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INFLUENCE OF A LOCAL OBSTRUCTION ON HEAT TRANSFER IN PACKED BEDS

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NOTATIONS

A, B	constant values depending upon type of obstruction and Reynolds number range	—
D_p	particle diameter	m
n	number of contact points between a sphere and surrounding spheres	—
ν	kinematic viscosity	m^2/sec
V_o	superficial velocity : fluid velocity upstream the packed bed	m/sec
T_s	surface temperature of a sphere	°C
T_g	coolant gas temperature	°C
$\Delta T = T_s - T_g$	driving temperature	°C
C_p	specific heat at constant pressure	kcal/kg.
Q	heat flux	Kcal/se
k	thermal conductivity	kcal/mse
h	heat transfer coefficient	$kcal/m^2s$
Nu	Nüsselt number defined by $Nu = \frac{hD_p}{kg}$	—
Re	Reynolds number defined by $Re = V_o \frac{D_p}{\nu}$	—
P_r	Prandtl number defined by $Pr = \frac{\mu C_p}{kg}$	—

SUMMARY

The purpose of this study is to find the influence of a local obstruction on heat transfer between one particle in a p packed bed and the coolant gas which is forced through it.

A method is chosen and developed, giving average as well as local heat transfer coefficients in the case of a packed bed containing spherical particles of constant diameter.

The results show :

- an important decrease of the average cooling of a sphere near the obstruction. The measurements can be correlated by an expression such as :

$$Nu = A.Re^{B}$$

where Nu is the Nusselt number, Re the Reynolds number and A, B constants depending upon the type and the amount of obstruction.

- important local variations of the heat transfer coefficient over the surface of a sphere.

INTRODUCTION

In the gas cooled thermal reactor field, fuel development has moved towards coated fuel particles, using packed systems.

This advanced technology leads to higher heat fluxes so that for a given power more compact reactors seem to be feasible.

A great amount of research has already been carried out in different laboratories but a few problems remain to be solved.

For example, retention of dust from the coolant gas by the packed bed or fuel particle ruptures can produce local obstruction whose effect on heat transfer is still unknown.

If the cooling of the particles near an obstruction is largely decreased, the safety of the reactor may be compromised.

The purpose of our study is to find the influence of such an obstruction on heat transfer between one element in a packed bed and the coolant gas which is forced through it.

In the first section, the test facilities are described and the geometrical characteristics are justified.

Then the principle of the heat transfer measuring technique is explained. It is a steady state method with which average as well as local heat transfer coefficients can be measured.

In the final section, the results are summaried and discussed, showing the importance of an obstruction on heat transfer in a packed bed.

Some of the material presented here is discussed in more details in reference (1).

<u>NOTE</u>

Le prix 1971 de la Société Royale Belge des Ingénieurs et des Industriels a été attribué à ce travail.

(1) "Transfert de chaleur dans un empilement compact en présence d'un blocage" - Etude bibliographique et Expérimentale par C. Joly.
Université Libre de Bruxelles - Institut von Karman
Septembre 1971.

2. TEST FACILITY

A schematic diagram of the test facility is shown in figure 1.

Air delivered by high pressure reservoirs passes through a regulating valve which maintains a constant and adjustable stagnation pressure upstream of the facility. The mass flow is measured by a diaphragm.

The air enters a settling chamber, the purpose of which is to produce a uniform flow at the entrance of the test section.

By using a 50 mm thick layer of packed particles of 5 mm diameter, followed by a wool screen and an honeycomb, the maximum velocity variations in a cross section were maintained smaller than about 10 % of the mean velocity.

The square test section (563 mm × 563 mm) contains a packed bed, of spherical elements of constant diameter, which simulates the core of a nuclear reactor using coated fuel particles.

The test section is followed by a channel of constant cross sectional area to minimize upstream effects caused by discharging the working air into the laboratory room.

The size of the test section and the diameter of the spherical elements were selected from the following considerations.

In a practical configuration of a nuclear reactor cooled by helium a typical Reynolds Number based on superficial velocity (V_o) and particle diameter (D_p) is of about 290.

The test set-up was then designed to cover the range 50 to 2000. Using air as a working fluid, a range for the product V_oD_p is thus fixed.

A heat transfer measuring technique is adopted (described in the next section) which enforces the use of one copper instrumented sphere which contains an electric resistance for power dissipation and thermocouples for temperature measurements.

This determines a minimum value of the diameter D_p which is one order of magnitude larger than the diameter of the coated fuel particles. The next problem is to select a sufficient number of inert spheres of equal diameter D_p surrounding the active one, so that a nuclear reactor core containing a large number of small particles can be simulated.

This number, on the otherhand, is limited by cost and total mass flow considerations.

Finally, the choice of table tennis balls was adopted for the inert spheres, thus giving a value of about 37 mm for the diameter D_p. A ratio of container width to sphere diameter of 15 was selected so that the square test section has dimensions mentioned above and giving a total number of 3375 spheres. They are laid in carefully one by one to form a "dense cubic" (or "octaedric) packed bed characterized by a void fraction of 0.26. In this arrangement half-spheres are used at the walls of the test section and one-quarter spheres in the corners. It is expected that, under these conditions, wall effects are minimized even in the presence of local obstructions.

Great care was taken to avoid the presence of a screen at the entrance of the test section supporting the packed bed.

This is done by using metallic wires stretched from opposite walls of the test section along which the spheres of the first lower layer of the bed are strung like beads on a string.

Figure 2-a and b are photographs of the test section.
Figure 2-B is taken during the packing operation. The instrumentated sphere can be seen among the inert ones.

3. HEAT TRANSFER MEASURING TECHNIQUE

As seen in figure 1 air enters the test section at room temperature (T_g) and flows around inert spheres which are also at or very near room temperature.

One of the spheres is made of copper and instrumented with an internal electric resistance, which can dissipate a maximum of about 30 watts, and thermocouples for temperature measurements.

In fact, the detailed design of the sphere is different as shown below whether one is interested in average or detailed distribution of heat transfer rates.

A steady air flow being established through the test section, a certain time (of the order of thirty minutes for average heat transfer measurements, and of more than one hour for local heat transfer measurements) is needed after switching on the power (Q) dissipated inside the instrumented sphere, to reach a steady surface temperature T_s.

Then the heat dissipated is exactly convected away by the coolant gas.

It should be noted that copper was purposely selected to manufacture the working sphere. It ensures a uniform temperature of its skin despite local surface variations of the heat transfer rate.

3.1 Measurement of average values

Figure 3 shows the sphere which was used for these measurements. It was machined into two parts, instrumented with thermocoax resistance and two thermocouples, and then assemblied.

Knowing the total heat flux Q from the measured power dissipated inside the sphere and the driving temperature $\Delta T = T_s - T_g$, one can calculate an "average" heat transfer coefficient $h = Q/S_p . \Delta T$ and Nusselt number $Nu = hD_p/kg$, where $S_p = \pi . D_p^2$ is the total skin area of the sphere and kg the thermal conductivity of air. From the mass flow measured upstream of the settlin chamber, the superficial velocity V_o is calculated thus giving the Reynolds number $Re = \frac{V_o D_p}{\nu}$

where ν is the kinematic viscosity of air.

The results of average values measurements are presented in a dimensionless form Nu = f(Re)

3.2 Heat transfer distributions

The design of the sphere used for local measurements of the heat rate is more complex as shown by figures 4-a and b. A small cylindrical element is thermally isolated from the rest of the sphere. Its outside looking base occupies only 1 % of the total surface of sphere and, in that sense, provides "local" values of the heat transfer rate.

As before, section 3-1, the sphere is heated up by inner power dissipation and its skin temperature stabilizes to a measured value T_s.

In addition, heat is supplied directly to the cylindrical element at a rate such that its outside looking face is also at temperature T_s. Everything being practically at uniform temperature and the cylindrical element being isolated from the rest of the sphere, this amount of heat is a direct measure of the local heat flux, which is then presented in the form : $Nu = h\ D_p/kg$ where h is now based on the power dissipated in the cylindrical element and on the outside looking face of this element. Distribution of Nu over the surface is obtained by rotating the sphere to change the position of the copper element with respect to the upstream flow.

To simplify the test set-up, it was decided to avoid remote control of this rotation. Therefore one has to unpack the bed each time.

It was verified that this procedure did not cause any errors in the repeatability of the measurements.

4. PRELIMINARY MEASUREMENTS

A series of preliminary tests were made to determine a suitable value for the driving temperature $\Delta T = T_s - T_g$ which could be varied by adjusting the amount of power dissipated into the instrumented sphere.

In addition, the relative importance of various heat transfe mechanisms was examined.

A maximum temperature of about 100°C is fixed by the materia of the table tennis balls and the coolant gas temperature is about 20°C. The driving temperature is thus limited to a maximum of 80°C. The preliminary tests showed that the heat transfer coefficient was independent of ΔT up to this maximum value.

Therefore a suitable value of 40 to 50°C was selected for ΔT. In addition to forced convection, one has to consider three possible mechanisms for heat transfer from the instrumented spher to its surroundings.

1. Conduction through contact points between the heated sphere and its neighbours
2. Natural convection at low Reynolds numbers
3. Conduction through surrounding non negligible air, when at rest.

Tests were made to determine their relative importance. The results are summarized in figure 5.

It gives the power dissipated in the sphere which is needed to maintain a given ΔT of about 45°C when the number of contact points between the heated sphere and the neighbouring ones is increased from zero to twelve in steps of four while $V_o = o$.

This was done in the presence of natural convection and without simply by inserting cotton in the various gaps between the spheres. Under normal operating conditions (12 contact points) it is seen from figure 5 that the three above mentioned mechanisms contribute for 0.082, 0.105 and 0.206 cal/sec respectively.

In the presentation of the results of the final tests, all the measurements were corrected by 0.187 cal/sec which is the sum of the two first effects.

Indeed these are specific aspects of the present technique of heat transfer measurement and not of the actual problem of the nuclear reactor core.

5. RESULTS

5.1 Average heat transfer

The tests were first made without local obstruction.

The results agree remarkably well with previously published data as shown in Figure 6.

This figure gives the measured Nusselt number versus Reynolds number as defined in section 3.2.

Some of the results (for example, curves Z2, L4, L8) indicate lower Nusselt numbers than the others. One reason is that in these cases, wall effects were present.

The effect of a local obstruction was then considered. In the real situation of the nuclear reactor core, partial obstruction of the packed bed is possible due to dust retention or breakage of some of the fuel particles.

It did not appear possible to simulate simply such a situation but rather to test a certain number of configurations in which the interestices between the working sphere and the neighbouring ones were progressively obstructed.

Examples of such obstructions by plexiglass plates are shown in figure 7.

The results are given in figure 8 for the various types of obstructions identified by the same numbers as those used in figure 7.

It is seen that in each case two different laws are obtained depending whether the Reynolds number is larger or smaller than 250.

In addition, the exponent B (i.e. the slope of the curves in figure 8) is nearly independent of the type of obstruction.

It is also concluded that the effect of a local obstruction may be very pronounced, inasmuch as it reduces the heat transfer by a factor which can be as high as three.

5.2 Heat transfer distribution

As the time needed to obtain steady flow conditions was large, the test program was limited to the three following situations :

- heat transfer without obstruction
- heat transfer in the presence of type 5 and 6 obstructions (see figure 7).

The measurements were made along a great circle of the sphere. The results are shown in figure 10 where Nu is plotted versus Re. As may be seen, large variations of local heat transfer exist over the surface of the sphere in the ratios 1/3, 1/6, 1/8 respectively for the three conditions which were tested.

6. CONCLUSIONS

Average and local measurements show the important influence of local obstructions on heat transfer between a sphere in the packed bed and the coolant gas.

Consequently, a uniform heat transfer is impossible if obstructions are present.

Under these conditions hot spots are expected which in turn away may cause new ruptures and further obstructions leading to unsafe operation in a practical configuration.

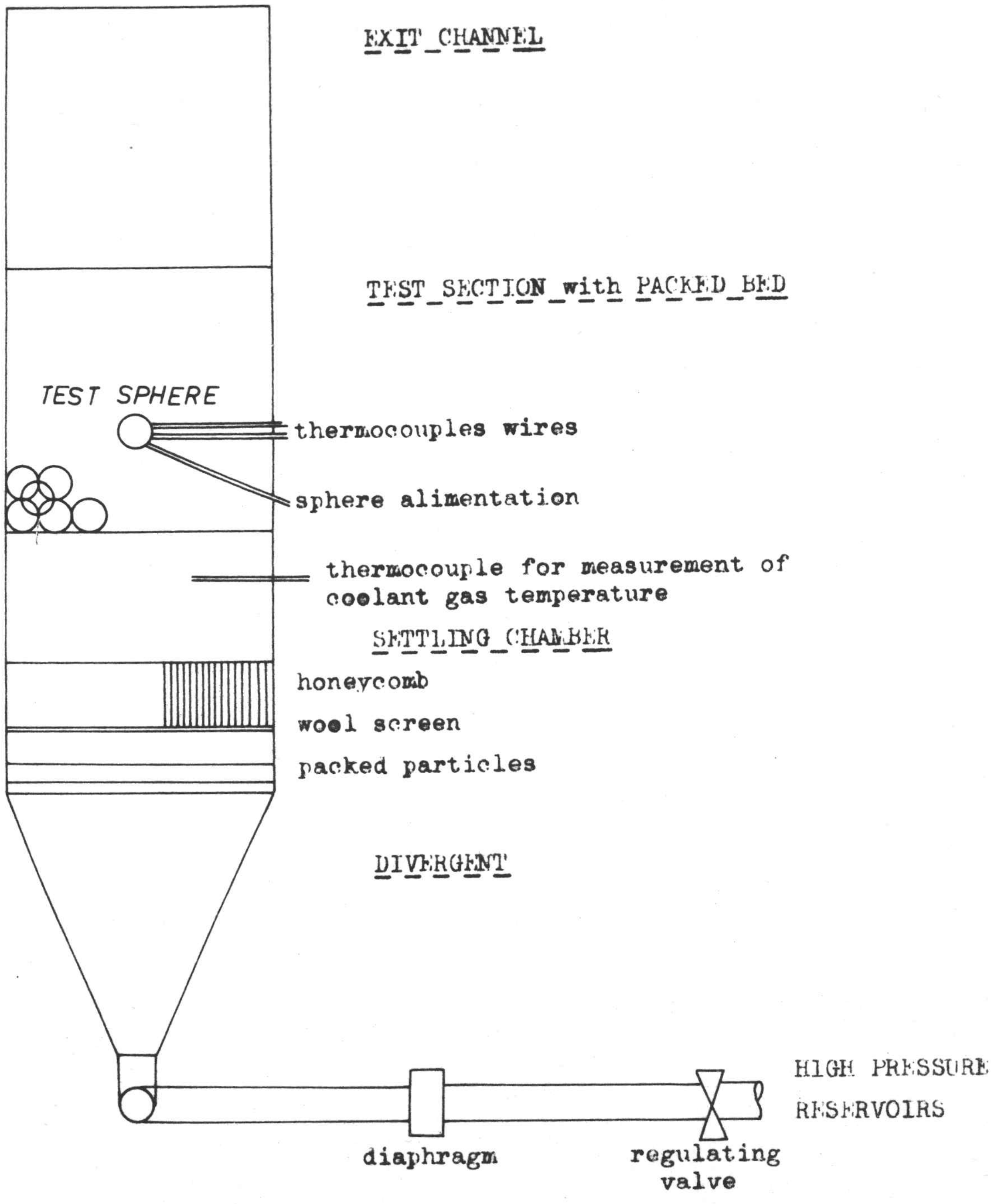
It thus seems necessary in a practical configuration to filte the coolant gas upstream of the packed bed and decrease the probability of ruptures by a careful construction of the particles.

ACKNOWLEDGMENTS

We wish to express our appreciation to Mr. F. Thiry, technica engineer, for his advice and continuous assistance in the realization of this work.

FIGURE 1

TEST FACILITY



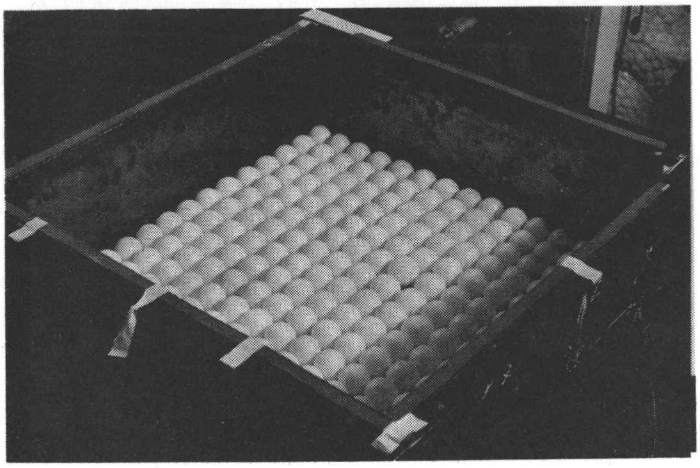
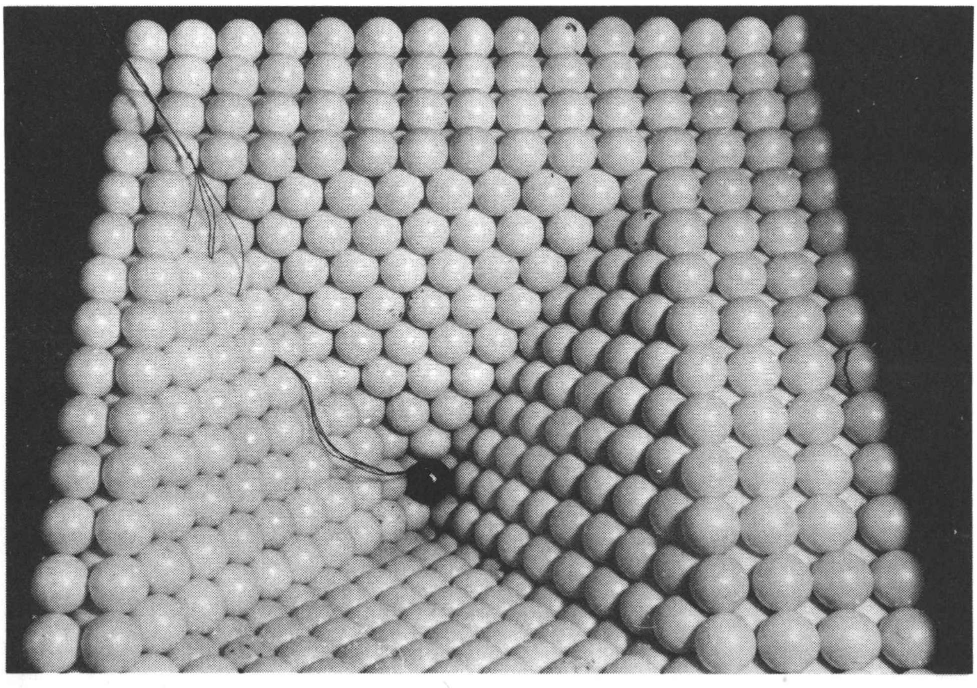


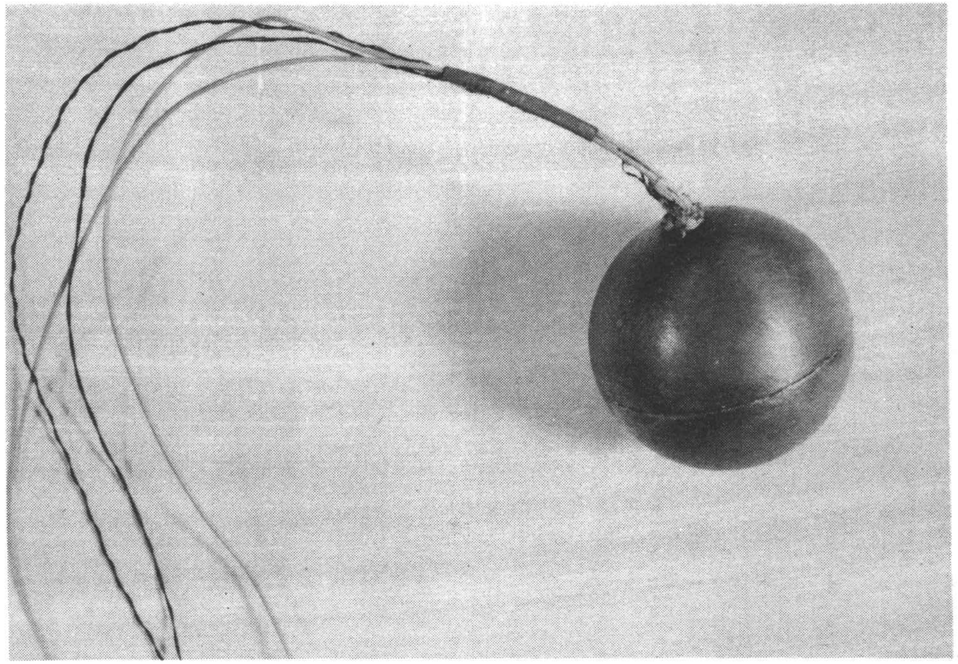
FIGURE 2

a

TEST SECTION

b





<u>FIGURE</u> 3 Test sphere(Average values)

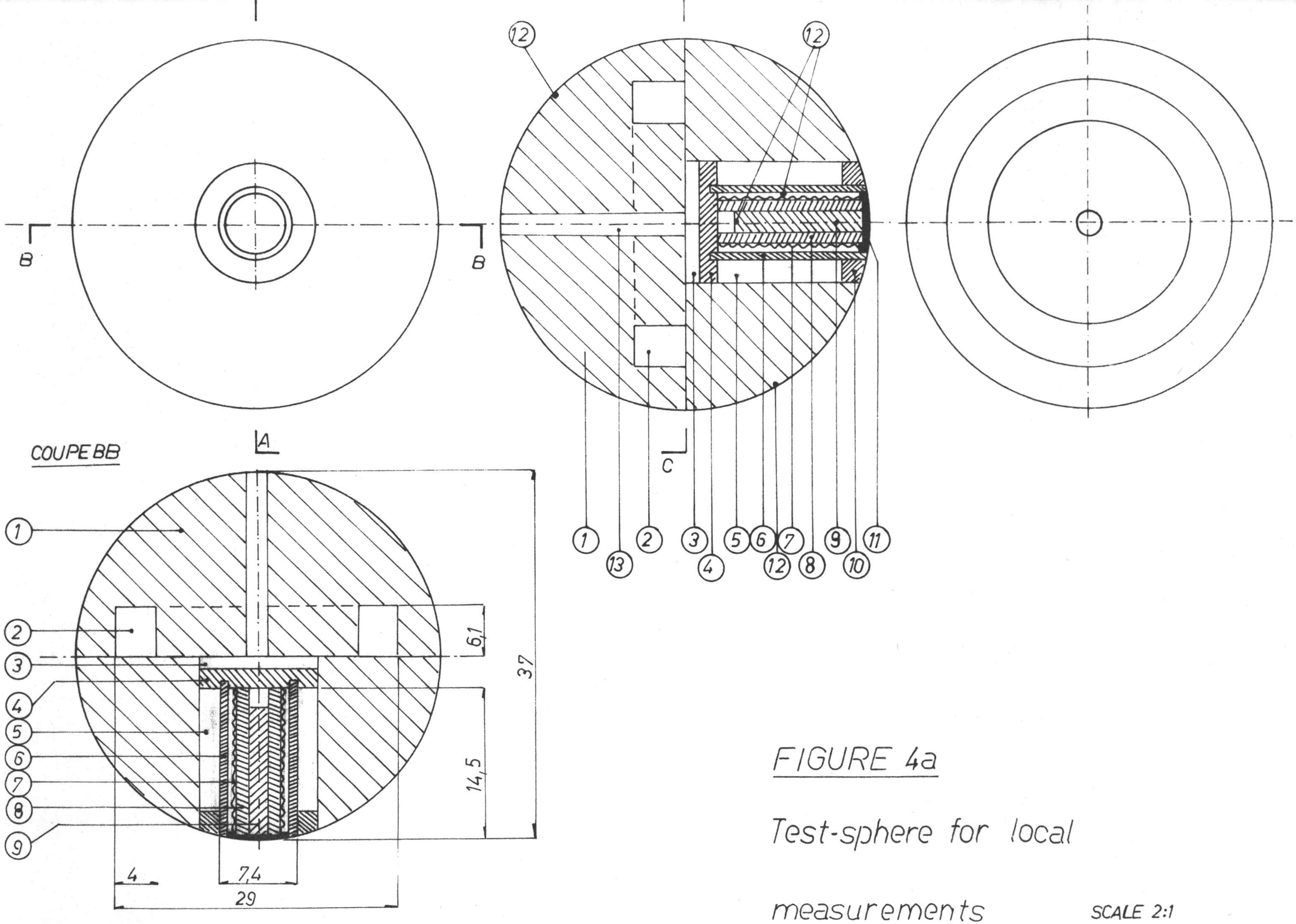


FIGURE 4a

Test-sphere for local measurements

SCALE 2:1

FIGURE 4-a

Test sphere for local measurements

Nomenclature

1 Test sphere; copper is used as material
2 Heating resistance (thermocoax)
3 Air film
4 Araldite
5 Air film
6 Hollow cylinder (copper)
7 Heating gage and air film
8 Hollow cylinder (copper)
9 Small cylindrical element heated by 7
10 Araldite
11 Tin welding
12 Thermocouple Cu-Ct
13 Exit for wires

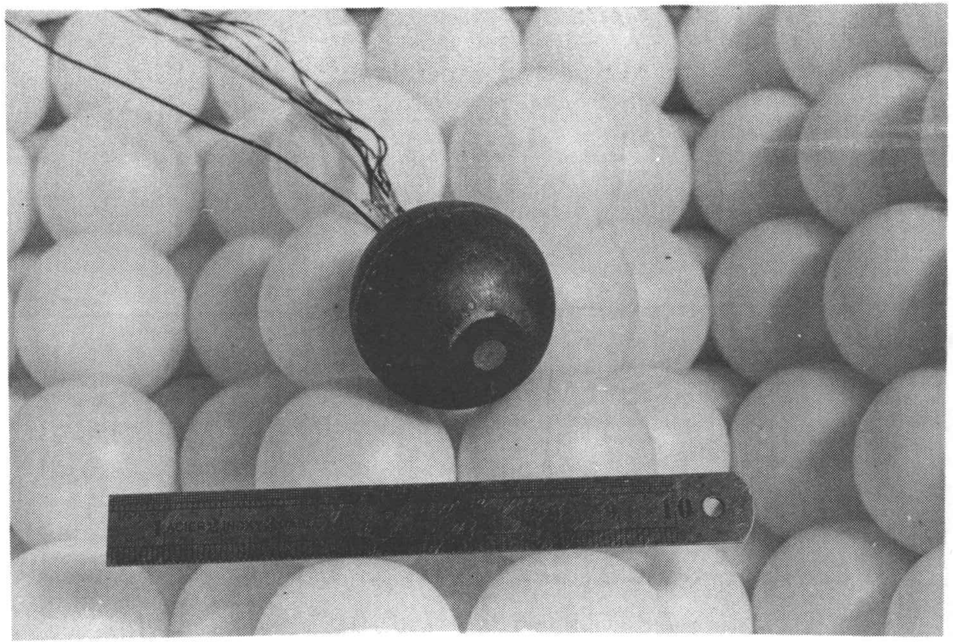
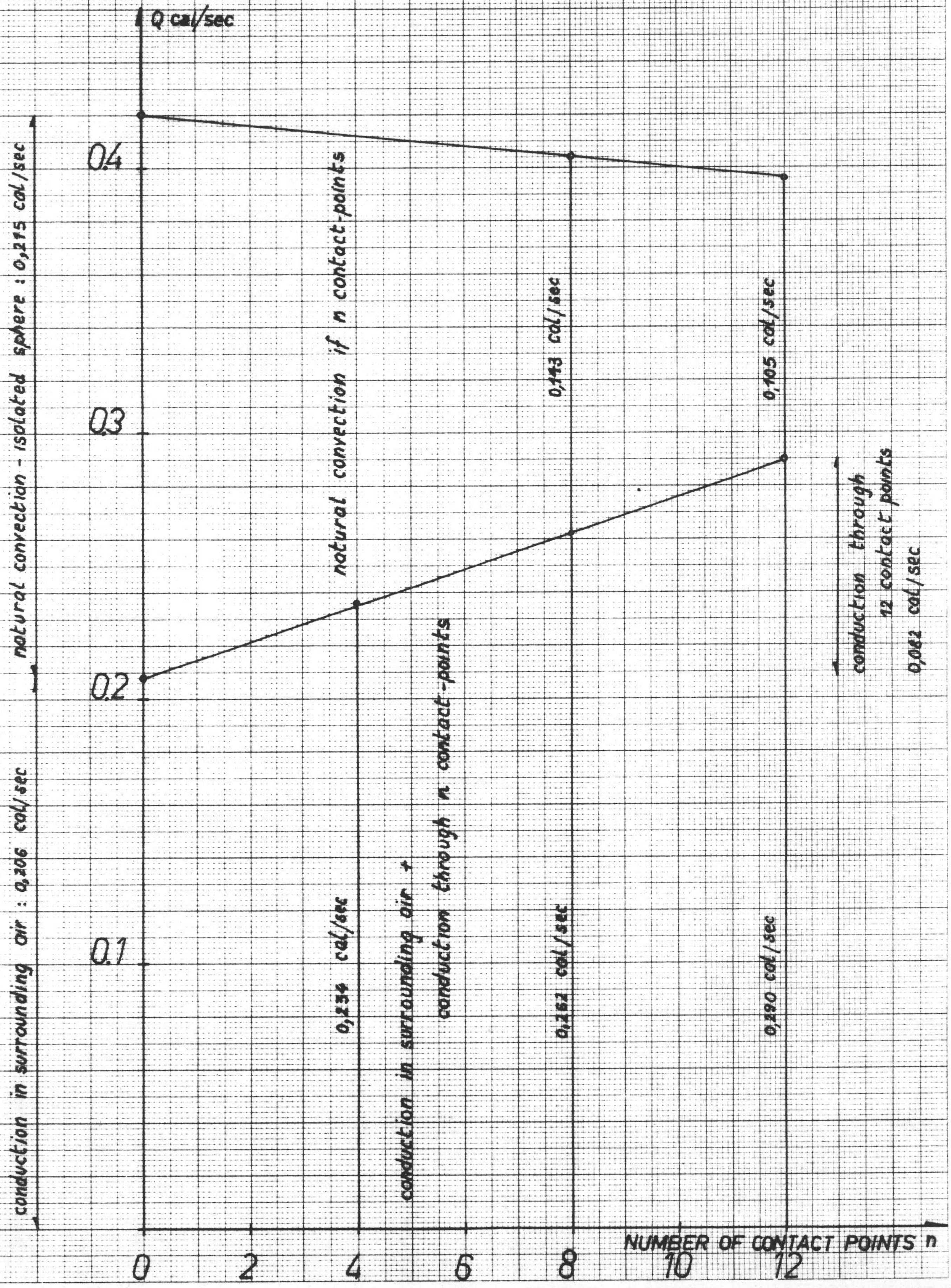
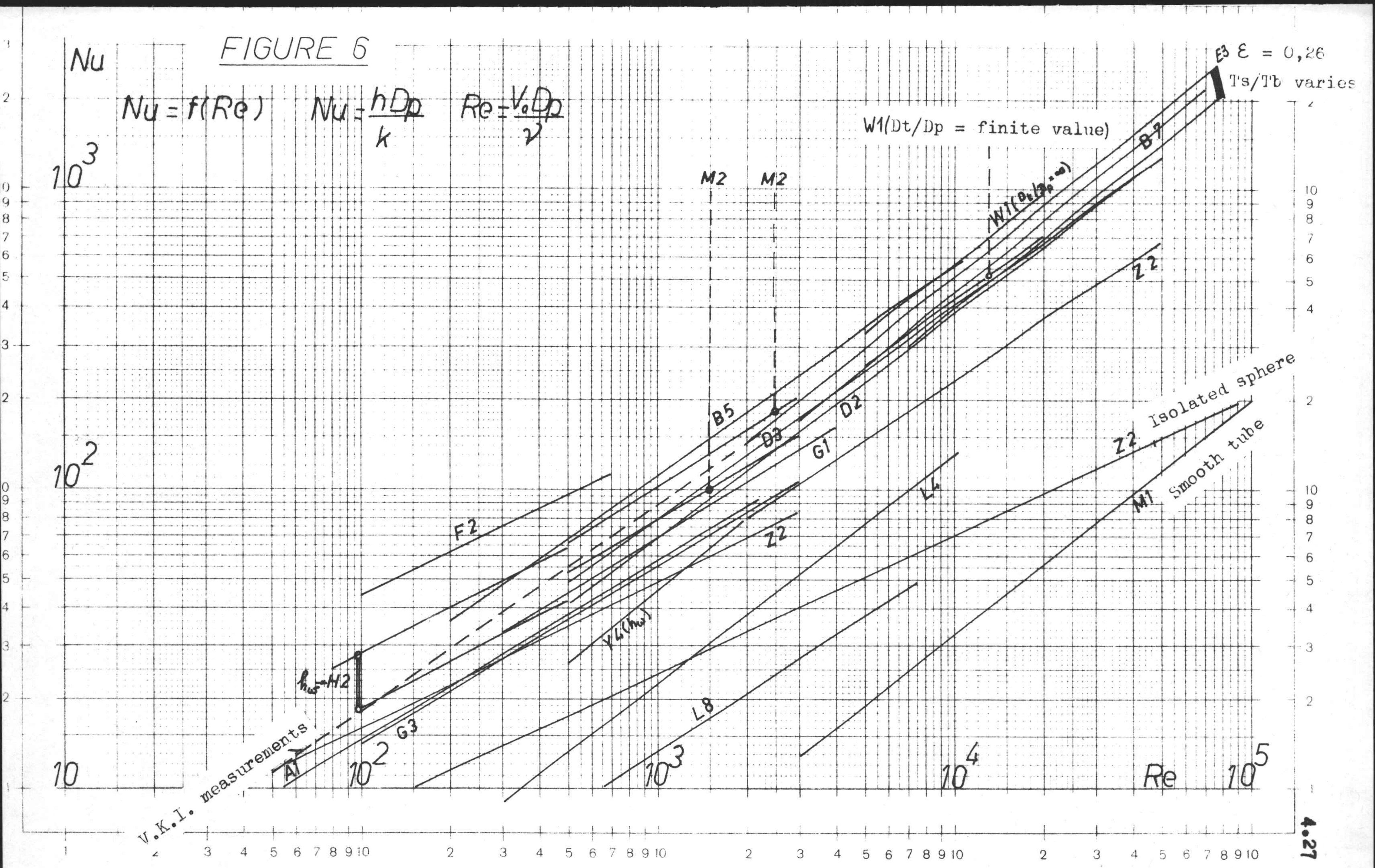


FIGURE 4b Test sphere (local values)

FIGURE 5

Contribution of various heat transfer mechanisms





Nr 369½ 1 P
Beide Achsen logar. geteilt von 1 bis 10000 und 1 bis 300 Einheit 62,5 mm

1

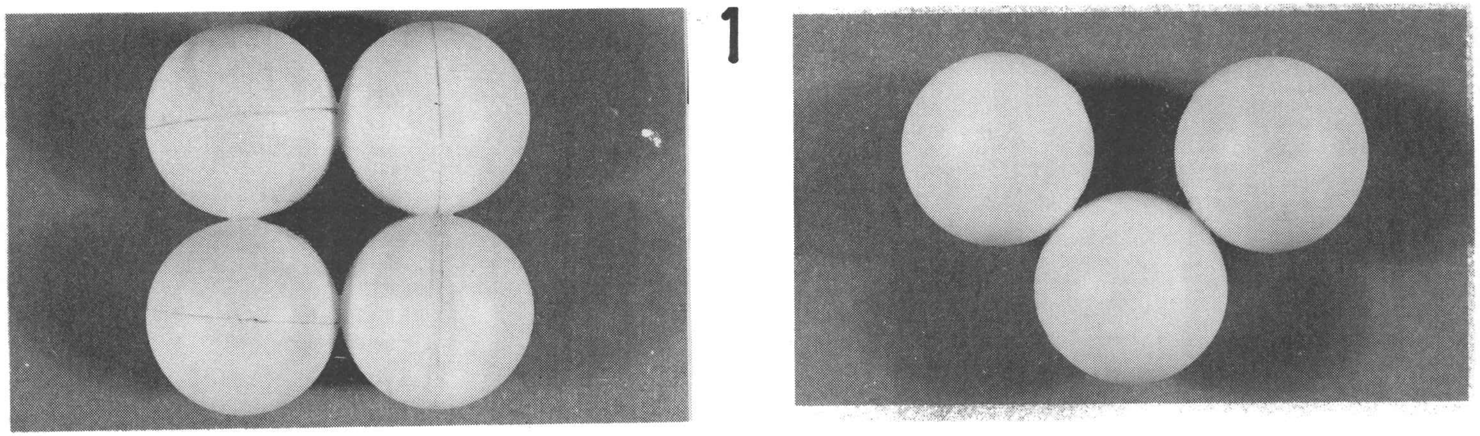
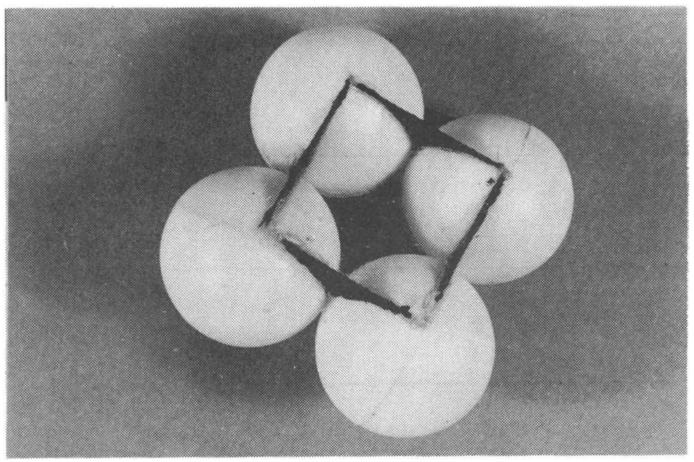


FIGURE 7a Considered Obstructions

2



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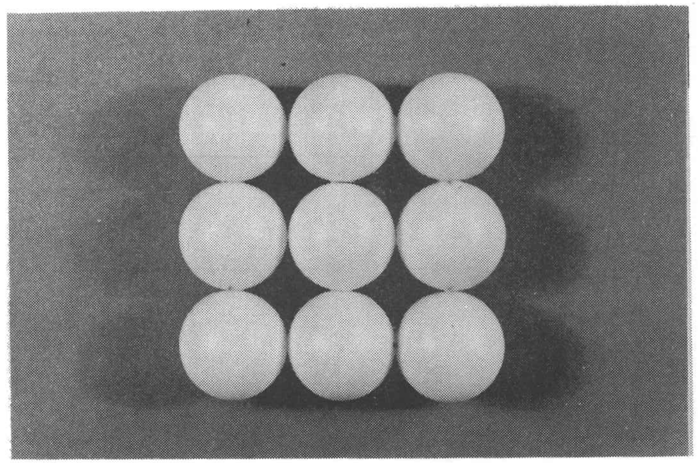

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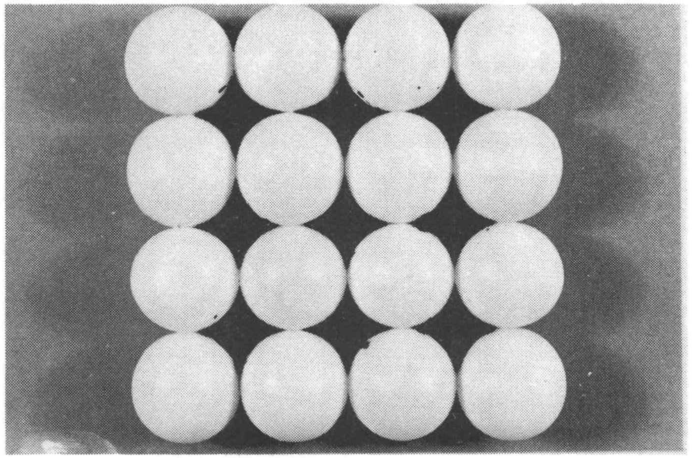

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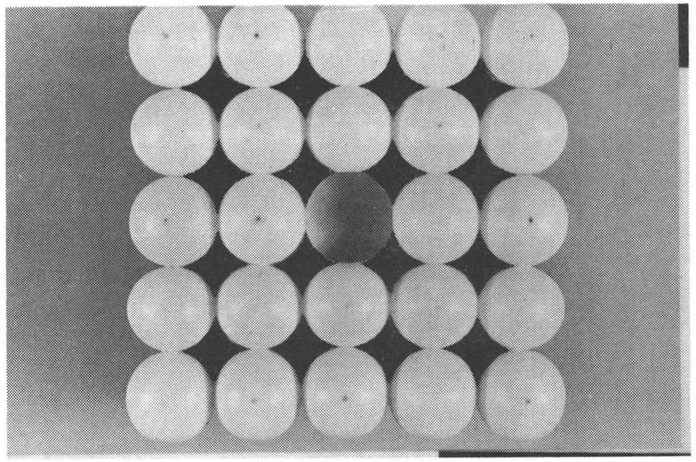
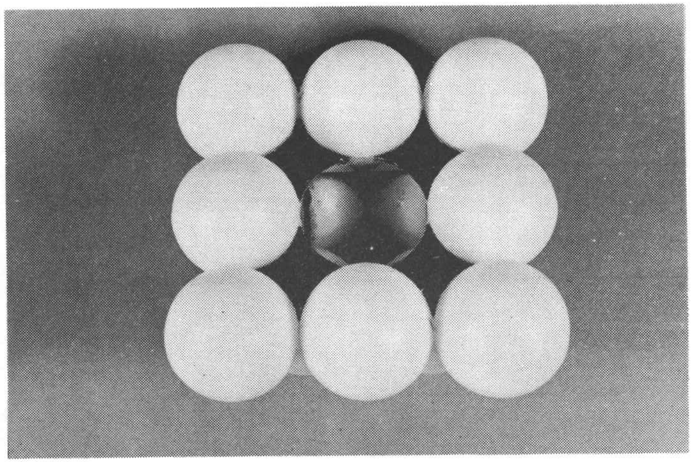


FIGURE 7b Considered Obstructions

6



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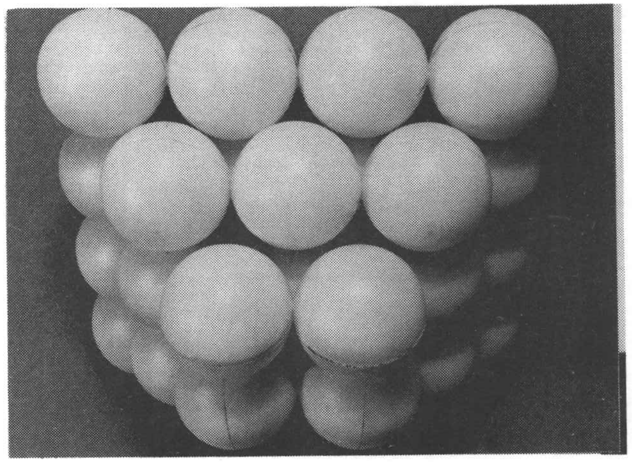

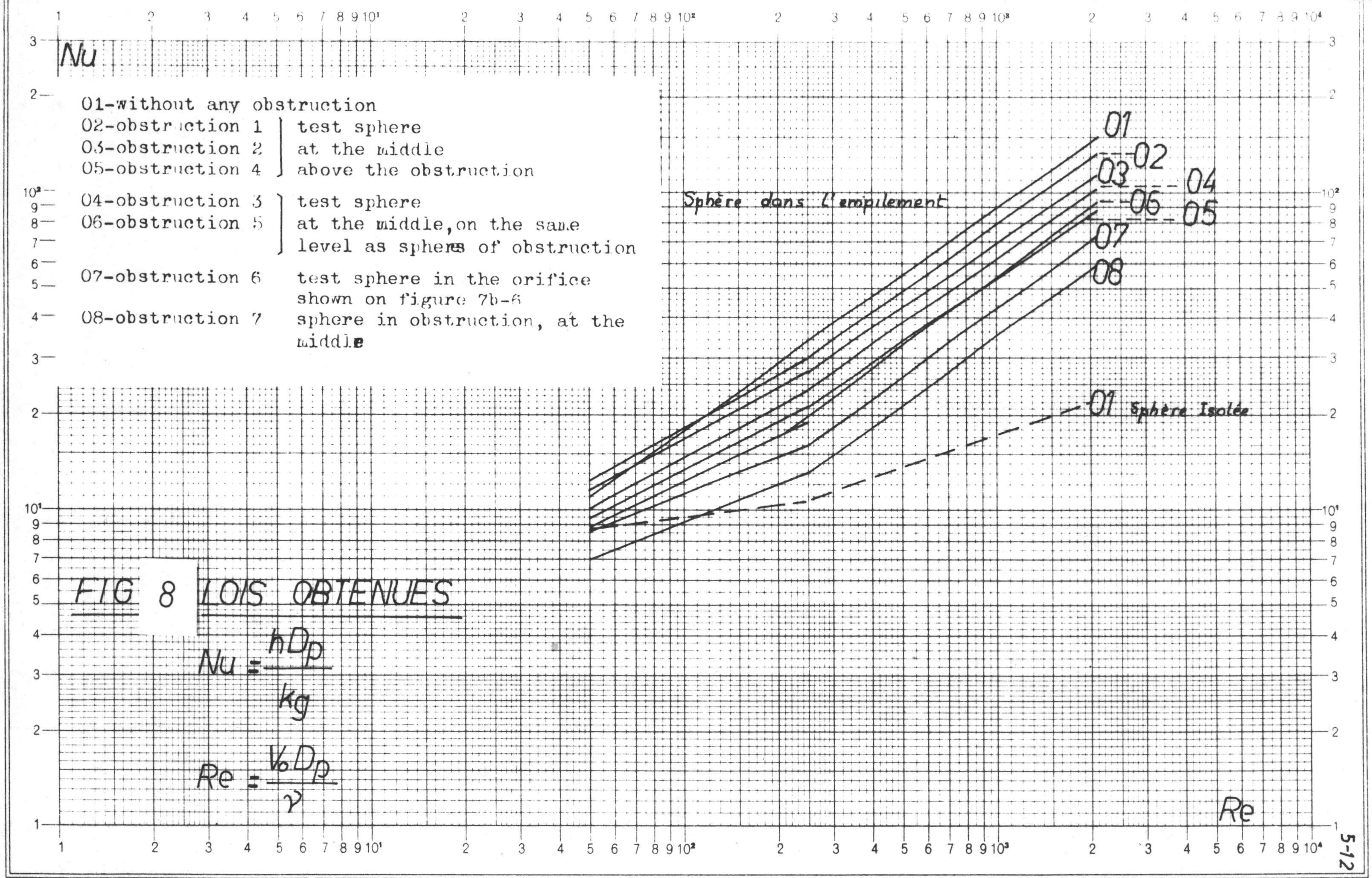

FIG 8 LOIS OBTENUES

5-12

Logar. Teilung / Division 1-300 u. 1-10000 Einheit / Unité 62,5 mm
Ed. Aerni-Leuch, Bern, Nr. 551

TABLE 9: OBTAINED LAWS - Nu = f(Re)

Coolant gas : Air - Prandtl number +0,7

CONSIDERED CASE		50 < Re < 250	250 < Re < 2000
Test sphere in the packed bed		$Nu = 0,716 . Re^{0,698}$	
Isolated sphere		$Nu = 4,555\ Re^{0,166}$	$Nu = 1,968\ Re^{0,317}$
OBSTRUCTION 1	Sphere at the middle of obstruction, above or under	$Nu = 1,452\ Re^{0,549}$	$Nu = 0,728\ Re^{0,674}$
OBSTRUCTION 2	Sphere at the middle of obstruction, above or under	$Nu = 1,555\ Re^{0,51}$	$Nu = 0,565\ Re^{0,694}$
OBSTRUCTION 3	Sphere at the middle of obstruction at the same level as spheres of the obstruction	$Nu = 1,192\ Re^{0,544}$	$Nu = 0,500\ Re^{0,703}$
OBSTRUCTION 4	Obstruction of 9 interstices, sphere at the middle	$Nu = 1,380\ Re^{0,500}$	$Nu = 0,628\ Re^{0,638}$
OBSTRUCTION 5	Obstruction of 16 interstices, sphere at the middle	$Nu = 1,318\ Re^{0,483}$	$Nu = 0,372\ Re^{0,723}$
OBSTRUCTION 6	Obstruction 2 + Obstruction 3. Sphere at the middle of obstruction 3, at the same level as spheres of this obstruction	$Nu = 1,724\ Re^{0,408}$	$Nu = 0,334\ Re^{0,702}$
OBSTRUCTION 7	Obstruction 1 + Obstruction 3 + Obstruction 4. Sphere at the middle of obstruction 3, at the same level as spheres of this obstruction.	$Nu = 1,568\ Re^{0,384}$	$Nu = 0,282\ Re^{0,694}$
General form of equations		$Nu = A.\ Re^{B}$	

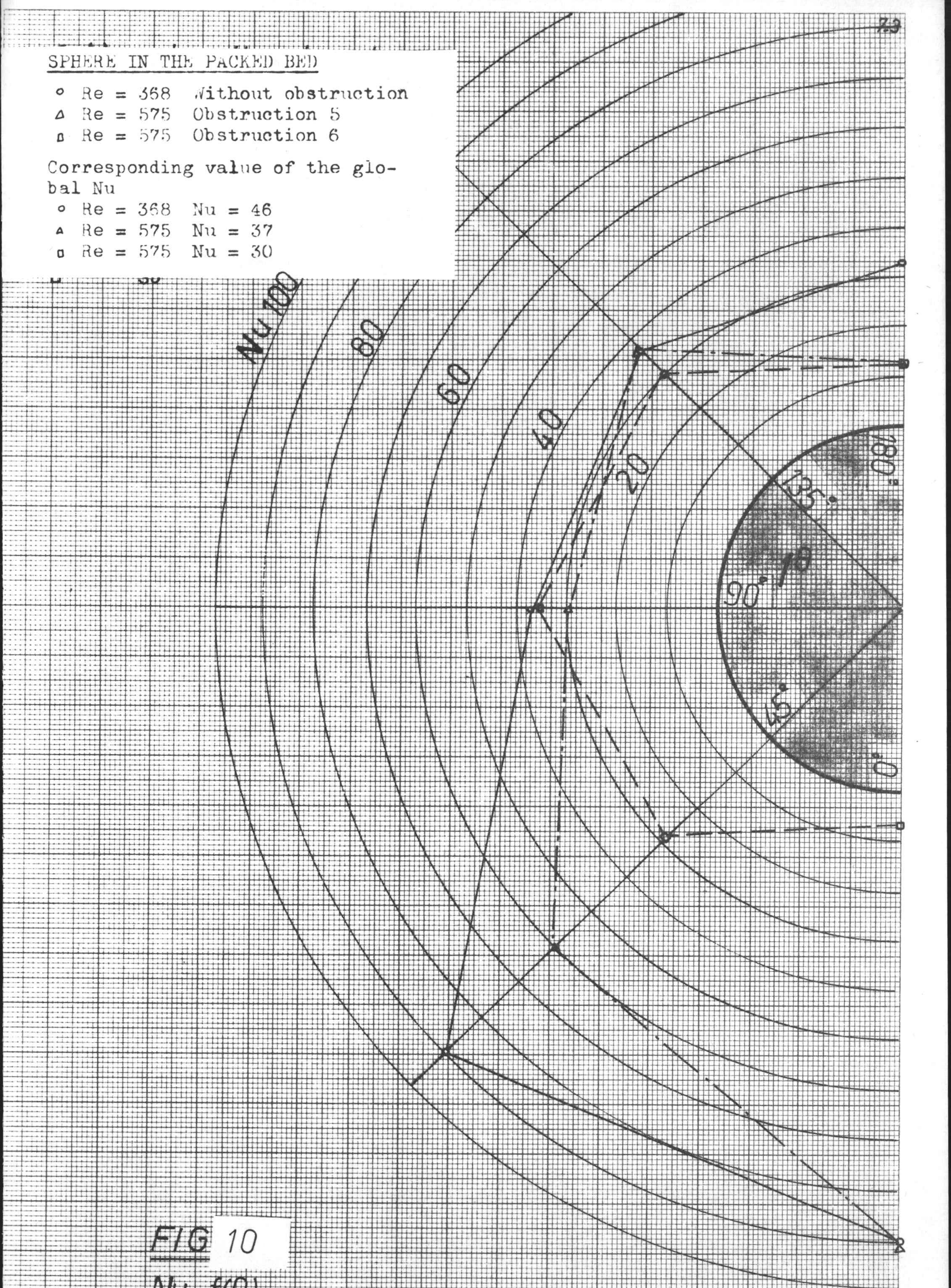

FIG 10

Nu = f(θ)

Local measurements

FABRICATION SUISSE