NATIONAL BUREAU OF STANDARDS REPORT

6842

THERMAL CONDUCTIVITY OF A SPECIMEN
OF POROUS SINTERED 316 STAINLESS STEEL

by

Thomas W. Watson and Frank J. Powell

Report to the
U.S. Naval Ordnance Laboratory
White Oak
Silver Spring, Maryland

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

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Heat Transfer Section
Building Technology Division

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Thermal Conductivity of a Specimen of Porous Sintered 316 Stainless Steel

by

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1. INTRODUCTION

A specimen of porous sintered 316 stainless steel was submitted by the U.S. Naval Ordnance Laboratory at White Oak, Maryland, for measurement of its thermal conductivity in the temperature range -150° to 640°C.

2. SAMPLE

The sample was a bar of 2.34 cm square cross-section and 37.0 cm long. It was stated to be 5 micron sintered spherical 316 stainless steel powder with binder. The porous bar had a 2.34 cm cylindrical solid stainless steel end (with a 1.35 cm drill-hole) fastened by threads for the coolant well. The porous material was described as having a density ratio 0.427 of that of stainless steel. No chemical analysis of the metal powder composition was furnished, or made at the National Bureau of Standards.

3. TEST APPARATUS AND METHOD

The thermal conductivity of the sample was determined by means of a steady-state flow of heat longitudinally in a bar specimen, with measurements of the temperatures existing at the ends of six consecutive, approximately 3.51 cm, spans along the central length of the bar. Each determination required a pair of tests at moderately different temperature conditions, and yielded values of thermal conductivity at six different mean temperatures.

The test apparatus is shown schematically in Figure 1.

The specimen, a bar approximately 37 cm long and of uniform external dimensions, is supported at the top (coolant) end concentrically within a stainless steel guard tube of 1-cm wall thickness, which in turn is held concentrically within a cylindrical outer container. The specimen is drilled at each end with a 1.35 cm hole 5.5 cm deep. An electrical heater is inserted and secured in the hole at the bottom (hot) end, and the supporting fixture at the top end provides a liquid-tight connection for circulating a coolant through the top drill-hole.

Temperatures along the specimen were indicated by seven thermocouples located symmetrically about the longitudinal center of the specimen, spaced approximately 3.51 cm apart, with one additional thermocouple near the bottom end of the specimen. Thermocouples were similarly located in almost exactly corresponding longitudinal positions on the guard tube.

The guard tube was equipped near its lower end with an external circumferential electric heater, as shown. The guard tube was cooled at the top by means of a copper-tube coil soldered circumferentially at a position corresponding in effect to that of the specimen coolant well. Coolant was pumped through the guard coil and specimen well in series connection, as shown.

The electric heater for the specimen consisted of a porcelain cylinder 1.27 cm in diameter and 5.2 cm long, threaded longitudinally with 26-gage nichrome heater wire. Its resistance was approximately 22 ohms. Current was brought to the heater through relatively large heater leads, to which separate potential leads were connected at the point where they entered the porcelain core. The heater was energized by an adjustable constant-voltage d-c source. Heater current and voltage drop measurements were made using standard resistors and the high precision manual potentiometer used for thermocouple observations. The guard was heated with constant voltage a-c power.

The thermocouples were made from calibrated chromel and alumel 26-gage wires, electrically welded to form a spherical junction about 0.10 cm in diameter. Junctions in the specimen were inserted into radially-drilled holes 0.11 cm in diameter and 0.17 cm deep in the side of the bar, and tightly secured by punch pricking the metal around the hole. The thermocouple wires were individually insulated electrically with fiberglass sleeving, and were wrapped around the bar (one in each direction) and tied at the back to secure them in the transverse plane of the junction. The wires were brought out through the powder insulation near the guard tube. The thermocouples in the guard tube were similarly attached to its exterior surface. The longitudinal positions of the thermocouple junctions were taken as those of the centers of the drilled holes, measured to the nearest 0.01 cm with a laboratory cathetometer.

After installation of the specimen, the space between it and the guard tube was filled with diatomaceous earth

powder insulation, which also was used to insulate the space surrounding the guard tube.

In principle, if there were no heat exchange between the specimen and its surroundings, the conductivity could be determined from the measured power input to the specimen and the average temperature gradient for each of the six spans along the specimen, all of uniform known cross-sectional area. In practice, a perfect balance of temperatures between the bar and guard all along their lengths is not possible because of differences in their temperature coefficients of conductivity, and the effect of the outward heat losses of the guard. In addition to heat exchanges between the bar and guard from this cause, a not insignificant longitudinal flow of heat occurs in the powder insulation surrounding the specimen, and the contribution of the specimen to this heat flow must depend somewhat on the bar-to-guard temperature unbalance.

In order to evaluate the heat flow in the bar at the center points of each of the six spans, a partly empirical procedure was used. Two steady-state test-runs were made with slightly different bar and guard temperatures and power inputs. In the two tests, the heat flow and the observed temperature drop from end to end of a given span differed, as did also the approximate integral with respect to length of the observed temperature differences between bar and guard, summed from the hot end of the bar to the span center point. It is thus possible to write for each span two equations (one for each test-run) of the form:

$$\frac{Ak\Delta t}{\Delta x} + fS = Q$$

where A is the cross-sectional area of the specimen,

k is the specimen conductivity at the mean temperature of the span,

Δt is the temperature drop from end to end of the span,

Δx is the length of the span,

fS represents the total net heat loss from the bar from its bottom end at the heater to the midpoint of the given span, expressed as the product of S, which is a close approximation of the integral $\int_0^x (t_{bar} - t_{guard})dx$, and an average heat transfer

coefficient f for the thermal path from bar to guard.

Q is the measured power input to the specimen heater.

By simultaneous solution of the two equations, the value of k for each span, corresponding to the mean span mean temperature, is obtained. All of the computation of results is effected by use of an IBM-704 digital computer, suitably programmed to compute the thermal conductivity and corresponding mean temperature for each of the six spans. The computer was used to fit a third-power equation to the thermal conductivity and temperature results, by method of least squares. Much time is saved by machine computation, and accidental errors in the considerable calculations are avoided.

4. RESULTS

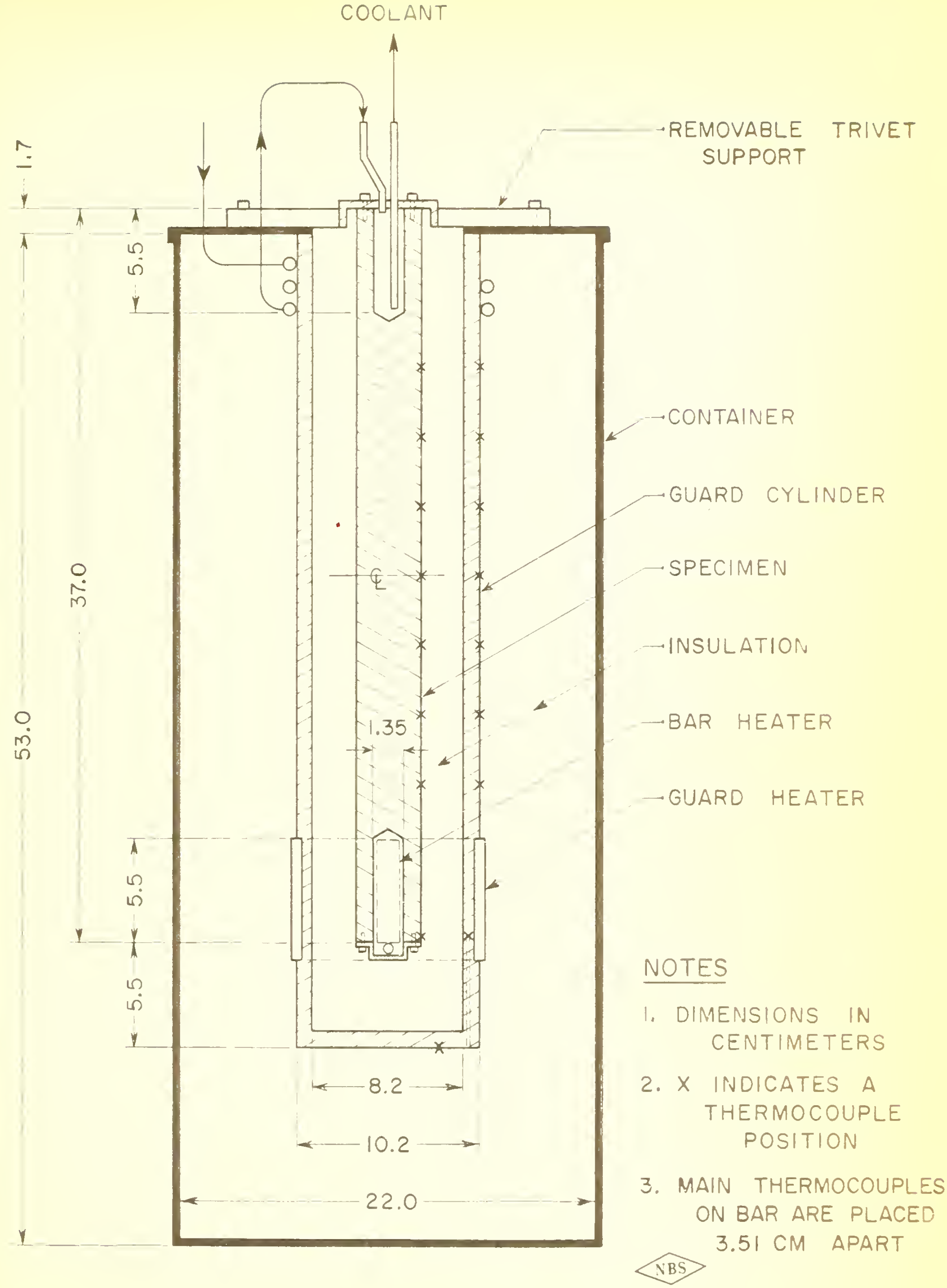
The results of the thermal conductivity determinations are shown in Figure 2 and the table below. The 36 individual values of thermal conductivity plotted represent six sets of tests, each with values for the six spans. The solid line represents the trinomial fitting the data, as determined by the computer and from which values are also tabulated below.

°C	watt/cm °C	°C	watt/cm °C
-140	0.010	300	0.019
-100	.012	340	.019
-60	.013	380	.019
-20	.014	420	.020
20	.015	460	.020
60	.016	500	.021
100	.017	540	.022
140	.017	580	.023
180	.018	620	.024
220	.018	640	.025
260	.018		

5. DISCUSSION OF RESULTS

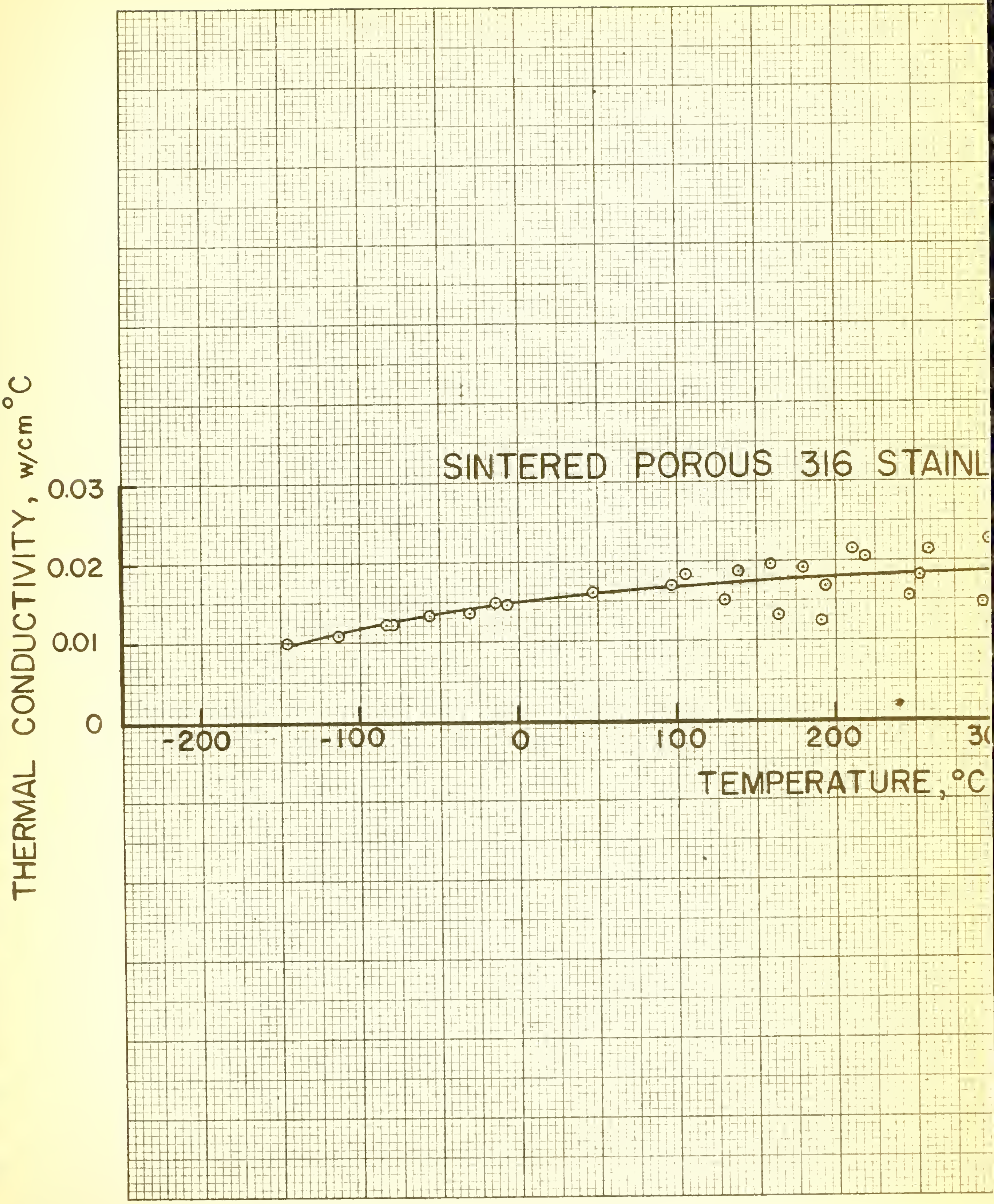
The individual values of thermal conductivity plotted in Figure 2 show considerable scattering from the smooth curve in the temperature range 125° to 425°C. Little scattering is shown over the temperature ranges -145° to 100°C and 450° to 645°C. The average departure from a smooth curve in the temperature range 125° to 425°C is about ± 13 percent; for other temperature ranges, about ± 1.7 percent.

Due to the extremely low conductivity of this material as compared to other metals, the inaccuracy of the results over the temperature range given is estimated to be within 10 to 15 percent of the absolute value.



APPARATUS FOR MEASURING THE THERMAL CONDUCTIVITY OF METALS

Figure 1



SINTERED POROUS 316 STAINL
THERMAL CONDUCTIVITY, w/cm °C
0.03
0.02
0.01
0
-200
-100
0
100
200
30
TEMPERATURE, °C

Figure 2

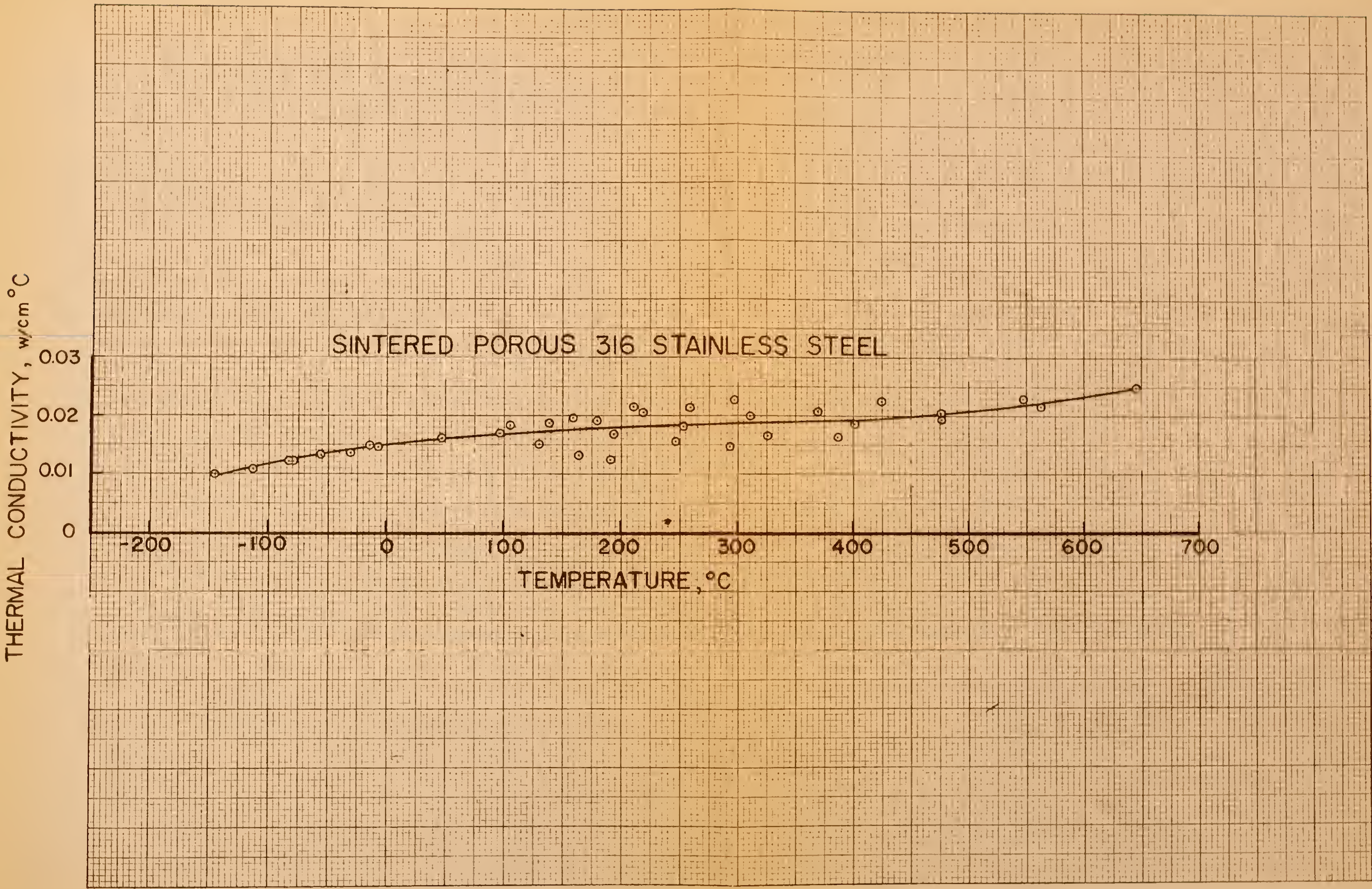

SINTERED POROUS 316 STAINLESS STEEL
THERMAL CONDUCTIVITY, w/cm °C
0.03
0.02
0.01
0
-200
-100
0
100
200
300
400
500
600
700
TEMPERATURE, °C

Figure 2

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Frederick H. Mueller, *Secretary*

NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

The scope of activities of the National Bureau of Standards at its major laboratories in Washington, D.C., and Boulder, Colorado, is suggested in the following listing of the divisions and sections engaged in technical work. In general, each section carries out specialized research, development, and engineering in the field indicated by its title. A brief description of the activities, and of the resultant publications, appears on the inside of the front cover.

WASHINGTON, D.C.

Electricity and Electronics. Resistance and Reactance. Electron Devices. Electrical Instruments. Magnetic Measurements. Dielectrics. Engineering Electronics. Electronic Instrumentation. Electrochemistry.

Optics and Metrology. Photometry and Colorimetry. Photographic Technology. Length. Engineering Metrology.

Heat. Temperature Physics. Thermodynamics. Cryogenic Physics. Rheology. Molecular Kinetics. Free Radicals Research.

Atomic and Radiation Physics. Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics. Neutron Physics. Radiation Theory. Radioactivity. X-rays. High Energy Radiation. Nucleonic Instrumentation. Radiological Equipment.

Chemistry. Organic Coatings. Surface Chemistry. Organic Chemistry. Analytical Chemistry. Inorganic Chemistry. Electrodeposition. Molecular Structure and Properties of Gases. Physical Chemistry. Thermochemistry. Spectrochemistry. Pure Substances.

Mechanics. Sound. Mechanical Instruments. Fluid Mechanics. Engineering Mechanics. Mass and Scale. Capacity, Density, and Fluid Meters. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics.

Mineral Products. Engineering Ceramics. Glass. Refractories. Enameled Metals. Constitution and Microstructure.

Building Technology. Structural Engineering. Fire Protection. Air Conditioning, Heating, and Refrigeration. Floor, Roof, and Wall Coverings. Codes and Safety Standards. Heat Transfer. Concreting Materials.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics.

Data Processing Systems. SEAC Engineering Group. Components and Techniques. Digital Circuitry. Digital Systems. Analog Systems. Application Engineering.

• Office of Basic Instrumentation.

• Office of Weights and Measures.

BOULDER, COLORADO

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Gas Liquefaction.

Radio Propagation Physics. Upper Atmosphere Research. Ionospheric Research. Regular Propagation Services. Sun-Earth Relationships. VHF Research. Radio Warning Services. Airglow and Aurora. Radio Astronomy and Arctic Propagation.

Radio Propagation Engineering. Data Reduction Instrumentation. Modulation Research. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation Obstacles Engineering. Radio-Meteorology. Lower Atmosphere Physics.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. High Frequency Impedance Standards. Electronic Calibration Center. Microwave Physics. Microwave Circuit Standards.

Radio Communication and Systems. Low Frequency and Very Low Frequency Research. High Frequency and Very High Frequency Research. Ultra High Frequency and Super High Frequency Research. Modulation Research. Antenna Research. Navigation Systems. Systems Analysis. Field Operations.

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