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NATIONAL BUREAU OF STANDARDS REPORT

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THERMAL CONDUCTIVITY OF A SAMPLE OF TYPE 316 STAINLESS STEEL

by

Thomas W. Watson and Henry E. Robinson

Report to

Applied Physics Laboratory
Johns Hopkins University
Silver Spring, Maryland

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

THE NATIONAL BUREAU OF STANDARDS

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to

Applied Physics Laboratory
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Thermal Conductivity of a Sample of Type 316 Stainless Steel

by

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1. INTRODUCTION

This report presents results of thermal conductivity measurements in the temperature range 90° to 850°C of a sample of fully-annealed Type 316 stainless steel submitted by the Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Maryland.

2. SAMPLE

The sample submitted was a bar about 2.54 cm in diameter and 46.0 cm long, from which the test specimen was machined to a uniform diameter of 2.54 cm and a length of 37.0 cm.

The chemical composition and mechanical properties of the specimen are given in Table 1, as supplied by the Applied Physics Laboratory, on the basis of a chemical analysis made by Joseph T. Ryerson & Son, Inc. The steel was identified as Alleghany Heat No. 327268.

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.[1/]

The specimen, a bar approximately 37 cm long and of uniform external dimensions over the metering length, was supported at the top (coolant) end concentrically within a stainless steel guard tube of 0.8-cm wall thickness, which in turn was held concentrically within a cylindrical outer container. The specimen was drilled at each end with a 1.35-cm hole 5.5 cm deep. An electrical heater was inserted and secured in the hole at the bottom (hot) end, and the supporting fixture at the top end provided a liquid-tight connection for circulating a coolant through the top drill-hole.

1/ See: "Thermal Conductivity of Some Commercial Iron-Nickel Alloys," by T. W. Watson and H. E. Robinson (Trans. ASME(C), 83, 403-408, 1961).

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 two external circumferential electric heaters, 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 (water at 40°C) was pumped through the guard coil and specimen well in series connection, as shown.

The electrical heater for the specimen consisted of a porcelain cylinder 1.25 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 alternating current governed by a sensitive temperature controller actuated by the guard temperature at a selected position.

The thermocouples were made from calibrated platinum:platinum-10% rhodium 15-mil wires, welded by gas-oxygen flame to form a butt joint about 0.042 cm in diameter.

The thermocouple junctions were pressed into transverse grooves 0.04 cm wide by 0.05 cm deep and 0.6 cm in length in the convex surface of the bar and tightly secured by hammering the metal around the groove. The bare thermocouple leads were individually brought out in the powder insulation in the same transverse plane as the junction (one wire in each direction around the bar) forming a 4-cm circle. The wires were then insulated with alumina tubing, and in cooler regions with fiberglas sleeving, and brought out through the powder insulation near the guard tube. The thermocouples in the guard tube were electrically welded to form a spherical junction about 0.10 cm in diameter. The junctions in the guard were inserted into radially-drilled holes 0.11 cm in diameter and 0.17 cm deep, and tightly secured by punch-pricking the metal around the hole. The wires were similarly brought out through the powder insulation. The longitudinal positions of the thermocouple junctions were taken as those of the centers of the grooves, or 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 alumina powder insulation, which also was used to insulate the space surrounding the guard tube. The tests were conducted with the insulation exposed to atmospheric air.

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 relatively 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

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

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

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

$\triangle t$ is the temperature drop from end to end of the span,

$\triangle x$ 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, x, of the given span, expressed as the product of S, which is 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.

The two equations written for each of the six spans of the bar can be solved simultaneously to determine k and f. For this to be strictly valid, k and f must have equal values in the two equations. Since the mean temperatures of the span in the two tests will in general differ slightly, and the conductivity of the bar may vary with temperature, a slight adjustment is made to the observed values of Δt so that k corresponds to the mean of the span mean temperatures in the two tests. The equality of f in the two tests is not so readily assured, but because the magnitude of fS in these tests was generally on the order of 5 percent of Q, a moderate difference in the values of f in the two equations would affect the solved value of $Ak/\Delta x$ only slightly.

The computation of results directly from the observed data was effected by an IBM 7090 digital computer suitably programmed to compute the thermal conductivity and the 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 the method of least squares.

4. RESULTS

The results of the thermal conductivity determinations are shown in Figure 2 and Table 2. The 30 individual values of thermal conductivity plotted represent five sets of tests, each with values for the six spans. The solid line represents the trinomial fitting the data, as determined by a digital computer, from which the values tabulated in Table 2 were taken. The trinomial equation obtained is

$$k = 0.1333 + 0.1727\left(\frac{T}{1000}\right) - 0.04334\left(\frac{T}{1000}\right)^2 + 0.0332\left(\frac{T}{1000}\right)^3$$

with k in w/cm C, T in °C ($90 < T < 840$). The standard deviation of the departures of the thirty data points from the trinomial equation is 0.001595 w/cm C. The extreme departure of an individual data point from the smooth curve (at 300°C) is less than 3 percent.

5. DISCUSSION OF RESULTS

The conductivity values obtained for this sample are about 8 percent higher at 100°C, and 2 percent higher at 700°C, than values reported in NBS Report 5748 (January 1958) for two specimens of another Type 316 sample made by a different manufacturer. The present sample contained less silicon (0.56% versus 1.2%). The value inferred for the present sample at 0°C (0.134 w/cm C) compares with the value 0.133 at 0°C given by Tyler and Wilson, 1952 (NBS Circular 556, pp43, 44), for Type 316 stainless steel.

TABLE I

Chemical Composition - Percent

C	Mn	P	S	Si	Ni	Cr	Mo
0.058	1.50	0.022	0.019	0.56	13.36	17.51	2.44

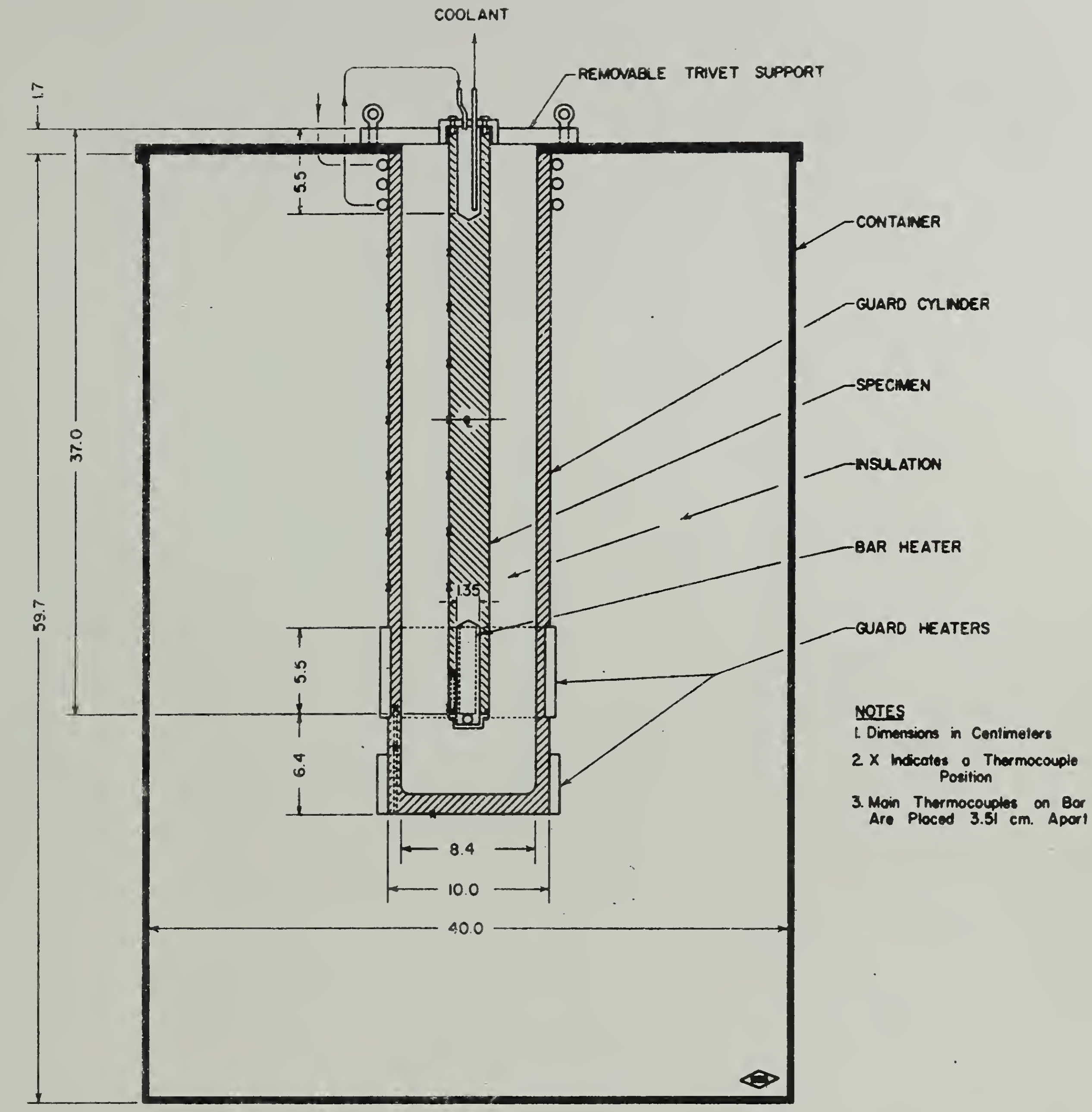
Mechanical Properties

Tensile psi	Yield psi	Elongation percent	Reduction of Area percent	Hardness
80,200	45,700	60	65.6	BHN 143

TABLE 2

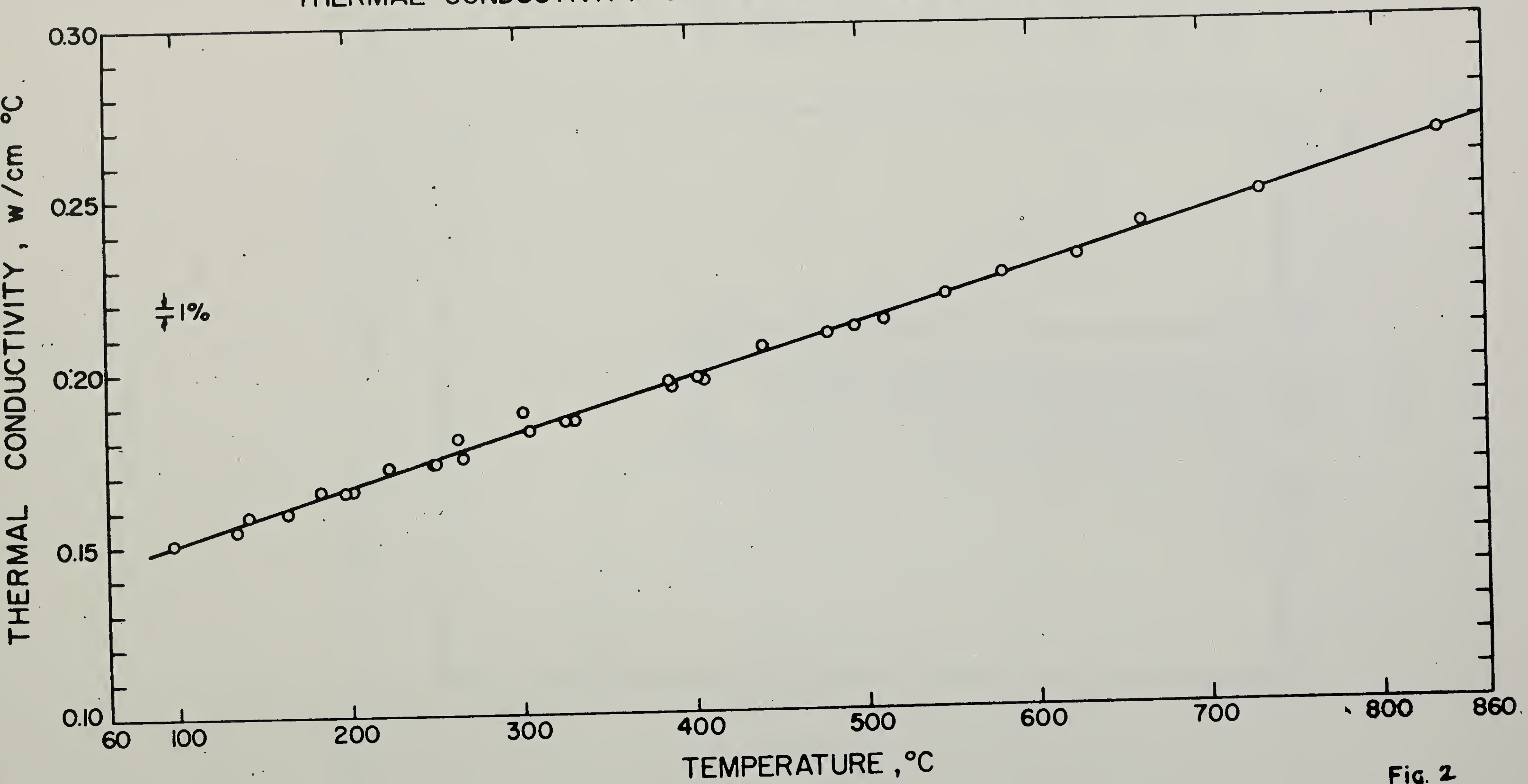
Thermal Conductivity of a Sample of Type 316 Stainless Steel

°C	Watt/cm°C	°C	Watt/cm°C
90	0.149	490	0.211
130	0.155	530	0.218
170	0.162	570	0.224
210	0.168	610	0.230
250	0.174	650	0.236
290	0.181	690	0.243
330	0.187	730	0.249
370	0.193	770	0.256
410	0.199	810	0.262
450	0.205	850	0.269



APPARATUS FOR MEASURING THE THERMAL CONDUCTIVITY OF METALS

Fig. 1



THERMAL CONDUCTIVITY OF A SAMPLE OF 316 STAINLESS STEEL

Fig. 2

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NATIONAL BUREAU OF STANDARDS
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THE NATIONAL BUREAU OF STANDARDS

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Electricity. Resistance and Reactance. Electrochemistry. Electrical Instruments. Magnetic Measurements. Dielectrics. High Voltage. Absolute Electrical Measurements.

Metrology. Photometry and Colorimetry. Refractometry. Photographic Research. Length. Engineering Metrology. Mass and Volume.

Heat. Temperature Physics. Heat Measurements. Cryogenic Physics. Equation of State. Statistical Physics.

Radiation Physics. X-ray. Radioactivity. Radiation Theory. High Energy Radiation. Radiological Equipment. Nucleonic Instrumentation. Neutron Physics.

Analytical and Inorganic Chemistry. Pure Substances. Spectrochemistry. Solution Chemistry. Standard Reference Materials. Applied Analytical Research. Crystal Chemistry.

Mechanics. Sound. Pressure and Vacuum. Fluid Mechanics. Engineering Mechanics. Rheology. Combustion Controls.

Polymers. Macromolecules: Synthesis and Structure. Polymer Chemistry. Polymer Physics. Polymer Characterization. Polymer Evaluation and Testing. Applied Polymer Standards and Research. Dental Research.

Metallurgy. Engineering Metallurgy. Metal Reactions. Metal Physics. Electrolysis and Metal Deposition.

Inorganic Solids. Engineering Ceramics. Glass. Solid State Chemistry. Crystal Growth. Physical Properties. Crystallography.

Building Research. Structural Engineering. Fire Research. Mechanical Systems. Organic Building Materials. Codes and Safety Standards. Heat Transfer. Inorganic Building Materials. Metallic Building Materials.

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

Data Processing Systems. Components and Techniques. Computer Technology. Measurements Automation. Engineering Applications. Systems Analysis.

Atomic Physics. Spectroscopy. Infrared Spectroscopy. Far Ultraviolet Physics. Solid State Physics. Electron Physics. Atomic Physics. Plasma Spectroscopy.

Instrumentation. Engineering Electronics. Electron Devices. Electronic Instrumentation. Mechanical Instruments. Basic Instrumentation.

Physical Chemistry. Thermochemistry. Surface Chemistry. Organic Chemistry. Molecular Spectroscopy. Elementary Processes. Mass Spectrometry. Photochemistry and Radiation Chemistry.

Office of Weights and Measures.

BOULDER, COLO.

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Radio Systems. Applied Electromagnetic Theory. High Frequency and Very High Frequency Research. Frequency Utilization. Modulation Research. Antenna Research. Radiodetermination.

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Radio Standards Engineering. High Frequency Electrical Standards. High Frequency Calibration Services. High Frequency Impedance Standards. Microwave Calibration Services. Microwave Circuit Standards. Low Frequency Calibration Services.

Joint Institute for Laboratory Astrophysics-NBS Group (Univ. of Colo.).

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