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DOCUMENT NUMBER COPD-57-41

~~This document consists of 10 pages~~
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May 3, 1957

MEMORANDUM

TO: Distribution

FROM: H. Brown, R. Herbst, J. Nuckolls.

SUBJECT: Nuclear Explosions in a Steam-Filled Hole and Their Effects in Walls.

This note summarizes some work by J. Nuckolls and R. Herbst and some speculations by H. Brown. The work is very preliminary and when it is further along will be separately reported on; its results are merely summarized here.

A hydrodynamic calculation was done by Herbst and then with finer zoning by Nuckolls, representing the explosion of a 0.5 MT bomb in a 984 foot radius hole with rigid walls, containing steam at 7 lbs. per ft^3 density, and with 3.0 MT energy already in the hole. The static pressure is then .34 kb (5100 psi). The equation of state for steam was interpolated where necessary between Keenan and Keyes' steam tables and the Fermi-Thomas model. The energy was initially assumed uniformly distributed in an isothermal sphere of about 50-70 ev temperature, which coresponds to a 8 to 10 meter radius. By ignoring radiation flow we are leaving out a mechanism which will broaden the shock front and reduce the shock overpressures. Visible light has an attenuation distance of the order of 10 meters in water, which would correspond to 300 feet in this steam; the effect would be to reduce the energy in the main shock by sending some energy out ahead. Except for the radiation flow effects, the assumption of an isothermal source of 8 to 10 meter radius rather than a point will not change the pressure profile at the wall since the wall radius of 300 meters (= 984 feet) is much larger than that of the isothermal sphere.

The shock front is about 35 meters width to half-height when it reaches the wall (Fig. 1), and about .27 kb above ambient pressure. Using the Taylor solution (which is not too applicable because the overpressure is not large compared with the ambient pressure), one would have $p = 0.133\, E_{tot}\, f/R^3$, with $f = 1.250$ for $\gamma = 5/3$, which gives $.133 \times 2 \times 10^{22} \times 1.250/27 \times 10^{12} = 1.25 \times 10^8$ ergs/cm^3 = .125 kb. for comparison

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On reflection, at a time of 205 msec, there is thus a sharp rise in pressure on the wall to 0.95 kb (Fig. 2), followed by a roughly exponential decay of the form $p = P_a + P_o e^{-\alpha t}$, with $\alpha \simeq 17$/sec (59 msec decay time). As the reflected shock moves toward the center, the wall pressure actually falls below ambient (Fig. 3). The shock reflected from the center is much broader and weaker (Fig. 5) but produces a pronounced pressure rise on the wall (Fig. 4) at 730 milliseconds.

If the medium surrounding the wall is assumed to be an infinite elastic one, and a pressure profile is applied to it, one can calculate the motions and stresses in the medium. Whether the medium so behaves depends on whether its elastic limits are exceeded. If not, the radial displacement in a spherically symmetrical case is given by U, with

$\frac{\partial}{\partial r}\left(\frac{\partial U}{\partial r}+\frac{2}{r}U\right) - \frac{1}{c^2}\frac{\partial^2 U}{\partial t^2} = 0$ the wave equation, the sound velocity c given by $\sqrt{(\lambda + 2\mu)/\rho}$ and the boundary condition being $-P_R(t) = \left[(\lambda + 2u)\frac{\partial U}{\partial r} + 2\lambda\frac{U}{r}\right]_{r=R}$, where R is the radius of the hole. For the case $P_R = P_o e^{-\alpha t}$, Herbst finds when $\lambda = 2\mu$ (which is the situation for the Poisson ratio $\sigma = 1/3$).

$$U(r,ct) = \frac{P_o R^3}{2\lambda r}\Bigg[e^{-\frac{\alpha}{c}(ct - r + R)}\left(\frac{1}{r} - \frac{\alpha}{c}\right)$$

$$+\, e^{-\frac{1}{2r}(ct-r+R)}\left\{\cos\frac{\sqrt{3}}{2r}(ct-r+R)\left(\frac{\alpha}{c} - \frac{1}{r}\right) + \sin\frac{\sqrt{3}}{2r}(ct-r+R)\left[\frac{\sqrt{3}}{2R} + \frac{2R}{\sqrt{3}}\left(\frac{\alpha}{c} - \frac{1}{2R}\right)\left(\frac{1}{r} - \frac{1}{2R}\right)\right]\right\}$$

at r = R (the surface of the hole) one has

$$U(R,ct) = \frac{P_o R}{2\lambda}\left[e^{-\alpha t}\left(1 - \frac{\alpha R}{c}\right) + e^{-\frac{ct}{2R}}\left\{\left(\cos\frac{\sqrt{3}ct}{2R}\right)\left(\frac{\alpha R}{c} - 1\right) + \left(\sin\frac{\sqrt{3}ct}{2R}\right)\frac{1}{\sqrt{3}}\left(\frac{\alpha R}{c} + 1\right)\right\}\right]$$

at $r >> R$ and c/α one has, with $y = ct - (r-R)$, for $y \geq 0$ ($U = 0$ for $y < 0$)

$$U(r,y) = \frac{P_o R^2}{2\lambda r}\left[+\frac{\alpha R}{c}e^{-\frac{\alpha y}{c}} + e^{-y/2R}\left\{\left(\frac{\alpha R}{c}\right)\cos\frac{\sqrt{3}\,y}{2R} - \frac{1}{\sqrt{3}}\left(\frac{\alpha R}{c} + 1\right)\sin\frac{\sqrt{3}\,y}{2R}\right\}\right],$$ the

pulse amplitude falling off approximately as $\frac{1}{r}$. These forms for U give a damped oscillating motion

Since the sound velocity in rock is $\sim\sqrt{\frac{2\lambda}{\rho}} = 6.3 \times 10^5$ cm/sec, and $\alpha = 17$/sec for the furst pulse, one has $\frac{\alpha R}{c} = \frac{17 \times 3 \times 10^4}{6.3 \times 10^5} = .82 \approx 1$. For this case $U(R,ct) \simeq \frac{P_o R}{\lambda\sqrt{3}} e^{-\frac{\alpha t}{2}} \sin\frac{\sqrt{3}}{2}\alpha t$. The maximum value of this function occurs at $\alpha t \sim 1.15$, and is $.275\,\frac{P_o R}{\lambda}$. Since $P_o = 6 \times 10^8$, $\lambda = 4 \times 10^{11}$

(for granite) and $R = 3 \times 10^4$, the maximum outward motion of the wall is $U_{max} = 12$ cm. Integrating the energy lost out through the wall from the motion produced by the pulse gives $4\pi R^2 \int_0^\infty P(t)\frac{\alpha U}{dt}dt = -4\pi R^2 \int_0^\infty U \frac{dP}{dt}\,dt$

(integrating by parts and noting that $U = 0$ at $t = 0$ and $t = \infty$)

$= -4\pi R^2 \frac{RP_o}{\lambda\sqrt{3}} \int_0^\infty (-\alpha)\, P_o e^{-\alpha t}\, e^{-\alpha t/2} \sin \frac{\sqrt{3}}{2}\alpha t = \frac{4}{3}\pi R^3 P_o \left(\frac{P_o}{2\lambda}\right)$. The initial energy in the fireball is given by about $\frac{1}{6}$ the ambient pressure, multiplied by $\frac{1}{\gamma-1}$. $\frac{E_{lost}}{E_{in\ fireball}} = (\gamma - 1)\frac{P_o}{P_a}\left(\frac{P_o}{2\lambda}\right)\frac{E_{container}}{E_{fireball}} =$

$\frac{5}{3} \times \frac{.6}{.35} \times \frac{6 \times 10^8}{4 \times 10^{11}} \times 6 = .03$; 3% is lost out through the walls.

The tangential tension at $r = R$ is given by $T_\theta(R,\gamma) = -\frac{1}{2}P_R(t) + 2\lambda\frac{U(R,t)}{R}$. The results are shown in Fig. 6, for $\alpha R/c = 1$ and $\frac{\alpha R}{c} = \frac{1}{2}$. The tangential stress starts out negative (indicates compressive stress) when the shock hits, and is 1/2 the peak pressure. It changes sign and reaches a smaller negative value, then oscillates with an amplitude damped with a time constant determined by the longer time of $\frac{1}{\alpha}$ and $\frac{2R}{c}$. For a slowly falling pressure such as the shock reflected from the center of the hole (Fig. 4) where α is quite small (~ 2/sec) $e^{-ct/2R}$ becomes small before $e^{-\alpha t}$ and

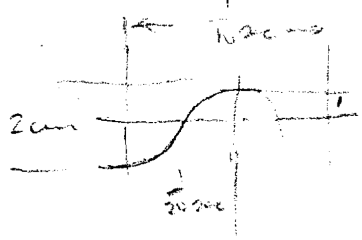
$$T_\theta(R,t) = -P_o\left[e^{-\alpha t}\left(\frac{\alpha R}{c}-\frac{1}{2}\right) - e^{-\frac{ct}{2R}}\left(\cos\frac{\sqrt{3}}{2R}ct\left(\frac{\alpha R}{c}-1\right) + \sin\frac{\sqrt{3}ct}{2R}\left(\frac{1}{\sqrt{3}}\left\{1+\frac{\alpha R}{c}\right\}\right)\right)\right]$$

$\sim + \frac{P_o}{2} e^{-\alpha t}$, approaching the static case, where $T_\theta = \frac{P_o}{2}$. For a narrower pulse such as the first shock, with $\frac{\alpha R}{c} \sim .8$, we will have a peak dynamic tangential tension of only about $.35\,P_o$, lasting over a time of the order of $\frac{1}{2} \sim 60$ msec for this case. The first shock has $P_o \sim \underline{.6}$ kb and the second has $P_o \sim \underline{.3}$ kb, so the tensions are about .2 and .15 kb respectively. These are to be added to the static tension $= \frac{P_a}{2} \sim .18$ kb from the ambient pressure, and the sum of each with the static tension compared with the compression from the overburden (about $\frac{3}{2}$ the overburden pressure which is $\frac{3}{2} \times \frac{5000}{34} \times 1.7$ atm $= .38$ kb for a rock density of 2 gm/cm^3 at a 5000 ft depth). This looks close to being safe so far as tangential stresses are concerned. Since pressure is always maintained inside the hole, there will in general be a compressive stress normal to the surface of the hole, but it may be that radial tensions develop further out.

P_o	.6	.3
DYNAMIC TENSION	.20	.15
STATIC TENSION	.18	.18
	.38	.33
INITIAL COMPRESSION	.38	.38
NET COMPRESSION	0	.05 Kb

Evaluating the motion at a distance from the hole, one obtains a peak motion $U_{max}^{(r)}$ for the case of $\frac{\alpha R}{c} \sim 1$ of $\sim .3 \frac{P_o R^2}{\lambda r}$. For the first shock, at the surface (1 mile) one would then have $U_{max} \sim 2$ cm. The acceleration is quite large, since the period is so short, being at its ? peak ~~80~~ 3600 $\frac{cm}{sec^2}$ (almost 4 g's) since the time is of the order of $\frac{1}{20}$ sec. These would be very severe accelerations, but their short period may make the ? effect small, both because of the lack of response of structures in these times and because short periods are probably more strongly attenuated in transmission (this would not appear in our calculations because the medium was assumed to be non-dissipative). The second shock has a decay period of the order of $\frac{1}{4}$ sec, and the amplitude is down by a factor of 2, so that the acceleration should be down by a factor of 50, to give .06 g's. There is a long period oscillation representing the gradual change of pressure between reflections, as can be seen from the P (t) history. The period of this oscillation is about 1 second, which corresponds to the most damaging seismic waves, but its pressure amplitude is only about .02 kb, so that the amplitude of motion at the surface (1 mile) would be only 0.07 cm.

HB:RH:JN:ar



$a = A\omega^2 \sin \omega t$

$\omega = 2\pi f = \frac{2\pi}{period} = \frac{2\pi}{\frac{1}{10}} = 63$

$a = 1(63)^2 = 3600 \frac{cm}{sec^2}$

Distribution

Cy 1/8A H. York
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7/8A File
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* Shock at surface may be smaller if hole is not spherical. This is because shock will not reach all walls simultaneously. Same effect should occur if bomb is off center of spherical hole. Stresses in spherical hole with eccentric bomb should be figured:

* Harold says this would be small effect

Harold figured 3% of bomb energy goes into ground for 200 KT bomb this would give an earthquake of M=6.0

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Figure 1.

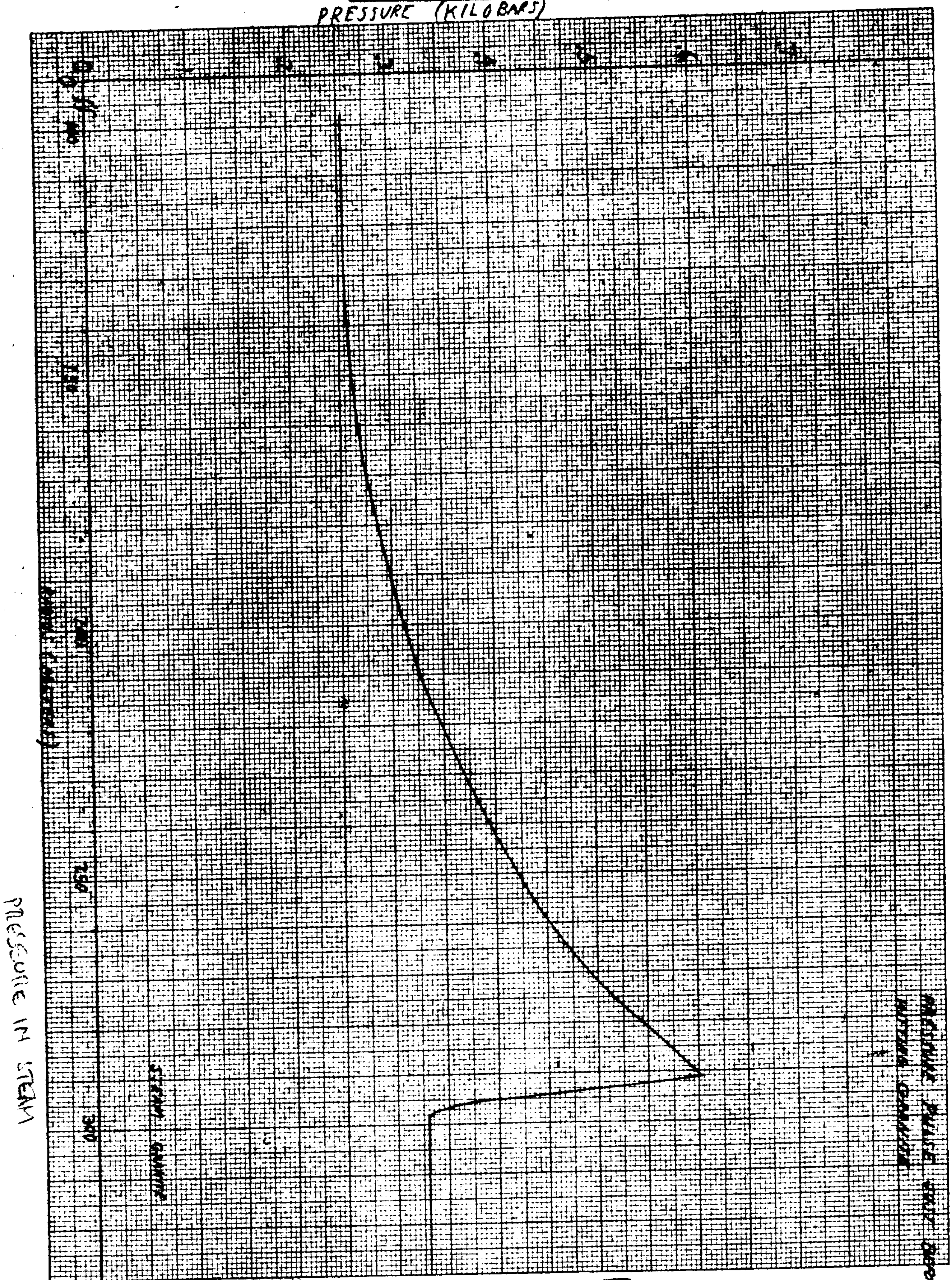

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Figure 2.

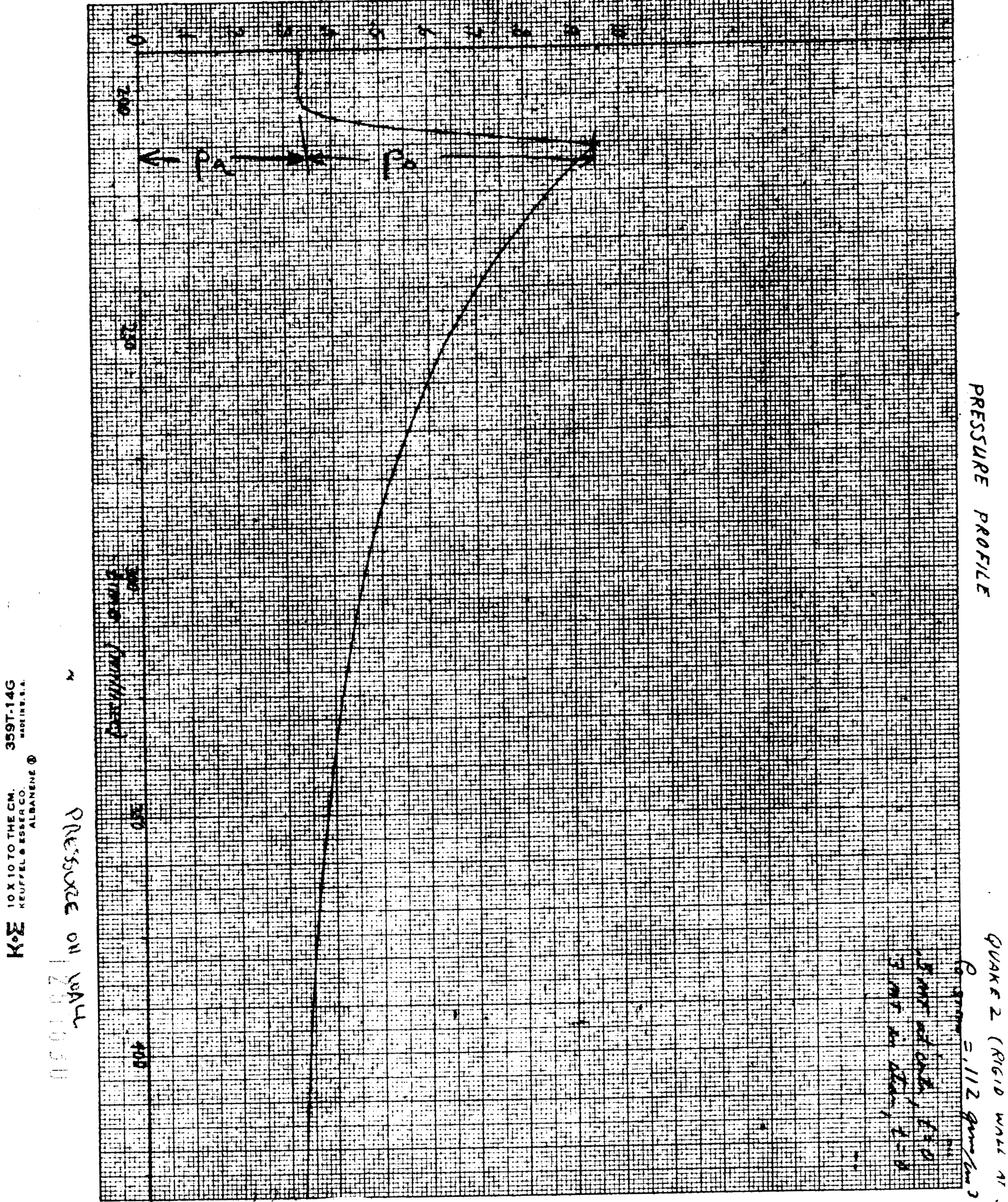
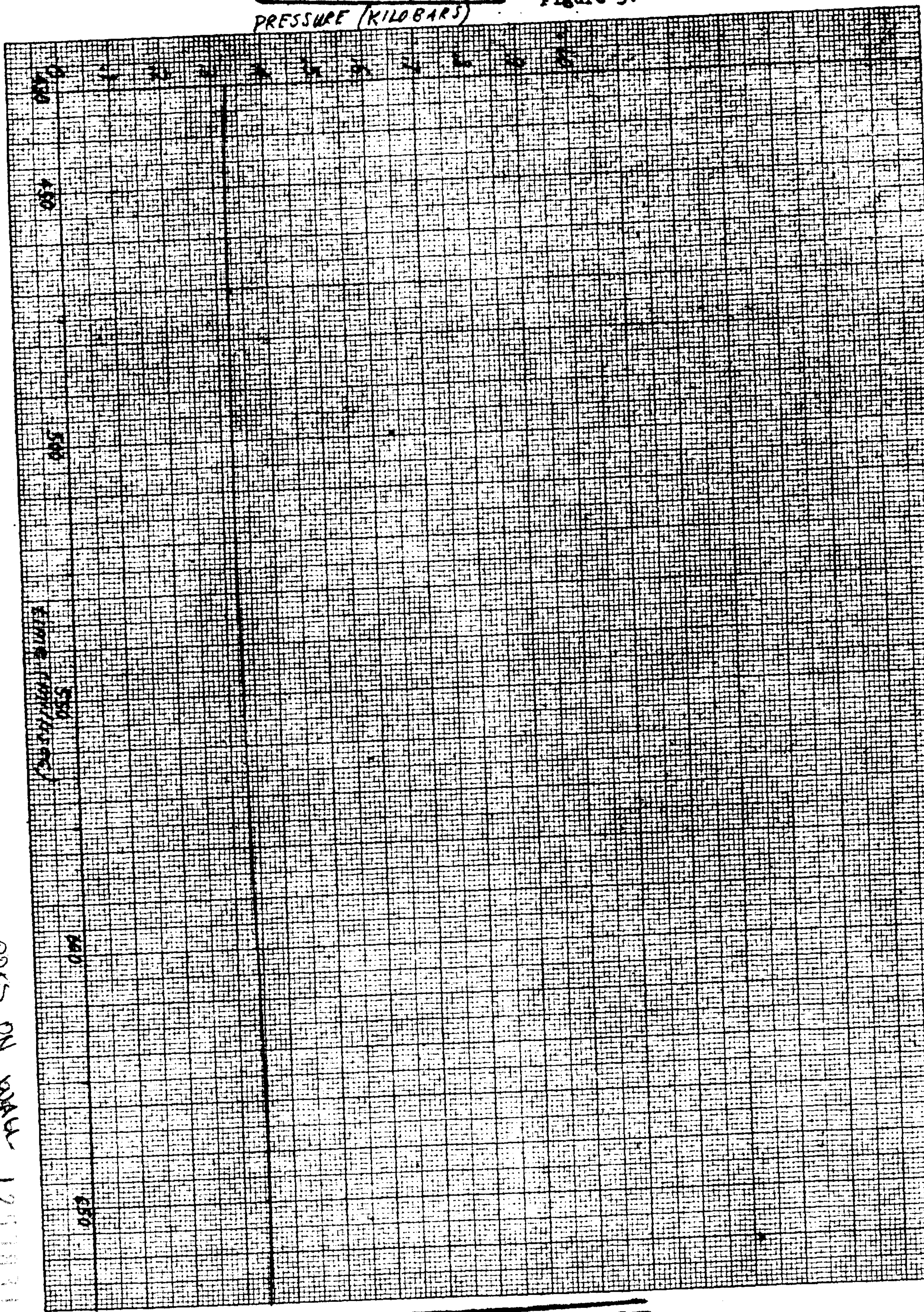

PRESSURE PROFILE
Pa
Po
0
200
250
300
350
400
PRESSURE ON WALL
QUAKE 2 (RIGID WALL AT 500 ft)
K&E 10 X 10 TO THE CM. 359T-14G
KEUFFEL & ESSER CO. MADE IN U.S.A.
ALBANENE

Figure 3.

PRESSURE (KILOBARS)



PRESSURE PROFILE (CONT)

QUAKE (RIGID WALL)

PRES ON WALL

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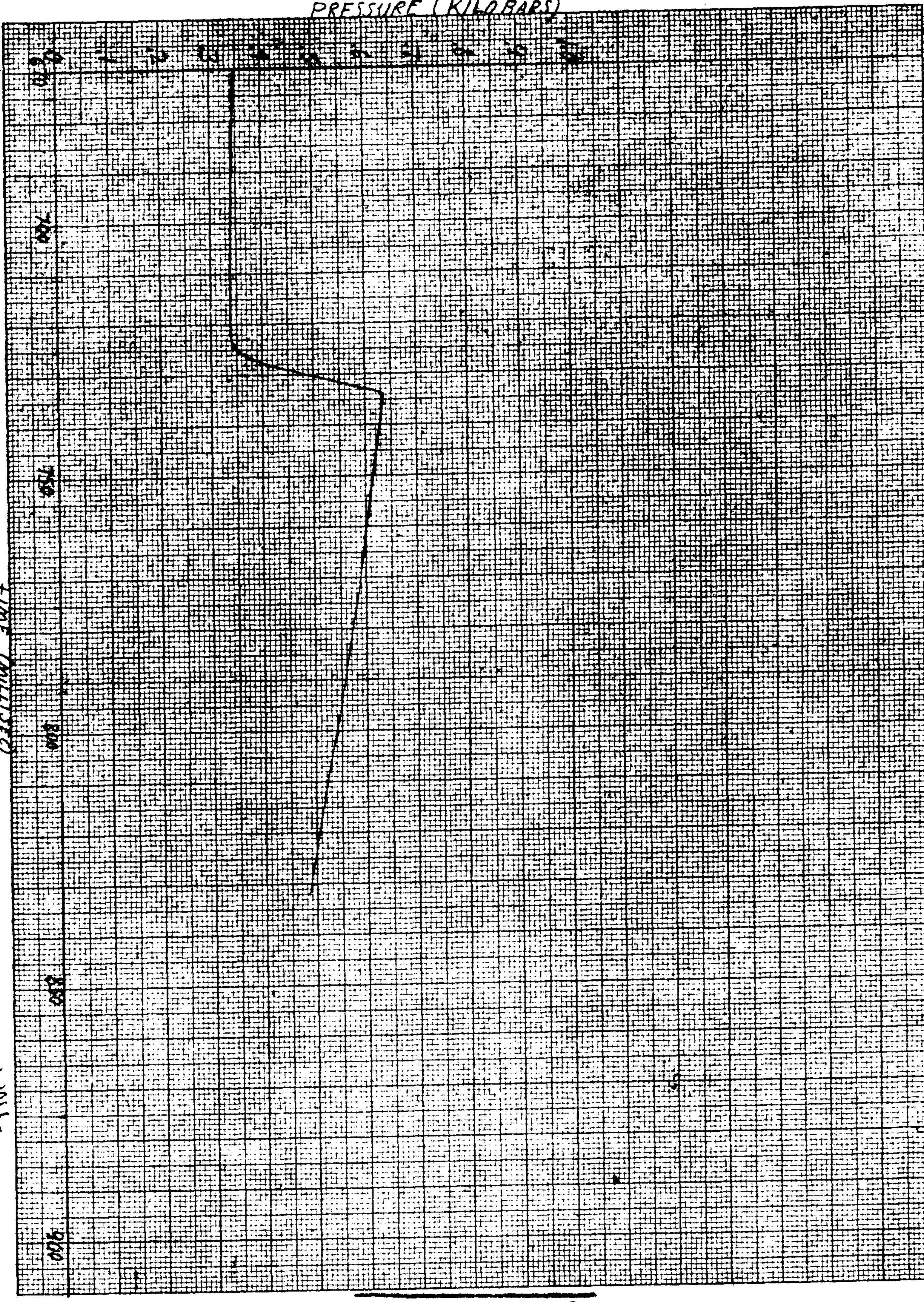
Figure 4.

PAGE 3



PRESSURE PROFILE (CONT.)

QUAKE 2
RIGID WALL

K&E 10 X 10 TO THE CM. 359T-14G
KEUFFEL & ESSER CO. MADE IN U.S.A.
ALBANENE

PRES ON WALL

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Figure 5.

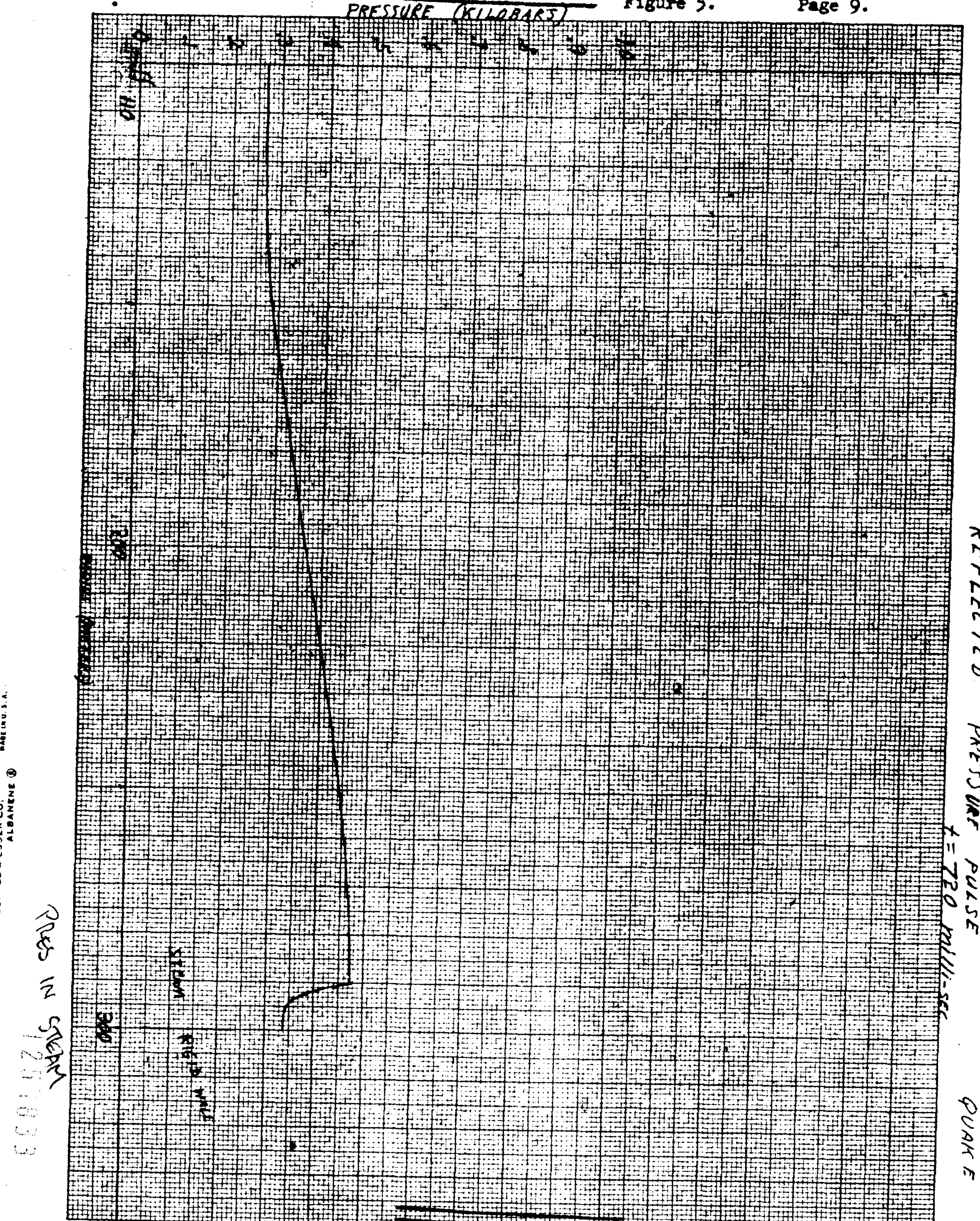

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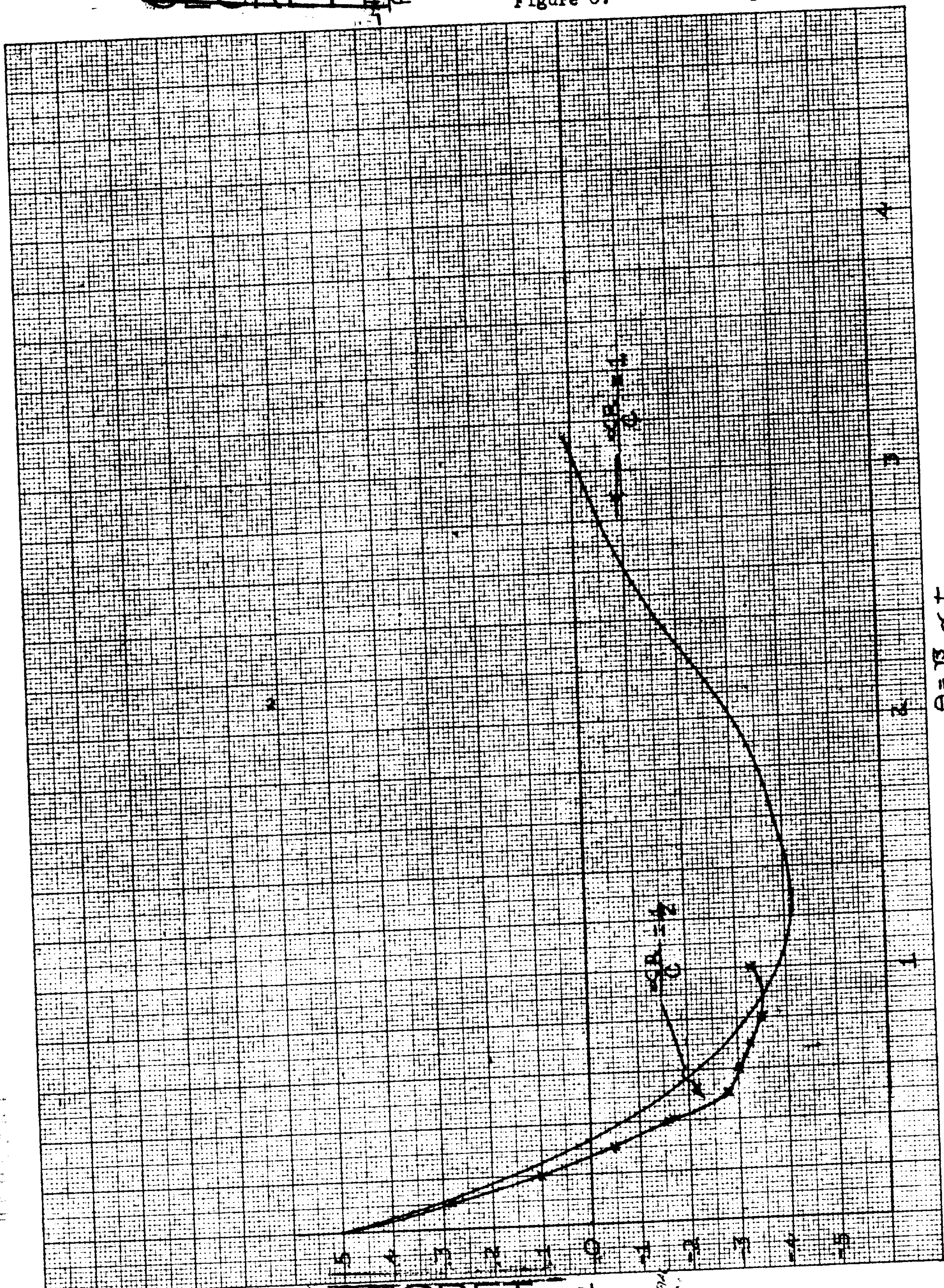
Figure 6.



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