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NATIONAL BUREAU OF STANDARDS REPORT

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THERMAL CONDUCTIVITY AND ELECTRICAL RESISTIVITY OF A SPECIMEN OF UDIMET 700 ALLOY

Report to

National Aeronautics and Space Administration
Lewis Research Center

NBS

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

NATIONAL BUREAU OF STANDARDS

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by

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Environmental Engineering Section
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1. Introduction

This report presents results of thermal conductivity and electrical resistivity measurements of a sample of "Udimet 700 Alloy" submitted by the Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio. Thermal conductivity and electrical resistivity were measured from 100 to 830 °C.

2. Sample

The sample submitted was a bar of cast nickel-base alloy about 1.91 cm in diameter and 31.2 cm long over the measuring section. A stainless steel cylinder 2.54 cm in diameter by 5.8 cm long was soft soldered to the cold end of the bar to conform to the coolant cap of the test apparatus (total length 37 cm).

The nominal chemical composition of the alloy in weight percent, as supplied by NASA, is as follows: 0.07 C, 0.10 Mn, 0.10 Si, 15.2 Cr, 18.6 Co, 4.9 Mo, 3.4 Ti, 4.4 Al, 0.35 Fe, 0.10 Cu, 0.0003 S, 0.029 B, 0.05 Zr and the balance Ni [1][1].

3. Thermal Conductivity Test Apparatus and Method

The thermal conductivity of the sample was determined by means of a steady-state flow of heat longitudinally in the 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 [2].

The test apparatus is shown schematically in figure 1.

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[1] Figures in brackets indicate the literature references at the end of this report.

The specimen, a bar approximately 37 cm long and of uniform outside diameter over the measuring section, was supported at the top (coolant) end coaxially within a stainless steel guard tube of 0.8 cm wall thickness, which in turn was held coaxially 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 by a completely enclosing metal cap (in lieu of the strap shown in figure 1), and the supporting fixture at the top end provided 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 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 24-gage nichrome heater wire threaded back and forth through longitudinal holes in a porcelain cylinder, 1.25 cm in diameter and 5.2 cm long.

Its resistance at 25 °C was approximately 14 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 Platinel II wires, welded by gas-oxygen flame to form a butt joint about 0.04 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. 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 3 cm circle. The wires were then insulated with alumina tubing, and in cooler regions with fiberglass sleeving, and brought out through the powder insulation near the guard tube. The thermocouples in the guard tube were 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.

Current leads (0.1-cm Pt) were attached to the two ends of the bar specimen for passing a direct current of about 10 amperes along the bar for making electrical resistivity measurements. The lead at the hot end was led in a flat spiral in the powder insulation, in a plane transverse to the bar axis, to near the inner radius of the guard tube, from which point it was electrically insulated with broken ceramic tubing and brought upwards through the powder insulation near the guard tube.

After installation of the specimen, the space between it and the guard tube was filled with fine aluminum oxide 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 smaller 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 it 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. Compensation is made for the temperature dependence of f by using an appropriate value for the temperature dependence of the thermal conductivity of the powder insulation.

Electrical resistivity measurements for each span were made at the temperature conditions existing at the end of each pair of runs for determining the thermal conductivity, by passing a d-c current of about 10 amperes along the bar, and observing the potential differences between adjacent positive leads of the span thermocouples, with the current direction forward and reversed. The average of the two potential drops between two adjacent leads indicated the net potential drop due to the current flowing in the span, and thus enabled calculation of its resistivity. Due to a slight warming of the bar during the period of current flow, the resistivity was assigned to correspond to the time-average of the span mean temperature over this period. An additional set of data was taken with the specimen isothermal at room temperature.

The computation of results directly from the observed data was effected by digital computer suitably programmed to compute the thermal conductivity, the electrical resistivity, and the corresponding mean temperatures, for each of the six spans.

4. Results and Discussion

The results of the thermal conductivity and electrical resistivity determinations, using the thermal conductivity apparatus described above, are shown in figure 2. The thirty individual thermal conductivity data points represent five sets of tests, each with values for the six spans. The electrical resistivity and thermal conductivity data points are shown as circles obtained on the thermal conductivity specimen and the smoothed values are given at 100 deg C intervals in table 1. The electrical resistivity values given in table 1 are estimated to be uncertain by less than ± 2 percent. The thermal conductivity values given in table 1 are estimated to be uncertain by less than ± 3 percent.

Powell [3] has recently surveyed the validity of correlations between the thermal conductivity (λ) of metals and the quotient T/ρ, where T is absolute temperature and ρ is electrical resistivity. In figure 3, some of these correlations for nickel and nickel-base alloys are shown. The straight line labeled "nickel", due to Fine [4], was fitted to nickel and nickel alloys. The straight line labeled "gamma iron and austenitic steels" is from the work of Powell [5]. The straight line labeled "Nimonic alloys" was fitted to data on a group of nickel-chromium alloys by Powell and Tye [6]. The solid curve labeled "Inconel 702" represents the actual smoothed data obtained by Laubitz [7] on a sample of this nickel-chromium alloy [2] which was in an age-hardened condition. The thermal conductivity of Inconel 702 has been measured with excellent agreement by several laboratories [7, 8, 9, 10] and hence is very well known. Measurements of the electrical resistivity of Inconel 702 made at NBS [11] are in excellent agreement with the data of Laubitz [7]. The solid and open circles give data on a NASA Taz-8A sample tested at NBS [12]. The points shown as open circles represent extrapolated values for the Taz-8A specimen. The solid triangles show the results of the Udimet 700 alloy specimen.

Table 1. Thermal conductivity and electrical resistivity of a sample of Udimet 700 alloy.

Temperature °C	Electrical resistivity Ω m	Thermal conductivity W m^{-1} deg^{-1}
25	133×10^{-8}	-
100	136	11.7
200	140	13.0
300	143	14.4
400	146	15.8
500	148	17.4
600	149	19.0
700	148	20.8
800	148	22.5
830	147	23.0

6. References

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[3] R. W. Powell, Correlation of metallic thermal and electrical conductivities for both solid and liquid phases, Int. J. Heat Mass Transfer 8, 1033 (1965).

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[7] M. J. Laubitz and K. D. Cotnam, Thermal and electrical properties of Inconel 702 at high temperatures, Canad. J. Phys. 42, 131 (1964).

[8] D. R. Flynn and H. E. Robinson, The National Bureau of Standards high temperature absolute cut-bar apparatus, Proc. Third Conf. on Thermal Conductivity (Gatlinburg, Tenn., Oct. 16-18, 1963).

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[10] R. W. Powell and R. P. Tye, New measurements on thermal conductivity reference materials, Int. J. Heat Mass Transfer 10, 581 (1967).

[11] D. R. Flynn, private communication.

[12] T. W. Watson and D. R. Flynn, Thermal conductivity and electrical resistivity of a specimen of Taz-8A superalloy, NBS Report 9810 (April, 1968).

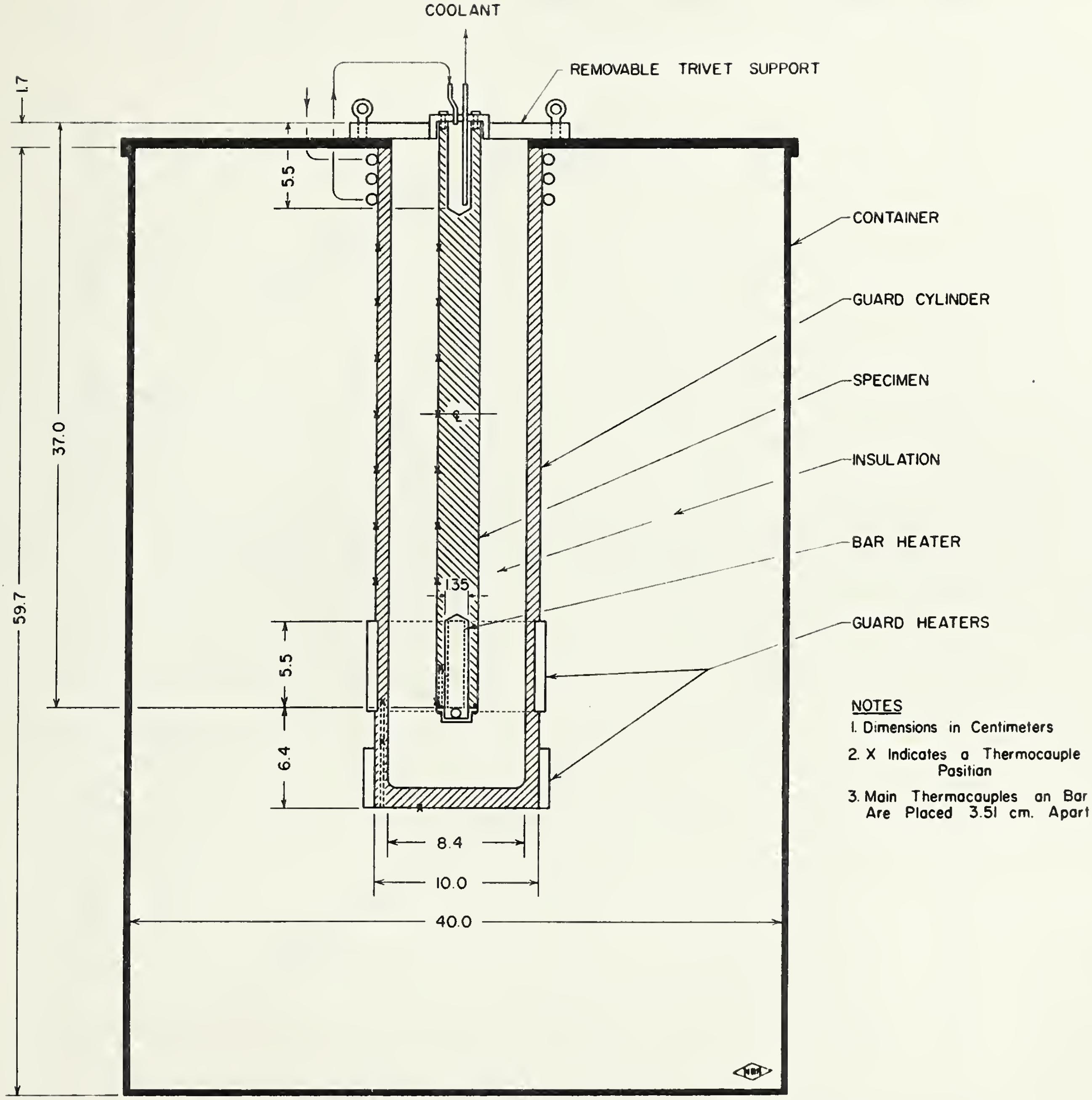


Figure 1. Apparatus used for measuring thermal conductivity of metal specimens.

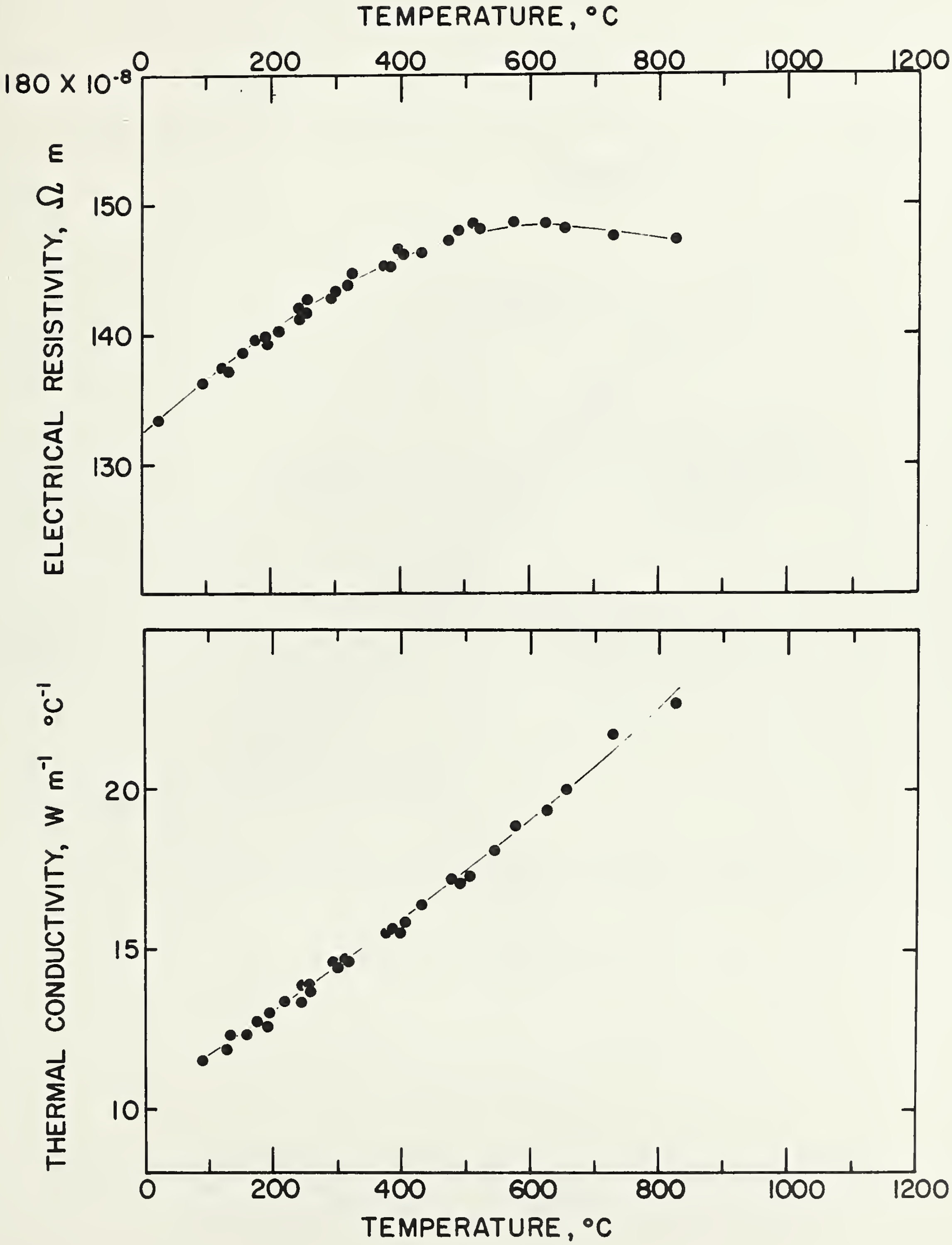


Figure 2. Thermal conductivity and electrical resistivity of a sample of Udimet 700 alloy. The symbols are described in the text.

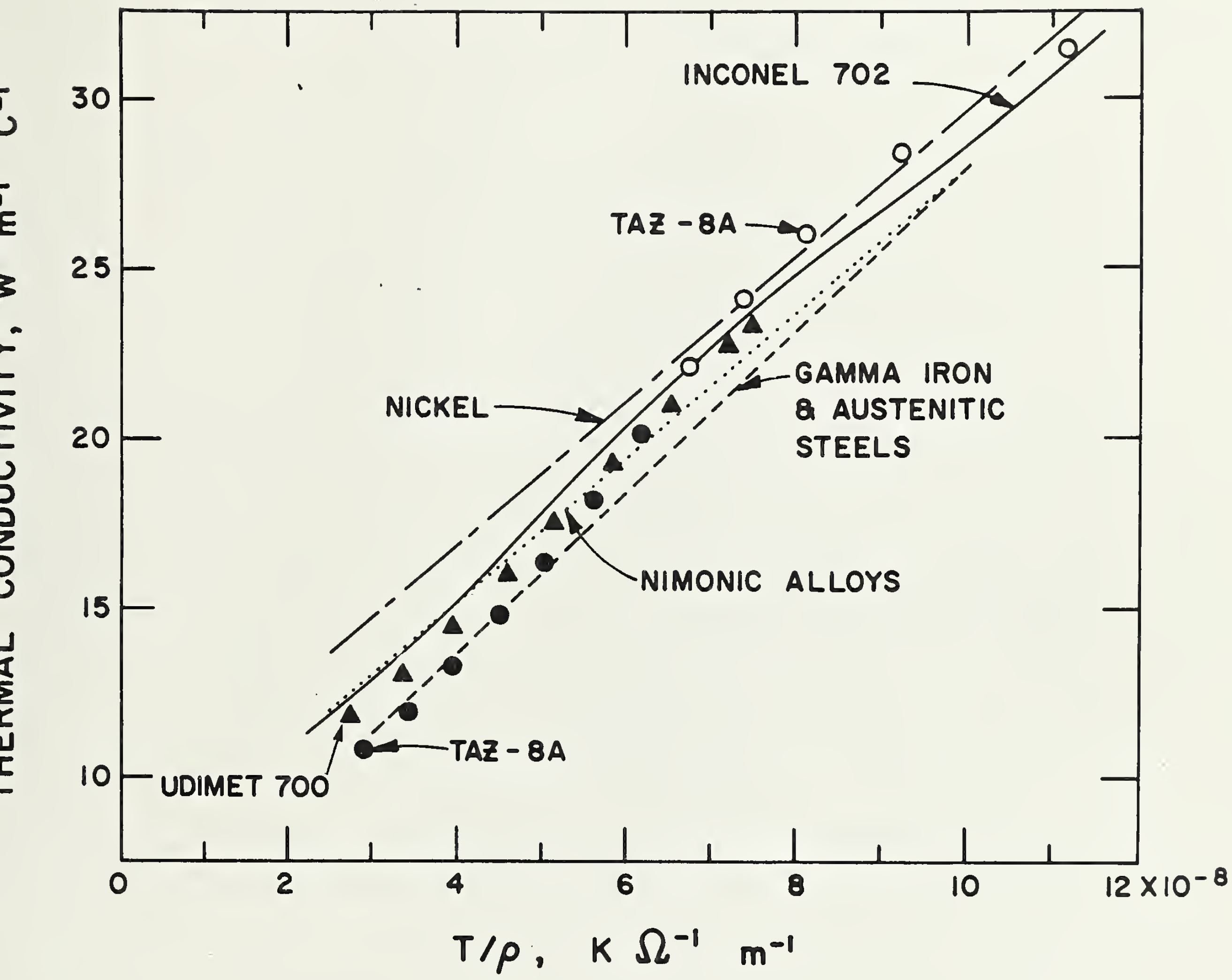
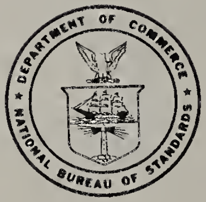


Figure 3. Nickel alloys: thermal conductivity as a function of absolute temperature divided by electrical resistivity. The different curves are identified in the text.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