# THE THERMAL CONDUCTIVITY OF SODIUM IN THE TEMPERATURE RANGE 90–850°C

ROBERTO EVANGELISTI and FRANCO ISACCHINI

Comitato Nazionale Energia Nucleare, Centro Studi Nucleari della Casaccia, Roma

**Abstract**—This work describes an experiment which was carried out in order to determine the effect of temperature on the thermal conductivity of sodium, in the temperature range 90–850°C. The experimental method is based on a mathematical model which is briefly examined in the first section. The apparatus and the test procedure are described in the second section, with reference to the major features of the measurement device. In the last section the experimental results are compared with previously published data.

## NOMENCLATURE

$z$,  co-ordinate in the vertical direction;

$r$,  co-ordinate in the radial direction;

$t$,  temperature (degree Celsius °C);

$T$,  absolute temperature;

$q$,  heat flux per unit time and area;

$g$,  temperature gradient;

$K$,  thermal conductivity;

$a$,  linear thermal expansion coefficient;

$p$,  thermoelectric power;

$l_w$,  radial length of the thermocouple well;

$v$,  thermoelectric force;

$\rho$,  density;

$\rho_e$,  electrical resistivity;

$c_p$,  specific heat at constant pressure;

$P_g$,  electrical power dissipated in the guard heaters;

Subscripts

av,  average;

$r$,  radial;

$z$,  vertical;

$m$,  mean;

$l$,  liquid metal;

$s$,  steel;

$g$,  guarding;

max,  maximum;

$o$,  at room temperature.

## INTRODUCTION

HEAT-TRANSFER systems utilizing liquid metals provide one method for efficiently exchanging large quantities of heat at high temperature levels. The fact that the first three alkali metals (lithium, potassium and sodium) have densities less than water and possess high latent heats makes them extremely attractive as heat carrier fluids in power cycles for space applications. The favourable combination of physical properties such as heat capacity, viscosity, thermal conductivity and high temperature liquid range makes alkali metals in principle among the best heat-transfer media available for use in nuclear reactors: of prime interest for this purpose is sodium. A few properties of this liquid metal, including the thermal conductivity, are not known with sufficient certainty up to high temperatures to permit optimization of design criteria for developing maximum efficiency coolant systems. The thermal conductivity directly affects a parameter of the greatest importance in the reactor thermal design, the film transfer coefficient: we have therefore thought it useful to carry out a measurement of this physical property of sodium. The average accuracy of the information obtained can be evaluated as $\pm 5\cdot 5$ per cent in the temperature range 100–850°C. When we make heat-transfer calculations, the effect of a $K$ error $\pm 5\cdot 5$ per cent is

1 – EDWARDS valves for vacuum
    and pressurizing.
2 – Vacuum and pressurizing line.
3 – Sodium filling line.
4 – Movable level thermocouple.
5 – Expansion reservoir tracing heater.
6 – Expansion reservoir.
7 – Insulation.
8 – Vacuum - manometer.
9 – Main heater.
10 – Guard heaters.
11 – Temperature trend in the reservoir.
12 – Thermal expansion joint.
13 – Measurement thermocouples wells.
14 – Heat sink.
15 – Device support.
16 – Vacuum chamber.
17 – Sodium.
18 – Standard material.
19 – Guarding control wells.

G.H.1
G.H.2
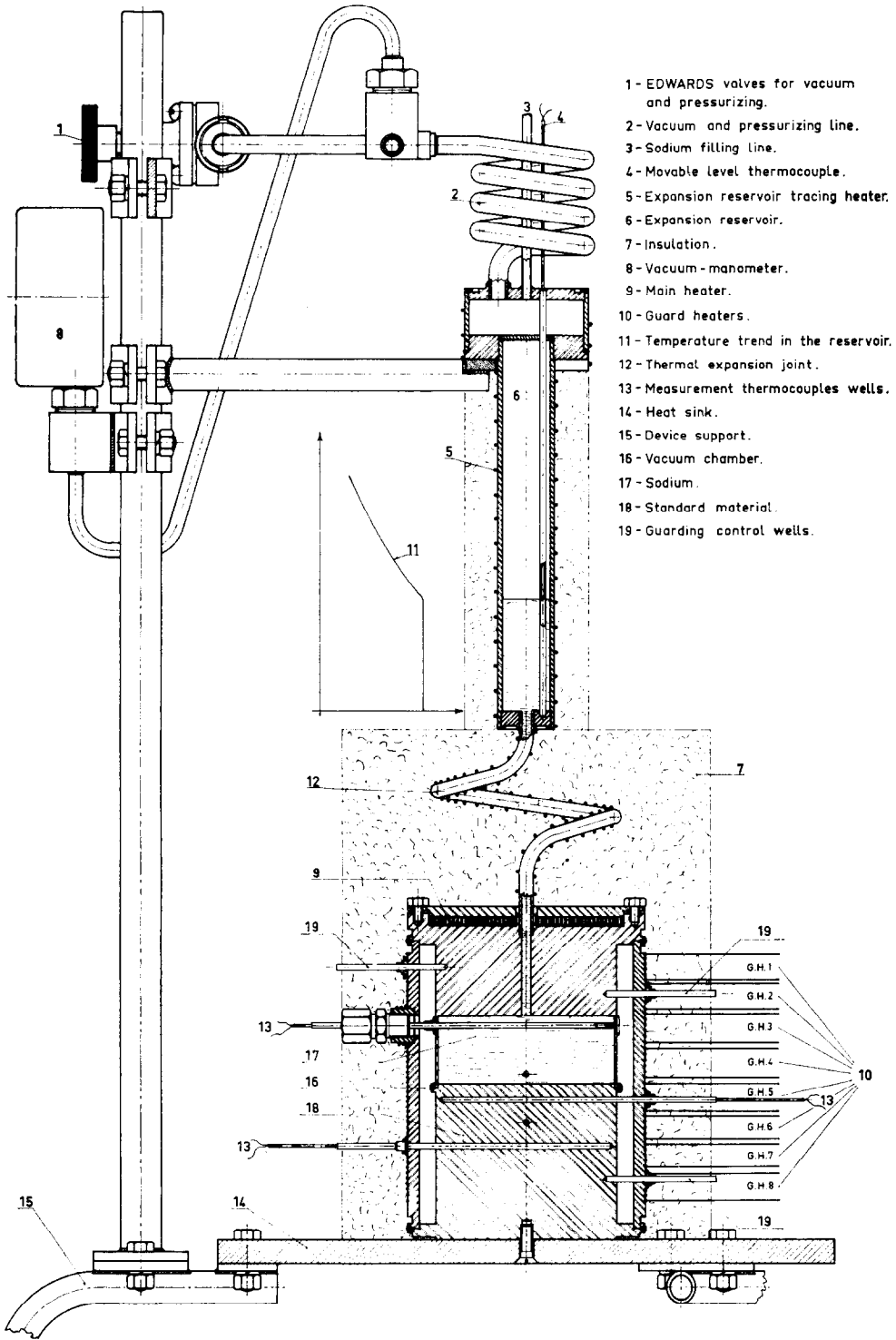G.H.3
G.H.4
G.H.5
G.H.6
G.H.7
G.H.8

FIG. 1. Thermal conductivity apparatus.

slight if the $K$ values are incorporated into the over-all heat-transfer coefficient.

## MEASUREMENT METHOD AND EXPERIMENTAL APPROACH TO THE MATHEMATICAL MODEL

The liquid metal was contained in an AISI-304 stainless steel capsule, bounded by a thin cylindrical shell. At several temperature levels the thermal conductivity is inferred from a temperature drop differential measurement in the sodium across a well-defined length along the vertical direction, i.e. the heat-flow direction $z$, and from a measurement of the heat flux $q$ per unit time and area through the stainless steel body–sodium configuration (see Figs. 1 and 2). The heat flux is derived by measuring in the capsule lower body the spatial temperature gradient in the $z$-direction and assuming that we know, with a high degree of accuracy, the thermal conductivity of the steel AISI-304,
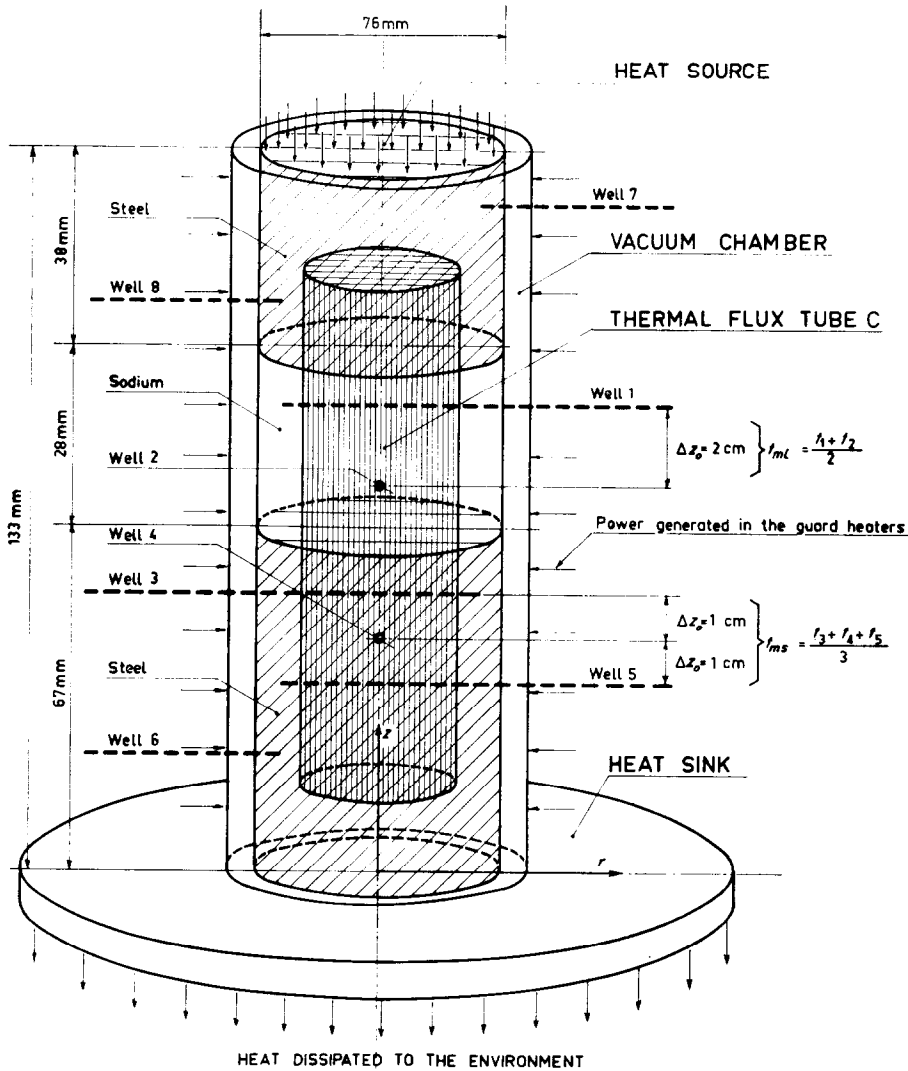
FIG. 2. Sketch of the measurement capsule.

chosen as a standard up to the highest temperatures. The measurement method employed in the device is therefore a comparative longitudinal heat-flow method. Before beginning the experiment, the AISI-304 was suitably stabilized for minimum change in grain structure. AISI-304 was chosen for the following reasons:

(a) the thermal conductivity values are well-established [1–6]

(b) this material is readily available

(c) the thermal conductivity of alloyed metals is not appreciably affected by small amounts of impurities and it is stable at high temperatures.

We call C an imaginary cylinder of cross section $S_c$ bounding a part of the sodium–steel configuration and whose axis is orthogonal to the measurement wells 1–5 (Fig. 2). Measuring the radial temperature profiles in these and obtaining a flat profile shape over a certain section $S_i(i = 1$–5), it follows that

$$t(r, z)_{z=z_i} \sim \text{constant} \qquad (1)$$

in $S_i$ within the measurement error. Comparing the average values of the gradients in $S_i$, one gets

$$g_r = (\partial t/\partial r)_{\text{av}} \ll g_z = (\partial t/\partial z)_{\text{av}} \qquad (2)$$

This relation means that the lateral cylindrical surface of C can be considered adiabatic: no flow of heat takes place across the generating lines parallel to the $z$-direction and the heat flux is continuous at the separation surface between the two media (sodium and steel) existing in the cylinder C, which is therefore a thermal flux tube. Thus one gets

$$q_l = q_s \qquad (3)$$

Using in the two media the diffusion equation solution

$$q = - K \, dt/dz \qquad (4)$$

and considering $K$ a linear function of $t$, according to our assumptions $q$ is constant with $z$ in the cylinder C and $K$ results:

$$K = K_1 + K_2 \, t \qquad (5)$$

Substitution of (5) into (4) yields

$$q = - (K_1 + K_2 \, t) \, dt/dz \qquad (6)$$

By integration within the limits $t_a$ and $t_b$, corresponding to the co-ordinates $z_a$ and $z_b$

$$q = [K_1 + K_2(t_a + t_b)/2] \, (t_a - t_b)/(z_b - z_a) \qquad (7)$$

where $K_1 + K_2(t_a + t_b)/2 = K_m$ is the average value of thermal conductivity between the temperatures $t_a$ and $t_b$. The heat flow can then be calculated essentially by means of the same equation (4) where $K$ is replaced by $K_m$. Using the equations (3) and (7), we have

$$q_{ml} = K_{ml}(t_{ml}) \, (\Delta t/\Delta z)_l = q_{ms}$$
$$= K_{ms}(t_{ms}) \, (\Delta t/\Delta z)_s \qquad (8)$$

If we call $a$ the linear thermal expansion coefficient of the container material, taking into account that

$$\Delta z_l = \Delta z_{ol}[1 + a(t_{ml}) \, (t_{ml} - t_o)]$$
$$\Delta z_s = \Delta z_{os}[1 + a(t_{ms}) \, (t_{ms} - t_o)]$$

the equation (8) becomes

$$K_{ml}(t_{ml}) = \gamma \, . \, [(\Delta t/\Delta z_o)_s/(\Delta t/\Delta z_o)_l] \, . \, K_{ms}(t_{ms}) \qquad (9)$$

where

$$\gamma = [1 + a(t_{ml}) \, (t_{ml} - t_o)]/[1 + a(t_{ms}) \, (t_{ms} - t_o)] \simeq 1 + a(t_m) \, (t_{ml} - t_{ms})$$

with $t_m = (t_{ml} + t_{ms})/2$. The thermal expansion can therefore affect the results owing to the temperature difference $(t_{ml} - t_{ms})$. From the data taken in the experiment, in Fig. 3 $(t_{ml} - t_{ms})$ vs. $t_{ml}$ is plotted, assumed to characterize the average temperature level at which the device operates: from this chart one gets

$$(t_{ml} - t_{ms})_{\text{max}} \simeq 120 \text{ degC}$$

Assuming approximately $a = 17 \, . \, 10^{-6} \text{ degC}^{-1}$, we obtain $\gamma_{\text{max}} \simeq 1{\cdot}002$: this proves that thermal expansion affects the results by a very small amount.

To infer the ratio between temperature drops in sodium and steel from the ratio between the corresponding potential drops, which are the measured quantities, another coefficient must be considered:

$$1 + \beta = p(t_{ml})/p(t_{ms})$$

*Table 1. Some experimental data*

$t_{i-j}$ = mean temperature between the wells $i$ and $j$; $\Delta v_{i-j}$ = thermoelectric voltage drop between the wells $i$ and $j$; $K_{i-j}$ = thermal conductivity calculated at $t_{i-j}$.

| $t_{m1}$ (°C) | $\Delta v_{m1}$ (μV) | $t_{3-4}$ (°C) | $\Delta v_{3-4}$ (μV) | $K_{3-4}$ (W/cm degC) | $t_{4-5}$ (°C) | $\Delta v_{4-5}$ (μV) | $K_{4-5}$ (W/cm degC) | $t_{3-5}$ (°C) | $\Delta v_{3-5}$ (μV) | $K_{3-5}$ (W/cm degC) | $q_{o3-4}$ | $q_{o4-5}$ (W μV/cm degC) | $q_{o3-5}$ | $q_{om}$ | $\beta$ | $\gamma$ | $K_i$ (W/cm degC) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 90 | 20 | 87.5 | 71 | 0.161 | 85.5 | 75 | 0.161 | 86.5 | 147 | 0.161 | 11.43 | 12.07 | 11.83 | 11.79 | +0.001 | ~1 | 1.180 |
| 95 | 21 | 92.5 | 80 | 0.162 | 90.5 | 77 | 0.162 | 91.5 | 162 | 0.162 | 12.96 | 12.47 | 13.12 | 12.85 | +0.001 | ~1 | 1.225 |
| 104 | 38 | ~99.5 | 104 | 0.163 | ~97.5 | ~100 | 0.163 | ~98.5 | 195 | 0.163 | 16.95 | 16.3 | 15.88 | 16.36 | +0.001 | ~1 | 0.862 |
| 141 | 79 | 134 | 191 | 0.168 | 129 | 199 | 0.168 | 131.5 | 400 | 0.168 | 32.1 | 33.4 | 33.7 | 33.04 | +0.0015 | ~1 | 0.838 |
| 184 | 127 | 173 | 290 | 0.173 | 165 | 305 | 0.172 | 169 | 593 | 0.173 | 50.17 | 52.46 | 51.29 | 51.30 | +0.0022 | ~1 | 0.809 |
| 244 | 187 | 229 | 410 | 0.182 | 219 | 405 | 0.182 | 224 | 801 | 0.182 | 74.6 | 73.7 | 72.9 | 73.7 | +0.005 | ~1 | 0.792 |
| 312 | 251 | 291 | 512 | 0.190 | 274 | 529 | 0.188 | 282 | 1022 | 0.189 | 97.28 | 99.45 | 96.58 | 97.8 | +0.007 | ~1 | 0.785 |
| 315 | 255 | 294 | 532 | 0.191 | 277 | 522 | 0.188 | 285 | 1020 | 0.189 | 101.61 | 98.14 | 96.39 | 98.71 | +0.007 | ~1 | 0.780 |
| 385 | 444 | 355 | 799 | 0.199 | 334 | 849 | 0.196 | 345 | 1666 | 0.198 | 159 | 166 | 165 | 163.4 | +0.007 | ~1 | 0.741 |
| 387 | 436 | 357 | 832 | 0.199 | 336 | 809 | 0.196 | 347 | 1648 | 0.198 | 165.5 | 158.5 | 163.1 | 162.4 | +0.007 | ~1 | 0.750 |
| 427 | 533 | 390 | 898 | 0.205 | 369 | 920 | 0.202 | 379 | 1838 | 0.203 | 184.09 | 185.84 | 186.56 | 185.5 | +0.0055 | ~1 | 0.700 |
| 476 | 657 | 436 | 1062 | 0.211 | 410 | 1027 | 0.208 | 423 | 2102 | 0.210 | 244 | 214 | 221 | 220 | +0.0025 | ~1 | 0.671 |
| 511 | 757 | 467 | 1154 | 0.215 | 440 | 1192 | 0.212 | 454 | 2370 | 0.213 | 248 | 253 | 252.4 | 251 | ~0 | 1.0010 | 0.664 |
| 564 | 1023 | 511 | 1453 | 0.223 | 476 | 1485 | 0.217 | 494 | 2982 | 0.220 | 324 | 322 | 328 | 325 | −0.003 | 1.0012 | 0.634 |
| 610 | 1116 | 553 | 1546 | 0.229 | 515 | 1491 | 0.223 | 534 | 3090 | 0.227 | 354 | 332 | 351 | 345.6 | −0.007 | 1.0013 | 0.616 |
| 653 | 1239 | 587 | 1571 | 0.236 | 549 | 1521 | 0.229 | 568 | 3207 | 0.232 | 371 | 348 | 372 | 364 | −0.008 | 1.0014 | 0.584 |
| 685 | 1279 | 615 | 1580 | 0.240 | 577 | 1558 | 0.233 | 596 | 3247 | 0.237 | 379.2 | 363 | 384.76 | 375.6 | −0.011 | 1.0015 | 0.582 |
| 717 | 1564 | 640 | 1754 | 0.245 | 597 | 1802 | 0.236 | 620 | 3620 | 0.241 | 430 | 424.8 | 436 | 430 | −0.013 | 1.0016 | 0.544 |
| 730 | 1542 | 654 | 1827 | 0.248 | 610 | 1809 | 0.240 | 632 | 3715 | 0.244 | 453.1 | 434.1 | 453 | 446.7 | −0.014 | 1.0017 | 0.572 |
| 772 | 1665 | 695 | 1850 | 0.256 | 650 | 1814 | 0.247 | 672 | 3740 | 0.251 | 473.6 | 448 | 469.4 | 463.6 | −0.018 | 1.0018 | 0.548 |
| 790 | 1861 | 703 | 1946 | 0.260 | 657 | 1938 | 0.248 | 680 | 3871 | 0.251 | 506 | 480 | 486 | 491 | −0.021 | 1.0019 | 0.518 |
| 832 | 2030 | 735 | 2040 | 0.264 | 687 | 2130 | 0.253 | 711 | 4213 | 0.259 | 538.6 | 538.9 | 545.5 | 541 | −0.026 | 1.0020 | 0.520 |
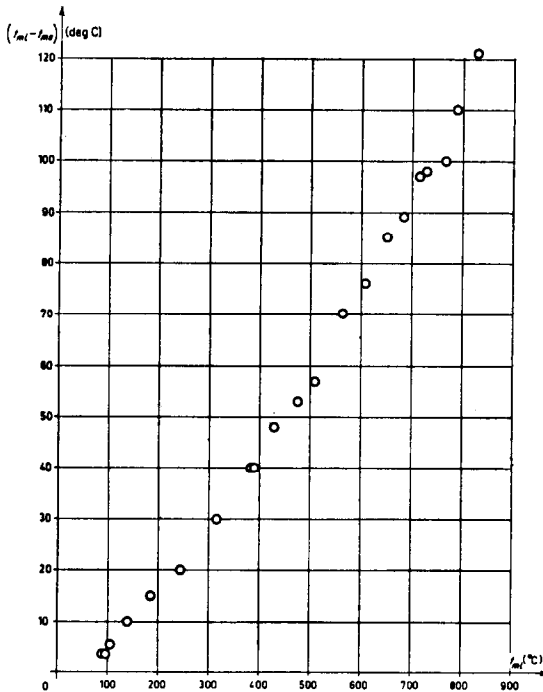
FIG. 3. Difference between sodium and steel temperatures vs. sodium temperature.

Such a parameter takes into account the thermoelectric power variation with temperature: in Fig. 4 its value is plotted vs. $t_{ml}$ for the Chromel–Alumel thermocouples employed in our experiment. In this way (9) becomes

$$K_{ml}(t_{ml}) = (1 + \beta) \cdot \gamma \cdot [(\Delta v/\Delta z_o)_s/(\Delta v/\Delta z_o)_l]$$
$$\cdot K_{ms}(t_{ms}) \qquad (10)$$

Since we measured in the steel three values of $(\Delta v/\Delta z_o)_s$ and therefore three values of thermal flux, the several $K(t)$ values for sodium have been calculated from the data taken according to the following formula:

$$K_{ml}(t_{ml}) = \frac{(1 + \beta) \cdot \gamma}{(\Delta v/\Delta z_o)_l} \cdot 1/3 \, (q_{o3-4} + q_{o4-5} + q_{o3-5}) \qquad (11)$$

where:

$$q_{oij} = K_{ij}(\Delta v_{ij}/\Delta z_{oij})$$

$K_{ij}$ = thermal conductivity at the mean temperature between the wells $i$ and $j$

$\Delta z_{oij}$ = distance, at room temperature, between these wells
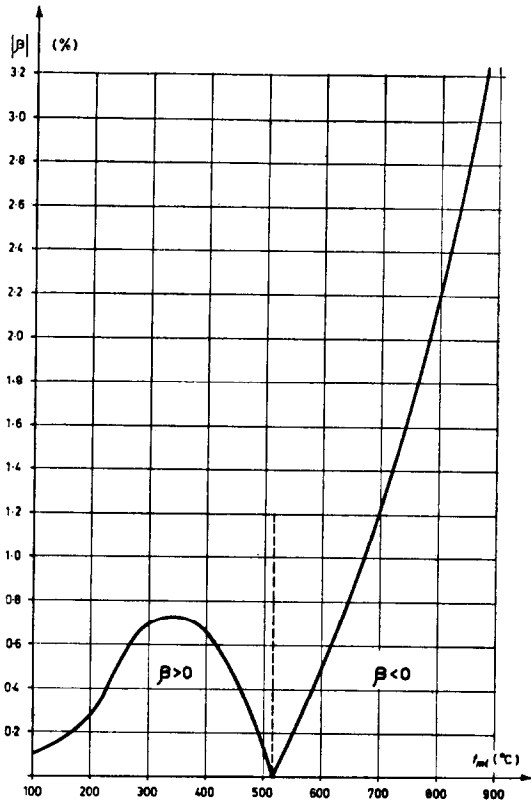


FIG. 4. Thermoelectric power coefficient vs. sodium temperature.

$\Delta v_{ij}$ = thermoelectric voltage drop between the wells $i$ and $j$.

The practical difficulty presented by the device is to obtain in the sodium–steel configuration a cylinder C, that is a tube of thermal flux, at sodium mean temperatures ranging from 90°C to 850°C. To this purpose a small vacuum chamber was welded around the capsule and some guard heaters were located on the outer wall of this chamber to prevent heat from radiating out of the measurement capsule surface. When the predetermined temperature level was approximately reached, steady state conditions were established with a certain value of the power generated in the several heaters: in each well a measurement of the temperature radial profile $t(r, z)_{z=z_i}$ was taken. During the process of approach to the condition (2), adjustments of

the electrical power in the guard heaters were made continuously in an effort to match all the guard temperatures with the corresponding radial temperature distribution in the capsule. The currents were adjusted until it was possible to get a flat shape of the profile over an area $S_i$, for each well. Supposing that the radial position of the five regions $S_i$ allows a common area $S_c$ to be defined, this becomes the transverse section area of the thermal flux tube C. In Fig. 5 some radial temperature profiles are shown corresponding to a $K(t)$ experimental point at $t_{ml} = 427°C$: we suppose to have reached the condition (2) in the regions $S_i$. High vacuums were attained by the use of two pumps: a mechanical fore pump and a water-cooled oil diffusion pump, with a liquid nitrogen cold trap. However, in order to simplify the operation, the

results obtained in some preliminary tests were of the greatest importance. These proved it was possible to have flat isothermal surfaces in a small region of the device even without vacuum, by employing a sufficiently high heating power in the guard windings. Owing to the much greater simplicity of operation, the apparatus was operated in most measurement runs without vacuum: therefore the radial heat losses were minimized only by the electrical guarding. In this case the possible heat exchange by convection in the vacuum chamber is not a source of error, if one is able to obtain a thermal flux tube by adjusting $P_g$. Furthermore it will be noted that such convection effects were also made small by means of the thermocouples located in the wells 7, 8 and 6. These allowed the temperature drop across the vacuum chamber to be measured, so that the guard heaters 1, 2, 8 could be controlled. By limiting one's considerations to the radial region where the condition (1) is satisfied, in a comparative measurement all effects of natural convection in the vacuum chamber and heat exchange by radiation between the inner and outer wall do not affect the accuracy of the data. The adjusting of the guarding power necessary to obtain the condition (2) anyway limits these effects, even if it does not nullify them. A possible source of error, on the contrary, could be the natural convection in the molten sodium. To eliminate it, the apparatus was designed with the heat source at the top and the heat sink at the bottom, as shown in Fig. 2. Nevertheless it was experimentally observed that the axial heat transfer by conduction at temperatures in sodium higher than about 550–600°C was disturbed, presumably by natural convection, near the edge of the container cross section. Such a perturbation was revealed in the $\Delta v_l$ measurement by a little noise: in the analysis of the method accuracy such a noise has been considered a source of error.
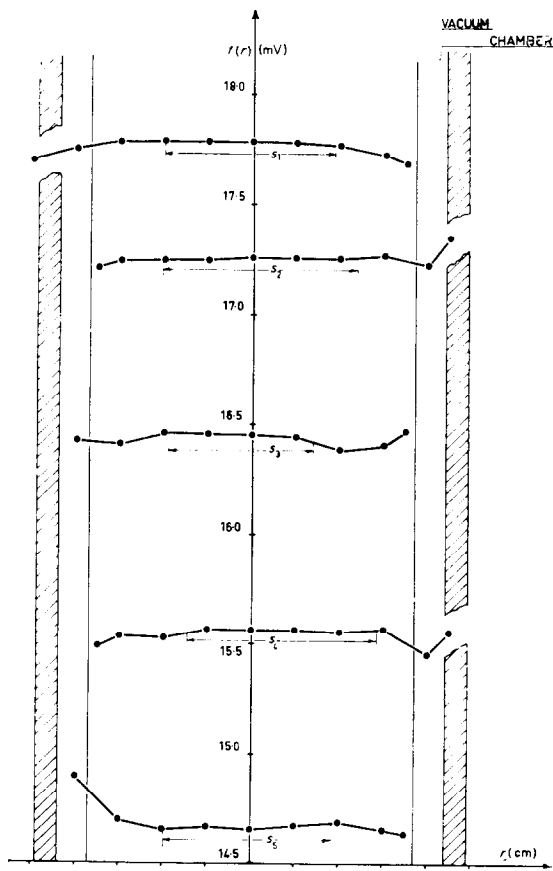
## EXPERIMENTAL APPARATUS AND TEST PROCEDURE

The apparatus developed was designed as a measuring device for steady state, one-dimensional flow, of the guarded cylinder type. The outer side of the guard cylinder was covered by Kawool insulation, as shown in Fig. 1, to



FIG. 5. Temperature radial profiles ($t_{ml} = 427°C$).

H.M.—4K

reduce the currents in the windings. A specified heater temperature was maintained with lower currents than without insulation: in this way heater failures were limited. Each guard heater consisted of some turns of a helix wrapped around the outer wall of the vacuum chamber: a Thermocoax resistance heating wire was employed. The capsule main heater was made up of very compact Thermocoax coils, located in three layers and pressed by a plate to the upper stainless steel body. The heat sink was a copper plate bolted to the lower capsule body and transferring by convection the heat to the environment. Each guard heater was supplied with a.c. voltage, stabilized $\pm 0 \cdot 1$ per cent and controlled by an autotransformer with coarse and fine regulation, to obtain a high sensitivity in the guarding power variation. To the same a.c. stabilized power supply were connected the power leads of the main heater, located at the top of the capsule (Figs. 1 and 2). All heaters currents were measured with ammeters whose accuracy was $\pm 0 \cdot 5$ per cent full scale range. Temperatures were measured by stainless steel covered Chromel–Alumel thermocouples, with thermojunctions electrically insulated from the sheath by magnesium dioxide and attached through a 12-point selector switch to a potentiometer whose accuracy was $\pm (1 \ \mu V + 0 \cdot 001$ per cent). The temperatures were measured by using a galvanometer null detector, connected with the circuit of the potentiometer. With the galvanometer unit placed approximately two meters from the projector, the current sensitivity was 220 mm/$\mu$A: the galvanometer and thermocouples resistance was about 210 ohms, therefore the voltage sensitivity in thermoelectric forces measurement was $\sim 1$ mm/$\mu$V. As shown in Fig. 6, stainless steel tubes were used to position the thermocouples in the liquid metal and in the standard material. The tubes employed as thermocouple wells in sodium were argon-arc-welded to the container wall, and the sealing on the outer wall of the vacuum chamber was provided by Conax glands. The thermocouples were inserted in the wells by means of steel tubes 0·9 $\times$ 0·6 mm, whether in sodium or in steel. The adoption of this method presents the following advantages from the temperature measurement viewpoint, in comparison with
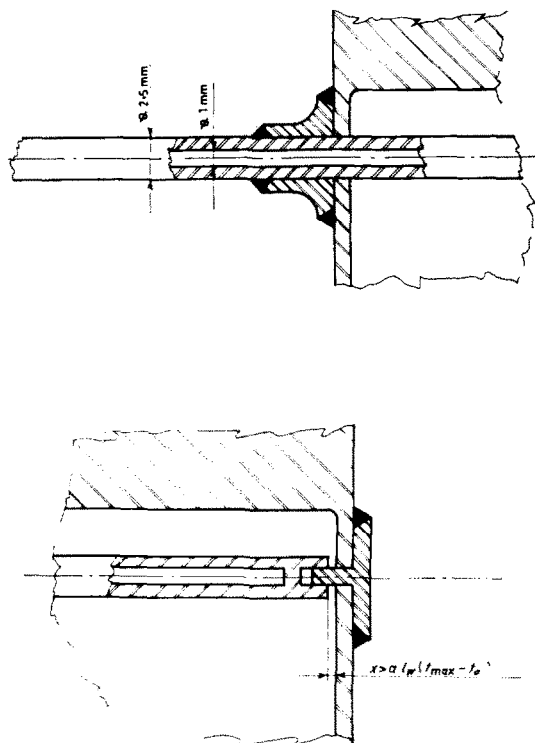


FIG. 6. Thermocouples wells arrangement.

welded thermocouples: (a) it is possible to measure the radial temperature profiles. In this way one checks the agreement between the mathematical model from which equation (11) is derived and the physical phenomenon; (b) it is possible to measure the spatial temperature gradient in sodium and in steel with the same thermocouple doublet. The influence of systematic thermocouple errors and ageing effects is therefore avoided; (c) it is possible to effect a continuous control through calibration of the employed thermocouples and the whole measurement circuit. The thermocouples can be shifted and readily interchanged or renewed at any moment during the experiment in the case of a failure. The possibility of substituting and interchanging the thermocouples during the measurement allows, also without calibration, a continuous indirect control of their response. It was proved that by mounting several doublets of thermocouples the temperature drop values were always duplicated better than $\pm 1 \cdot 2$ per cent.

This fact indicated that no erratic temperature readings were taken and the thermocouples' wires used were uniform. This solution nevertheless presents the disadvantage of interference with the measurement, but such a perturbation caused by the thermocouple wells can be taken into account in the error evaluation. However to avoid affecting the device symmetry, the wells were spaced 90 degrees apart along the z-direction. In order to detect any possible sodium spilling through the container wall, a sodium level measurement device was provided in the expansion reservoir on the filling line. The level was measured with an accuracy of $\pm 2$ mm by means of a movable thermocouple, using the temperature gradient discontinuity at the boundary between sodium and covering gas (helium). Such a discontinuity was due to the considerable difference between the thermal conductivities of sodium and helium. Before filling, and after assembly, all metal surfaces were cleaned according to the following standard procedure: a degreasing, an alkaline cleaning and a nitric acid-hydrofluoric acid dip, then distilled water. The device was filled by liquid metal distillation from a Pyrex-glass still on to a sintered glass filter, and through a glass–steel joint directly into the expansion reservoir and specimen chamber under a vacuum of about $5 . 10^{-5}$ mmHg. The connecting tube of the filling line was welded closed at the top under reduced pressure of purified helium: X-ray photographs of the specimen chamber with the sodium in the solid and liquid state indicated complete absence of voids.

During the experiment the test procedure was as follows: we measured the radial temperature profiles until it was possible to attain a flat shape of these, adjusting the guarding power. Afterwards, the thermojunctions of a doublet of two differential connected thermocouples were positioned in the centres of these regions for the spatial temperature gradient measurement along the z-direction. This enables one to neglect the correction due to the heat removal from the thermocouples' wires, whose hot junctions are located in approximately isothermal planes. Having taken some readings of the temperature drop between two wells distant $\Delta z$ along the heat flow direction (position a), we reversed the

axial location of the doublet (position b). The effects of systematic errors are eliminated when one takes as true temperature drops the means of the values obtained in positions a and b. This procedure was repeated $n$ times corresponding to one experimental point of the $K(t)$ function, in order to minimize the temperature error due to the location uncertainty of the thermojunctions. The average temperature in $\Delta z$ was also measured several times to control the thermal stability while the data were taken. Considering, at the beginning, the two thermocouples in position a, we call $L$ the one located in the well at the lower temperature and $H$ the one positioned at the higher temperature. The measurement was made by inserting $L$ in a tube, filled with silicon oil and contained in a thermos bottle with ice and water: in this way, the thermocouples being differentially connected, we took some readings of $t_a(z + \Delta z)$. Then we displaced $H$ in the other well and read $t_a(z)$. In the same manner we proceeded for thermocouples in position b and assumed as mean temperature in $\Delta z$

$$t_{m\Delta z} = \frac{t_a(z) + t_a(z + \Delta z) + t_b(z) + t_b(z + \Delta z)}{4}$$

As mean temperature $t_i$ in the well $i$ we assumed

$$t_i = \frac{t_{ia} + t_{ib}}{2}$$

As sodium average temperature and as steel average temperature we assumed respectively

$$t_{ml} = \frac{t_1 + t_2}{2} \quad \text{and} \quad t_{ms} = \frac{t_3 + t_4 + t_5}{3}$$

Up to the highest temperature, when data were taken, the thermal stability of the device was better than $\pm 1$degC. To avoid variations, during the measurement runs, of the mutual axial location of the thermocouple wells in sodium owing to a possible bending of these, the solution shown in Fig. 6 was provided. For obvious reasons it was chosen that

$$x > a . l_w . (t_{max} - t_o) \tag{12}$$

where:

$l_w$ is the radial length of the thermocouple wells;

$t_{max}$ is the highest temperature reached in the sodium during the experiment;

$x$ is the distance of the well end from the container wall.

The wells in the steel body during the assembly were similarly arranged.

### DISCUSSION OF THE RESULTS AND COMPARISON WITH EXISTING DATA

Taking into consideration the geometry and the features of the employed thermocouples, the dimensions of the wells, the distances along the $z$-direction between the wells axis, the accuracy of the standard material conductivity (evaluated as $\pm 3$ per cent), the radial heat exchange effects caused by imperfect guarding, the sensitivity of the instruments, etc., the total error $\Delta K/K$ results from an addition of several terms. Some of them vary with temperature: $\Delta K/K$ is therefore a function of the temperature. This function, plotted in Fig. 7, has a flat shape in the 200–
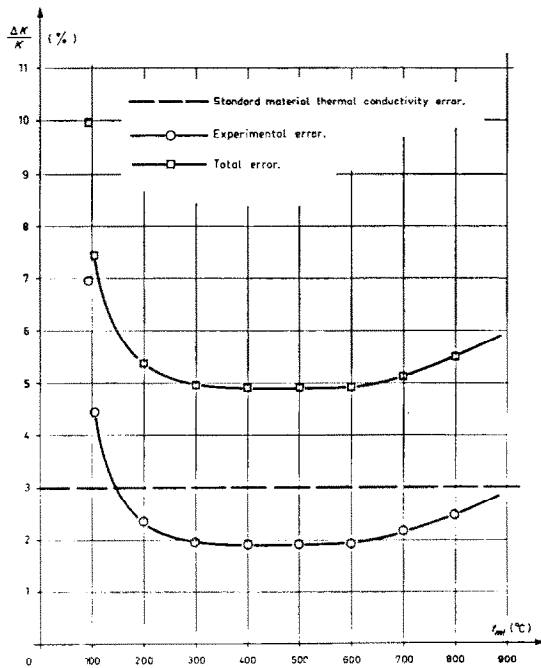


FIG. 7. Measurement error vs. sodium temperature.

750°C range and an average value $\Delta K/K \simeq 5$ per cent. The trend of the standard material thermal conductivity vs. temperature is plotted in Fig. 8. The experimental points of the sodium measured

$K(t)$ function are plotted in Fig. 9: they have been calculated by the relationship (11). Intercomparison of the three heat-flow quantities $q_{otj}$ showed extreme differences of 1–5 per cent. Equal weight was given to the three measurements and the arithmetic mean value was used to give the heat flow in sodium. Each reported $K(t)$ value represents a series of equilibrium measurements with the same settings over a period always of hours and, in some cases, days. Values at a given temperature were duplicated to better than $\pm 1.5$–2 per cent. In the several runs, measurements were taken going up and coming down in temperature in order to insure reproducibility. A least-squares fit of the experimental results was obtained over the measured range 100–850°C: it is given by the linear equation

$$K = 0.916 - 0.49 \cdot 10^{-3} \cdot t \quad \text{(W/cm degC)} \quad (13)$$

The maximum deviation of this equation from an experimental point is $+3.9$ per cent, the mean scatter of results is lower than $\pm 1.7$ per cent: this agrees very well with the experimental error evaluation. It will be noted that for sodium there is a lack of experimental data at temperatures higher than 550°C: some books report values of $K(t)$ in this range, but it is a matter of doubtful extrapolation. For this reason we have been concerned in extending this physical property of sodium up to ~850°C. The upper sodium temperature limit reached in our experiment represents the maximum attainable with commercial heater windings with the geometry chosen for the device. On the other hand, this choice is a compromise between the difficulty of obtaining an efficient guarding (the easier, the smaller is the ratio length/diameter of the capsule) and the necessity to make the error due to the location uncertainty as small as possible (this error increases with decreasing ratio length/diameter). The device dimensions shown in Fig. 2 are the result of such considerations. Within the evaluated total error, it is possible to compare our experimental results with the sodium thermal conductivity values obtained by other experimenters only in the 0–550°C temperature range. In this range experiments have been carried out by Hornbeck, Bidwell, Hall, Miller, Nikol'skii, Ewing and by
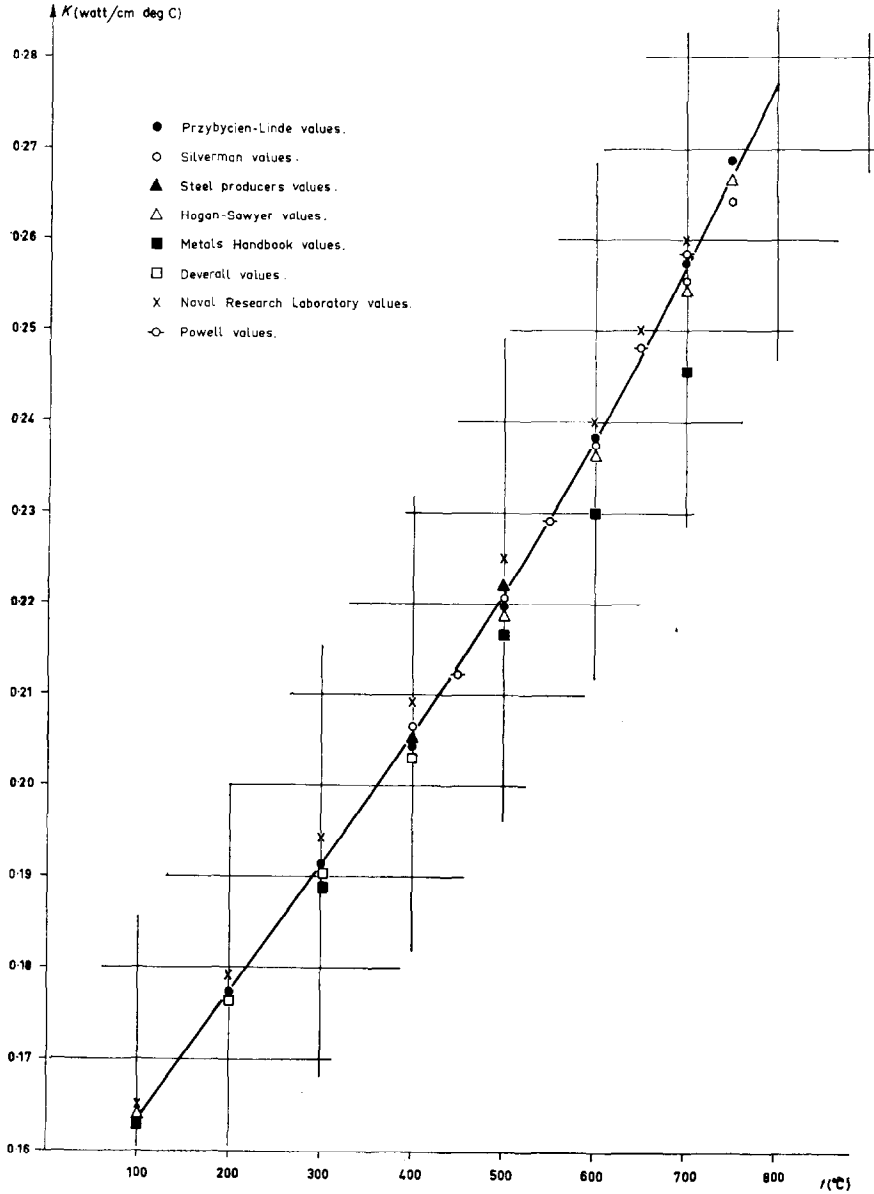
FIG. 8. Stainless steel AISI-304 thermal conductivity vs. temperature.

some researchers of the Wright Air Development Center [7–13]. Although the trend of the function $\Delta K/K = f(t_{ml})$ rapidly increases for

$$t_{ml} < 150°C,$$

we have considered it interesting to test our device also at temperatures lower than 97·81°C, i.e. the sodium solidification temperature. In Fig. 9 the two points obtained with solid sodium are reported for comparison with the experimental results of Bidwell and Hornbeck: these experimenters measured $K$ in the ranges $-200-+80°C$ and $6–88°C$ respectively. Our results agree within the error with those of the previous
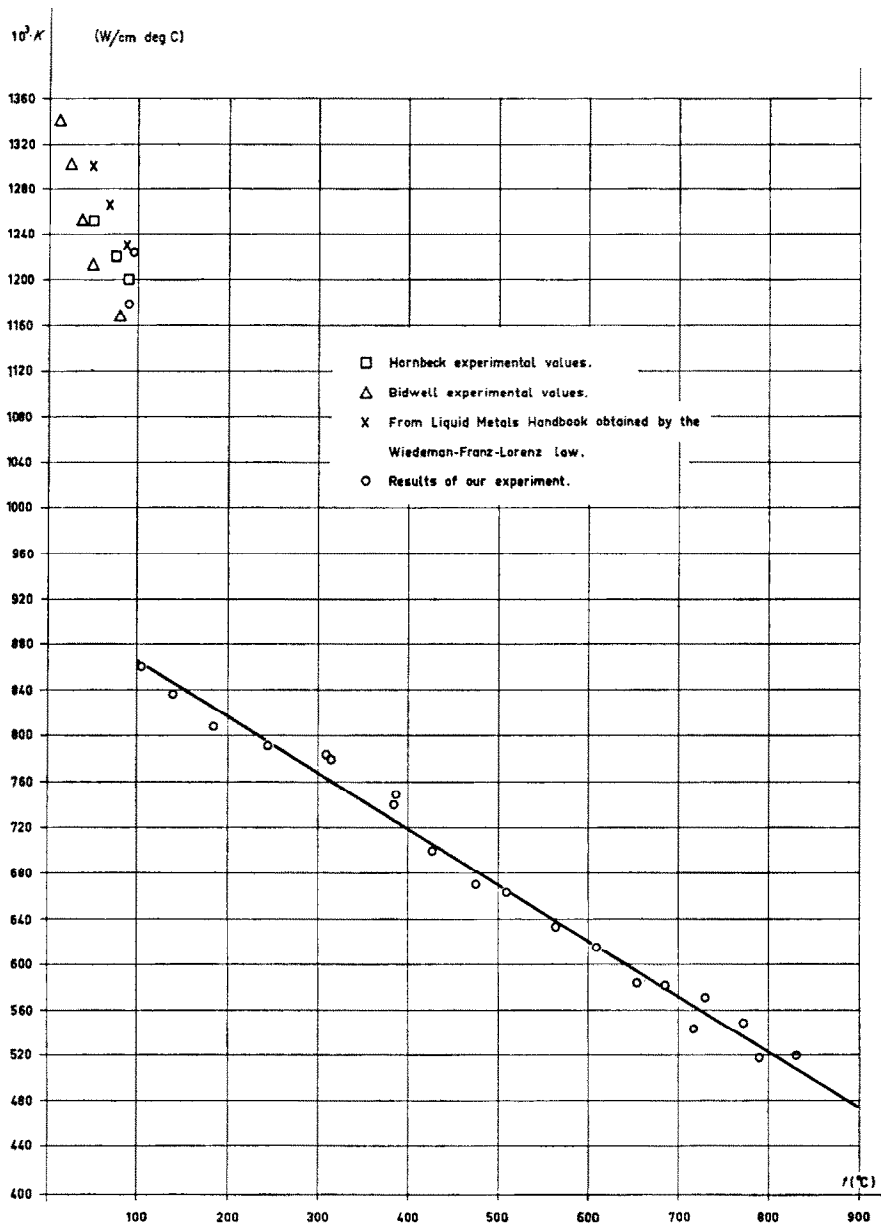
FIG. 9. Sodium thermal conductivity vs. temperature.

observers and prove clearly the discontinuity of the sodium behaviour in the passage through solidification. This discontinuity of the function is surely associated with the break-down of the crystal lattice: in the Sittig work [14] the ratio which characterizes such discontinuity is also indicated:

$$K_{solid}/K_{liquid} = 1{\cdot}31{-}1{\cdot}39$$

From our experiment it can be found that

$$K_{solid}/K_{liquid} = 1{\cdot}39$$

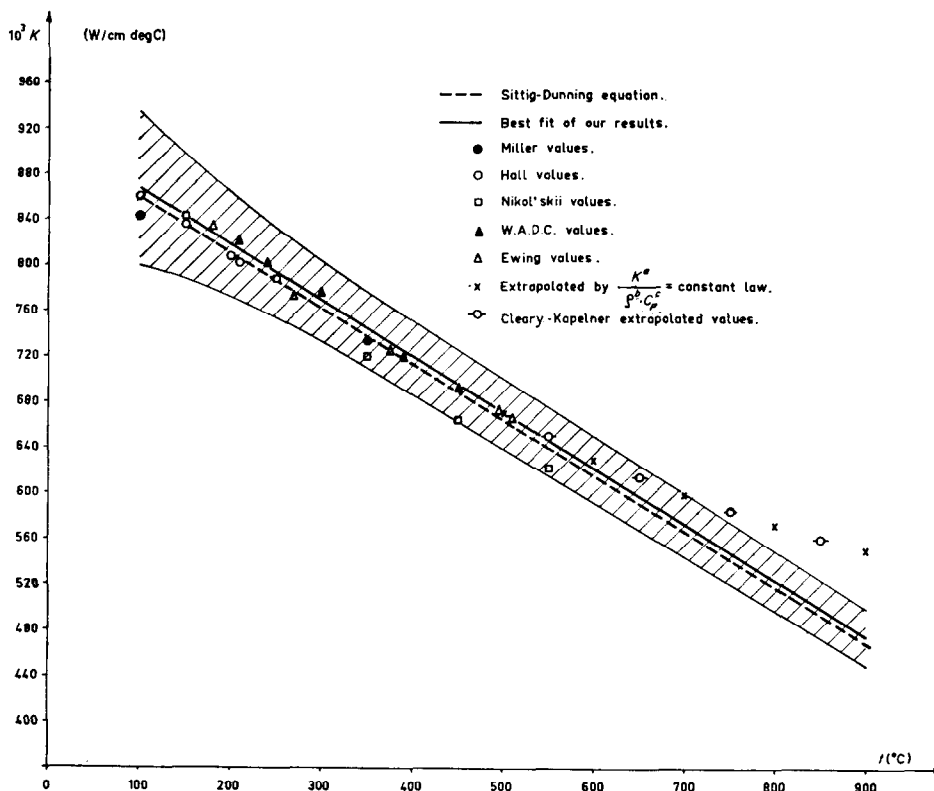The published experimental values of sodium conductivity in the 100–500°C range and the

Fig. 10. Comparison of our experimental results with existing data.

best fit of our results are shown in Fig. 10: the discrepancies are small and always within the total error which affects the results. The ranges covered are: in the Hall experiment 100–210°C, in the first Miller experiment 100–350°C, in the W.A.D.C. experiment 210–450°C, in the Ewing experiment 170–512°C, in the Nikol'skii experiment 250–550°C. E. Dunning [15] of the Argonne National Laboratory reviewed in 1960 the whole meagre literature on the subject of sodium conductivity. Using experimental data which seemed to be the most reliable, he proposed to evaluate the $K(t)$ function for the sodium in the 100–550°C range according to Sittig's theory, by the equation

$$K(t) = 0,908 - 0,485 \cdot 10^{-3} \cdot t \quad \text{(W/cm degC)} \tag{14}$$

which fits the values found by Hall, Ewing, etc.

Owing to the need for liquid metal conductivity values at higher temperatures, it was desirable to find some method for extrapolating the measured values. The possible semi-empiric ways have been essentially the following three: (a) mere extrapolation to higher temperature levels of the equation (14) which fits experimental points obtained in the lower temperature range; (b) correlations in the literature [16] have shown specific heat, density and thermal conductivity to be interrelated. To this purpose a relationship can be developed which closely approximates the literature sodium conductivity data measured in the range 100–550°C:

$$K^a(t) \cdot c_p^b(t) \cdot \rho^c(t) = \text{constant} \tag{15}$$

By the least-squares method it is found that $a = 1, b = -1, c = -5/3$. Having obtained the $c_p(t)$ and $\rho(t)$ variation with temperature from
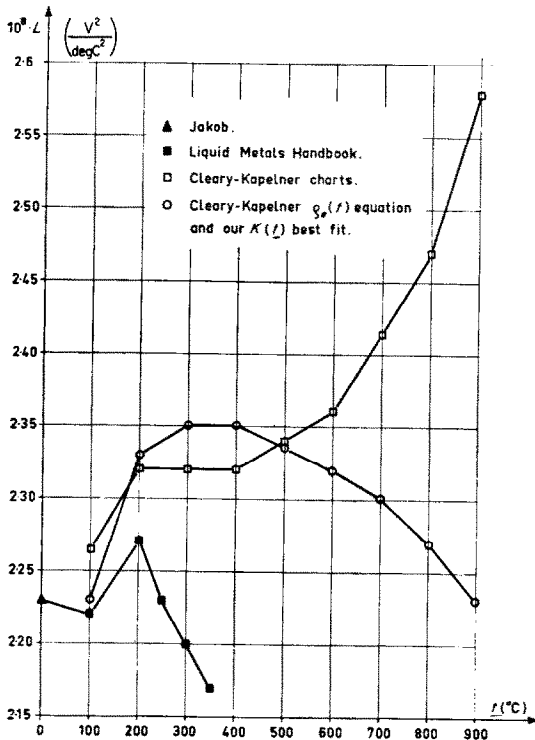
FIG. 11. Lorenz number vs. temperature.

the charts reported in the Dunning work, we have calculated some points of the $K(t)$ curve in the unexplored temperature range (Fig. 10): the value of the constant which appears in equation (15) was derived from equation (13); (c) for a metal a simple relation exists between the thermal and the more easily measurable electrical conductivity, that is the Wiedemann–Franz–Lorenz law

$$L = (K \, \rho_e)/T = \text{constant} \qquad (16)$$

where $L$ is called Lorenz number. The value of $L$ is predicted in the electronic theory to be

$$L = 2 \cdot 23 \div 2 \cdot 44 \cdot 10^{-8} \quad (V^2/\text{degC}^2)$$

In this way Cleary and Kapelner [17] obtained the more recent results of sodium thermal conductivity: in the range 100–850°C they measured the electrical resistivity $\rho_e$, in order to compute from these data the sodium thermal conductivity. This procedure in extending thermal conductivity data to the high temperature

region is partly justifiable by the good agreement between calculated and theoretical values of $L$ for sodium, in the 0–350°C range. According to the data reported in the Liquid Metals Handbook [10] we have calculated the $L$ values plotted in Fig. 11. From Fig. 10 appears a somewhat surprising agreement between the Cleary–Kapelner extrapolated results and those obtained by correlating specific heat, conductivity and density. Generally, however, we raise many doubts about the validity and the accuracy that one can get out of this information obtained by extrapolation. In fact, how doubtful the $K$ values plotted in the Cleary–Kapelner chart are, is proved by Fig. 11. Here we have plotted the $L$ values calculated from the electrical resistivity equation indicated by these researchers

$$\rho_e = 5 \cdot 9 + 3 \cdot 7 \cdot 10^{-2} \cdot t - 9 \cdot 36 \cdot 10^{-7} \cdot t^2$$
$$+ 2 \cdot 29 \cdot 10^{-8} \cdot t^3 \quad (\mu\Omega \text{ cm}) \qquad (17)$$

(where $t$ is expressed in Celsius degrees) and from their $K(t)$ chart, from our results and from equation (17). The value of $L$ chosen to calculate $K$ is correct up to 600°C but at higher temperatures it inexplicably rises, while the opposite occurs to the values derived from our experiment. In this range the Cleary–Kapelner $K(t)$ values, which in Fig. 10 are out of the uncertainty band of our best fit, are therefore essentially highly doubtful.

### REFERENCES

1. L. SILVERMAN, Thermal conductivity data presented for various metals and alloys up to 900°C, *J. Metals, NY* 5, 631 (1953).
2. C. L. HOGAN and R. B. SAWYER, The thermal conductivity of metals at high temperature, *J. Appl. Phys.* 23, 177 (1952).
3. R. W. POWELL, Thermal conductivities of solid materials at high temperatures, *Research, Lond.* 7, 492–501 (1954).
4. J. E. DEVERALL, The thermal conductivity of a molten Pu-Fe eutectic, *LA*-2269, *TID*-4500, Los Alamos (1958).
5. *Metals Handbook.* Amer. Soc. for Metals, Cleveland, Supp. Vol. (1954).
6. W. K. PRZYBYCIEN and D. W. LINDE, Thermal conductivities of gases, metals and liquid metals, *KAPL-M-WMP-I*, (1957).
7. L. HORNBECK, Thermal and electrical conductivities of the alkali metals, *Phys. Rev.* 2, 217 (1913).

8. C. C. BIDWELL, Thermal conductivity of Li and Na by a modification of the Forbes bar method, *Phys. Rev.* **28**, 9 (1926).

9. W. C. HALL, The thermal conductivities of mercury, sodium and sodium amalgams in the liquid state, *Phys. Rev.* **53**, 1004 (1938).

10. R. R. MILLER, Physical properties of liquid metals, p. 43, in *Liquid Metals Handbook*, chapter 2, A.E.C. Dept. of the Navy (1952).

11. Y. I. NIKOL'SKII, Heat transfer and thermal simulation, Acad. Sci. USSR Press, Moscow. (In Russian) (1958).

12. C. T. EWING, J. A. GRAND and R. R. MILLER, Thermal conductivity of liquid sodium and potassium, *J. Amer. Chem. Soc.* **74**, 11–14 (1952).

13. WRIGHT AIR DEVELOPMENT CENTER, Properties of inorganic coolants for space applications, *WADC TR* 59/598 (1959).

14. M. SITTIG, *Sodium, its Manufacture, Properties and Uses*. Reinhold Publ. Co., New York (1956).

15. E. L. DUNNING, The thermodynamic and transport properties of sodium and sodium vapor, ANL-6246-AEC Research and Development Report, Argonne (1960).

16. C. C. BIDWELL, *Phys. Rev.* **58**, 561 (1940).

17. R. E. CLEARY and S. M. KAPELNER, Alkali metals physical properties program at Pratt–Whitney Aircraft–Canel, Proceedings of 1962 High Temperature Liquid Metals Heat Transfer Technology Meeting, *BNL* 756, *C*-35, *TID*-4500 (1963).

**Résumé**—Cette étude décrit une expérience qui a été conduite afin de déterminer l'effet la de température sur la conductivité thermique du sodium, dans la gamme de température allant de 90 à 850°C. La méthode expérimentale est basée sur un modèle mathématique qui est examiné rapidement dans la première partie. L'appareillage et la méthode d'essai sont décrits dans la seconde partie, en se référant aux caractéristiques principales de l'appareil de mesure. Dans la dernière partie, les résultats expérimentaux sont comparés avec les résultats publiés auparavant.

**Zusammenfassung**—Diese Arbeit beschreibt einen Versuch, der durchgeführt wurde, um den Einfluss der Temperatur auf die Wärmeleitfähigkeit von Natrium im Temperaturbereich von 90 bis 850°C zu bestimmen. Die Versuchsmethode basiert auf einem mathematischen Modell, welches im ersten Abschnitt kurz untersucht wird. Im zweiten Abschnitt werden die Apparatur und der Versuchsverlauf unter Hinweis auf die wichtigen Eigenarten der Messvorrichtung beschreiben. Im abschliessenden Teil werden die Versuchsergebnisse mit früher veröffentlichten Daten verglichen.

**Аннотация**—В работе описываются эксперименты, проведенные с целью выяснения влияния температуры на теплопроводность натрия в температурном интервале 90–850°С. Экспериментальный метод основан на математической модели, рассмотренной вкратце в первом разделе. Во втором разделе дано описание экспериментальной установки и методики эксперимента, а также приведено общее описание измерительного устройства. В последнем разделе приводится сравнение экспериментальных результатов с ранее опубликованными данными.