MEASUREMENTS OF THE TEMPERATURES ON A HEATED NIOBium-WALL IN SUBCOOLED HELIUM

(*)

W. Wittenborn

1. INTRODUCTION

If one heats a wall in subcooled He (≈ 100 mW/cm²), the resulting temperature-increase is quite big, about a factor 20 bigger than in saturated He. This effect is used for examining RF-losses in superconducting cavities: One measures the temperature-increase $\Delta T$ on the cavity-wall resulting from an electromagnetic field and estimates from this the dissipated power inside the cavity [1,2].

The measurements described below were intended to determine empirically the dependence of the temperature difference $\Delta T$ on the heating power: I heated part of a niobium wall (fig. 1) in subcooled He and measured the resulting temperature differences as a function of various factors that is the heating power, the bath temperature and the position of the thermometer relative to the heat source, the angle between the wall and the force of gravity. I also tested the dependence on the layout of the carbon thermometers.

This work is the continuation and improvement of the measurements from H. Piel and R. Romijn [2] who measured the temperature difference only as a function of the heating power. They had a simpler test set-up (fig. 2 and [2]) with a poor insulation of the heating resistor.

(*) Summer student from University Bielefeld, West Germany.
There are still some problems and parameters which should be measured; I could not do that, because my time as a summer-student at CERN was over.

2. TEST SET-UP AND METHODS

The measurements were done with the help of a stainless steel box (fig. 1). The circular lid of the measuring box is made of niobium. Its material is similar to the one used in the 500 MHz superconducting Nb cavity measured recently at CERN [1] (Nb of 99.98% purity and \( \approx 40 \) \( \mu \)m grain size). Its thickness is 1.5 mm and nearly equal to the thickness of the Nb cavity wall (2 mm). This thin part of the wall had a diameter of 30 mm (fig. 1). After the first measurement this diameter was increased to 50 mm. The box was evacuated to \( 10^{-2} \) torr for thermal insulation of the heating resistor which is a Manganin wire (0.2 mm diam., and 1 m long) wound on a cylinder (diam. 10 mm) on the wall (fig. 1); above this an aluminium foil is wound as a radiation shield.

This construction has the advantage, that one can measure the temperature distribution on the surface around the heat source. But it has the disadvantage, that one cannot relate the \( \Delta T \) exactly to the power per area, because one does not know exactly, which part of the heating power is dissipated directly from the area of the heat source, i.e. the circular area of 1 cm diameter and which part escapes sidewise.

The box hangs in the cryostat (inner diameter: 25 cm; filled with about 25 l He) in a frame and can be turned within 200° (fig. 1).

The measurement resistances (150 \( \Omega \), 1/4 W, Allen Bradley type) are fixed on copper beryllium springs, pressing them onto the wall (fig. 1) with a force of 1 N (\( \pm 20\% \)). Different constructions for the carbon thermometer were tested. The common principle was to grind off the bakelite insulation from the carbon resistors down to about 0.2 mm and then glue the resistor into a copper tube with varnish (fig. 3). The copper tube is intended to make a good thermal contact between resistor and wall.
For one type \((R_1)\) this tube is soldered onto the spring. For the other type \((R_2, R_3, R_4, R_5)\) the tube is insulated against the spring and the bath with a block of vetronite, a glass fibre plastic (fig. 3). These thermometers were used in the first experiment; for the following experiments the contact area to the wall was filed flat (precision: \(\pm 0.1\) mm) to the size of \(2 \times 6\) mm in order to improve the thermal contacts and in order to see, how sensitive the measured \(\Delta T\)'s are against changes in the contact area (which may be caused by imperfections of a test set-up).

In the first two measurements the resistors were connected to thick \(0.6\) mm diam. copper wires leading to the top of the cryostat. In the third measurement the copper wires were fixed on the box and connected to the thermometers with thin manganin wires \((0.2\) mm diam.) in order to reduce the heat flux through the wires and in order to see how big this effect is.

The electronic set-up is shown in fig. 4: A constant current source \((10\) mA) can be switched onto the different thermometers. The resulting voltage across them is measured by a digital voltmeter \((5\) digits), its change in time is controlled with a storage oscilloscope. The noise \((50\) Hz) was about \(0.6\) mV peak to peak. The heating resistor is connected to a power supply; its resistance and the voltage are measured with a multimeter \((4\) digits).

The measurement process was as follows: The temperature of a thermometer was measured. Then a known voltage was switched onto the heating-resistor in the box. So the temperature increased to a new approximately stationary value \((90\%\) of the \(\Delta T\) was reached in about \(1\) s). This was measured then after about \(3\) s. After this the heat source was switched off. For the next measurement one had to wait now, until the thermometers showed again approximately the old temperature \((10-60\) s). Each measurement begins with pumping down the \(\text{He}\) pressure for lowering the \(\text{He-bath}\) temperature. During this the resistances and the pressures are measured at some points in order to calibrate the resistances as thermometers (fig. 6). For the reproducibility and a mathematical fit of the calibration curves see Appendix 1.
After pumping down the cryostat it was repressurized to 1000 mbar in order to get the subcooled state. Then the measurements were made, while the bath temperature increased slowly (typically 2.4° + 2.5° in half an hour).

3. MEASUREMENTS AND DISCUSSION

Essentially three measurements N1, N2, N3 were made:

- N1: thermometer arrangement according fig. 5(a), only one position (vertical wall), bath thermometer R4, R1 has no vetronite insulation, R1-R3 have no flat contact region. Diameter of the region with 1.5 mm wall thickness: 30 mm.

- N2: Thermometer arrangement according fig. 5(b). 5 positions, thermometers filed flat, bath thermometer R4. R1 has no vetronite insulation. Diameter of the region with 1.5 mm wall thickness: 50 mm.

- N3: Thermometer arrangement according to fig. 5(c), 3 positions, thermometers connected with thin manganin wires.

The results of the first measurements are shown in fig. 7: R₂ shows that ΔT increases first a bit less than proportional to the heating power until about 100 mW and then stops increasing at about 1.5°K until about 4 W. This is interpreted as following: Until 100 mW the cooling mechanism is convection. Then nucleate boiling appears as an additional cooling mechanism, which is so effective, that the temperature does not increase more until 4 W (producing more bubbles does not need more temperature, but only more heat).

R₃ shows that the temperature in 5 mm distance from the heat source is lower by a factor 2.5 to 3 in the convection range. R₃, which should see the same wall temperature as R₃ shows that a non-insulated thermometer shows only about half the ΔT as an insulated one in the convection range.
Now a problem is whether the thermometers show a $\Delta T$ near to the real $\Delta T$. To answer this (and for other reasons, see above) I filed the thermometers flat. This decreases the heat resistance $R_{TW}$ between the wall and the thermometer and increases the heat resistance $R_{TB}$ between the thermometer and the bath the last because the He cannot flow around the flat area and cool it). I estimate that the ratio $R_{TW}/R_{TB}$ may be changed by a factor $\sqrt{2}$. The temperature shown by the thermometers depends on the heat resistances as follows:

$$\frac{T_W - T_T}{T_T - T_B} = \frac{R_{TW}}{R_{TB}}$$

- $T_W$: wall temperature, $T_T$: thermometer temperature.
- $T_B$: bath temperature.

So $(T_W - T_T)$ should go down to about a half because of that change (if $T_W - T_T \ll T_T - T_B$) and so the variations in the values for $\Delta T$ (which is the same as the variation in $T_T$) should be in the same order of magnitude as the remaining $(T_W - T_T)$ after the change. In other words, the variation in $\Delta T$ due to the change in layout is an estimation for the difference between the real wall temperature and the temperature shown by the thermometer. This effect was measured in the second experiment N2, (fig. 8). The result for the insulated resistor $R_2$ is: $\Delta T$ increases by 10% in the lower convection range, 30% in the upper convection range and 10% in the nucleate boiling range; so the measured $\Delta T$'s are about 90% of the real $\Delta T$'s for the insulated resistors.

That is not the case for the non-insulated resistor $R_1$: The change in $\Delta T$ due to the flattening cannot be seen directly from the curves, because in N2 $R_1$ was moved onto the heat source in order to compare it directly with $R_2$. But the change in $\Delta T$ can be estimated from the change in the ratio to $R_2$; the result is, that the change in $\Delta T$ due to the flattening is +40 to +100% (as calculated from different curves) for $R_1$. With the argument from above that means, that the non-insulated thermometer shows only 50-60% of the real $\Delta T$ (Appendix 2).
This is consistent with the above result, that the ΔT shown by R₂ is near to \((T_W - T_B)\), together with the ratio between the ΔT's from R₁ and R₂ according to fig. 8. The above estimation for the real \(T_W\) from the changes in ΔT is also confirmed by the fact, that the wall temperature should be 4.2 K in the nucleate boiling region, leading to a ΔT of 1.8 K, which is in agreement with the ΔT from R₂ in fig. 8, corrected with the above estimation. Another result is, that it is more difficult to get reproducible measurements with a non-insulated thermometer than with an insulated one, because the first is quite far away from the wall temperature so that its temperature is more sensitive to slight changes in contact resistance which may be caused by the mechanical set-up. In contrary the insulated thermometers are much less sensitive against that, because they are already near to the wall temperature. The change in ΔT due to the different insulations of the resistors is low in the lower convection range, bigger in the upper convection range and again low in the upper nucleate boiling range. This behaviour was observed several times. A possible explanation is the following: in the convection range the difference in ΔT increases with \(P_H\) because the convection increases and a poorly insulated thermometer is more sensitive to this. Then in the nucleate boiling region the difference in ΔT decreases, because the bad insulated thermometer is warmed up a bit by the bubbles (whose temperature is 4.2 K) whereas the well insulated thermometer is already approximately at 4.2°K. So the non-insulated thermometers also have an advantage: In the nucleate boiling range they show a clear increase of ΔT with \(P_H\) in spite of the fact, that the real ΔT is nearly constant. Therefore one can conclude from ΔT to \(P_H\) with better resolution than with the insulated thermometer, provided that one knows the right calibration curves \(ΔT = f(P_H)\). But here one has the problem with the worse reproducibility: perhaps one has to calibrate every single thermometer in every equipment again? To answer this question one should make further measurements.

For convenience we have plotted in fig. 17 the ΔT-\(P_H\) curves for the non insulated resistors for different positions. This resistor type is similar to the one hitherto used for the temperature mapping of the 500 MHz s.c. cavity.
In fig. 8 a further increase of $\Delta T$ beyond the nucleate boiling region of about 2 W can be seen; this is interpreted as film boiling: The heat flux evaporates so much He, that an insulating gas film is formed on the wall, so that its temperature increases. In fig. 7 this effect is not seen. This may be due to the fact that in N1 the thin part of the wall had only a diameter of 30 mm (whereas in N2 it was 50 mm) so that more heat could be lost sidewise through the wall.

In measurement No. 3 I connected the thermometers with thin manganin wires. The result is shown in fig. 12. The hole curve seems to be shifted to powers smaller by a factor 0.8. That is hard to explain, and it does not fit well with my above estimation, that $R_2$ is already near to the wall temperature in N2. So perhaps in N2 there was a systematic error causing the shift in power: such as an extra contact resistance or something else (but I could not find one afterwards). In any case: this error in power would be small compared to the error in scaling to power per area (see below); and for other "relative results" such as the dependence on the bath temperature it can be compensated, if one compares the curves only within N2 or N3.

In N2 and N3 the dependence of the $\Delta T$ on the position of the wall was examined. The results are shown in figs 9-14. The variations are less than a factor 1.5 (if one excludes the film boiling range). The most typical results are given from the vertical wall (fig. 7, 8, 12). The deviations from this position can be summarized as follows:

\[ T \] (figs 14 and 15): no significant change (sign for: wall upwards and horizontal, the other signs have to be interpreted correspondingly).

\[ \triangleleft \] (figs 8 and 10): $\Delta T$ decreases by 20% in the lower convection range, by 30% in the upper convection range and by 10% in the nucleate boiling range. This position shows the best cooling behaviour!

\[ \triangleright \] (fig. 8 and 9): no significant change.
(fig. 12 and 13): no change in the lower convection range, +10% in the upper convection and nucleate boiling range, film boiling seems to start earlier indicating poor cooling.

In N2 and N3 the temperature distribution was also examined. R₃, R₅, R₆ (fig. 5(c)) measure the temperatures 5 mm away from the heat source. If the wall is at the top and horizontal, the temperature distribution should be circular symmetric, so R₃, R₅ and R₆ should show the same temperature. That is the case in good approximation (fig. 14). The difference between the temperatures shown by R₆ and R₅ (ca. 15%) may be interpreted as an estimate for the reproducibility of temperature measurements will different resistors; but probably this is better and the difference is due to a small deviation from the horizontal position (the precision in angle is about 5°) which would disturb the circular symmetry. The good agreement between R₃ and R₅/R₆ shows, that the temperature shown by the latters is a good measure for the temperature at 5 mm distance from the heat source, in spite of the fact, that R₅ and R₆ extend between 2 and 8 mm distance (fig. 5(c)). In the convection region, the outer thermometers show about 1/3 of the temperature at the heat source; in the nucleate boiling region this ratio is up to \( \sqrt{2}/3 \). If the wall is vertical (fig. 12), the upper thermometer R₆ shows twice the \( \Delta T \) from the lower one R₅, whereas R₃ shows the mean temperature. This is obviously an effect of the convection stream going up the wall (this effect depends on the bath temperature, compare figs 12 and 16). The measurement for the position \( \frac{1}{2} \) (fig. 13) shows still a big difference (\( \approx \) factor 1.7) between R₆ and R₅, so that one can conclude, that the wall was not exactly horizontal and that in this position the temperature distribution depends strongly on the angle. Already this measurement with a non perfectly horizontal wall shows a flattening of the temperature distribution. The mean \( \Delta T \) shown by the outer thermometer is lower by a factor 0.4 with respect to the inner one (compared with 1/3 for the \( \frac{1}{2} \) position)\(^*\).

\[\text{(*) Due to one measurement in N2, probably spoiled in part by the wires which probably lifted R₁ and R₂ a bit from the wall, I expect the following ratios for an exact horizontal wall: } \Delta T \text{ on the heat source } +20\% \text{ compared with a vertical wall, } \Delta T \text{ outer is } \approx 0.42 \text{ from } \Delta T \text{ inner}.\]
The measured $\Delta T$'s depend on the bath temperature $T_B$. This can be seen from figs 8 and 11 and from figs 12, 15, 16. All curves show that the $\Delta T$ in the nucleate boiling range decreases proportional with $(4.2^\circ - T_B)$ which is clear if one makes the sensefull assumption, that nucleate boiling starts, if the wall is on $4.2^\circ$. The temperature dependence in the convection region should be not so simple; it follows from the temperature dependence of various parameters of the He such as thermal conductivity, viscosity, density and specific heat. But if the bath temperature varies not too much $(2.4^\circ - 3^\circ)$, the temperature dependence in the convection range seems to be the same as in the nucleate boiling range: The curve in fig. 11 is shifted relative to that in fig. 8 everywhere by the same factor to lower $\Delta T$'s. In fig. 18 the ratio $[\Delta T(T_B) : \Delta T(T_B = 2.4^\circ)]$ calculated from figs 8, 11, 12, 15, 16 is plotted with error intervals for convection and nucleate boiling range, and it is compared with

$$\frac{4.2^\circ - T_B}{4.2^\circ - 2.4^\circ}$$

In the film boiling range the $\Delta T$ seems to be approximately independent of the bath temperature (fig. 12, 15 and 16). The only difference is, that at lower bath temperature film boiling starts at a higher power, so that all curves run into the same curve in the film boiling range. This shift is probably due to the fact that at lower bath temperature the $\Delta T$ in the upper nucleate boiling region is higher so that the bubbles are more rapidly recondensed.

In order to generalize the above results obtained with the chosen test set-up one needs $\Delta T$ as a function of the power per unit area. This can only be estimated from this experiment. One wants to know the power density at the heat source; one knows the integral power, one has an idea of the temperature distribution and one knows the area of the heat source. So one has to estimate which part $A_s$ of the integral power $P_s$ is dissipated at the area as of the heat source. For this I estimate (the temperature distribution in mind) the power $P_R$ dissipated from the wall without the area $A_s$ of the heat source to be roughly the same as the power, that would be dissipated from the circular area $A_R$ between $r = 0.5$ cm and $r = 1.5$ cm if there would be a constant power density $P_R$ of c times the power density $P_s$ in the heat source. So
\[ p_H = p_s + p_r = p_s \cdot A_s + p_r \cdot A_r = p_s (A_s + cA_r) \]

and hence

\[ p_s = \frac{p_H}{A_s + cA_r} \]

with \( A_s = 0.785 \text{ cm}^2 \) and \( A_r = 6.28 \text{ cm}^2 \) one gets

\[ p_s \left[ \text{mW/cm}^2 \right] = (0.49 \text{ to } 0.30) \cdot \frac{p_H}{3} \]

This ratio between \( p_s \) and \( P_H \) probably increases a bit in the nucleate boiling range, because here the wall at the heat source is cooled more effectively (nucleate boiling), so that a bigger part of \( P_H \) is dissipated here.

The error intervals for the different measurements can be estimated as follows:

- Pressure: ±3%.

- From these errors one gets for the temperature: ±30 mK at 4°, ±20 mK at 3°, ±13 mK at 2.2°.

- \( \Delta T \) error resulting from temperature fit: ±7% (for 2.2° < T < 4.2°).

- Reproducibility of the \( \Delta T \) measurements with the same thermometer (deduced from successive equal measurements): maximum of ±3% and ±1.5 mK with different thermometers: ca. ±10% (rough estimation, see above).

- Position of the thermometers: ±1 mm.

- Position of the box (angle): ±5°.
4. SUMMARY AND CONCLUSIONS

The wall temperatures of an improved heater set-up have been measured for different wall positions inside a subcooled He-bath. The differences in ΔT for a given heater power and for different positions are less than a factor 1.5. The power density is about 30% of the integral power \( p_H \) shown in the diagrams, e.g. fig. 8. The dependence of ΔT on the bath temperature can be fitted by a simple law involving the difference (\( T_B = 4.2 \) K; fig. 18). The non-insulated resistors show only about 50% of the real ΔT as compared with 90% for the insulated ones.

Further measurements should be done in order to examine the dependence of the film boiling limit on the position and the bath temperature and in order to check the reproducibility (especially of the non-insulated thermometers) with different thermometers of the same type; also one could improve some of the curves with more measurement-points and try to get the curves for the position, in which the wall is down and exactly horizontal.

Hard to explain is the big discrepancy between my results and those from H. Tsuruga [3] (fig. 7). According to my results nucleate boiling starts at about 30 mW/cm², according to his results at about 3 mW/cm²; the ΔT at the "nucleate boiling plateau" is about 1.8°K (≈ wall temperature of about 4.2°) according to my results, about 0.5°K (≈ 3° wall temperature) according to his results. Especially in the last case my results seem to be the right ones, because the wall should be on 4.2°K, if there is boiling (*); if it would be only on 3°, no bubbles could be generated, because they would be compressed at once.

Acknowledgements

I had stimulating discussions with H. Heinrichs, H. Lengeler, H. Piel and others. I want to thank R. Romijn and many others for practical help, M. Firth for fruitful advice.

(*) In both experiments there was atmospheric pressure (≈ 1000 mbar) above the subcooled He, which is the vapour pressure of He of 4.2°).
In the literature one can find different opinions concerning the reproducibility of carbon thermometers. My experience with six resistances was the following: The change in resistance of one thermometer between different measurements (warming up to 300°K, cooling down to 4°K) is less than 1%; if the difference between two resistors of the same type is less than 1% at room temperature, it is less than 10% between 4° and 2°K.

In order to get the ΔT rapidly from the ΔR, I made a fit for the T(R) function. I tried several fits and used then commonly (for all resistors) the following one:

\[ R = K_1 \cdot \exp \left( \frac{K_2}{T} \right) = \frac{c_2}{c_1 + \lg R} \]

with \( R \) in kΩ, \( T \) in °K, \( c_1 = 0.5194528876 \) and \( c_2 = 3.08959453 \).

With this common fit the error in temperature is less than 30 mK (fig. 6) between 4.2° and 2.2°, the error in ΔT is less than 7%.

I also get ΔT's exceeding the temperature interval in which I could calibrate the thermometers: here I had to extrapolate with a fit. For this purpose I tried also the fit according to ref. [4].

\[ \left( \frac{\ln R}{T} \right)^{0.552} = a(\ln R)^2 + b \ln R + c. \]

But I do not consider this as a very good fit because it changes if one changes the units and because the agreement with my measurements was not much better than with my "common fit".
From comparisons of different fits I estimate, that the temperatures above 4.2°K calculated with the common fit may deviate from the real temperatures as following:

<table>
<thead>
<tr>
<th>T[°K]</th>
<th>4.64 ± 0.05</th>
<th>6.40 +0.2 -0.5</th>
<th>8.33 +0.2 -1</th>
</tr>
</thead>
<tbody>
<tr>
<td>R[Ω]</td>
<td>1400</td>
<td>920</td>
<td>710</td>
</tr>
</tbody>
</table>
CALCULATION OF THE REAL $\Delta T (\Delta T_{\text{real}})$ FROM THE ALTERATION OF THE MEASURED $\Delta T$'s

($\Delta T \rightarrow \Delta T'$) DUE TO A KNOWN CHANGE IN THE HEAT-RESISTANCE

In the general case one has to calculate more exactly than on p. 5, because $T_W - T_T << T_T - T_R$ is no longer right. For simplification I do that in the electrical model

$$\begin{align*}
\begin{cases}
U_1(= T_W - T_T) & \quad R_1 \\
U_2(= T_T - T_B = WT) & \quad R_2
\end{cases}
\end{align*}$$

Known:

(a) $U_2, U_2'$ (the primed variables refer to the situation after the change).

(b) The change $a = \frac{R_1'}{R_2/R_1} \approx 2$

Aim: U.

Calculation:

$$\begin{align*}
U_2 &= U \cdot \frac{R_2}{R_1 + R_2} \\
U_2' &= U \cdot \frac{R_2/R_1}{1 + R_2/R_1} \\
\frac{U}{U_2} &= 1 + \frac{R_2/R_1}{R_2/R_1 + 1}
\end{align*}$$

Similar for $U_2'$

$$\begin{align*}
\frac{U}{U_2'} &= 1 + \frac{R_2/R_1}{R_2/R_1 + 1}
\end{align*}$$

Both equations combined:

$$\frac{U}{U_2} - 1 = \frac{R_2/R_1}{R_2/R_1 + 1} \quad (\approx a)$$
So we have the wanted relation between $U$, $U_2$, $U'_2$ and $a$.

\[
\frac{U}{U_2} - 1 = \frac{aU}{U'_2} - a
\]

\[
a - 1 = U \left( \frac{a}{U'_2} - \frac{1}{U_2} \right)
\]

\[
a - 1 = U \left( \frac{a}{U_2} - \frac{U'_2/U_2}{U'_2} \right)
\]

\[
U = U'_2 \cdot \left( \frac{a - 1}{a - U'_2/U_2} \right)
\]

Or, for our case

\[
\Delta T_{\text{real}} = \Delta T' \cdot \left( \frac{a - 1}{a - \Delta T'/\Delta T} \right)
\]

For $a = 2$ and $\Delta T'/\Delta T = 1 + \epsilon$ with $\epsilon \ll 1$ that gives the estimation from p. 5:

\[
\Delta T_{\text{real}} = \Delta T' \cdot \frac{a - 1}{a - 1 - \epsilon} = \Delta T' \cdot \frac{\epsilon}{1 - \frac{\epsilon}{a - 1}} \approx \Delta T' \cdot \left( 1 + \frac{\epsilon}{a - 1} \right) \approx \Delta T' (1 + \epsilon)
\]
REFERENCES


FIGURE CAPTIONS

Fig. 1 Test set-up: the inoxbox with the niobium lid hangs in a support made of inox stripes, 1.5 mm thick and 20 mm broad. A: to roughing pumps, B: evacuated inoxbox, C: Nb lid (1.5 mm thick), D: heating resistor, E: support, F: spring, R: measuring resistor.

Fig. 2 Test set-up of ref. [2].

Fig. 3 Construction of the carbon thermeters. 1: copper, 2: resistor, 3: Ge varnish, 4: springs, 5: solder, 6: vetronite.

Fig. 4 Electronic set-up.

Fig. 5 Arrangement of the resistors for the three measurements, if one looks on the Nb-wall in vertical position. Note that R1 has no vetronite insulation (see also text).

Fig. 6 Typical calibration curves for the thermometers.

Fig. 7 Results from the first measurement (N1), compared with those from [2] and [3] (resistor arrangement from fig. 5(a)).

Fig. 8-11 Results from the second measurement (N3) for different positions of the Nb wall (resistor arrangement from fig. 5(b)).

Fig. 12-16 Results from the third measurement (N3) for different positions of the Nb wall (resistor arrangement from fig. 5(c)).

Fig. 17 Collection of the curves for the non-insulated thermometer on the heat source; is measured, the others are partly estimated.

Fig. 18 Temperature dependence of AT. The ratio shown can be filled with the indicated temperature law.
Fig. 8
N 3
$T_B = 2.5 \, K$

$\Delta T \, (mK)$

$P_H \, [mW]$

Fig. 13
N 3
$T_B = 2.72 \text{ K}$

$\Delta T \text{ (mK)}$

$P_H \text{ [mW]}$

Fig. 15
$T_B = 2.4 \text{ K}$

non isolated resistors

![](image)

Fig. 17