−131,7	2 295
500	−142,9	2 141
550	−149,8	2 023
600	−156,6	1 909
650	−162,2	1 803
700	−166,4	1 709
750	−169,3	1 625
800	−170,4	1 557
850	−169,8	1 503

Table 2 (continued)

Temperature T K	Seebeck coefficient S $\mu\text{V/K}$	Electrical conductivity σ S/cm
900	-167,4	1 464
950	-163,2	1 441
1 000	-156,9	1 437

10.2 Variation of Seebeck coefficient as a function of temperature

The example of temperature-dependent Seebeck coefficient is shown in [Figure 6](#).



Key

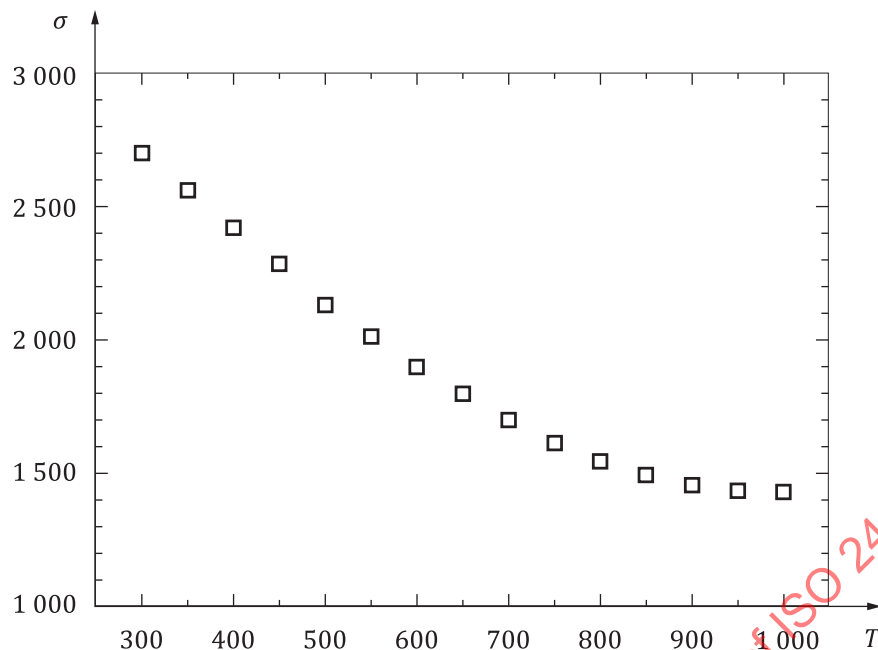
T temperature (K)

S Seebeck coefficient ($\mu\text{V/K}$)

Figure 6 — Example of temperature-dependent Seebeck coefficient

10.3 Variation of electrical conductivity as a function of temperature

The example of temperature-dependent electrical conductivity is shown in [Figure 7](#).

**Key** T temperature (K) σ electrical conductivity (S/cm)**Figure 7 — Example of temperature-dependent electrical conductivity****11 Test report**

The test report shall be in accordance with the reporting provisions of ISO/IEC 17025 and shall contain the following information if available:

- a) the name of the testing establishment;
- b) the date of the test, report identification and number, operator and signatory;
- c) the temperature and relative humidity in the laboratory;
- d) a reference to this document, i.e. ISO 24687:2023;
- e) all details for identification of test material (material type, manufacturer, batch or code number);
- f) the shape and the dimensions of the test specimens and the distance between two thermocouple probes;
- g) methods used for measuring Seebeck coefficient and electrical conductivity;
- h) all details of test conditions (e.g. currents, ambient temperatures, temperature differences);
- i) environmental conditions, e.g. vacuum, inert gas, gas pressure;
- j) calibration procedures, if applicable;
- k) the results for Seebeck coefficient and electrical conductivity;
- l) the plots of measurement of Seebeck coefficient and electrical conductivity;
- m) the number of tests carried out and the number of valid results obtained;
- n) comments about the test or test results;

- o) details of any occurrence which could have affected the result.

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Annex A (informative)

Interlaboratory evaluation of Seebeck coefficient and electrical conductivity of bulk-type thermoelectric materials

A.1 General

An interlaboratory test was undertaken by nine laboratories using two types of samples. Details and the results of the interlaboratory test are as follows.

A.2 Sample

A.2.1 Material

- a) p-type $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ sintered bulk.
- b) n-type $\text{Ti}_{0.5}\text{Hf}_{0.5}\text{NiSn}_{0.98}\text{Sb}_{0.02}$ sintered bulk.

A.2.2 Material dimension

2 mm × 2 mm × 8 mm.

A.3 Test conditions

A.3.1 Temperature range

- a) 300 K – 520 K for p-type $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ sintered bulk.
- b) 300 K – 1 000 K for n-type $\text{Ti}_{0.5}\text{Hf}_{0.5}\text{NiSn}_{0.98}\text{Sb}_{0.02}$ sintered bulk.

A.3.2 Method

Off-axis four-terminal method.

A.3.3 Environment

Backfilled with He (99,999 %).

A.4 Laboratories participating in the interlaboratory test

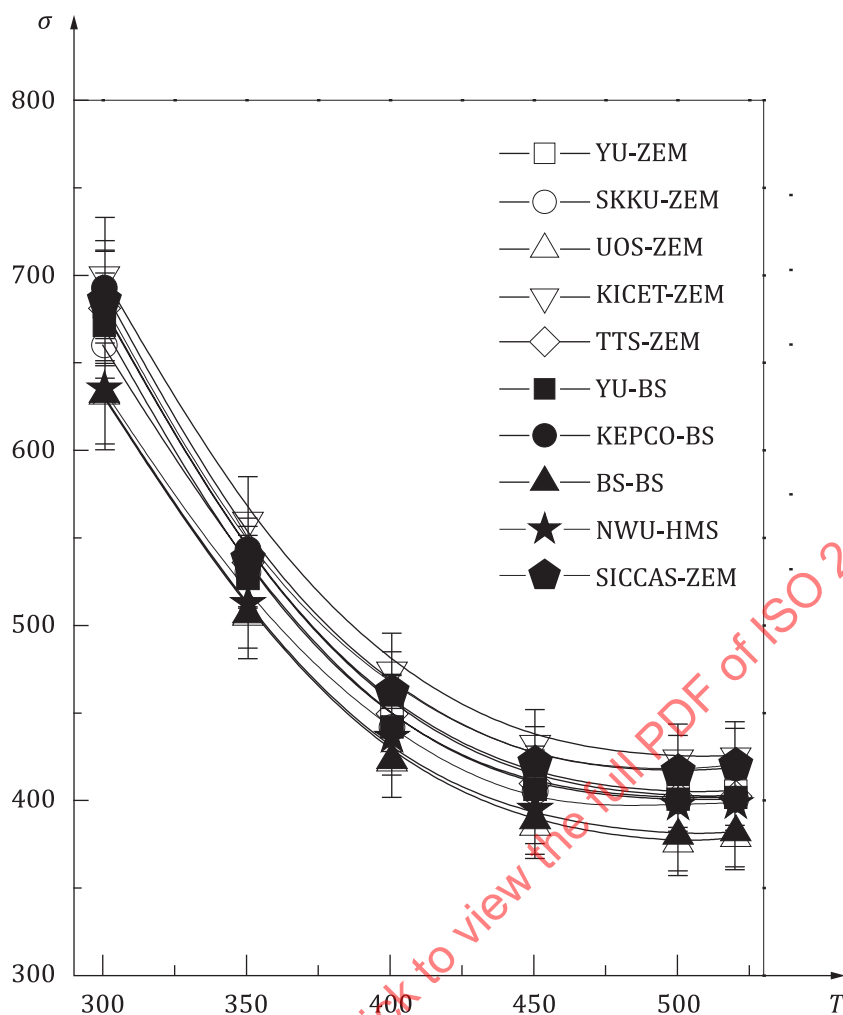
The information of 9 laboratories participating in the interlaboratory test is shown in [Table A.1](#).

Table A.1 — Information on participating laboratories

Country	Institute	Testing system	Sample name
The Republic of Korea	Yonsei University	ZEM-3 (ULVAC, Japan) BS-1 (BlueSys, Korea)	YU-ZEM YU-BS
	Sungkyunkwan University	ZEM-3 (ULVAC, Japan)	SKKU-ZEM
	University of Seoul	ZEM-3 (ULVAC, Japan)	UOS-ZEM
	Korea Institute of Ceramic Engineering and Technology	ZEM-3 (ULVAC, Japan)	KICET-ZEM
	Thermoelectric Total Solution	ZEM-3 (ULVAC, Japan)	TTS-ZEM
	Korea Electric Power Corporation	BS-1 (BlueSys, Korea)	KEPCO-BS
	BlueSys	BS-1 (BlueSys, Korea)	BS-BS
USA	Northwestern University	In-house system	NWU-HMS
China	Shanghai Institute of Ceramics, Chinese Academy of Sciences	ZEM-3 (ULVAC, Japan)	SICCAS-ZEM

A.5 Results

Electrical conductivity and Seebeck coefficient from 9 laboratories for the p-type $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$ are shown in [Figure A.1](#) and [Figure A.2](#), respectively.

**Key** T temperature (K) σ electrical conductivity (S/cm)**Figure A.1 — Electrical conductivity from nine laboratories for the p-type $\text{Bi}_{0.5}\text{Sb}_{1.5}\text{Te}_3$**