NINETEENTH DRAGON COUNTRIES PHYSICS MEETING

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EXPERIMENTAL DETERMINATION OF THE K_{∞} FUEL TEMPERATURE COEFFICIENT FOR AN HTGR LATTICE (°)

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1) INTRODUCTION

This report outlines a measurement of the fuel temperature coefficient of k_{oo} for a HTGR lattice studied on in the RB-2 reactor of AGIP NUCLEARE, operating at the Montecuccolino Center in Bologna.

The measurement was closely linked to the k_{oo} determination carried out by oscillated zero reactivity technique [1] (this measurement, made by AGIP NUCLEARE is described in another communication presented in this meeting).

Basically the measurement consisted in the evaluation of poison amount which compensated the reactivity variation of the lattice element consequent to an increase of the fuel element temperature, and in the conversion of this poison amount ΔN_{Cu} in terms of Δk_{oo}, using the standard PCTR formalism.

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(1) The k_{oo} fuel temperature coefficient $\beta(T_f)$ is here defined as $\beta(T_f) = \frac{\Delta k_{oo}}{\Delta \sqrt{T_f}}$, where T is expressed in degrees Kelvin and the index f refers to fuel.

1 G.GHILARDOTTI et al:

"Misure del k_{oo} di un elemento di reticolo di tipo HTGR eseguite con la tecnica dell'oscillatore a reattività nulla impiegando il Reattore RB-2 dalla AGIP NUCLEARE installato e funzionante presso i Laboratori Nucleari di Montecuccolino".

Relazione AGIP NUCHELARE n° 429/FNU (agosto 1974).

The measurement was performed in the RB-2 reactor, using the configurations of the central HTGR experimental zone (see figs. 1 and 2) which, in the previous room temperature measurement made by AGIP NUCLEARE, showed to meet best the neutron spectrum and space distribution requirements of the experiment.

The measurement was performed by a reactor oscillation method, with the following procedure:

1) A special 2-m-long test element (described in detail in para.2) was built, with a test section placed at 2/3 of its height from the bottom, heated by electrical resistors.

2) The AGIP NUCLEARE oscillator, in the version capable to achieve a 2-m-stroke, was employed.

3) The pile neutron modulation signal induced by the periodic substitution of the (cold) HTGR fuel by the heated section, was interpreted in terms of a Fourier series expansion obtaining (A/P) = (first harmonic amplitude/mean value).

4) The (A/P) values measured as a function of temperature were converted into equivalent poison (Cu) amount, using the (A/P) vs. poison relationship obtained in the room temperature k_{oo} experiment [1], leading, as a final result, to $k_{oo} = f(T)$.

A fuel temperature coefficient experiment requires an elaborate and careful experimentation and interpretation. In fact a requirement to be-met for an effective interpretation of this kind of experiment is the uniform temperature distributions over the heated fuel segment. This means radial and axial insulations, implying modifications of the fuel cell standard geometry, as well as addition of foreign materials, which however should do not perturb appreciably the typical HTGR spectrum. Some heat leakage from the heated element to the reactor core also accours: its effect on reactivity must be accounted for, e.g. heating a test section without fuel.

Obviously the interest is to achieve test fuel temperatures close to the power reactor core values, but, in this sense, a serious limitation is the resistance of the experimental set-up to high temperatures.

The criteria used to approch the above requirements are summarized in the following chapter.

2) HEATED FUEL SECTION AND OSCILLATING ELEMENT

The heated zone was a 137 mm-high segment of fuel element (fig. 3 and 4), with electrical resistors(KANTHAL "A", Ni-Cr 0.3 mm dia.wire) wounded around two graphite tubes (19.2,27 mm dia.and 42 and 49.8 mm dia. resp.) containing the fissile particles. Electrical insulation was provided by an Al_2O_3 coating (0.5 mm thick, initial resistance 5÷10 MΩ) sprayed on the graphite before winding the Ni-Cr wire, which was kept in place by an additional 0.5 mm thick Al_2O_3 deposit. Axial thermal insulation was provided by suitably machined "wonderstone" (SiO_2 55%, Al_2O_3 35%) end-plates which also centered the heated element in the containment tube.

The two electrical resistors (11Ω, 23Ω on outer and inner tube respectively) had indipendent regulation through 0÷270 V, 500 W, variable autotransformers,connected to the mains by an insulation transformer. By a proper adjustement of the inner to the outer heating power, it was possible to flatten the radial temperature distribution in the fuel at each selected temperature.

The temperature distribution in the heated fuel element was measured by chromel-alumel thermocouples, with 0.8 mm dia. stainless steel cladding, inserted into 1.5 mm dia. axial holes through the inner and outer graphite tube walls. In order to limit the complexity of the assembly, only four thermocouples were placed inside the heated fuel segment: two were positioned at the section midplane and two could be moved to obtain a detailed axial temperature mapping.

The "cold point" of the thermocouples was thermally connected to the cover plate of the oscillating element containment tube; the temperature of the cold point was monitored by an additional thermocouple with head embedded into this plate. The thermocouple signals were transferred to a Leeds and Northrup SPEEDOMAX 12-point recorder. Only the thermocouple monitoring the cold point needed to be connected through chromel-alumel compensated wires.

The heated element was inserted between two HTGR fuel segments inside a 60 mm dia. 1 mm thick, 3655 mm long Zr2 containment tube. The segments length was 1033 mm (upper fuel) and 2339 mm (lower fuel), respectively. The segments facing the heated element had an additional insulation in wonderstone (10 mm thick). The temperature beyond the insulation was monitored by a thermocouple inserted in the upper fuel segment, 10 mm above the bottom. The containment tube was exhausted to a residual pressure around 10^{-3} mm Hg, which was maintained dynamically by a vacuum pump. The 3 mm vacuum gap, between the outer tube of the heated fuel section and the Zr2 tube inner surface, represented an effective radial heat barrier up to the highest temperature achieved in the experiment.

The oscillating fuel element was centered and guided through a 61.7 mm dia. channel on the HTGR core axis by two sets of rollers, fixed to the upper and lower cover plates.

Preliminary calculations indicated that the modifications in the lattice geometry and composition introduced by the experimental equipment either had negligible effect or could be theorically corrected for. These indications were substantially confirmed through a series of experimental tests, in part reported in the following.

3) OSCILLATOR DEVICE

A detailed description of the oscillator and related instrumentation is reported in ref. [1] (see fig.5).

The oscillator parameters fixed fo the experiment were: stroke = 120 mm, transit time = 2 sec. .

In these conditions the max. axial accelerations impressed to the oscillated load did not exceed 0.3 g, as measurd by a wide band accelerometer.

4) EXPERIMENTAL PROCEDURE (REACTIVITY MEASUREMENTS)

The experimental procedure consisted of the following steps:

a) heating up of the test section to the specified temperature, with the test-section in the off-core position to avoid any heat trasmission to the HTGR core, in the shortest time - compatible with a reliable operation of the heaters - in order to minimize heating of the cold segments of the oscillating element (typical values to reach a test-section temperature of about 600°C: 66 V, 6A for the outer resistor; 69 V, 3A, for the inner resistor; 10 min. rise time);

b) temperature stabilization and radial flattening by fine adjustement of the inner to the outer heating power (typical values at 600°C: 64 V, 5.7 A and 25 V, 1.1 A for the outer, respectively inner, resistor);

c) starting of test section oscillation in-off the reactor core (1250-mm-stroke, 120-sec-period);

d) reactor stabilisation at 1 W average;

e) recording the reactor neutron density modulation over 20÷40 oscillation periods.

The experiment was carried out for the following nominal fuel temperature values: 20,200,300,400,500,600°C.

The radial temperature gradient across the 6.5 mm-thick fuel annulus was made negligible by the inner-to-outer heating power adjustement; the axial temperature variation expressed as the ratio of the boundary-to-center value, was typically 3% at 600°C.

Due to the fact that the U^{238} resonance absorption was concentrated in the outer layer of the fuel element it was deemed of interest to investigate situations with a radial temperature gradient across the fuel.

To this effect a series of fuel temperature coefficient determinations was performed, where no current was supplied to the test fuel inner heating resistor.

This procedure resulted in a significant radial temperature variation, (about 10%) tipically 50°C for an average fuel temperature around 600°C.

5) AUXILIARY MEASUREMENTS

5.1 Check of correct spectral matching

Although in principle the circumstance that the HTGR test lattice used for the fuel temperature coefficient measurement was the same as the test lattice used for the room temperature k_{oo} determination should imply the identity of the neutron spectra, it was felt advisable to perform a direct experimental test of the above assumption.

Since previous experience showed that the fuel initial conversion ratio ICR (i.e. the ratio of fissile production by fertile capture to fissile consumption) is a very sensitive index of the so called matching of the finite test zone spectrum to the asymptotic spectrum (for infinite medium), this parameter is the measured at different levels in the fuel test-element not heated, and compared to the value measured during the room temperature k_{oo} experiment.

The measurement was performed by a standard activation method using as detector the same coated fuel particles contained in the fuel section.

The agreement between the two sets of measured values (2.18 ± 0.02 vs. 2.22 ± 0.02, mean values) extends up to the outer 1-cm-thick layer of the heated fuel section whose ICR value is about 10% higher.

This increase is attributed to the higher local U^{238} resonance capture caused by streaming of resonance neutrons through the gaps between the heated fuel section and the upper and lower cold fuel segments.

Since the discrepancy reduced to a negligible value within 1.5 cm from the heated fuel section ends, it had a trivial effect on the experimental results.

5.2 Check of the (A/P) vs. poison mass relationship

Although the present experimental parameters *), were such that the same (A/P) vs. poison mass relationship found in the room temperature k_{oo} experiment applied to the fuel temperature coefficient experiment, it was felt advisable to perform an experimental check of this fundamental condition, namely measuring directly A/P vs. various poison amounts fixed to the outer surface of the aluminum tube containing the fuel in the oscillating element. This was possible because the length of the lower segment of the oscillating was such that the "standard" HTGR lattice configuration was reproduced, when the element was rised to bring the heated fuel section to the "off-core" position. (The only difference, which consisted in the presence of a Zr2 containment tube had no relevance).

In fig.6 the different positions of the poison for the room temp.k_{oo} experiment [1] and for the present experiment are indicated.

The A/P vs.poison mass relationship measured in the present experiment with poison mass normalized to the room temp.k_{oo} exp. through the thermal fluxes ratio

(*) i.e. The same HTGR lattice configuration and identical oscillation conditions.

(1.02)calculated by the THERMOS code,is shown in fig.7. The angular coefficient of the straight line fitted through the measured points is 5.65 , in good agreement with the corresponding value (5.71) inferred from the previous experiment.*)

5.3 Correction for heat leakage and spurious resonance capture [1]

Heat leakage from the heated fuel section resulted in a moderate temperature rise in the adjacent cold fuel segments ends, contributing to the measured A/P vs. fuel temperature.

An additional contribution came from heating of the foreign materials included in the instrumented element (e.g. due to the Doppler-effect on the neutron resonance capture of the Ni-Cr resistors).

Both contributions were simultaneously corrected for by subtracting the (A/P) values measured at varying temperatures of the heated section without fuel in it, from the (A/P) values of the fuel section heated to the same temperatures.

The approximations involved in this procedure were acceptable also in view of the small magnitude of the correction.

(*) N_{Cu} is expressed in 1.10^{+20} and A/P in 1.10^{-3}.

6) EXPERIMENTAL RESULTS

The A/P values measured for various temperature are reported in the graphs of figs. 9 and 10 in which the abscissa is in units of $(\sqrt{T_f} - \sqrt{T_{f_o}})$.

Since the temperature coefficient of HTGR fuel is mainly due to the Doppler-effect on U^{238} resonance capture, which usually exhibits a linear dependence on $(T_f - T_{f_o})$, we have fitted with a straight line, using the leastes square methods, the data points in fig.9. The interpolating lines equations so obtained are:

$$A/P = 6.615 \times 10^{-4} \ (\sqrt{T_f} - \sqrt{T_{f_o}}) \quad \text{(uniform temp.case)} \qquad (1)$$

$$A/P = 6.88 \times 10^{-4} \ (\sqrt{T_f} - \sqrt{T_{f_o}}) \quad \left\{\begin{array}{l}\text{radial gradient} \\ \text{temp.case}\end{array}\right\} \qquad (2)$$

NOTE:
This report was written shortly after the conclusion of the experiment; thus the interpretation is under way.

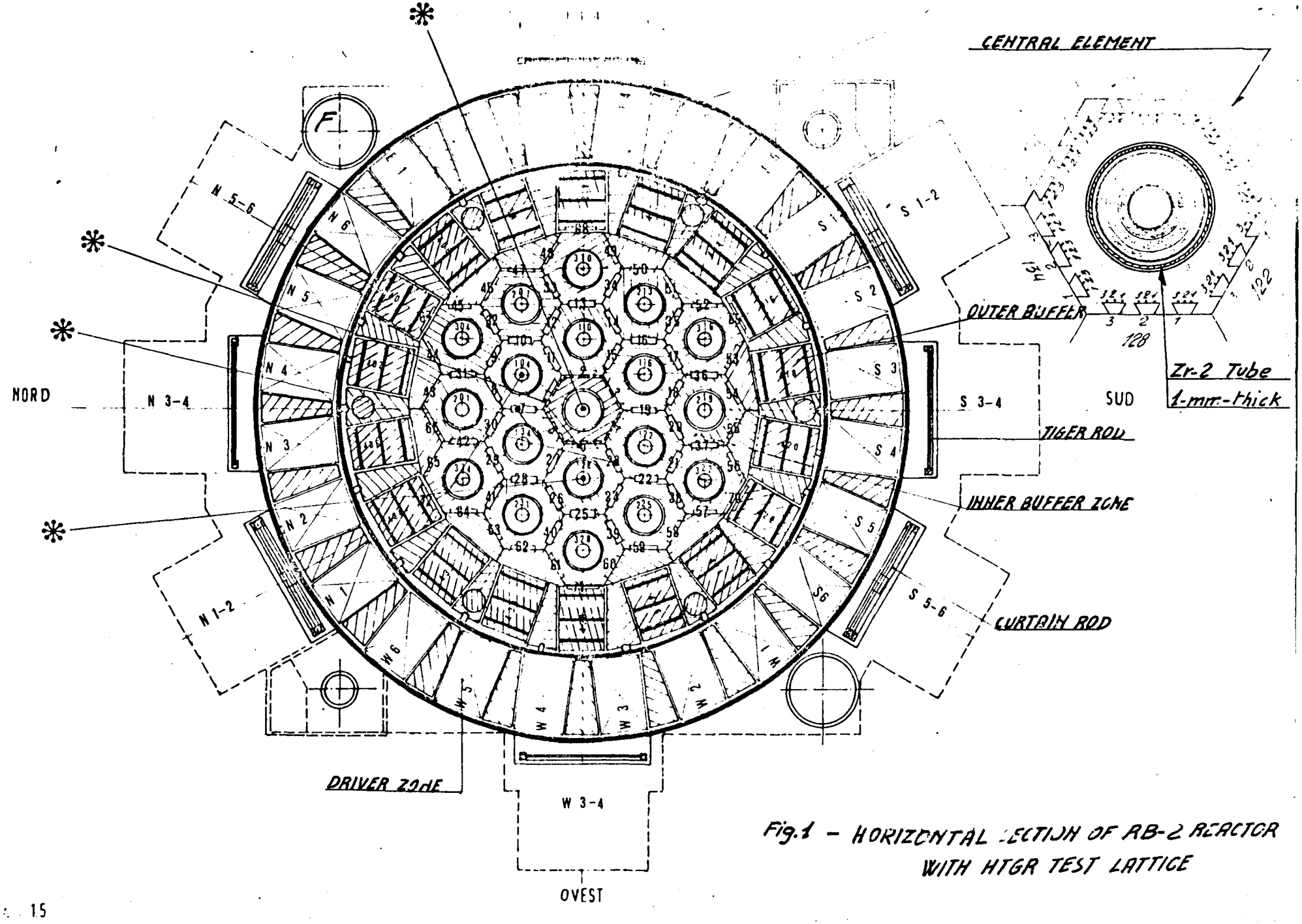


Fig. 1 – HORIZONTAL SECTION OF AB-2 REACTOR WITH HTGR TEST LATTICE

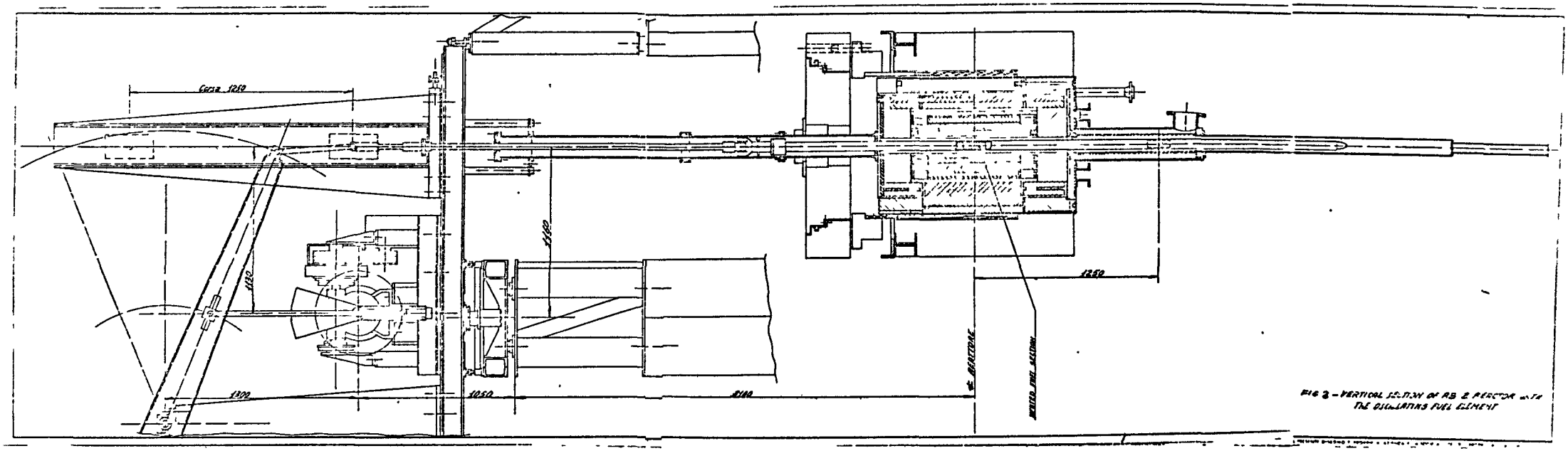


FIG 2 – VERTICAL SECTION OF AB 2 REACTOR WITH THE OSCILLATING FUEL ELEMENT

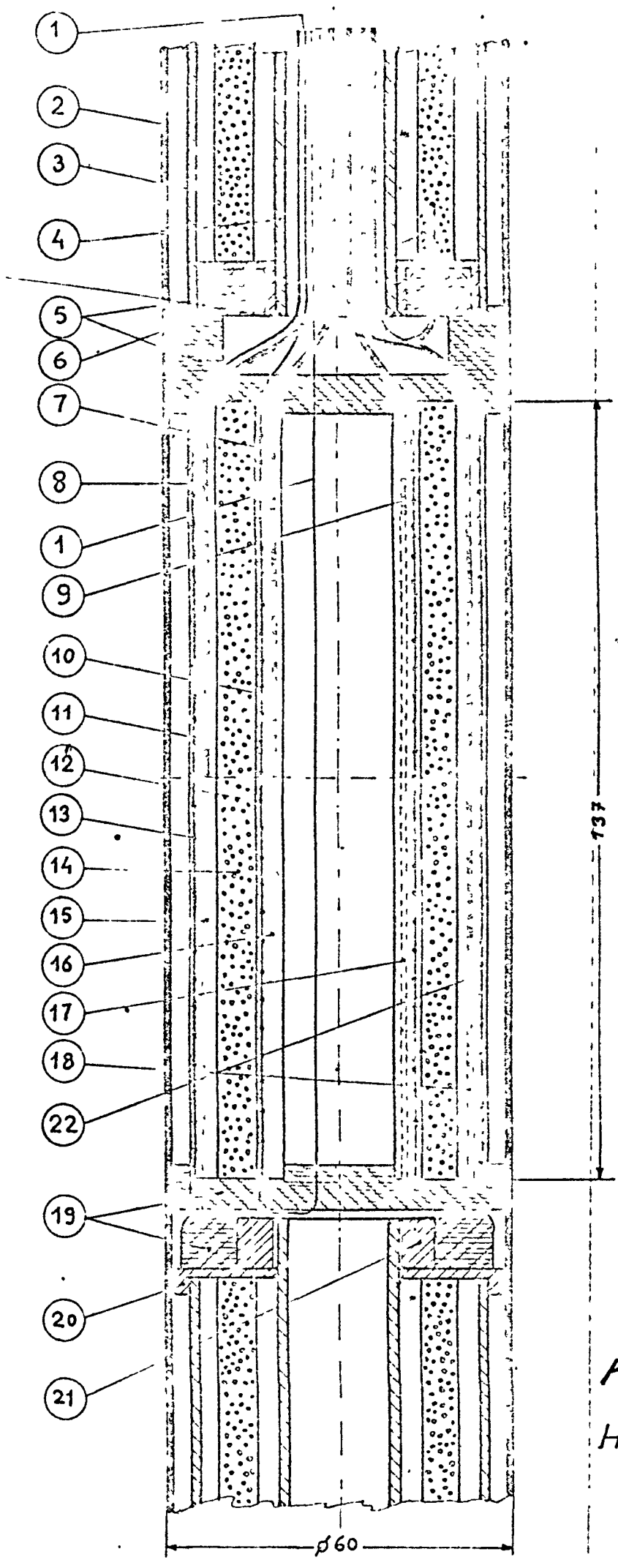


Fig. 3

Heated fuel section

Scale 1 1

HEATED FUEL SECTION

1. Electrical power supply
2. Zr2 containment tube
3. Outer Al tube
4. Inner Al tube
5. "Wonderstone" thermal insulation
6. Cold fuel thermocouple
7. Inner Al_2O_3 electrical insulation
8. Outer Al_2O_3 electrical insulation
9. Inner scanning thermocouple
10. Inner midplane thermocouple
11. Outer midplane thermocouple
12. Inner KANTHAL A resistance
13. Outer KANTHAL A resistance
14. Fuel microspheres
15. Outer graphite tube
16. Inner graphite tube
17. Inner tube through hole for thermocouple
18. Outer tube through hole for thermocouple
19. "Wonderstone" thermal insulation
20. Al cover of lower fuel section
21. Cover fixing ring
22. Outer scanning thermocouple

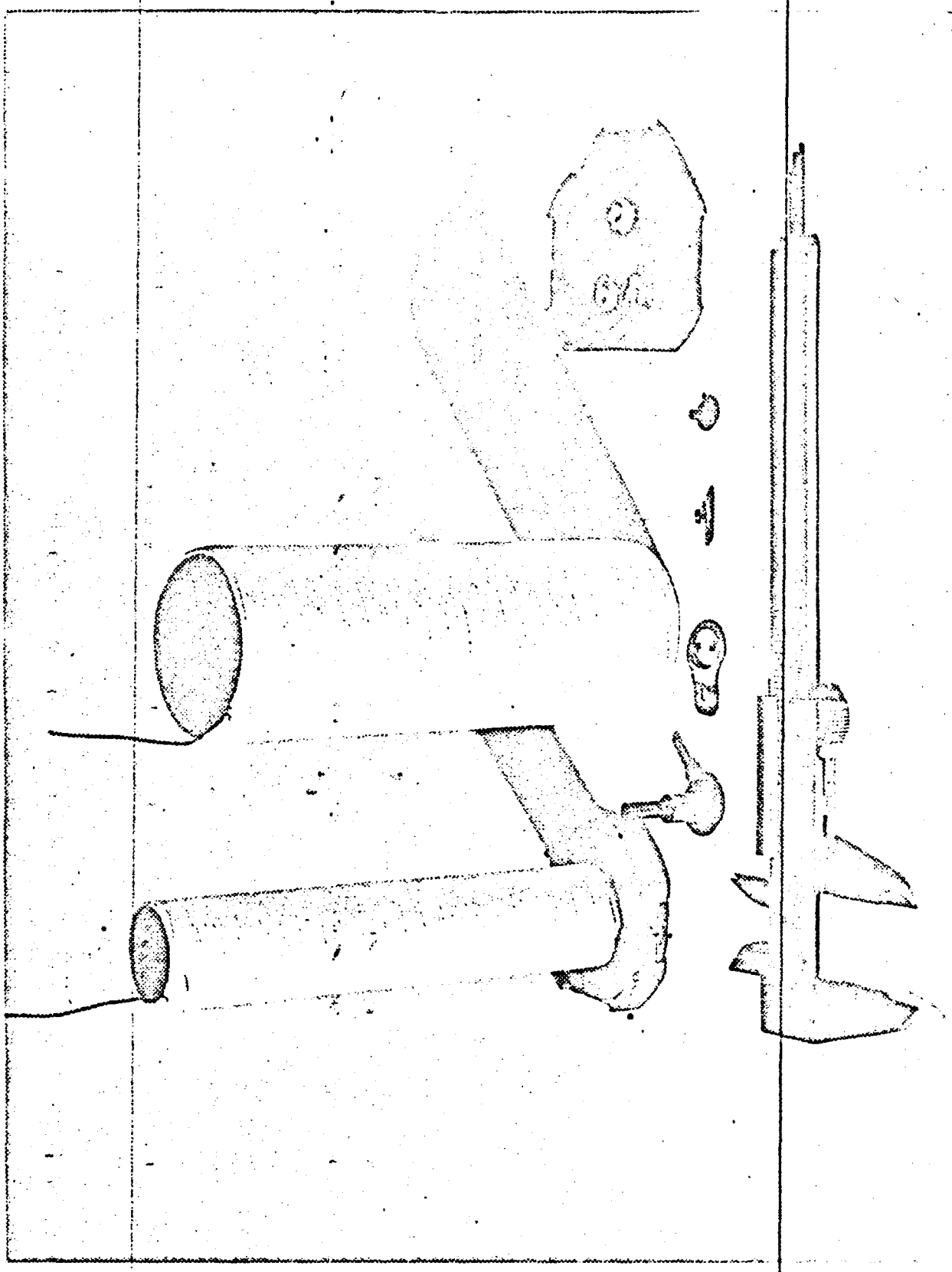


Fig. 4 — HEATED FUEL ELEMENT: components.

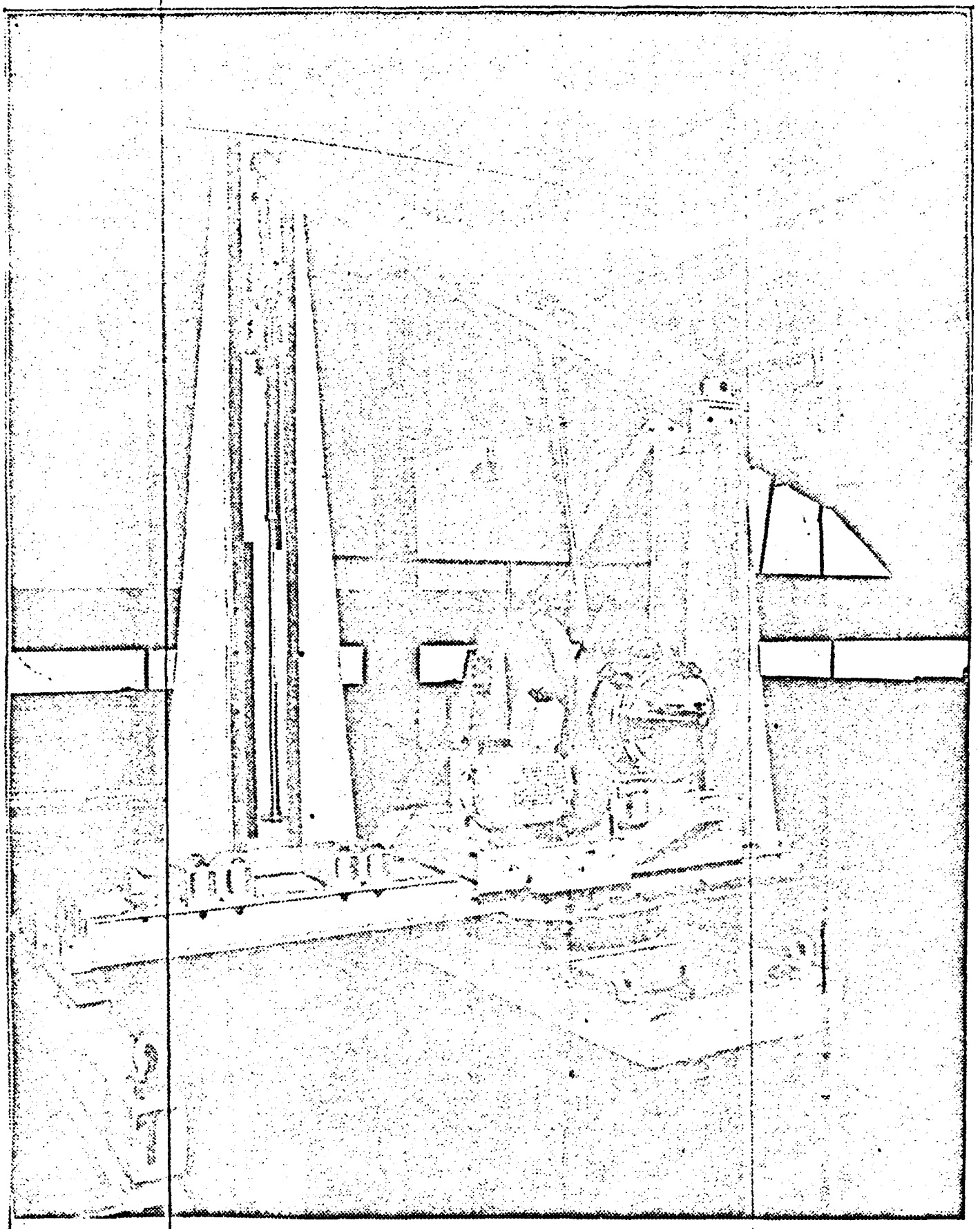
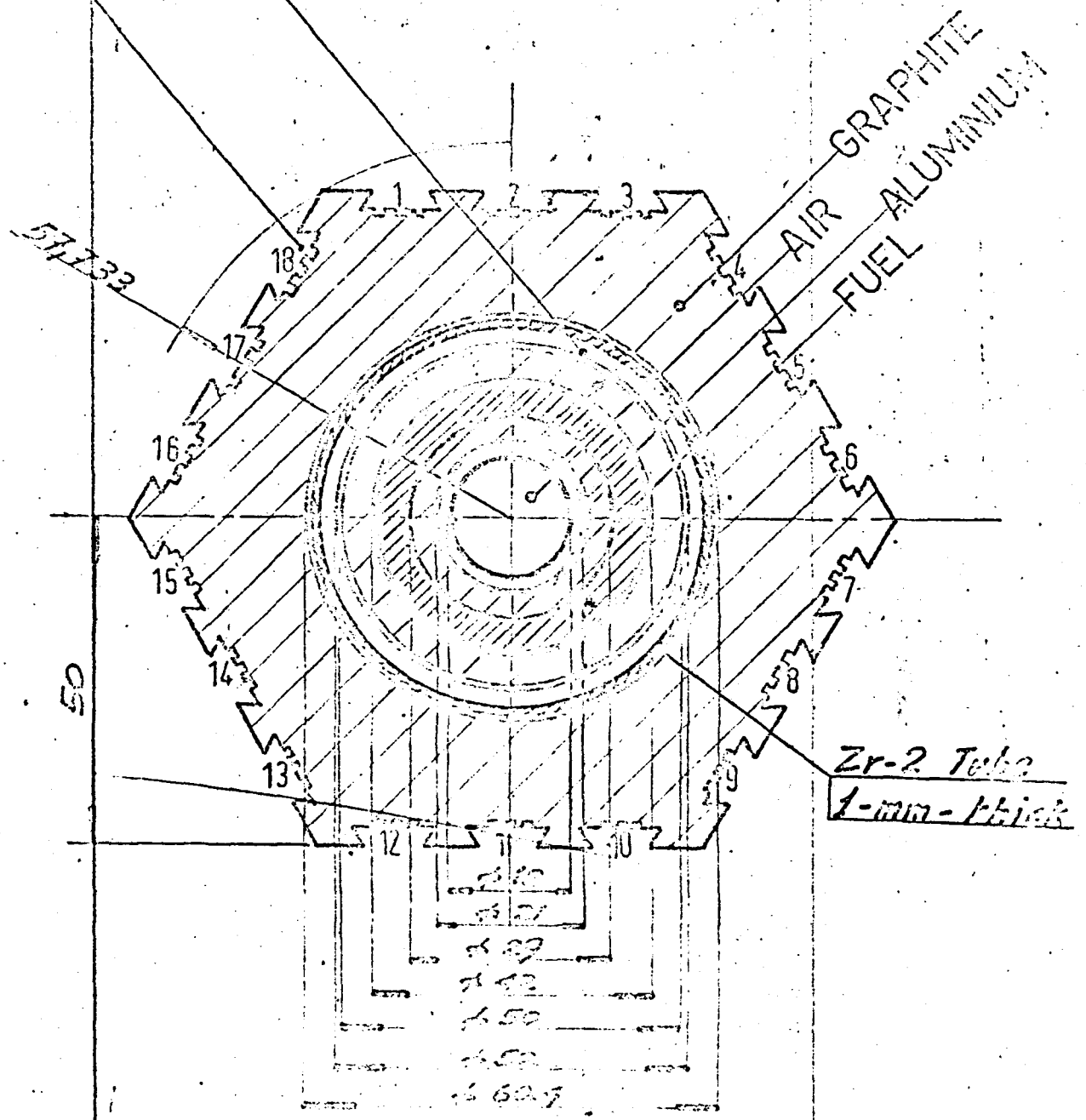


Fig. 5 _ MECHANICAL OSCILLATOR
in 2-m-stroke arrangement

Fig. 6 – HTGR CENTRAL LATTICE CELL WITH INDI
TYPICAL POISONING LOCATIONS: (a) and

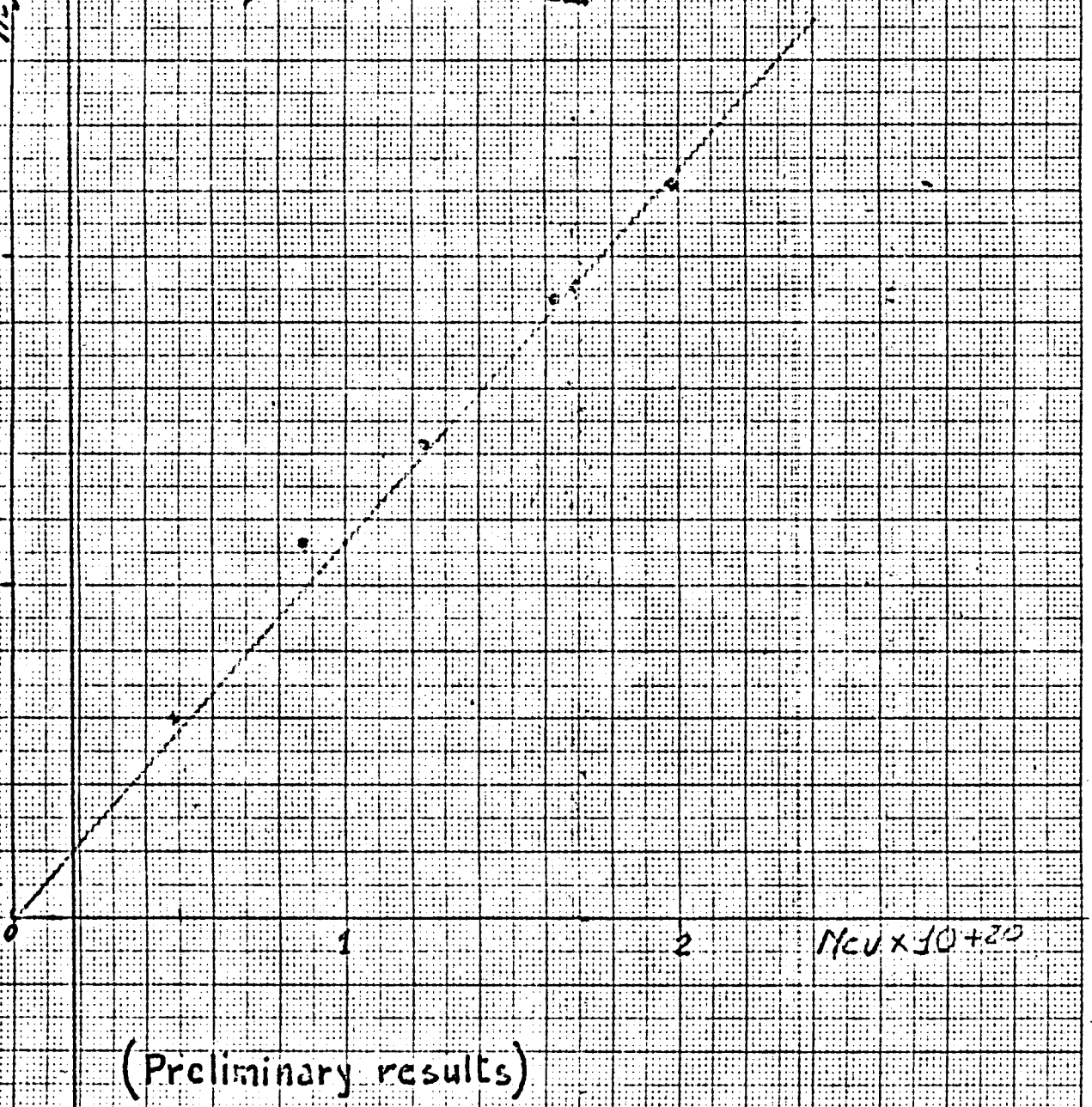
a) Reactor temperature experiment

b) Temperature coefficient measurements



R.M.L. = 1,01 gr/cm³
Nc / Nu = 277
Nc/Nu²³⁵ = 5035
K∞ = 1,391
Cv/Cr = 2,2

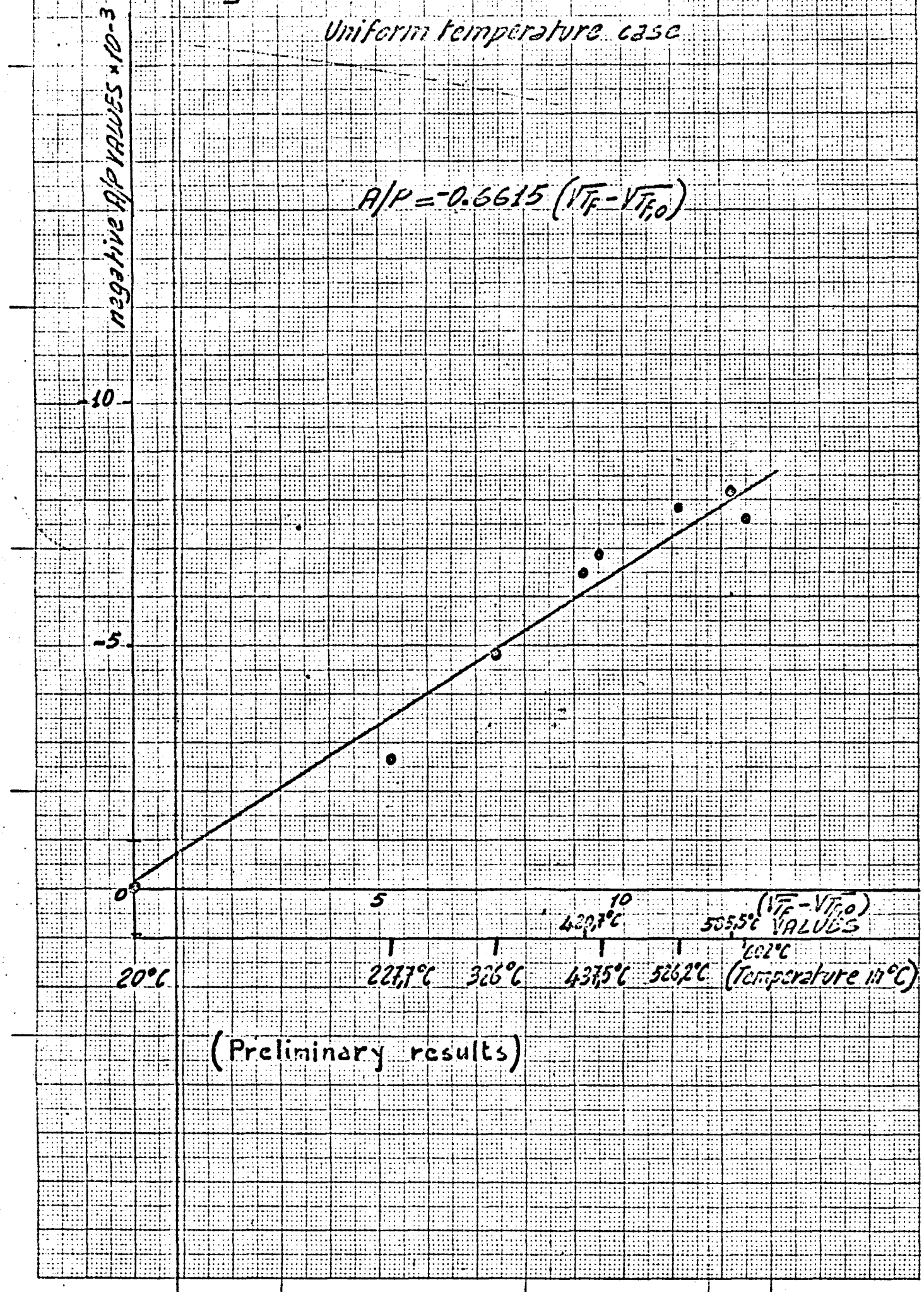
Fig. 7 - MEASURED (A/P) VS. POISON (α_{Cu}) MASS DEPENDENCE



(Preliminary results)

Fig. 8 – EXPERIMENTAL RESULTS:

Uniform temperature case



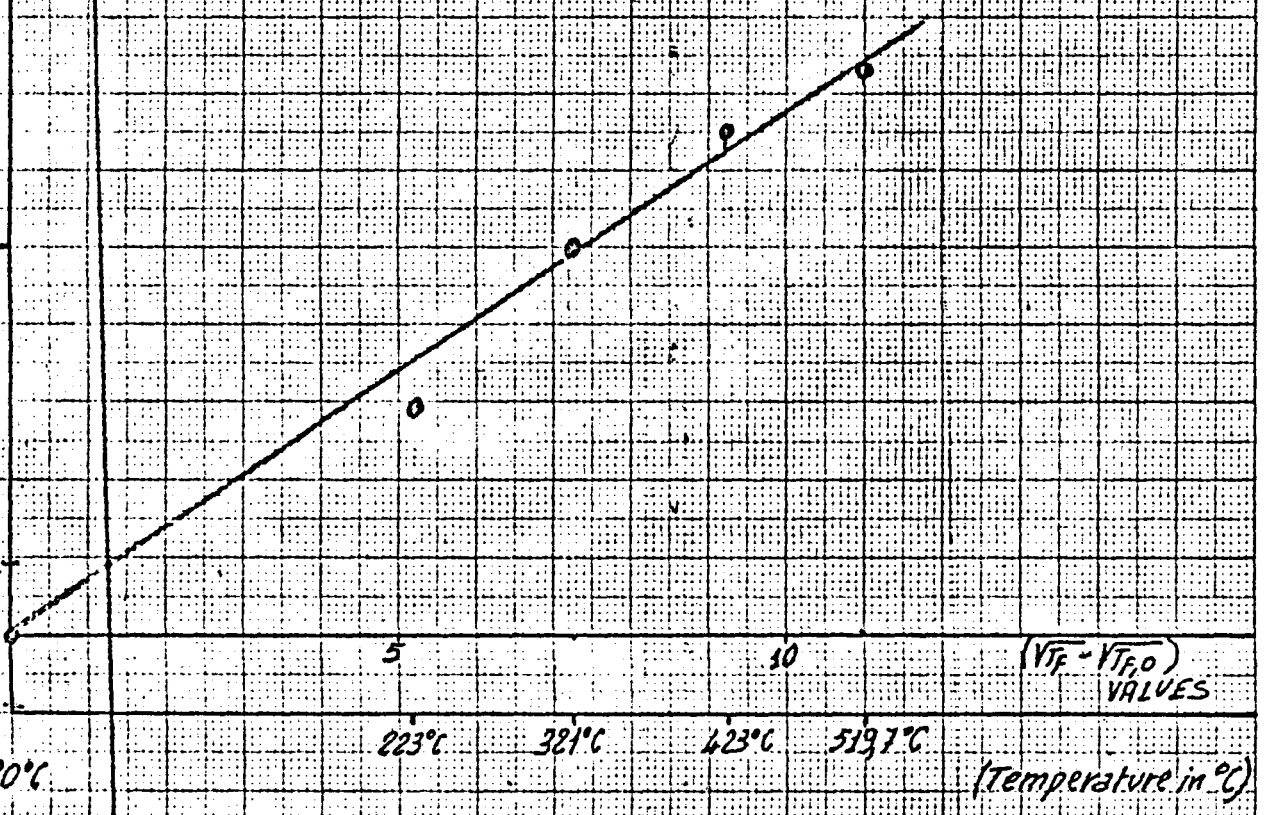
(Preliminary results)

DIN – A 4 210 x 297 mm

Fig. 9 _ EXPERIMENTAL RESULTS:

Radial temperature gradient case

$$A/P = -0.683\,(\sqrt{T_F} - \sqrt{T_{F,0}})$$



(Preliminary results)

DIN – A 4 210 x 297 mm.