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HEAT TRANSFER IN A FUEL ELEMENT GAS GAP

by

S. GIULIANI and C. MUSTACCHI

1964

ORGEL Program

Joint Nuclear Research Center
Ispra Establishment - Italy

Materials Department
Physical Chemistry Service

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C O N T E N T S

HEAT TRANSFER IN A FUEL ELEMENT GAS GAP

INTRODUCTION

Cold clearances between fuel and clad in ceramic fuel elements are usually in the range of 20 to 200 microns. A typical carbide element clad with sintered aluminium powder will operate at temperature of, say, 450°C for the clad and 900°C for the fuel surface. Under these conditions, since SAP and UC have expansion coefficients of about 22 x 10^{-6}/°C and 10 x 10^{-6}/°C, operating clearances are expected to be of the same order as cold assembly clearances.

In the case of actual contact, there is still a contribution due to conduction in the gas, the relevant separation being of the order of .1 to 1 micron.

However, whether or not there is contact between fuel and clad, distances are such that macroscopic gas conductivity is expected not to hold. Mechanisms of gas collision on the solid wall and approach to kinetic equilibrium must be taken into account. The aim of the present study was therefore the determination of a reliable model for the estimate of conduction across narrow gaseous gaps.

CHOICE OF A MODEL

A commonly used, model to evaluate heat transfer in small gaseous gaps assumes that the apparent gas width, is increased by two "extrapolation widths" g, given by:

$$g = \frac{2 - \alpha}{\alpha} \cdot \frac{2\epsilon}{\gamma + 1} \cdot L$$

where α is the accommodation coefficient between gas and wall, defined as the fractional attainment of thermal equilibrium,

$\gamma = Cp/Cv$

$\epsilon = (9\gamma - 5)/4$, and

L = gas mean free path in cm

ϵ = ranges from 1 to 2,5.

It should be born in mind that even with perfect accommodation, i. e. $\alpha = 1$, the extrapolation width does not vanish, but reduces to about two mean free paths.

An alternative model is also possible. One assumes the existence of three gas layers in series. Two of these layers have a thickness L and are located along the walls. In these layers heat is transferred by molecular conduction, i.e. the energy exchanged in watt/cm^2 is:

$$Eo = \alpha \Lambda o P \sqrt{\frac{273}{T1}} (T_s - T_1)$$

where T_s and T_1 are the temperatures of the wall and of the impinging molecule, and Λo is the "free molecule conductivity " at 0°C (§). The central layer is sufficiently large as compared with L for "classical" gas conductivity to hold. Summing the heat resistances of these three layers, we obtain, for a cylindrical gap:

$$\frac{\Delta T}{E-Er} = \frac{1}{\pi \Lambda o P d \sqrt{273}} \left(\frac{\sqrt{T_1}}{\alpha_1} + \frac{\sqrt{T_2}}{\alpha_2} \right) + \frac{S - 2L}{\pi d K} \qquad (1)$$

where d is the mean gap diameter in cm

S is the gap width in cm

K is the gas conductivity in watt/cm x degree

Subscripts 1 and 2 refer to each wall.

ΔT is the temperature drop across the gap in °C

E is the energy transferred in watt per cm length

Er is the radiated energy in watt per cm length

(§) Λo is given by:

$$\Lambda o = \frac{1468 \times 10^{-5}}{M^{\frac{1}{2}}} \quad \frac{\gamma + 1}{\gamma - 1} \quad \text{watt/cm}^2 \text{ x deg x micron)}$$

when P is pressure in microns.

Since L can be assumed to vary inversely with pressure, we set:

$$L = 10^3 \, L'/P \text{ and } \sqrt{T_1} = \sqrt{T_2} = \sqrt{T}$$

where L' is the mean free path at 1 mm Hg, and rewrite equation (1):

$$\frac{\Delta T}{E-Er} = \left[\frac{T^{\frac{1}{2}}}{\pi \Lambda o \; d \; \sqrt{273}} \left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2} \right) - \frac{2000 \; L'}{\pi \; d \; K} \right] \frac{1}{P} + \frac{S}{\pi d K} \qquad (2)$$

Equation (2) shows that a plot of $\Delta T/E - Er$ versus $1/P$ is linear. The intercept yields the thermal conductivity K and the slope yields the harmonic mean of the accommodation coefficients. Measurements in a good vacuum will yield values of Er.

EXPERIMENTAL

The first series of experiments was performed with UC pellets and aluminium tubes having radial gaps of 2 to 5 mm. At temperatures around 500°C the radiation correction was an order of magnitude higher than gas conduction. We therefore reduced the gap to 0,6 mm; in addition Al - Al walls were used so that the experiment yield only α gas-Al. At a later stage UC-Al experiments were resumed and α UC-gas obtained by correcting α harmonic mean with the known values of α gas-Al.
As shown in fig.1, the pellets were heated by an axial tungsten wire insulated with an alumina sleeve and having connections for current and voltage probes. One Pt/Pt-Rh thermocouple was inserted in the centre pellet and one in the clad. Both pellets and clad were essentially isothermal at the low power ratings used in the runs (1 to 5 watt per cm length). Radiation determinations were made with a vacuum better than 10^{-5} mm Hg. In both series of runs, i.e. Al-Al and UC-Al the five gases H_2, He, Ar, Kr and Xe were used.
Pressures ranged from to 10 to 100 cm.

Figures 2 to 7 show the experimental results. Ordinates represent the temperature drop divided by the conducted power per unit length. Linearity appears to be quite good in most runs. A least square regression was used for data fitting.

RESULTS AND DISCUSSION

Analysis of the preceding runs yielded values for the accommodation coefficients as plotted in fig. 8 and tabulated in Table 1.

TABLE n. 1

Harmonic mean accomodation coefficients

Gas	Al-Al surfaces	Al-UC surfaces
H_2	.28	.25
He	.41	.35
Ar	.77	.48
Kr	.63	.47
Xe	.42	.31

Accommodation coefficients did not vary by detectable amounts in the range 450-750°K.

Figure 8 shows also a plot of:

$$\alpha = 1 - \left(\frac{M - m}{M + m} \right)^2 \qquad (3)$$

calculated with the assumption that the surfaces involved are not Al and UC but Al_2O_3 and UO_2. M and m are the masses of the gas and wall atoms respectively. The relative collision probability of gas atoms with Al and O or U and O was estimated as proportional to the 2/3 power of atomic weight.

It is seen that experimental results show the same trend as the calculated plot, but with values roughly 30% lower. It is therefore proposed to use as working values for estimating temperature drops across small gasfilled gaps equation (2) together with accommodation coefficients obtained from (3), but reduced by 30%.

APPENDIX 1: Mean free paths

To estimate the mean free path at the mean temperature of the gas, a Sutherland-type formula (§) was used:

$$\frac{L'_T}{L'_o} = \frac{T}{273} = \frac{1+\frac{C}{273}}{1+\frac{C}{T}}$$

with the following values of C and L'_o

Gas	C	L'_o
H_2	84.4	8.39×10^{-3} cm
He	86	13.32×10^{-3} cm
Ar	142	4.71×10^{-3} cm
Kr	188	3.69×10^{-3} cm
Xe	252	2.64×10^{-3} cm

(§) Scientific foundations of vacuum technique - S.Dushman, J.M. Lafferty Editor (1962).

APPENDIX 2: Extrapolation widths

Analysis of our data yields the following values for extrapolation widths:

Surfaces	Gas	g at 1 atm and 250 to 500°C
Al-Al	Ar	2.9×10^{-5} cm
Al-Al	He	18.8×10^{-5} cm
Al-Al	Xe	4.4×10^{-5} cm
Al-Al	Kr	3.3×10^{-5} cm
Al-Al	H_2	18.9×10^{-5} cm
Al-UC	Ar	5.2×10^{-5} cm
Al-UC	He	16.8×10^{-5} cm
Al-UC	Xe	6.0×10^{-5} cm
Al-UC	Kr	4.7×10^{-5} cm
Al-UC	H_2	14.2×10^{-5} cm

APPENDIX 3: Application to a fuel element

For a cylindral fuel rod, the following equations will hold:

$$S = C + a_{clad} \frac{d}{2} (T_{clad} - 300) - a_{fuel} \frac{d}{2} (T_{fuel} - 300) \quad (4)$$

$$T_{fuel} - T_{clad} = \Delta T \quad (5)$$

$$\frac{\Delta T}{E} = \left(\frac{2T^{\frac{1}{2}}}{\pi \Lambda_o \, d \alpha \sqrt{273}} - \frac{2000 \, L'}{\pi \, d \, K} \right) \frac{1}{P} + \frac{S}{\pi d \, K} \quad (6)$$

$$J = E/4\pi \quad (7)$$

where:

d = the fuel diameter in cm
s = the operating gap in cm
C = the assembly gap in cm
J = the conductivity integral in watt cm^{-1}
T = temperature in °K
a = expansion coefficient in $°K^{-1}$

In the case of an SAP clad UC fuel pellet, assuming:

$a_{SAP} = 22 \times 10^{-6}$ $°K^{-1}$
$a_{UC} = 10 \times 10^{-6}$ $°K^{-1}$

and $T_{SAP} = 723°K$ (450°C), equation (4) yields:

$$S = C + .00253 \, d - 5 \times 10^{-6} \, d \times \Delta T \quad (8)$$

and combination of (8), (5), (6) and (7) gives

$$\Delta T = \frac{4J}{dK} \cdot \frac{\dfrac{2T^{\frac{1}{2}}K}{P\Lambda_{o\alpha}\sqrt{273}} - \dfrac{2000\ L'}{P} + C + .00253\ d}{1 + 2 \times 10^{-5}\ J/K}$$

Figures (9) and (10) show the actual temperature drop in the case of a 2,8 cm diameter fuel element filled with Ar or Xe at 1 atm pressure.

It is to be noted that this temperature drop cannot exceed in any case the value for actual contact, i.e. that obtained with equation (8) when S = 0.
Fig. (11) shows this maximum possible temperature drop as a function of the ratio (radial assembly clearance) / (fuel diameter).

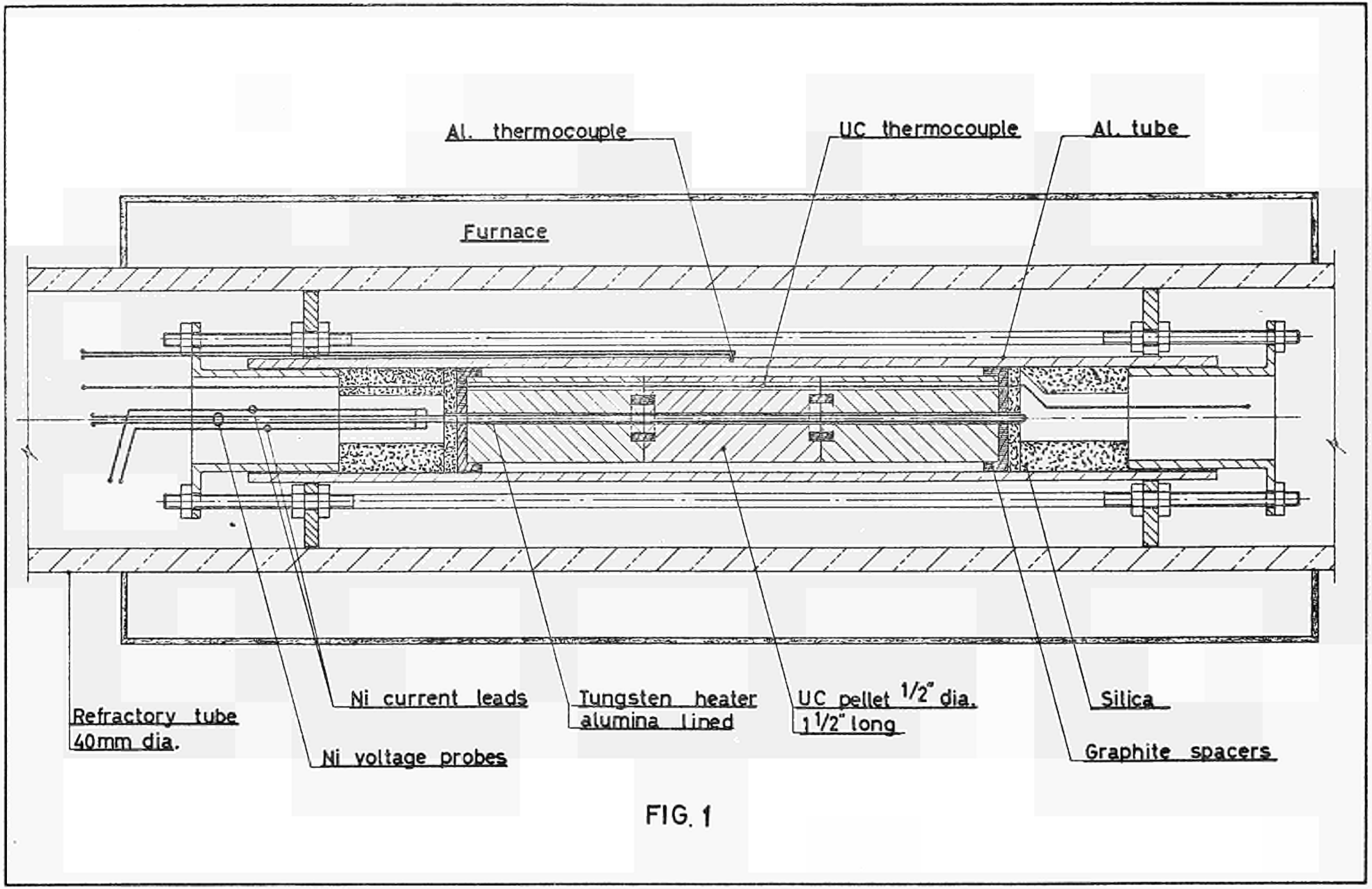

Al. thermocouple
UC thermocouple
Al. tube
Furnace
Refractory tube
40mm dia.
Ni current leads
Ni voltage probes
Tungsten heater
alumina lined
UC pellet 1/2" dia.
1 1/2" long
Silica
Graphite spacers

FIG. 1

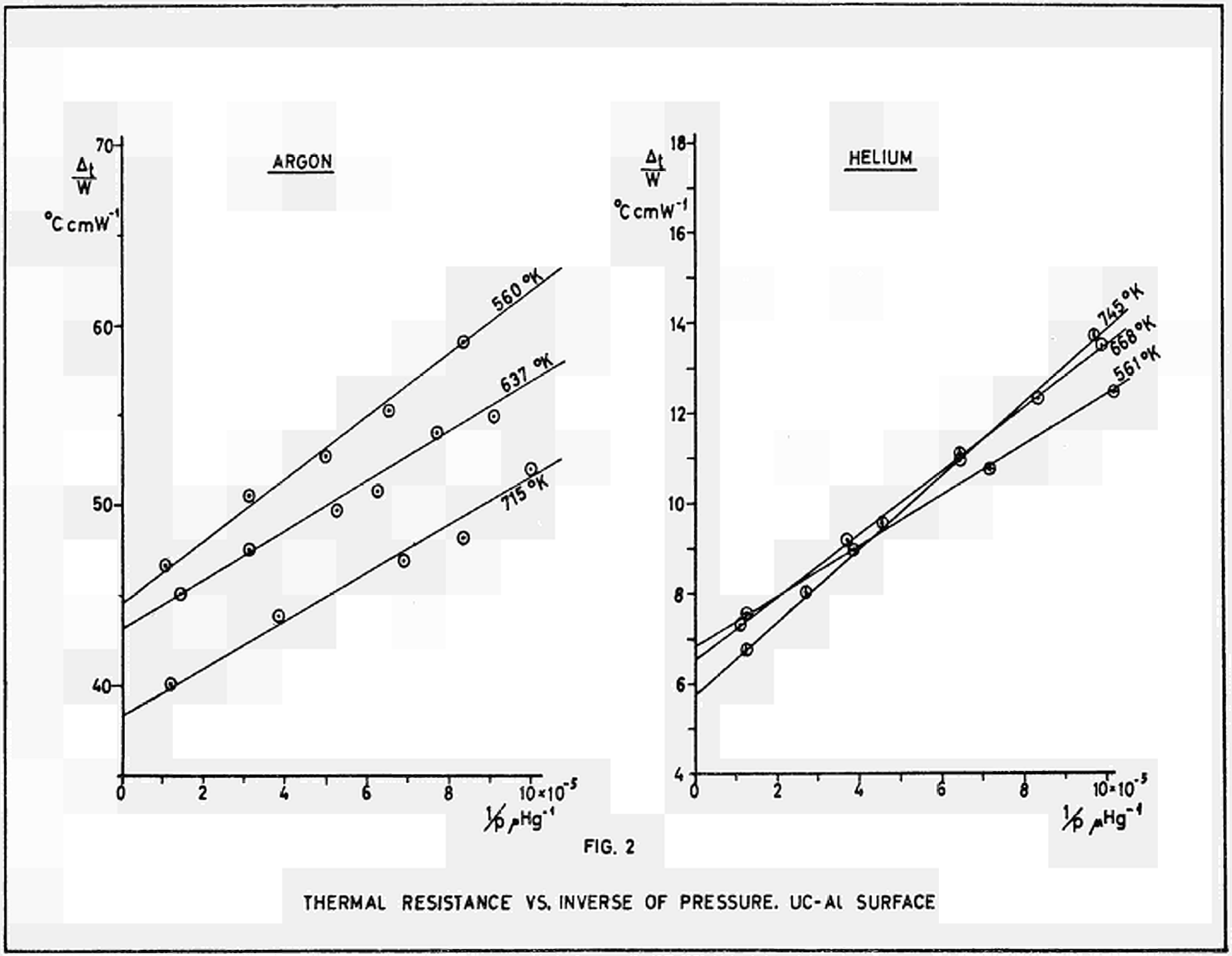


FIG. 2

THERMAL RESISTANCE VS. INVERSE OF PRESSURE. UC-Al SURFACE

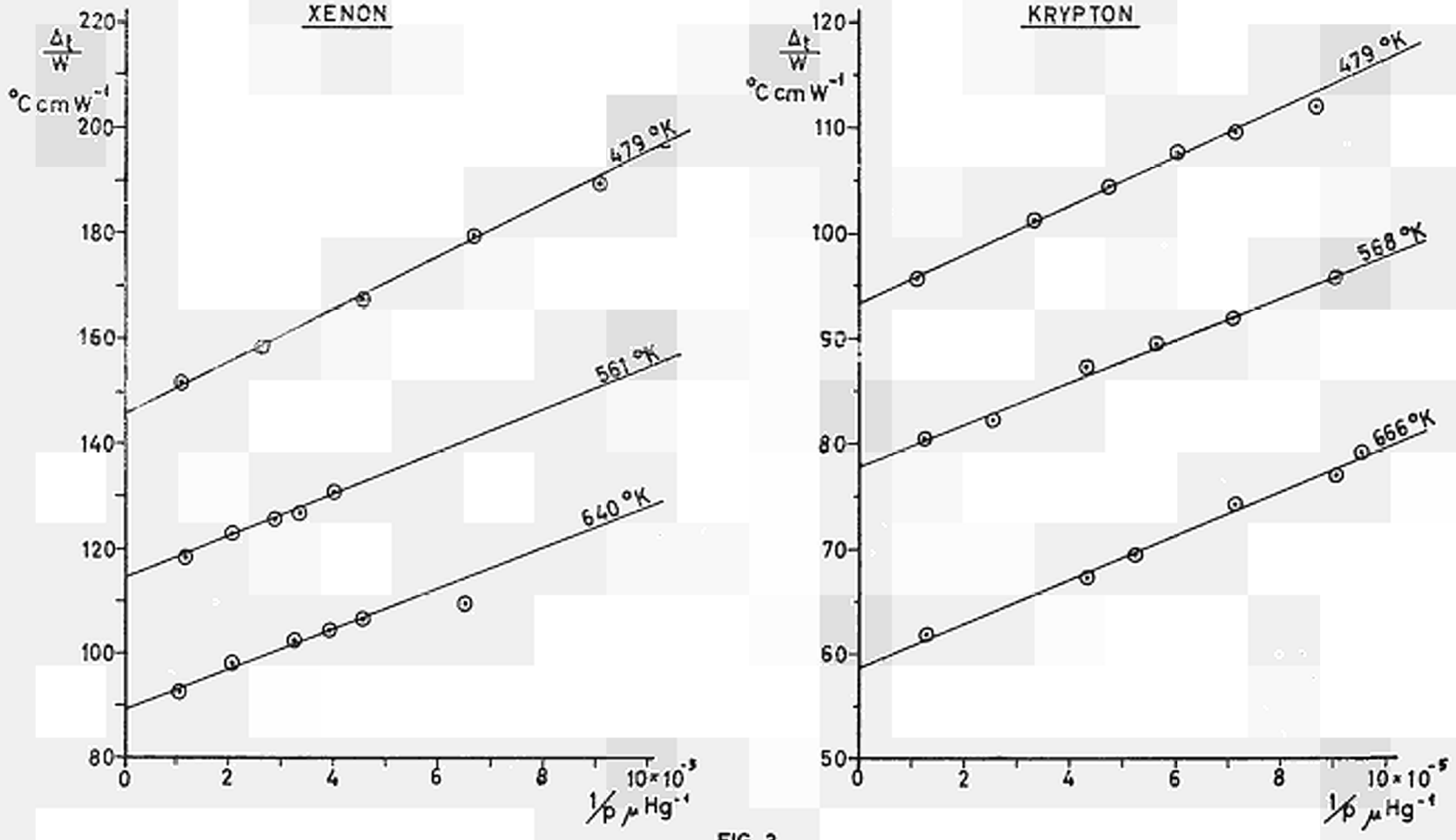


FIG. 3

THERMAL RESISTANCE VS. INVERSE OF PRESSURE. UC-Al SURFACE

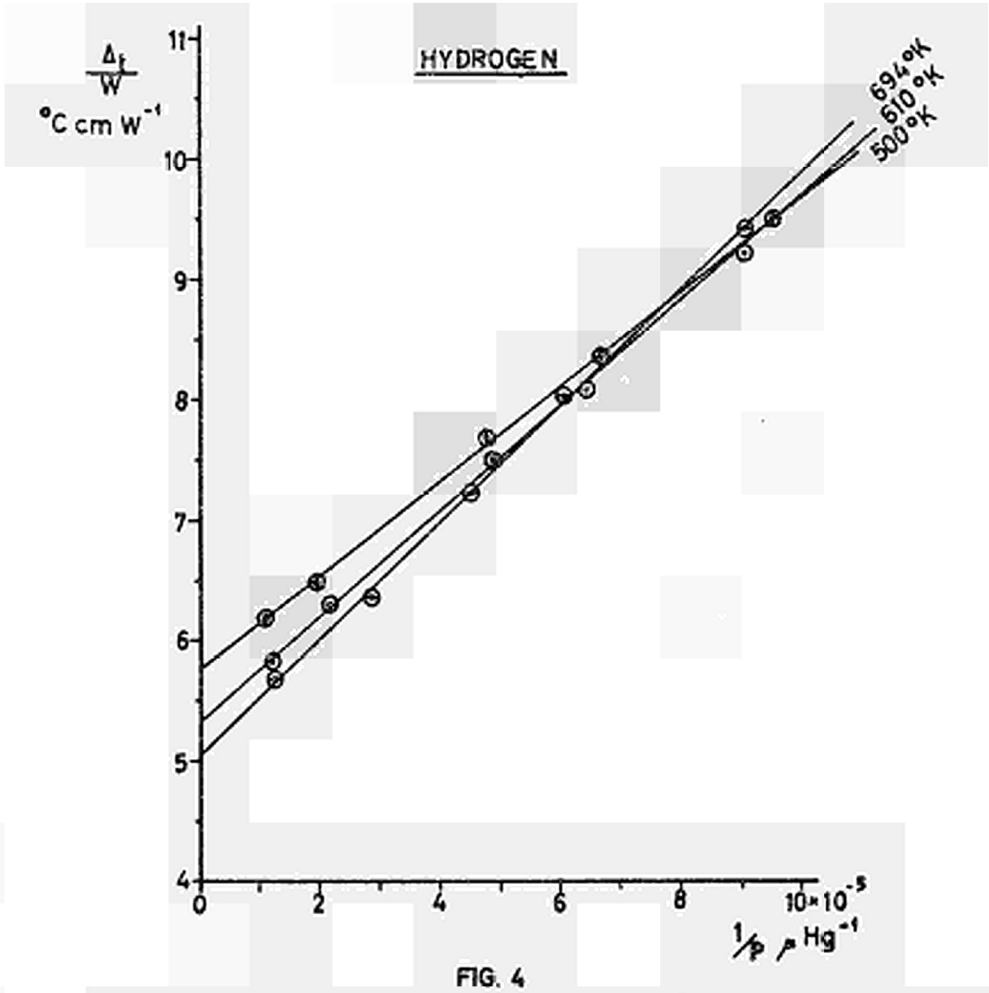


FIG. 4

THERMAL RESISTANCE VS. INVERSE OF PRESSURE. UC-Al SURFACE

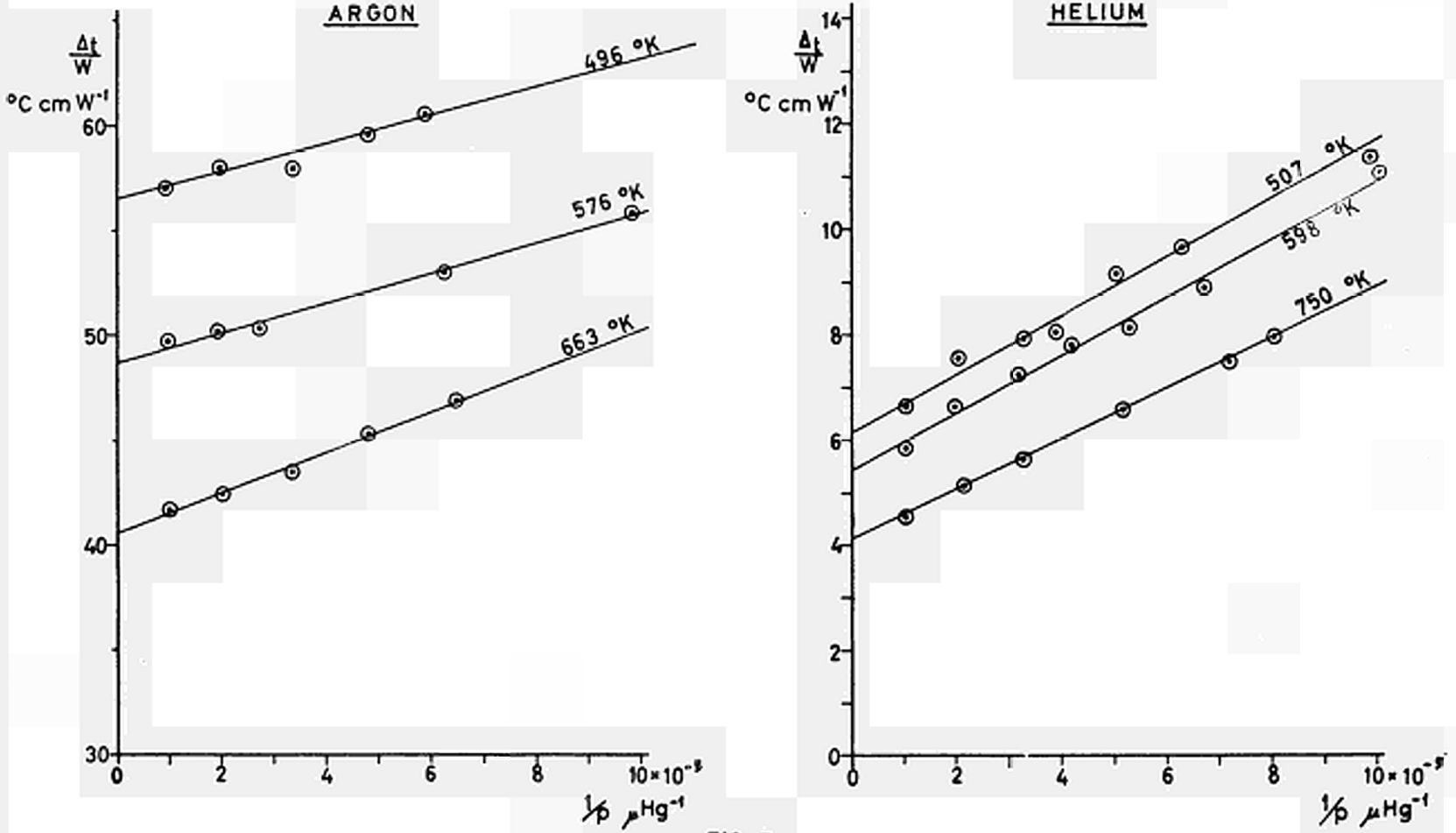


FIG. 5

THERMAL RESISTANCE VS. INVERSE OF PRESSURE. Al-Al SURFACE

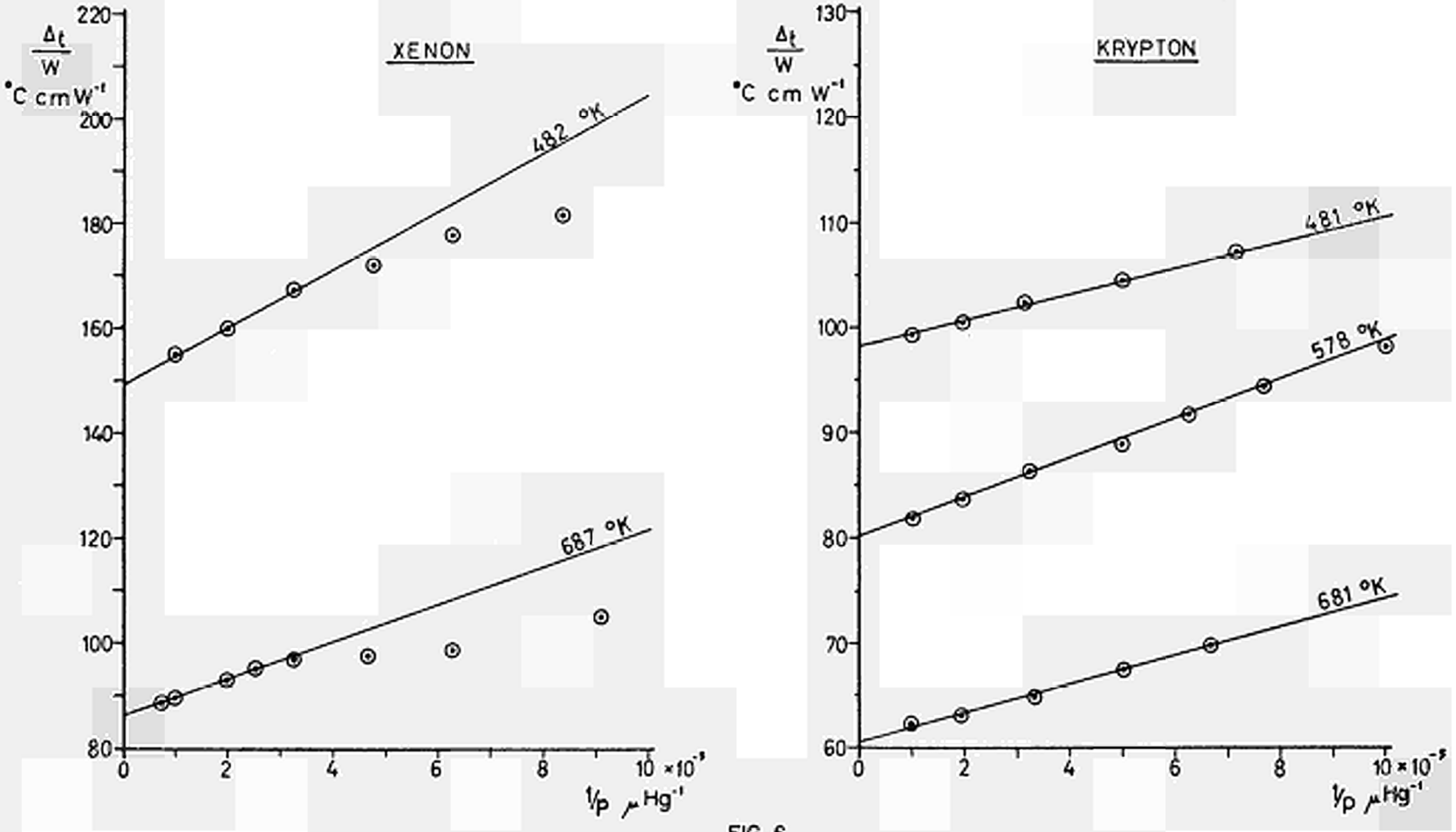


FIG. 6

THERMAL RESISTANCE VS. INVERSE OF PRESSURE. Al - Al SURFACE

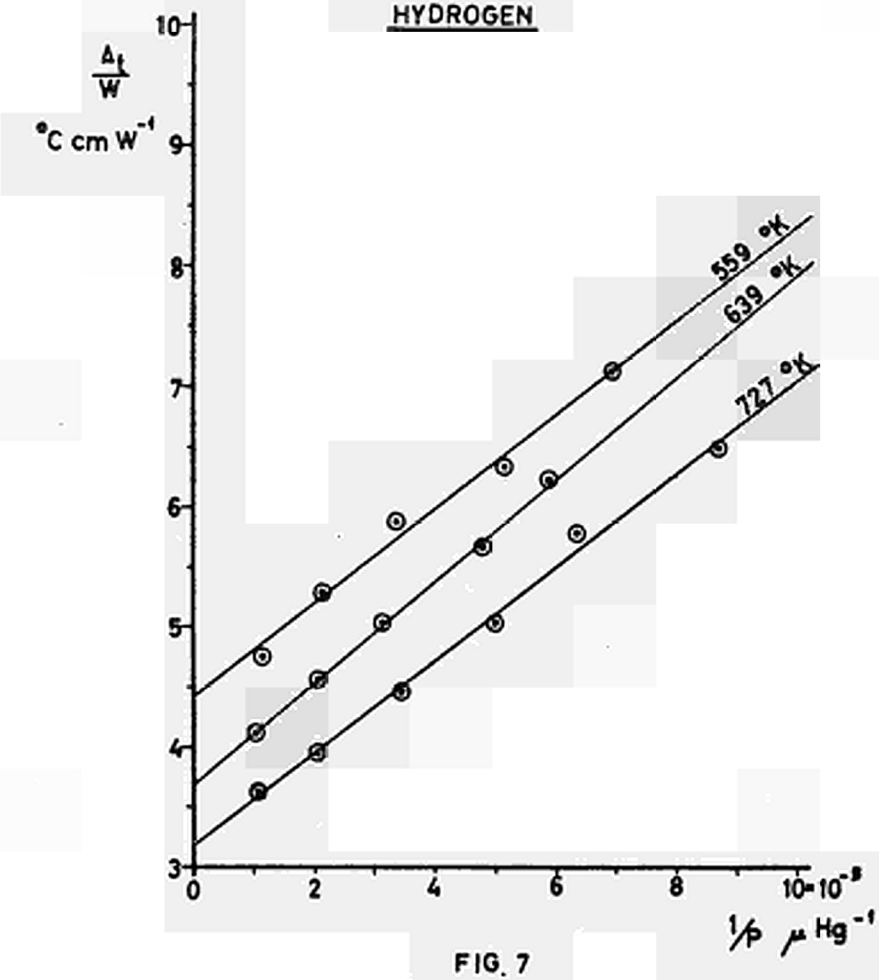


FIG. 7

THERMAL RESISTANCE VS. INVERSE OF PRESSURE Al-Al SURFACE

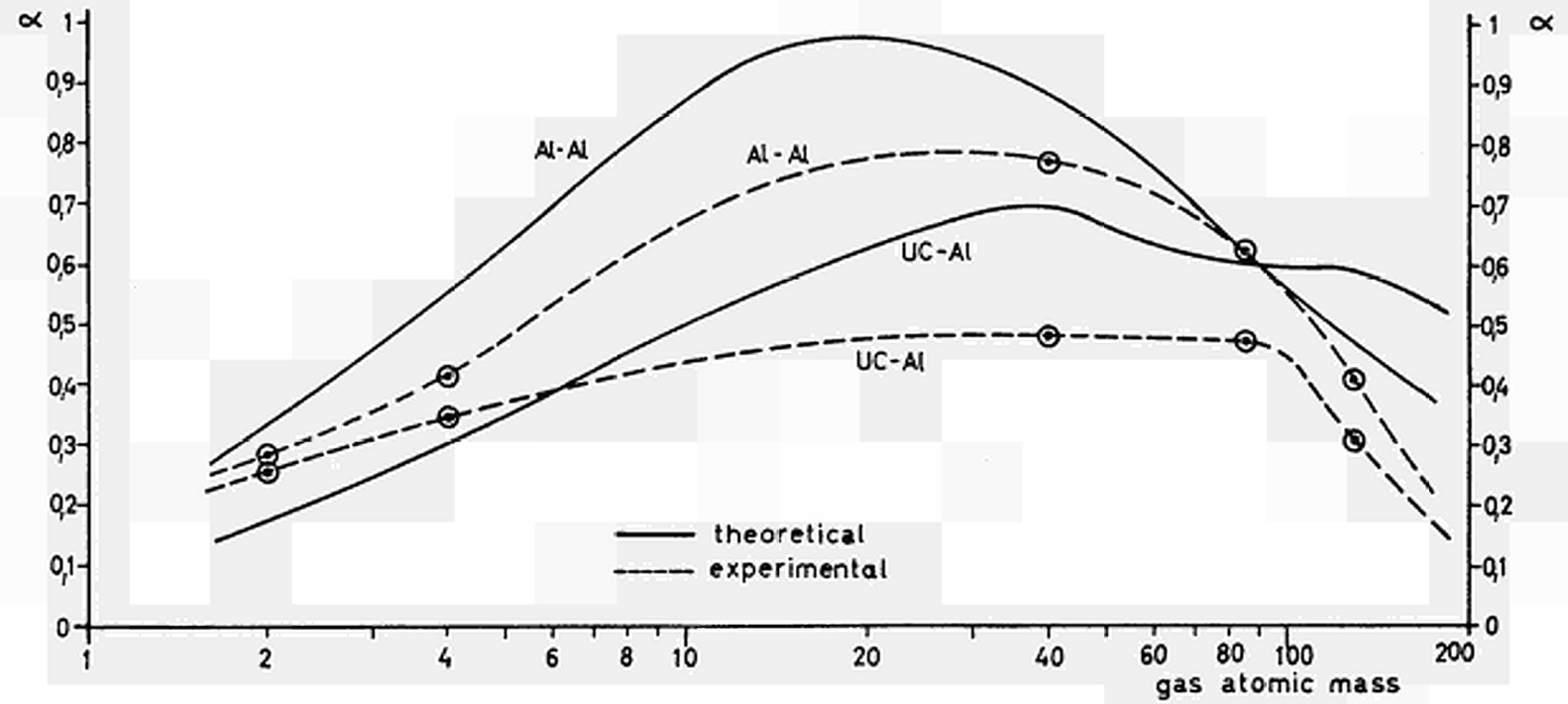


FIG. 8

ACCOMODATION COEFFICIENTS OF RARE GASES
ON ALUMINIUM AND URANIUM CARBIDE SURFACE

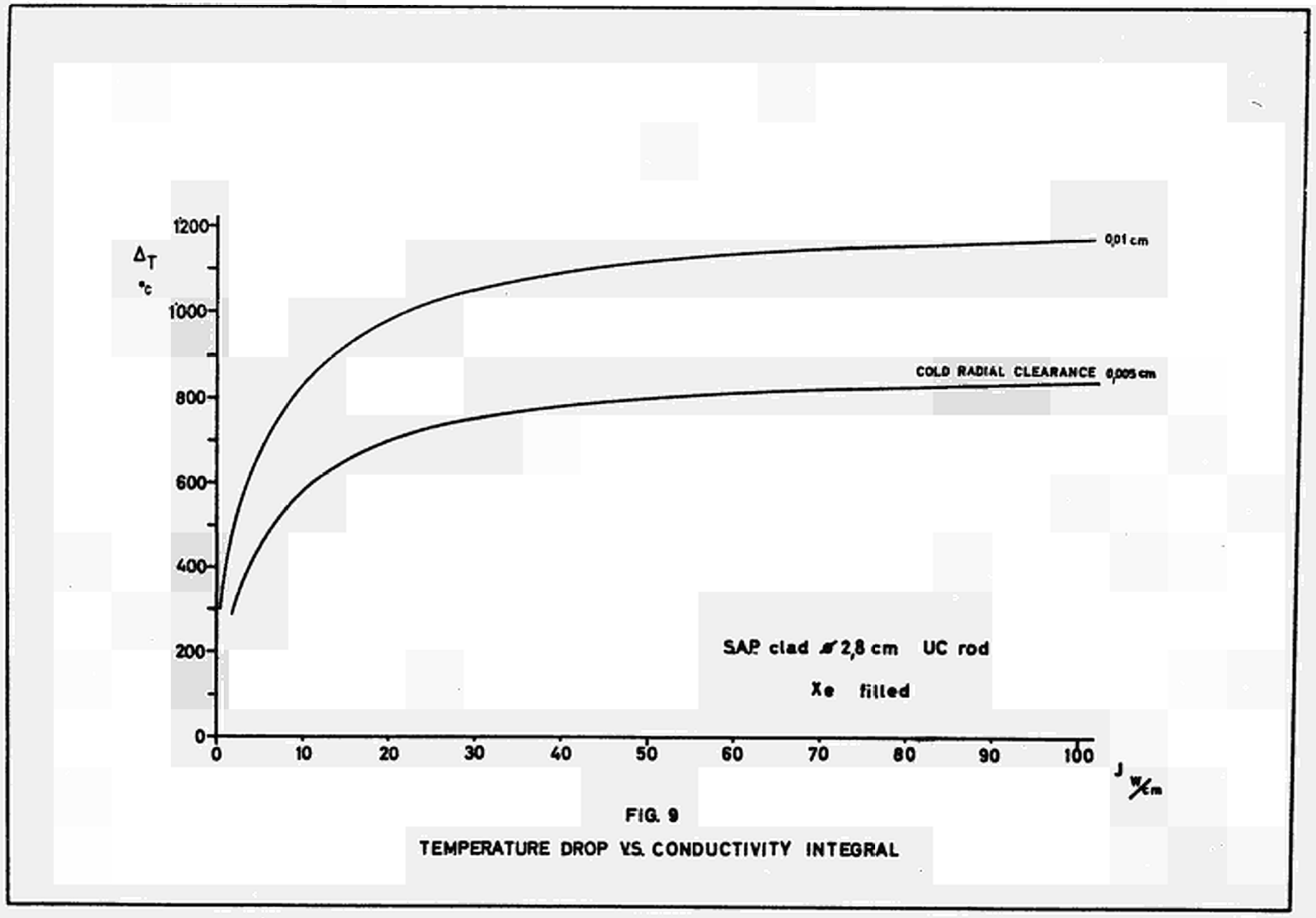


FIG. 9

TEMPERATURE DROP VS. CONDUCTIVITY INTEGRAL

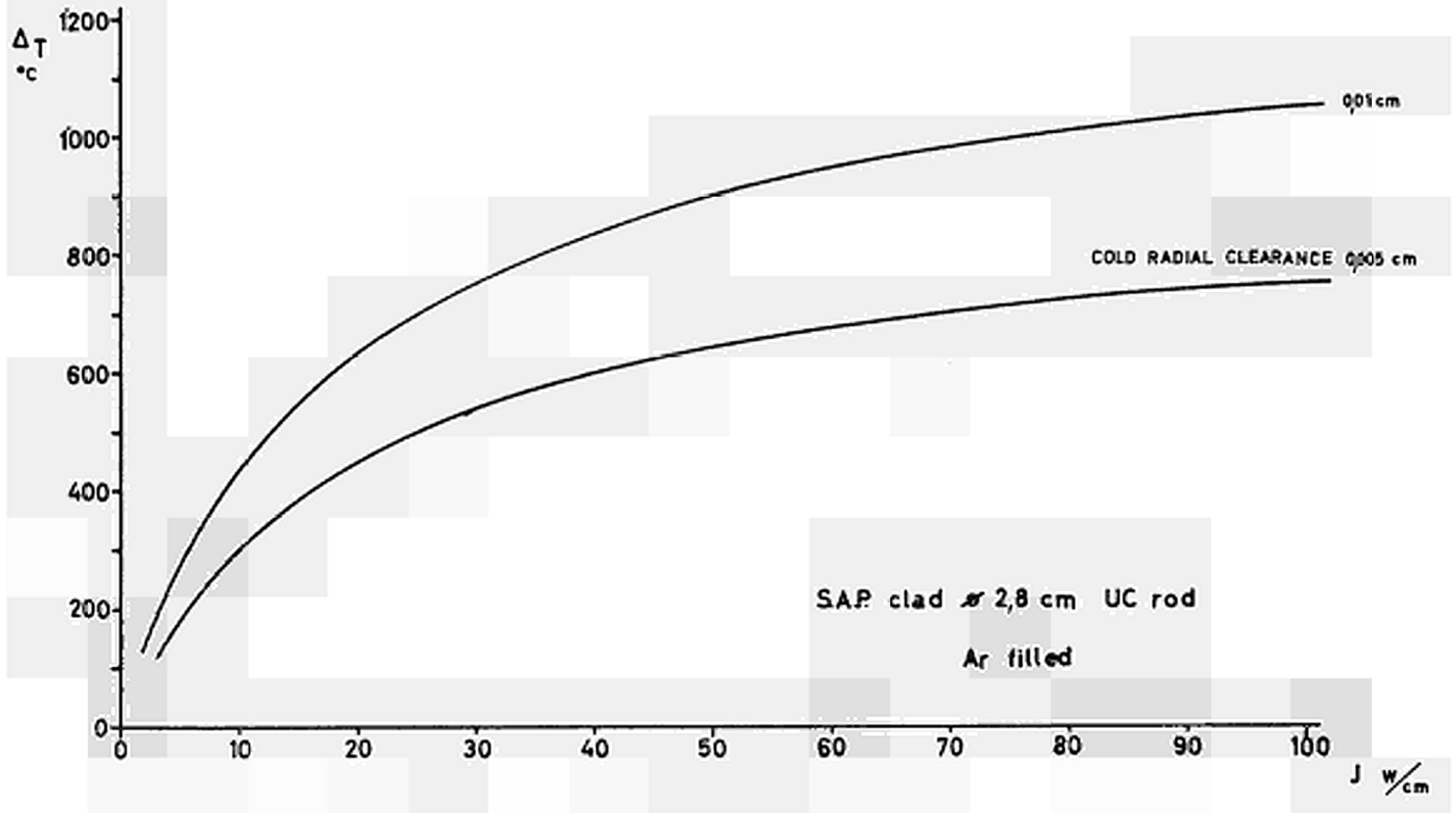


FIG. 10

TEMPERATURE DROP VS. CONDUCTIVITY INTEGRAL

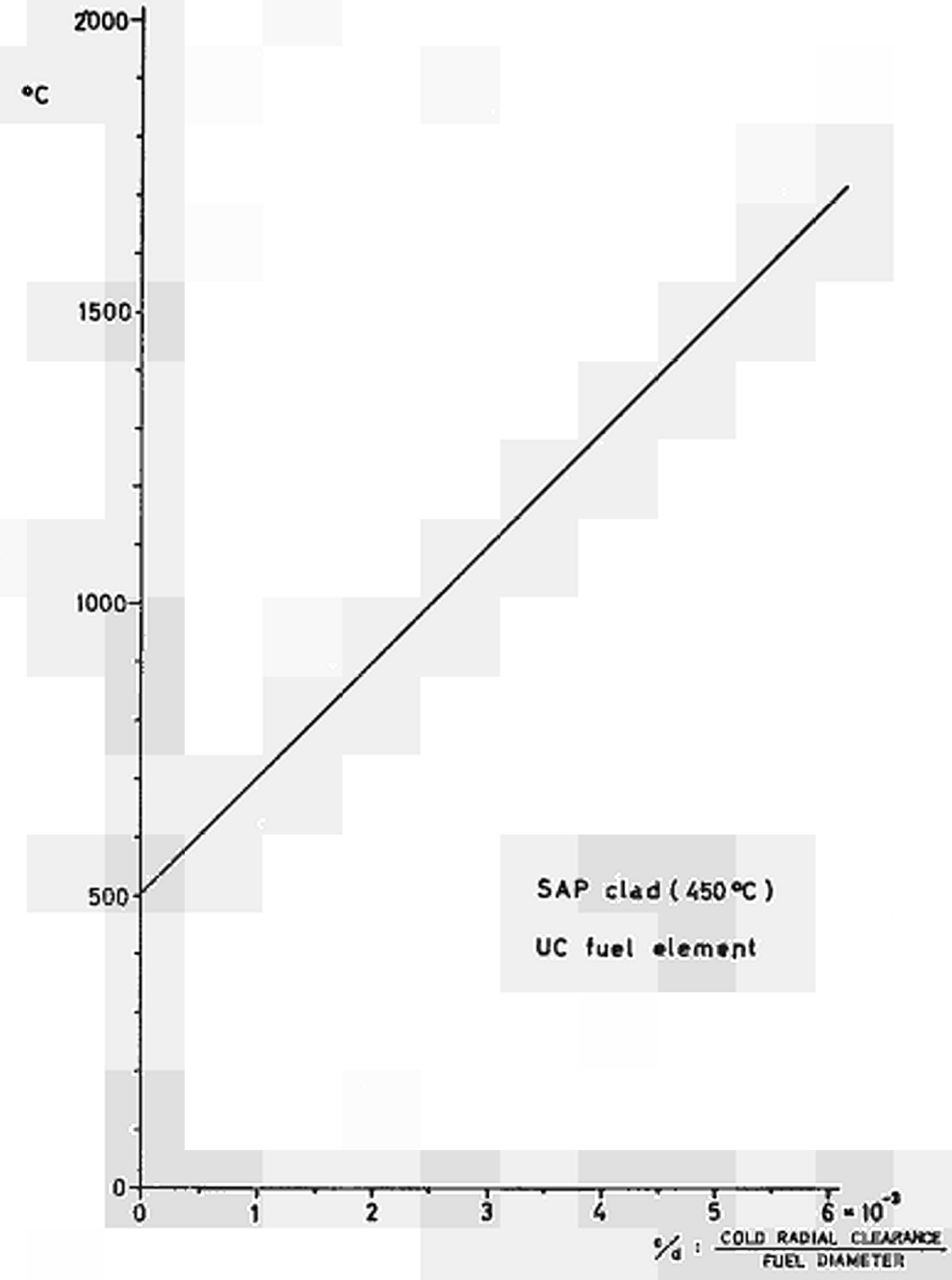
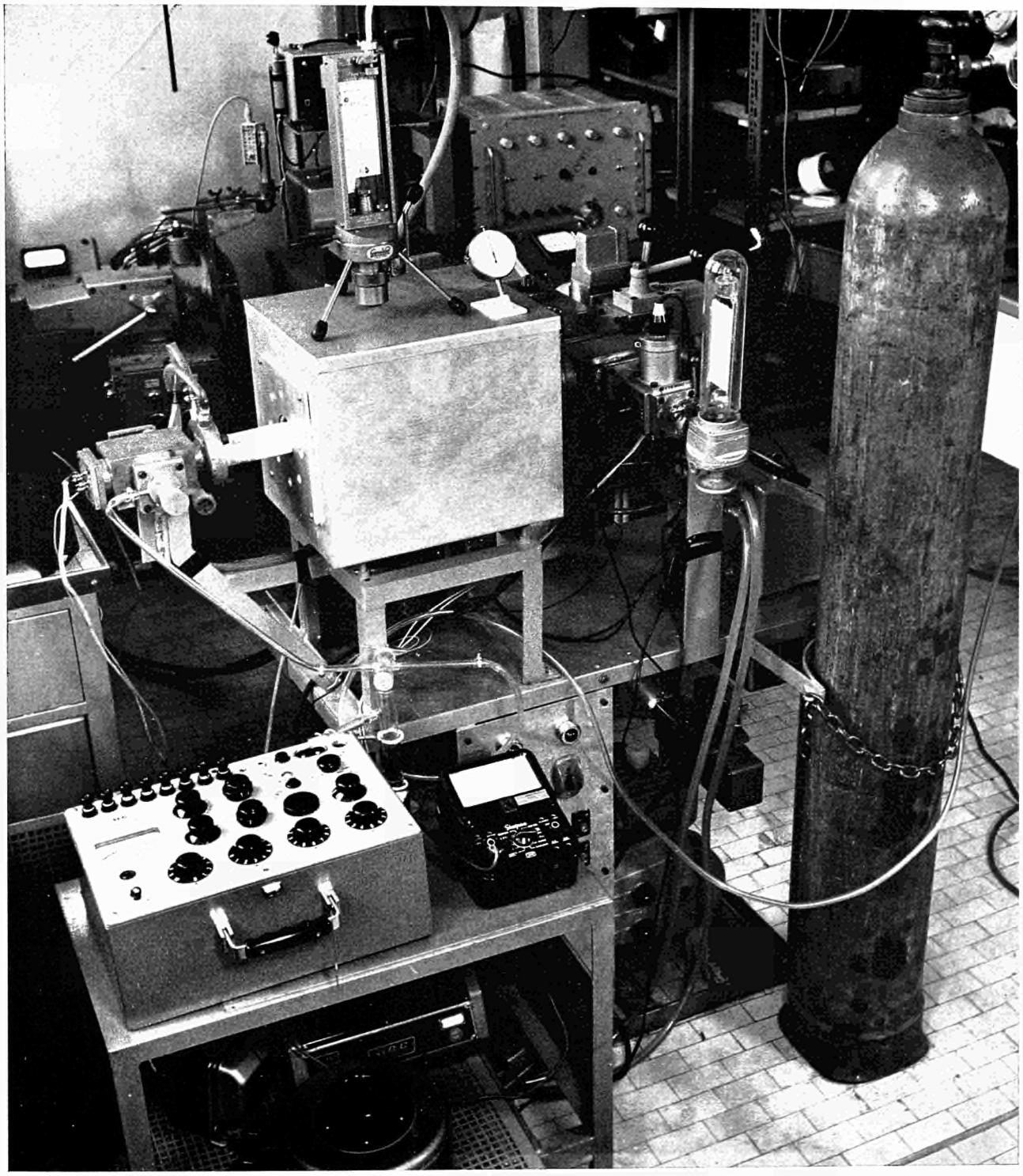


FIG. 11

MAXIMUM POSSIBLE TEMPERATURE DROP VS. c/d



Experimental Assembly

CDNA00521ENC