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Methods for Calculating the Shielding Effect of Solid-Shell Enclosures Against EMP

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Summary

A method is presented for determining the shielding effectiveness of solid-shell enclosures against the nuclear EMP (Electro-Magnetic Pulse). For this purpose the EMP is expressed in analytical models. The shielding enclosure is approximated by one of three basis shapes, namely: two parallel plates, a cylinder and a sphere.

With the EMP models and the transfer function of the basic shape the field inside the enclosure is calculated. The computer programmes for the three basic shapes are given.

In many practical shielding problems the EMP can be replaced by a delta function with corresponding spectral amplitude. Representing the EMP by a unit delta function incident field the field inside the enclosure is calculated with simplified computer programmes and is plotted as a family of universal curves.

With these curves the shielding effectiveness of nearly each solid-shell enclosure to an EMP can be approximated in a relatively simple way. The effects of apertures in the enclosure and the countermeasures are briefly discussed.

CONTENTS

1.0 INTRODUCTION

During nuclear explosions very much energy is released in a very short time in several ways. The most well-known ways are: nuclear radiation, thermal radiation, blast, shock and fall-out.
Not generally known is the electro-magnetic pulse (EMP). The EMP, recognized since about 1960, consists of a transient pulse of high-intensity electromagnetic fields.
The waveform and spectrum of the EMP differ from those of other natural or man-made sources. For example the waveform of the EMP has a larger amplitude and a much faster rise time than fields generated by near-by lightning strokes. Furthermore the EMP fields are widely distributed, whereas lightning is only of local importance.

The EMP can induce very high peak voltages in electrical conductors. Sensitive electronic components like transistors or integrated circuits connected to these conductors may be damaged [1-2-3-4].
Experiments have shown that a piece of wire with a length of some tens of centimetres or a loop with an area of some square decimetres deliver sufficient energy to damage sensitive semi-conductors.

One of the most effective countermeasures is shielding these conductors and components against the EMP. Other or supplementary countermeasures are: to apply current or voltage limiters, to avoid loops in cabling, to choose a correct way of grounding, etc.
This report deals with the shielding and is devided into the following sections:
- first the characteristics of the EMP will be summarized,
- after that the characteristics of the shielding enclosure are studied, and,
- finally some methods are given with which the shielding effectiveness can be calculated.

2.0 THE CHARACTERISTICS OF THE EMP

The time function of an EMP depends on many factors and varies from one case to the other. A very important factor is the height of the explosion. An exo-atmospheric explosion (above the atmosphere) causes a very large area on the earth's surface where damage to sensitive components is possible.

Assuming a height of 400 km this area is bounded by a circle centered at ground zero with a radius of 2200 km.
The other nuclear effects in this area are of little or no importance.
A near-ground explosion causes an EMP damage circle with a much smaller radius. The other nuclear effects must be taken into consideration.

For a coarse study of the effects it suffices to use a representative pulse shape, which is characterised by three important parameters, namely: the rise time , the peak value and the pulse width. It is possible to compose a model in which the worst characteristics of the EMP are combined. Fig. 1 gives some models for exo-atmospheric explosions.

model I

This model is an EMP used in the USA for civil defense purposes [5].
The time history can be expressed as

$$E(t) = E_b \{e^{-\alpha t} - e^{-\beta t} - D(e^{-\gamma t} - e^{-\delta t})\} \qquad (1)$$

The values of the symbols are given in table 1.
Throughout this report the SI symbols and units have been used, see table 5.

model II

With respect to the effects of the EMP it makes little difference when model I is simplified to

$$E(t) = E_b \, (e^{-\alpha t} - e^{\beta t}) \qquad (2)$$

The models are largely theoretical. The total energy density in these pulses

$$\varepsilon_T = \int_0^\infty \frac{E^2(t)}{120\ \pi} \, dt \qquad (3)$$

has a value above average [6].

model III

It is fairly common to use a somewhat narrower pulse with a total energy density of 1...2 joules per square meter [6]. Model III is a version of model II modified to have an $\varepsilon_T = 1\ J/m^2$ with the same rise time t_r and peak fieldstrength E_{pk} as model I and II.

In equation (2) the time constant α is a measure for the half width time t_w, defined as the time interval between the 50% values of the peak fieldstrength. Time constant β is a measure for the rise time t_r, defined as the time interval between the 10% and 90% value of the peak fieldstrength.

The first derivative $\frac{dE}{dt} = \dot{E}$ is a measure for the output voltage of a short piece of wire, $\dot{H}$ for the voltage induced in a loop, and the area:

$$\int_0^\infty E(t)dt = E_b\left(\frac{1}{\alpha} - \frac{1}{\beta}\right) \qquad (4)$$

for the spectral amplitude of the pulse. The value of (4) is of particular importance in shielding, compare (6).

The spectra of the EMP can be found by fourier transformation. The spectrum of (2) is

$$E(\omega) = E_b\left(\frac{1}{\alpha+j\omega} - \frac{1}{\beta+j\omega}\right) \qquad (5)$$

At ω=o the spectral amplitude

$$|E(\omega)| = E_b\left(\frac{1}{\alpha} - \frac{1}{\beta}\right) \qquad (6)$$

At $\omega=\alpha$ the spectral amplitude is 3 dB down and decreases from then with 6 dB/octave or 20 dB per decade. The first cut-off frequency defined by the pulse width can be derived from

$$f_{c_1} = \frac{\alpha}{2\pi} \qquad (7)$$

The rise time causes a second cut-off frequency

$$f_{c_2} = \frac{\beta}{2\pi} \tag{8}$$

From $\omega = \beta$ the spectral amplitude decreases with 40 dB per decade.
The spectral amplitude $|E(f)|$ of model I and II is given in fig. 2.
The magnetic component of the electromagnetic field of an exo-atmospheric explosion can be derived with

$$H = \frac{E}{120\ \pi} \tag{9}$$

Endo-atmospheric explosions have generally much larger pulse widths. When using the same model as (2) and if $\beta >> \alpha$

$$\alpha \approx \frac{0.7}{t_w} \tag{10}$$

The spectral amplitude at low frequencies is:

$$|E(\omega)| \approx 1.43\ E_b\ t_w \tag{11a}$$

or

$$|H(\omega)| \approx 1.43\ H_b\ t_w \tag{11b}$$

The polarity of the EMP with respect to earth can be both, positive or negative. The polarisation can have any direction.

3.0 GENERAL SHIELDING CONSIDERATIONS

Electronic circuits and systems can be shielded against incident fields by placing them in a metal enclosure.
In calculating the field inside the enclosure the following assumptions have been made:

- The shielding enclosures are totally closed.
- The incident fields are plane waves.
  Fields reflected by the earth or other objects will not be taken into consideration.

- The dimensions of the enclosure are small in relation to the wavelengths of interest.
- The materials used for the enclosure are not saturated by the magnetic field.

3.1 The electric field

At low frequencies the electric component of the electromagnetic field will be effectively shielded, even with thin shells , as all electric field lines will end on the metal surface.
At zero frequency the charges are in rest and the electric field inside the enclosure is zero. At increasing frequencies the charges will move over the surface causing an electric current which, on its turn, gives rise to potential differences on the surface as a result of the impedance of the material. The current $i = \frac{dQ}{dt}$ in the enclosure is proportional to the frequency and hence very small at low frequencies. The shielding decreases with frequency with about 6 dB per octave until the skin effect sets in causing the shielding to increase again.
For an instrument cabinet a minimum shielding efficiency of about 200 dB is easily obtained.

The attenuation of the electric field is so high compared with the attenuation of the magnetic field that from now on we only will pay attention to the magnetic field.

3.2 The magnetic field

The shielding effect with regard to magnetic fields is based on the interaction of the external field on one hand and the currents induced in the enclosure by the external field, on the other hand.
The shielding increases with frequency.

Heinrich Kaden, professor at the Technische Hochschule in München has investigated the magnetic field in the following three parts of space [7]:
- the space outside the enclosure
- in the material of the enclosure
- the space surrounded by the enclosure.

For each of these parts the maxwell equations must be solved.
Kaden solved the equations for three idealised cases:
- two flat parallel plates, connected to each other at a large distance,
- an infinitely long cylindrical solid-shell,

- a spherical solid-shell

Almost every practical case of shielding can be treated with these three basic shapes (table 2). For example a cubical enclosure is substituted by the largest possible sphere inside the cube, a long enclosure with a square cross-section or a shielded cable by a cylinder, a large room with a relatively small height by two parallel plates.

For a good design it is necessary to know the shielding effect of the enclosure at particular frequencies. Therefore the shielding against sinusoidal magnetic fields will be studied first.

4.0 SHIELDING AGAINST SINUSOIDAL FIELDS

The shielding efficiency for sinusoidal magnetic fields can be expressed as

$$S_H \text{ (dB)} = 20 \log_{10} \left|\frac{H_o}{H_i}\right| \tag{12}$$

where H_o is the magnetic field outside and H_i the field inside the enclosure (in the centre of the space surrounded by the enclosure). The time functions of both fields are the same.

Table 2 gives the transfer function defined as

$$T_H(\omega) = \frac{H_i(\omega)}{H_o(\omega)} \tag{13}$$

where

$$\gamma = \sqrt{j\,\omega\,\mu\,\sigma} \tag{14}$$

and

$$k = \frac{\gamma r}{\mu_r} \tag{15}$$

From the transfer functions the shielding efficiency S_H is derived, in which

$$p = \frac{r}{\mu_r \delta} \tag{16}$$

$$q = \frac{d}{\delta} \tag{17}$$

$$\delta\ (\mathrm{mm}) = \frac{66.1}{\sqrt{\mu_r \sigma_r f}} \tag{18}$$

δ is the skin-depth. Fig. 3 gives δ versus frequency for the most used materials. The constants of these materials are listed in table 3.

It is very easy to program S_H on a simple computer or desk calculator like the HP 9810 A to prepare a family of curves S_H versus q with $P = \frac{p}{q}$ as parameter.

Fig. 4 through 8 give S_H for the three basic shapes.
With these figures the shielding efficiency of a solid-shell enclosure for sinusoidal magnetic fields can be determined.

Example 1

A metal cabinet housing an electronic circuit consists of 1 mm thick steel. $\mu_r = 200$ and $\sigma_r = 0.17$. The dimensions l x w x h are 40 x 30 x 30 cm. The cabinet is approximated by a sphere of 15 cm radius. Read the skin depth at a number of frequencies with help of fig.3. Calculate q, see table 4.
Calculate further $P = \frac{r}{\mu_r d} = 0.75$ and read S_H in fig.8. S_H is represented in fig.9.

If the cabinet had been made of aluminium of equal thickness with $\mu_r = 1$ and $\sigma_r = 0.4$, the shielding efficiency would have been considerably lower, particularly at high frequencies. See fig. 9.
In the same figure S_H is given of a cabinet of the same dimensions but made of stainless steel, say chrome-nickel steel N 129, with $\mu_r = 1.01$ and $\sigma_r = 0.024$. This material is often used. The shielding efficiency is inferior to that of ordinary steel plate.

Example 2

Given a piece of cable with a shield of lead, inner diameter 2 cm, thickness d = 1.5 mm.

The enclosure is now approximated with a cylinder.

Calculate $P = \frac{r}{\mu_r d} = 6.67$

S_H can be read with figs. 3 and 4 and is represented in fig.10.

Fig. 10 also shows that S_H will be much higher if the cable is laid in a steel pipe of the same dimensions, instead of being covered with a lead shield.

Example 3

An existing room comprising sensitive equipment must be shielded against strong ambient fields with frequencies above 10 kHz. The dimensions of the room are 10 x 8 x 6 meters.

To shield this room one could very well choose plates of tinned iron (steel) with a thickness d = 0.5 mm, which is cheap and can be easily joined by soldering. $\mu_r = 200$ and $\sigma_r = 0.17$.

Approximate this enclosure by a sphere with radius r = 3 m. With this conservative approximation P = 30 . Fig. 11 gives S_H versus frequency.

When the same room is shielded with copper sheet with thickness d = 0.1 mm or 0.2 mm S_H is much smaller at the higher frequencies.

4.1 Some particular characteristics

a. The time function of the field H_i inside the enclosure is the same as that of the external field H_o.

b. The attenuation of H_o is defined by the ratio of the peak values or r.m.s. values of H_o and H_i.

c. The non-magnetic materials have a $\mu_r = 1$ by which $P = \frac{r}{\mu_r d} \gg 1$.

From $P \geqslant 10$ and $S_H > 10$ dB the attenuation of H_o increases directly proportional to r. See fig. 4,5 and 7.

d. Enclosures with a small radius r and made of ferromagnetic materials have a $P = \frac{r}{\mu_r d} < 1$. At the low frequencies, where $\frac{d}{\delta} < 1$, the shielding efficiency S_H reaches a constant value, see figs. 6 and 8.

This is the so called magneto-static shielding, or the ducting effect. The magnetic field lines are turned off and concentrated in the material.

This effect is maximum at zero frequency and decreases with increasing frequency, because the effective cross-section of the material becomes smaller as a result of the eddy currents.
From P = 0.1 and lower the attenuation of H_o is inversely proportional to P.

e. At very low frequencies and very thin material with a large μ_r the shell may be locally saturated if the amplitude of H_o is too large.

f. When the enclosure is made of a non-magnetic material at all but very low frequencies equation (15) has a value $|k|>>1$. In that case the terms $\frac{1}{k}$ and $\frac{2}{k}$ in the transfer functions of table 2 can be neglected. The attenuation of H_o by two plates, cylinders and spheres is related to each other in the center of the enclosure and with the same distance between the center and the enclosure as 3 to 1.5 to 1.

g. The μ of ferromagnetic metals is dependent on frequency and flux density. One has to choose a constant value.

h. The shielding efficiency S_H in the corners of a rectangular enclosure, outside the sphere, is appreciably lower than in the sphere.
This is caused by current concentration in the corners. The effect can be reduced by rounding the corners or reinforcing them with thicker material. The reduction of S_H in the corners can be approximated with

$$\left|\frac{H}{H_i}\right| = \pi\left(\frac{4}{3\pi}\,\frac{r}{\Delta r}\right)^{4/3} \sin\frac{\pi}{12}\left\{1 + \frac{1}{5}\left(\frac{3\pi}{4}\,\frac{\Delta r}{r}\right)^{2/3}\right\} \qquad (19)$$

See fig. 12 [7 - p. 105]

i. In spite of carefully constructing necessary interruptions in the walls - such as doors, ventilation holes, filters, etc.-in practice the maximum shielding efficiency of a shielded room will not be more than about 100 to 120 dB.

j. Enclosures of very thin material and with dimensions around 1/4 λ and multiples of 1/4 λ may show dips of tens of dB's in the attenuation curve as a result of resonances in the enclosure.

Note 1 Another way of studying the shielding effect is given by Schelkunoff. In this case the transmission of an electromagnetic wave in an infinitely flat plate is treated in the same way as with ordinary transmission lines, i.e. based on reflection and absorbtion.

In U.S. literature this method is often used for calculating the attenuation of an enclosure without taking into account the shape of the enclosure. This will easily yield faulty results [8].

Note 2 The electric field as a result of the magnetic field inside the enclosure is not considered here.

5.0 SHIELDING AGAINST TRANSIENT FIELDS

When we are looking again to the spectrum of the EMP we see we have not to do with only one frequency but with a lot of frequencies.
One can imagine the EMP being built-up of very many sinusoidal components, each with its own amplitude, phase and frequency. Fig. 2 is a plot of the envelope of the amplitudes versus frequency. The spectrum of a single shot phenomenon is continuous, that means it contains components at all frequencies from $-\infty$ to $+\infty$.
Table 2 or fig.9 show that the transfer of the amplitude and phase of the components is a function of frequency. When the components inside the enclosure are joined together the shape of the pulse differs from that outside the enclosure.
It can be seen from example 1 through 3 that the components with high frequencies are attenuated more than the components with low frequencies. As a result the pulse inside the enclosure has not only a smaller amplitude but also a larger rise time and half-width time. This may have important consequences upon the effects of the EMP to electronic equipment.

The time function of the internal field $H_i(t)$ can be calculated in several ways, namely with:

a. the fourier transform integral
b. the convolution integral
c. special computer codes.

5.1 The fourier transform integral

In fig.13 a schematic diagram is given of a frequency domain analysis. In general: the response $r(t)$ as a result of a frequency dependent transfer $T(\omega)$ of a phenomenon $g(t)$ is:

$$r(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} T(\omega) G(\omega) e^{j\omega t}\, d\omega \tag{20}$$

where $G(\omega)$ is the fourier transformation of $g(t)$.
In our case:

$$H_i(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} T_H(\omega) H_o(\omega) e^{j\omega t}\, d\omega \tag{21}$$

The transfer function $T_H(\omega)$ of the three basic shapes is given in table 2, the spectrum $H_o(\omega)$ can be derived from equations (5) and (9) and table 1.
For example, the fourier transform integral for a sphere is:

$$H_i(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \frac{1}{\cosh \gamma d + 1/3(k+2/k)\sinh \gamma d}\; H_b\left(\frac{1}{\alpha+j\omega} - \frac{1}{\beta+j\omega}\right) e^{j\omega t}\, d\omega$$

This integral cannot be solved in an analytical way. By modifying the transfer functions (see appendix A) it is possible to solve fourier transform integral (21) by the computer in a numerical way (see appendix B, programmes J7...J9).

If the EMP has a complex analytical form (e.g. if the fine structure has been taken into account) which cannot easily be transformed, it may be advantageous to carry out a time domain analysis.

5.2 The convolution integral

In a time domain analysis two alternatives are possible (see fig.14):

a. Determine the step response g(t) of the system.
   Then calculate the response for an arbitrary signal with help of the convolution integral.

b. Determine the impulse response h(t) of the system and calculate the response for an arbitrary signal with help of the associated convolution integral.

   The convolution integral indeed looks a bit simpler, however, this helps us not so much, because the problem is now how to determine the analytic expression for the step response or impulse response of the enclosure.

5.3 Computer codes

If the transfer is not linear, e.g. if the material would be getting saturated, the two methods mentioned in the preceding paragraphs cannot be used. In that case the differential equations describing the system must be solved with special computer codes.

In this report we assume the material is not saturated since nearly all energy is expected at those frequencies where the skin effect is dominating, see chapter 4 paragraph 1d.

5.4 The equivalent delta function method

This method is a variant to the frequency domain analysis. A delta function is a rectangular impulse with a very short duration $\delta \to 0$ and a very large amplitude $Y \to \infty$, where δY has a finite value. Fig. 15 shows a delta function with its spectrum. The spectral amplitude $|Y(\omega)| = \delta Y$ (the area of the impulse). δY has a constant value from frequency $f \to -\infty$ to $f \to +\infty$. A unit delta function (UDF) has an area $\delta Y = 1$.

In many cases the attenuation of the components with frequencies higher than f_{c1} is so large that they give only a very small contribution to the field inside the enclosure. Compare for instance fig.2 and 9. In such cases the EMP may be replaced by a delta function of appropriate spectral amplitude A. This is an equivalent delta function (EDF).
In order to judge whether this approximation is justified or not the shielding efficiency S_H at the first cut-off frequency f_{c1} must be calculated with the method of section 4.0.

For cases where S_H at f_{c1} is on the small side or at frequencies higher than f_{c1} is increasing too slowly the approximation of the EMP by an equivalent delta function is a conservative one.
When the EMP is replaced by a unit delta function incident field with $|Y(\omega)| = \tilde{\delta}Y = 1$ it is possible to calculate the response

$$h(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} T_H(\omega) e^{j\omega t} \, d\omega \tag{22}$$

This integral is solved by the computer CDC 6400 for the three basic shapes. The results are plotted as a family of universal curves B^2h versus $\frac{t}{B^2}$ with C as parameter in fig. 16 through 24.

With these curves the response $H_i(t)$ of the enclosure to an equivalent delta function incident field can be determined.
The procedure is as follows:

- calculate the value of B^2 and parameter C
- select or interpolate for the correct curve
- multiply B^2h by $1/B^2$ and t/B^2 by B^2.

The result is h(t), the response to a unit delta function incident field. To obtain $H_i(t)$ one only needs to multiply h by A, the spectral amplitude of the EMP at zero frequency. For example $A = |H(\omega)|_{pk}$ in table 1 or $A = |H(\omega)|$ in equation (11b).

Example 4

Let us calculate the shielding effectiveness of the aluminium cabinet in example 1 to an EMP of an exo-atmospheric explosion, model II. According to table 1, f_{c1} = 239 kHz and $A = 9.11 \times 10^{-5}$ A/m/Hz.
In fig.9 the shielding efficiency S_H at 239 kHz is 86 dB. Assume this is large enough as to justify the substitution of the EMP by a delta function of spectral amplitude A.

Calculate $C = \frac{r}{3\mu_r d} = 50$,

and $B^2 = d^2\mu\sigma = 2.92 \times 10^{-5}$.

Multiply the values of B^2h and t/B^2 of the curve with parameter C = 50 in fig.23 by $1/B^2$ and B^2 respectively.

The result is $h(t)$, the response to a unit delta function incident field. Multiply h by A to obtain $H_i(t)$, the response of the cabinet caused by a delta function incident field equivalent to EMP model II.
In fig. 25 this response is indicated with EDF.
If the response is calculated to the EMP itself - equation (21), computer programme J9 in appendix B - there is only a small difference.
When the cabinet is made of steel, there is no difference between the responses of the EMP and the EDF.
Fig. 26 shows the responses of the same cabinet made of stainless steel. In this latter case the equivalent delta function method results in a conservative approximation of the EMP.

Let us continue with the calculation of the shielding effectiveness of the aluminium cabinet.
Read from fig.23 $B^2 h_{pk} = 1.96 \times 10^{-2}$ and $t_r/B^2 = 0.23$

$$h_{pk} = B^2 h_{pk} \times \frac{1}{B^2} = 672$$

$$H_{i\ pk} = A\ h_{pk} = 61.2 \text{ mA/m}$$

$$H_{o\ pk} = 133 \text{ A/m (table 1)}$$

The attenuation of the peak fieldstrength is:

$$20 \log \frac{H_{o\ pk}}{H_{i\ pk}} = 66.7 \text{ dB.}$$

$$t_r = \frac{t_r}{B^2} \times B^2 = 6.7\ \mu\text{s}$$

The rise time is increased by a factor 859.
The voltage induced in a loop with area A is:

$$U_i = \mu\ A\ \dot{H} \tag{23}$$

The largest possible loop in the cabinet has an area $A = 0.12\ m^2$.
The induced peak voltage during the rise time t_r is:

$$U_{i\ pk} \approx \mu\ A \frac{0.8\ H_{pk}}{t_r} \tag{24}$$

In this loop $U_{i\ pk} = 1.1$ mV.
Even when a larger fieldstrength in the corners of the cabinet is taken into account one can say that such a small voltage will not cause damage to sensitive components.

The induced peak voltage in the loop is decreased both by a smaller fieldstrength and by a larger rise time. Here the knife cuts both ways.

In this case the total attenuation of $U_{i\ pk}$ - the shielding effectiveness - is 66.7 + 58.7 = 125.4 dB.

Without the shielding enclosure the induced peak voltage in the loop would be 2200 volt.

The EDF method results in a rise time which is 7.6% too short.

This means the shielding effectiveness is only 0.7 dB higher than 125.4 dB.

The following table also gives the results of the steel and stainless steel cabinet for EMP model II and its EDF.

results	aluminium		steel		stainless steel	
	EDF*	EMP	EDF	EMP	EDF	EMP
$H_{i\ pk}$ (mA/m)	61.2	61.2	36.6	36.6	1020	995
t_r (μs)	6.7	7.25	220	220	0.402	1.42
$U_{i\ pk}$ (mV)	1.1	1.02	0.02	0.02	306	85
shielding effectiveness (dB)	125.4	126.1	160	160	77	88
S_H at f_{c1} (dB)	86		very high		43	

* EDF is the equivalent delta function of the EMP

Example 5

A computer placed in a room $l \times w \times h = 15 \times 10 \times 3$ m must be shielded against the EMP of an endo-atmospheric explosion. Assume the EMP may be represented by the model of equation (2) and $\beta \gg \alpha$. Suppose that for the case in question $t_w = 7$ µs and $H_b = 137.5$ A/m (these values are arbitrarily chosen).

Substituting t_w in equation (10):

$$\alpha \approx \frac{0.7}{t_w} = 10^5.$$

From equation (7):

$$f_{cl} = \frac{\alpha}{2\pi} = 15.9 \text{ kHz}.$$

The shielding efficiency at 15.9 kHz is 83 dB (use fig.3 and 4).

The spectral amplitude can be calculated with equation (11b):

$$A = |H(\omega=o)| \sim 1.43\ H_b\ t_w = 1.38 \times 10^{-3} \text{ A/m/Hz}.$$

Approximate this room by two plates with a distance $r = 3$ m.

Use for example steel plates (tinned iron) $l \times w = 2 \times 1$ m and thickness $d = 0.5$ mm, $\mu_r = 200$ and $\sigma_r = 0.17$.

$$\text{Calculate } C = \frac{r}{2\mu_r d} = 15$$

$$B^2 = d^2\ \mu\sigma = 6.195 \times 10^{-4}$$

Read $B^2\ h_{pk} = 6.3 \times 10^{-2}$ from fig. 23.

$$h_{pk} = 101.76$$

$$H_{i\ pk} = A\ h_{pk} = 140 \text{ mA/m}$$

$$\frac{t_r}{B^2} = 0.216$$

$$t_r = 133.8\ \mu s$$

The largest possible loop has an area $A = 150$ m^2.

Using equation (24) and supposing the rise time is not affected by this large loop, $U_{i\ pk} = 158$ mV.

If this value is thought too high, or if the spectral amplitude would be larger it is advisable to choose thicker steel plate.

In this latter case it is also advisable to investigate if saturation of the material may occur.

The responses of this enclosure to the EDF and the EMP are presented in fig.27. The rise time of $H_i(t)$ to the EMP is only 4.9% shorter. This means that in this case the applied EDF method is a justified procedure.

Example 6

The room in example 3 has to be shielded against the EMP of an exo-atmospheric explosion model III.

Read from table 1:

f_{c1} = 605 kHz and A = 3.73×10^{-5} A/m/Hz.

Use for example steel plate with d = 0.5 mm, μ_r = 200 and σ_r = 0.17.

The shielding efficiency S_H at 605 kHz in fig.11 is very large. Use therefore the EDF method.

Calculate $C = \frac{r}{3\mu_r d} = 10$

$B^2 = d^2\mu\sigma = 6.195 \times 10^{-4}$

The response of the shielded room to the EDF of model III can be determined with help of fig.22.

Fig.28 shows the result. There is no difference between the responses of the EDF and the EMP.

If copper sheet is used the EDF method gives conservative results. The largest possible loop has an area A = 80 m^2.

Neglecting the corner effect the shielding effectiveness has the following values.

results	steel		copper 0.1 mm		copper 0.2 mm	
	EDF	EMP	EDF	EMP	EDF	EMP
$H_{i\,pk}$ (mA/m)	5.56	5.56	5.11	5.10	2.55	2.55
t_r (μs)	129	129	0.172	0.635	0.690	0.925
$U_{i\,pk}$ (mV)	3.47	3.47	2389	646	297	222
shielding effectiveness (dB)	172	172	115	127	133	136
S_H at f_{c1} (dB)	very high		89		99	

If the room is shielded with copper sheet the rise time t_r is much shorter than with steel plate.
The induced peak voltages are too low to cause damage. If loops would be created with an area $A = 80\ m^2$ it may be possible that in the case of copper sheet malfunction of sensitive equipment may occur.

Shielding with thin copper sheet is a very attractive method. Copper sheet can easily be handled and soldered and may offer a pretty good shielding as in this example.
If the construction of loops cannot be avoided it is important to make their area as small as possible and to keep them away from the corners of the enclosure.

The largest dimension of the enclosure is 10 m.
This means that the lowest resonant frequency of the enclosure is 7.5 MHz, corresponding to $\lambda/4 = 10$ m.
As a result sharp dips of tens of dB's in the curve S_H versus frequency may occur at 7.5 MHz and multiples of this frequency.
A high absorption loss S_A in the metal sheet reduces this effect. The absorption loss $S_A(\text{dB}) = 8.7\ q$.
For copper sheet with d = 0.2 mm or 0.1 mm S_A is 72 dB and 36 dB respectively.
In this respect it is better to choose the thickness d = 0.2 mm.

Note 1. Thin aluminium sheet connected on a lot of places with staples in an overlap of some centimetres to a wall of wood may also be considered. Aluminium is a factor 4 cheaper than copper.

Note 2. At present copper sheet with d = 0.05 mm and width of 50 cm is in the market. This sheet contains a conductive gluten and can be adhered to walls like wall-paper. The resistance in the seams we have measured is 5.3 Ω/cm^2. For this reason it does not seem very suitable for shielding purposes.

5.5 Some striking characteristics

a. If the half width time t_w of the EMP is not too large and the thickness d of the enclosure is not too small, $H_i(t)$ can easily and quite accurately be determined with help of the parametric curves. However, if S_H at f_{c1} is too small or is increasing at higher frequencies too slowly the equivalent delta function method leads to rise times which are too short. In these cases it is better to use the computerprogrammes J7...J9 of appendix B.

b. If the rise time of the EMP is very short, this rise time will have no influence upon the rise time of $H_i(t)$.

c. The area $\int_0^\infty H_o(t)\,dt$ of the EMP is a measure for the amplitude of the field $H_i(t)$ inside the enclosure.

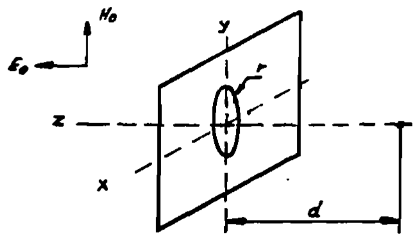
d. In nearly all cases the time history of H_i is completely determined by the material (electrical characteristics), the dimensions and the shape of the enclosure.
Only the rise time of $H_i(t)$ may be influenced by the pulse width of the EMP.

e. From $C \geqslant 10$ the value of $B^2 h_{pk} \approx 1/C$ and $\frac{t_r}{B^2} \rightarrow 0.24$ (fig.16 through 24).

f. It is also possible to calculate and plot parametric curves for a specific EMP (e.g. model II or III). Use therefore the computer-programmes J7...J9 in appendix B.
An advantage is that the rise time of $H_i(t)$ may be more accurate.

g. The computed responses $H_i(t)$ apply to enclosures which are totally closed. Apertures or seams in the solid-shell may seriously affect the shielding characteristics.

6.0 THE EFFECTS OF APERTURES IN ENCLOSURES



Suppose we have a plane sheet with an infinitely large area and conductivity. In this metal sheet is a circular hole with radius r which is small compared to the smallest wavelength of interest λ in the incident field E_o and H_o.

The shielding efficiency to a sinusoidal incident field at a distance d ` r and small compared to the λ of interest is in the worst case:

$$S_E \text{ (dB)} = 20 \log_{10} \frac{3\pi d^3}{2r^3} \text{ (upon the z-axis)} \tag{25}$$

$$S_H \text{ (dB)} = 20 \log_{10} \frac{3\pi d^3}{4r^3} \text{ (upon the y-axis, close to the shield)} \tag{26}$$

Equations (25) and (26) may also be used to calculate the field H_i inside finite enclosures if the hole is located in a flat part of the enclosure and provided the amplitudes of reflected fields inside the enclosure are negligible.
Kaden has also obtained solutions for more complicated situations like spheres, etc. [7, p.221-p.252].

Equations (25) and (26) are not dependent on frequency. This means that with the assumptions made before,the time history of a transient field which penetrates through the hole is indentical to that of the incident field.

Example 7

Suppose the room in example 6 has a circular hole in one of the steel walls. The radius r = 25 cm.
At a distance d = 100 cm a loop or piece of wire is located. The loop has an area A = 50 cm x 50 cm and the wire has a length l = 50 cm.
The field inside the enclosure near the hole is identical to the EMP, only the amplitude is attenuated.
S_E = 49.6 dB and S_H = 43.6 dB.

This means t_r = 7.8 ns, $E_{i\ pk}$ = 166 V/m and $H_{i\ pk}$ = 0.88 A/m.
Using equation (24) $U_{i\ pk}$ = 28 V in the loop.
In the wire $U_{i\ pk} = \frac{1}{2} E_{i\ pk}$ = 41.5 V with respect to earth. When this loop or wire is connected to sensitive components malfunction of equipment may be the result.

6.1 The application of waveguides

An excellent method for protection against penetrating fields through holes is the installation of pipes acting like waveguides. Necessary apertures like air intake and exhaust holes, and other holes for passing nonconducting materials may be carried out as ducts acting like "waveguides - beyond - cut-off". Above the cut-off frequency electromagnetic waves pass without attenuation in many modes of transmission. Waves with lower frequencies are attenuated.
Any waveguide has many cut-off frequencies, associated with the modes of transmission.
The lowest cut-off frequencies are:

$$f_c = \frac{15}{b} \text{ GHz for square waveguides} \tag{27}$$

$$f_c = \frac{17.6}{d} \text{ GHz for circular waveguides} \tag{28}$$

b = the inside width in cm
d = the inside diameter in cm

The shielding efficiency of waveguides with a square cross-section can be calculated with:

$$S(\text{dB}) = \frac{27.3\ l}{b}\sqrt{1-\left(\frac{f}{f_c}\right)^2} \tag{29}$$

where l is the waveguide length in cm.
For frequencies $f < 0.1\ f_c$ the shielding efficiency per unit length is about:

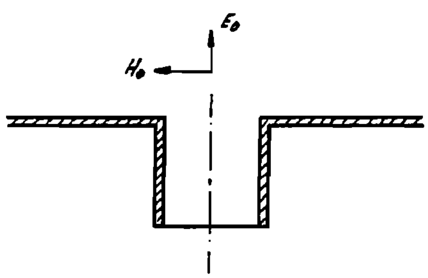
$$S_H = \frac{27.3}{b} \text{ dB/cm (square)} \tag{30}$$

$$S_H = \frac{32}{d} \text{ dB/cm (circular)} \tag{31}$$

$$S_E = \frac{27.3}{b} \text{ dB/cm (square)} \tag{32}$$

$$S_E = \frac{41.8}{d} \text{ dB/cm (circular)} \tag{33}$$

In equations (30) through (33) it is assumed that the waveguide stub is on the inside of the enclosure.



The material of the waveguide stub can be chosen to have a sufficient stiffness.

The shielding efficiency of rectangular waveguides can be approximated by using equations (30) and (32), where b = the largest inside dimension in cm.

Example 8

The shielding efficiency of the shielded room with the circular hole in example 7 must be improved. Assume a shielding efficiency of 100 dB up to 40 MHz is needed.
The lowest cut-off frequency of a circular waveguide with diameter d = 50 cm can be calculated with (28):

$$f_c = \frac{17.6}{50} = 352 \text{ MHz.}$$

This frequency is sufficiently higher than 40 MHz.
Therefore use equations (31) and (33):
S_H = 0.64 dB/cm and S_E = 0.84 dB/cm.
Choose a length l = 156 cm.
Remember the rule of thumb:
for S_H = 100 dB a length is needed $l \approx 3\ d$.

The cross-section of square and rectangular waveguides are very well suited to subdivide in a number of smaller square waveguides, the so-called honeycomb structures. This has two advantages, namely a higher f_c and smaller l.

Example 9

The shielded room in example 6 must be provided with ventilation holes. A shielding efficiency of 140 dB up to 40 MHz is needed. Construct waveguides with a square cross-section.
For a good design choose f_c = 10 x 40 = 400 MHz.

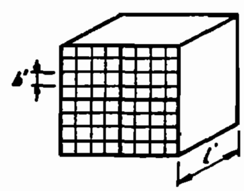
$$b = \frac{15}{f_c} = 37.5 \text{ cm}$$

$$S_H = \frac{27.3}{b} = 0.728 \text{ dB/cm}$$

$$l = \frac{140}{0.728} = 192 \text{ cm}$$

Subdivide this waveguide in smaller stubs, for instance with $b' = \frac{b}{8}$, then $l' = \frac{l}{8}$ = 24 cm and f_c = 3.2 GHz.

Waves with a frequency up to about 320 MHz are attenuated with 140 dB. This means that the attenuation of the components in nearly the whole frequency spectrum is the same.



7.0 CONCLUSIONS

1. If, as has been done in this report, the EMP is expressed in simple analytical models the field inside a solid-shell enclosure can be calculated with help of the computer programmes presented.

2. In many practical shielding cases - an EMP of short duration, or enclosures of sufficient shielding efficiency at low frequencies - the field inside the enclosure can easily be determined with help of the universal curves presented.

3. The rise time of the EMP has a very small influence on the rise time of the pulse inside the enclosure. The rise time of the latter is almost completely determined by the material used for the enclosure (permeability, conductivity and thickness).

4. The pulse inside the enclosure - as compared to the EMP - shows an increased rise time, an increased pulse width and a reduced peak amplitude.

5. The electric field component of the EMP is much more attenuated than the magnetic field component.
As the induced voltages in loops are proportional to $\dot{H}$ the protection offered to circuits shielded by a simple solid-shell enclosure may be relatively large.

6. In most cases it is relatively easy to design a solid-shell enclosure with sufficient shielding effectiveness. However, apertures and seams may largely affect the shielding properties of the enclosure. Normal shielding practice may not be forgotten, as filtering the in- and outgoing conductors, avoiding large currents in the solid-shell, etc.

7. Finally, the universal curves are also applicable to other short lasting phenomena like impulsive radio frequency interference.

ACKNOWLEDGEMENTS

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APPENDIX A

Modification of the transfer functions

The transfer functions derived by Kaden (table 2) must be modified before they can be handled by the computer.

The transfer function for two parallel plates and cylinders in an axial magnetic field is:

$$T_H(\omega) = \frac{1}{\cosh \gamma\, d + \frac{1}{2} k \sinh \gamma\, d} \tag{A1}$$

where $\gamma = \sqrt{j\,\omega\,\mu\,\sigma}$

and $k = \dfrac{\gamma r}{\mu_r}$

Introducing $B = d\sqrt{\mu\cdot\sigma}$ in equation (A1) gives:

$$T_H(\omega) = \frac{1}{\cosh B\sqrt{j\omega} + \frac{1}{2}k \sinh B\sqrt{j\omega}} \tag{A2}$$

By applying $C = \dfrac{r}{2\mu_r d}$ equation (A2) can be modified in:

$$T_H(\omega) = \frac{1}{\cosh B\sqrt{j\omega} + CB\sqrt{j\omega}\sinh B\sqrt{j\omega}} \tag{A3}$$

Substituting in (A3):

$$\sqrt{j\omega} = j\sqrt{-j\omega}$$

$$\cosh B\sqrt{j\omega} = \cos B\sqrt{-j\omega}$$

and

$\sinh B\sqrt{j\omega} = j.\sin B\sqrt{-j\omega}$
results in:

$$T_H(\omega) = \frac{1}{\cos B\sqrt{-j\omega} - CB\sqrt{-j\omega}\,\sin B\sqrt{-j\omega}} \qquad \text{(A4)}$$

The transfer function for cylinders in a transverse magnetic field can be modified with the same procedure,

$$T_H(\omega) = \frac{1}{\cos B\sqrt{-j\omega} - (CB\sqrt{-j\omega} - \dfrac{1}{4CB\sqrt{-j\omega}})\sin B\sqrt{-j\omega}} \qquad \text{(A5)}$$

where $C = \dfrac{r}{2\mu_r d}$.

For spheres the modified transfer function is:

$$T_H(\omega) = \frac{1}{\cos B\sqrt{-j\omega} - (CB\sqrt{-j\omega}.- \dfrac{1}{4.5\ CB\sqrt{-j\omega}})\sin B\sqrt{-j\omega}} \qquad \text{(A6)}$$

where $C = \dfrac{r}{3\mu_r d}$.

Equations(A4), (A5) and (A6) are used in the programmes J1...J9 of appendix B.
Constant B and the concerning parameter C are given once more in each of the figures 16 through 24.

APPENDIX B

Computer programmes

The computer programmes have been composed for the computer CDC 6400 (Fortran 4).

Input

J, K, N, C, begin T, end T, ΔT, B, H, α and β.

With J the shape of the enclosure and the type of incident field H_o is chosen.

H_o \ shape	two plates	cylinder	sphere
UDF	J 1	J 2	J 3
EDF	J 4	J 5	J 6
EMP	J 7	J 8	J 9

UDF = unit delta function

EDF = equivalent delta function

With K_1 the output is tabulated. K_2, the plotting of the output, is not implemented yet.

N is the number of values for C.

C is the parameter derived in appendix A

Begin T, end T and ΔT(or DT) must be chosen. $T = t/B^2$

B is the constant derived in appendix A. For UDF B = -0, in the other cases $B = d\sqrt{\mu\sigma}$.

For UDF: H = -0, α = -0 and β = -0.

EDF: H = A, α = -0 and β = -0

EMP: H = H_b (H_b, α and β can be read from table 1).

Output

For UDF: the output is B^2h versus t/B^2, where $T = t/B^2$

EDF: $H_i(t)$, where T = t

EMP: $H_i(t)$, where T = t

Example 10

The response of the shielded room in example 6 to EMP, model III has to be calculated.

J = 9, K = 1, N = 1, C = 10.

Choose T with help of fig. 22:

begin $T = 10^{-2}$, end $T = 1$, $\Delta T = 10^{-2}$ (rise time)

begin $T = 0.5$, end $T = 70$, $\Delta T = 0.5$ (decay time)

$B = \sqrt{6.195 \times 10^{-4}}$, $H = 144$, $\alpha = 3.8 \times 10^{6}$, $\beta = 2.4 \times 10^{8}$

The ouput H_i versus t is tabulated, where T = t.

The response is given in fig. 28.

Programme listing

```
      PRØGRAM EMP5119(INPUT,ØUTPUT)
C
C      INPUT
C      J = 1   TWØ PARALLEL PLATES UDF
C      J = 2   CYLINDERS UDF
C      J = 3   SPHERES UDF
C      J = 4   TWØ PARALLEL PLATES EDF
C      J = 5   CYLINDERS EDF
C      J = 6   SPHERES EDF
C      J = 7   TWØ PARALLEL PLATES EMP
C      J = 8   CYLINDERS EMP
C      J = 9   SPHERES EMP
C      K = 1 NUMERICAL TABLE IS PRINTED
C      K = 2 A GRAPH IS PLØTTED
C      PLØTTING IS NØT IMPLEMENTED YET
      CØMMØN B2,C,H,ALFA,BETA
      EXTERNAL FØURIER
      DØUBLE FØURIER,B2,XLAPLIN,T,C,H,ALFA,BETA
      DIMENSIØN C1(5),C2(5),X(1003),Y(1003)
10    READ 20,J,K,N,(C1(I),I=1,N)
20    FØRMAT (3I1,5F10)
      IF(N.EQ.0)130,35
35    READ 30,IPAG,BEGINT,ENDT,DT,B,H1,A1,B1
      PRINT 36,J,K,N,(C1(I),I=1,N)
36    FØRMAT(1H1,///////,5X,*J = *,I1,/,5X,*K = *,I1,/,5X,
     1*N = *,I1,/,5X,*C = *,5E17.10)
      PRINT 37,BEGINT,ENDT,DT,B,H1,A1,B1
37    FØRMAT(5X,*BEGINT = *,E17.10,/,5X,*ENDT    = *,E17.10,
     1/5X,*DT      = *,E17.10,/,5X,*B       = *,E17.10,/,
     25X,*H       = *,E17.10,/,5X,*ALFA    = *,E17.10,/,
     35X,*BETA    = *,E17.10)
40    B2=B*B $ H=H1 $ ALFA=A1 $ BETA=B1
30    FØRMAT(I3,7F10)
      IREG=0
      T=T1=BEGINT
60    IF(T.LE.0)T=DT/10.0
      DØ 70 L=1,N
      C=C1(L)
      C2(L)=XLAPLIN(FØURIER,26,T,J)
70    CØNTINUE
      J2=(J-1)/3+1
      GØTØ(80,72,72)J2
72    T=T*B2
      DØ 73 I=1,N
      C2(I)=C2(I)/B2
73    CØNTINUE
80    L=IREG-50*(IREG/50)
      IF(L.EQ.0)90,110
90    PRINT 100,IPAG,(C1(L),L=1,N)
100   FØRMAT(1H1,//,30X,*PAGINA*,I4,//,7X,*T*,6X,5(2X,E20.8),//)
      IPAG=IPAG+1
110   PRINT 120,T,(C2(L),L=1,N)
120   FØRMAT(2X,F12.6,5(2X,E20.8))
      IREG=IREG+1
      T=T1=T1+DT
      IF(T.GT.ENDT)10,60
130   PRINT 140
140   FØRMAT(1H1)
```

```
      DØUBLE FUNCTIØN FØURIER(S,J)
      CØMMØN B2,C,H,ALFA,BETA
      DØUBLE S,P,A,C,PAB,ØNE,TWØ,AB,B2,C1,FØUR1,FØUR2,H,ALFA,BETA
      DATA(ØNE=1.0D0),(TWØ=2.0D0)
      FØUR1(H)=TWØ*H/((ØNE-PAB)/C1+(ØNE+PAB)*C1)
      FØUR2(H)=ØNE/(ALFA+S/B2)-ØNE/(BETA+S/B2)
      IF(H.EQ.0.0D0)H=1.0D0
      A=DSQRT(S)
      AB=A*C
      C1=DEXP(A)
      IF(J.LT.1.ØR.J.GT.9) GØTØ 100
      J2=(J-1)/3+1
      J1=J-(J2-1)*3
      GØTØ(30,10,20)J1
10    P=4.5D0
      GØTØ 25
20    P=4.0D0
25    PAB=AB+ØNE/(P*AB)
      GØTØ 35
30    PAB=AB
35    GØTØ(40,40,60)J2
40    FØURIER=FØUR1(H)
      RETURN
60    FØURIER=FØUR1(H)*FØUR2(S)
      RETURN
100   PRINT 110
110   FØRMAT(*  WRØNG PARAMETER -J-*)
      END
```

```
      DØUBLE FUNCTIØN XLAPLIN(P,N,T,J)
C
C     PURPØSE
C
C     CØMPUTE APPRØXIMATE INVERSE LAPLACE TRANSFØRM ØF FUNCTIØN P(S)

C     AT TIME-INSTANT T
C
C     TRANSLATED FRØM ALGØL ALGØRITHM NØ. 368 CØMM. A.C.M.
C     VØL 13, NØ. 1, JANUARY 1970, PAGES 47 - 49.
C     N IS THE NUMBER ØF TERMS USED IN APPRØXIMATING THE INVERSE ØF P(S)

C     N MUST BE EVEN
C     FØR THE CDC-6000 N = 26 IS ADVISED FØR ØPTIMUM ACCURACY
C     CØMPUTING TIME EQUALS N TIMES CØMPUTINGTIME ØF P(S)
C     S = LN(2)*I/T
C
C     ØN THE FIRST CALL A TABLE V(N) IS CØNSTRUCTED
C     DIMENSIØN V(N),H(N/2),G(N+1)
      DØUBLE A,AIDUM,FB,G,H,ØLDG,R,T,V,P
      DIMENSIØN V(70),H(35),G(71)
C     H AND G ARE NEEDED ØNLY DURING THE FØRMATIØN ØF TABLE V
```

```
C
      INTEGER SN,M
      DATA(M=-1)
C     ERRØR CHECK ØN N
      IF(N.LT.2.ØR.N.GT.70) STØP
      IF(N.NE.2*(N/2)) STØP
C
C     CHECK IF TABLE V MUST BE CALCULATED
      IF(M-N)1,6,1
C
C     FØRMATIØN ØF TABLE V
1     G(1)=ØLDG=1.0D0
      NH=N/2
      NK=NH+1
      N1=N+1
      DØ 2 I=2,N1
2     G(I)=ØLDG=(I-1)*ØLDG
      H(1)=2.0D0/G(NH)
      DØ 3 I=2,NH
      NL=NK-I




      AFLØAT=FLØAT(I)
3     H(I)=AFLØAT**NH*G(2*I+1)/(G(NL)*G(1+I)*G(I))
      NHX=NH-(NH/2)*2
      SN=1
      IF(NHX.EQ.0) SN=-SN
      DØ 5 I=1,N
      DUM=0.0D0
      KSTART=(I+1)/2
      KEND=I
      IF(I.GE.NH) KEND=NH
      DØ 4 K=KSTART,KEND
      IK=I-K+1
      KI=K-IK+2
4     DUM=DUM+H(K)/(G(IK)*G(KI))
      IF(SN)10,5,15
10    V(I)=-DUM
      GØTØ 5
15    V(I)=DUM
5     SN=-SN
      R=DLØG(2.0D0)
      M=N
C
C     CØMPUTE APPRØXIMATE INVERSE ØF P(S)
C
6     FB=0.0D0
      A=R/T
      DØ 9 I=1,N
      AI=A*I
      DUM=P(AI,J)*V(I)
9     FB=FB+DUM
      XLAPLIN=A*FB
      RETURN
20    END
```

EMP characteristics		Model		
Symbol	Unit	I	II	III
α	s^{-1}	1.5×10^{6}	1.5×10^{6}	3.8×10^{6}
β	s^{-1}	2.6×10^{8}	2.6×10^{8}	2.4×10^{8}
γ	s^{-1}	2×10^{5}		
δ	s^{-1}	5×10^{5}		
E_b	Vm^{-1}	5.18×10^{4}	5.18×10^{4}	5.43×10^{4}
H_b	Am^{-1}	137.5	137.5	144
D		2.21×10^{-1}		
t_r	ns	7.8	7.8	7.8
E_{pk}	kVm^{-1}	50	50	50
H_{pk}	Am^{-1}	133	133	133
t_{pk}	ns	16.4	19.9	17.6
t_w	ns	450	475	202
f_{pk}	kHz	70		
f_{c1}	kHz		239	605
f_{c2}	MHz	41.4	41.4	38.2
$\lvert E(\omega)\rvert_{pk}$	$Vm^{-1}Hz^{-1}$	3.47×10^{-2}	3.44×10^{-2}	1.41×10^{-2}
$\lvert H(\omega)\rvert_{pk}$	$Am^{-1}Hz^{-1}$	9.21×10^{-5}	9.11×10^{-5}	3.73×10^{-5}
ε_T	Jm^{-2}	2.28	2.33	1.01

Table 1 Characteristics of the three EMP models of fig.1

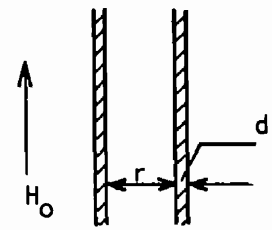
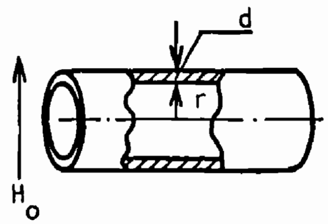
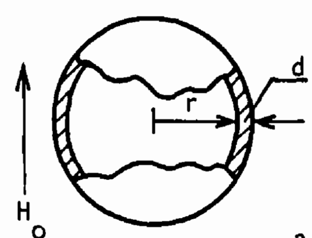
shape	nr	transfer function $T_H(\omega) = \frac{H_i(\omega)}{H_o(\omega)}$	$S_H(\mathrm{dB}) = 20 \log_{10} \left| \frac{H_o}{H_i} \right|$
	1	$\frac{1}{\cosh \gamma d + \frac{1}{2} k \sinh \gamma d}$	$10 \log \left\{ \frac{p^2}{4} (\cosh 2q - \cos 2q) + \frac{p}{2} (\sinh 2q - \sin 2q) + \frac{1}{2} (\cosh 2q + \cos 2q) \right\}$
	2	$\frac{1}{\cosh \gamma d + \frac{1}{2} (k + \frac{1}{k}) \sinh \gamma d}$	$10 \log \left\{ (\frac{p^2}{4} + \frac{1}{16p^2}) (\cosh 2q - \cos 2q) + \frac{p}{2} (\sinh 2q - \sin 2q) + \frac{1}{4p} (\sinh 2q + \sin 2q) + \frac{1}{2} (\cosh 2q + \cos 2q) \right\}$
cylinder with axial field H_o		see shape nr.1	see shape nr. 1
	3	$\frac{1}{\cosh \gamma d + \frac{1}{3} (k + \frac{2}{k}) \sinh \gamma d}$	$10 \log \left\{ (\frac{p^2}{9} + \frac{1}{9p^2}) (\cosh 2q - \cos 2q) + \frac{p}{3} (\sinh 2q - \sin 2q) + \frac{1}{3p} (\sinh 2q + \sin 2q) + \frac{1}{2} (\cosh 2q + \cos 2q) \right\}$

Table 2 The transfer function $T_H(\omega)$ and shielding efficiency S_H of three basic shapes (derived by Kaden)

Table 3 Electrical characteristics of some metals

metal	μ_r	σ_r	$\mu\sigma$	$\sqrt{\mu\sigma}$	δ(10 kHz)
stainless steel	1.01	0.024	1.77	1.33	4.3 mm
lead	1	0.084	6.1	2.47	2.28 "
brass {66 % Cu, 34% Zn}	1	0.27	19.7	4.44	1.27 "
aluminium, hard	1	0.4	29.2	5.4	1.04 "
aluminium, soft	1	0.585	42.6	6.53	0.864 "
copper	1	1	73	8.5	0.661 "
iron (steel)	200	0.17	2478	49.8	0.113 "
μ-metal	20,000	0.029	24,273	205.6	0.027 "

Table 4 Shielding efficiency S_H of cabinet in example 1

frequency	δ(fig.3)	$q = d/\delta$	S_H
0.1 kHz	1.1 mm	0.91	7 dB
1 "	0.35 "	2.86	25 "
4 "	0.175 "	5.7	53 "
10 "	0.11 "	9.1	85 "
20 "	0.08 "	12.5	116 "
30 "	0.065 "	15.4	144 "

Table 5 List of symbols

symbol	designation	unit
E	electric fieldstrength	$V\ m^{-1}$
H	magnetic fieldstrength	$A\ m^{-1}$
t	time	s
t_r	rise time (10%...90%)	s
t_w	half width time (50%...50%)	s
ε_T	total energy density	$J\ m^{-2}$
E_{pk}	peak value of E	$V\ m^{-1}$
H_{pk}	peak value of H	$A\ m^{-1}$
$\alpha, \beta, \gamma, \delta$	time constants	s^{-1}
E_b	constant	$V\ m^{-1}$
H_b	constant	$A\ m^{-1}$
D	constant	-
$\omega=2\pi f$	radian frequency	$rad\ s^{-1}$
f	frequency	Hz
$\lvert E(\omega)\rvert$	spectral amplitude of E(t)	$V\ m^{-1}\ Hz^{-1}$
$\lvert H(\omega)\rvert$	spectral amplituce of H(t)	$A\ m^{-1}\ Hz^{-1}$
f_c	cut-off frequency	Hz
i	current	A
Q	electric charge	C
$S_E = \frac{E_o}{E_i}$	shielding efficiency sin. E-field	-
E_o	E outside the enclosure	$V\ m^{-1}$
E_i	E inside the enclosure	$V\ m^{-1}$
$S_H = \frac{H_o}{H_i}$	shielding efficiency sin. H-field	-
H_o	H outside the enclosure	$A\ m^{-1}$
H_i	H inside the enclosure	$A\ m^{-1}$
$T_H(\omega) = \frac{H_i(\omega)}{H_o(\omega)}$	transfer function enclosure (H-field)	-
$\gamma = \sqrt{j\omega\mu\sigma}$	complex propagation factor	-

symbol	designation	unit
j	complex operator	$\sqrt{-1}$
$\mu=\mu_r\ \mu_o$	magnetic permeability	$H\ m^{-1}$
μ_r	relative magnetic permeability	-
$\mu_o=4\pi 10^{-7}$	constant	$H\ m^{-1}$
$\sigma=\sigma_r\ \sigma_o$	electrical conductivity	$S\ m^{-1}$
σ_r	relative electrical conductivity	-
$\sigma_o=5.8\times 10^7$	constant	$S\ m^{-1}$
r	radius, distance	m
d	thickness, distance, diameter	m
$\delta=\frac{1}{\sqrt{\pi\mu\sigma f}}$	skin depth	m
P	parameter for curves S_H versus $\frac{d}{\delta}$	-
l	length	m
w	width	m
h	height	m
λ	wavelength	m
A	constant equivalent to $\vert H(\omega=o\vert$	-
$B=d\sqrt{\mu\sigma}$	constant for curves B^2h versus t/B^2	-
C	parameter for curves B^2h versus t/B^2	-
$h(t)$	response to unit delta function	$A\ m^{-1}\ Hz^{-1}$
A	area of loop	m^2
U_i	induced voltage in loop or wire	V

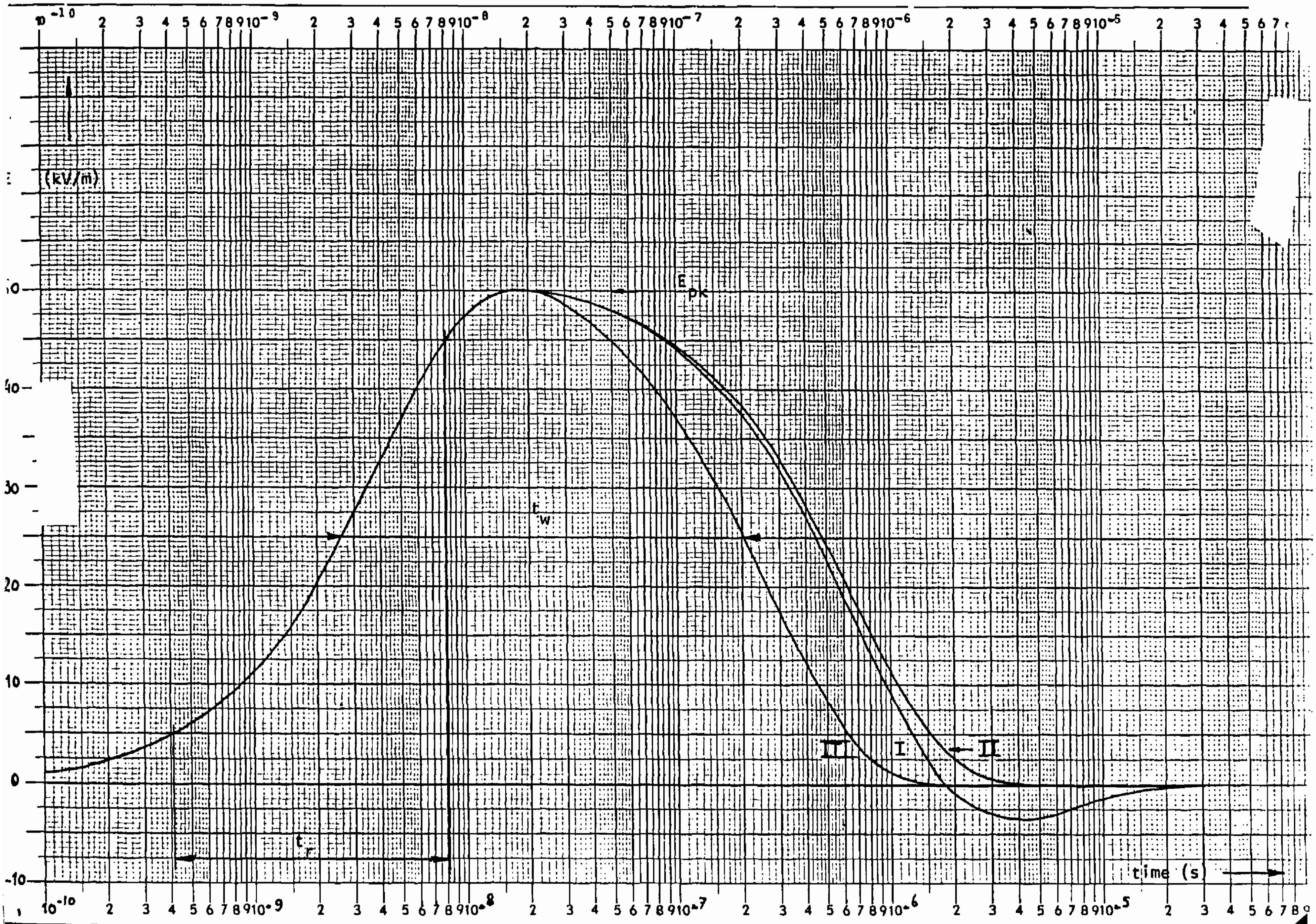


Fig.1 Three EMP models for exo-atmospheric explosions.

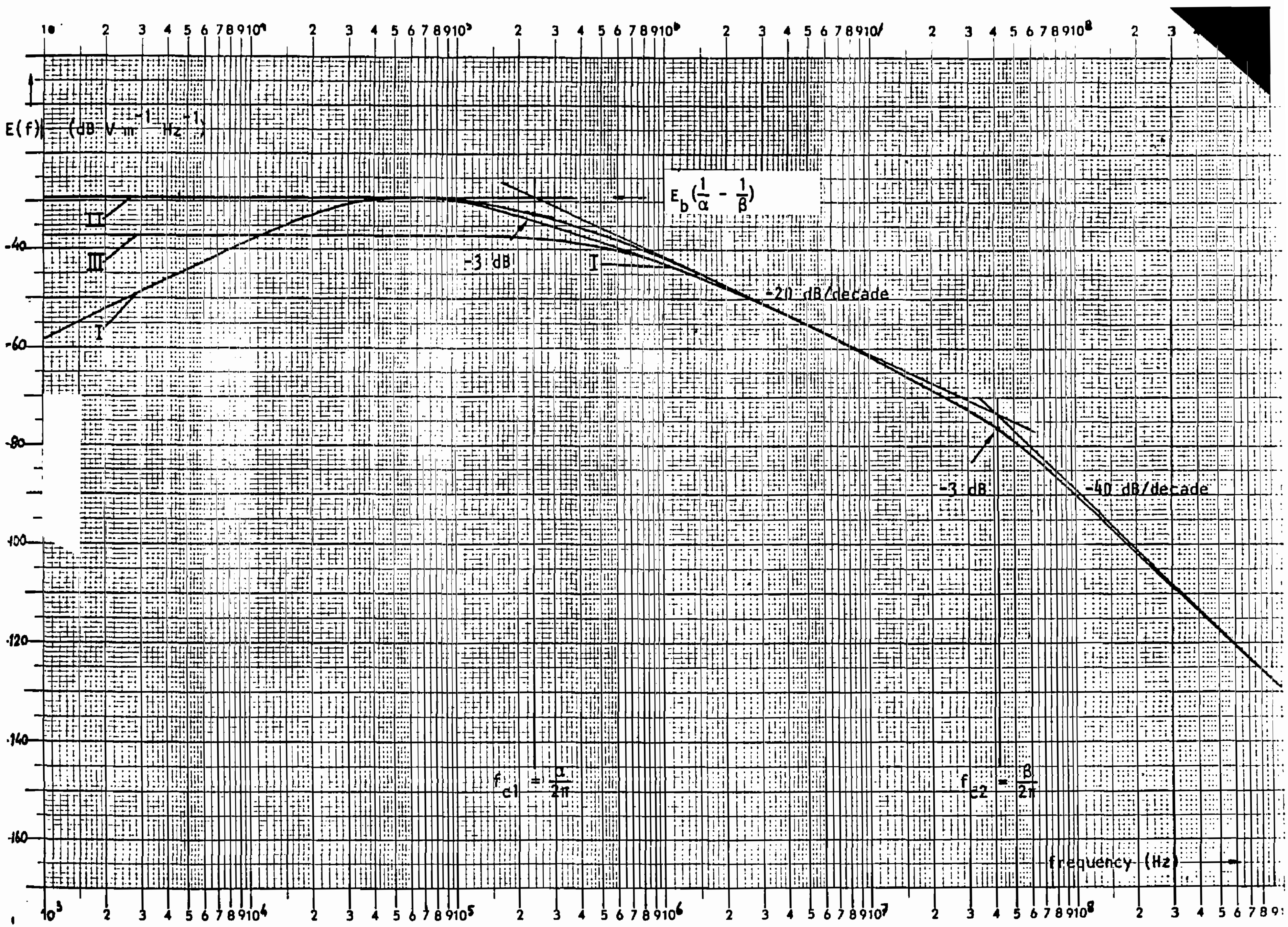


Fig.2 Spectral amplitude of models I and II

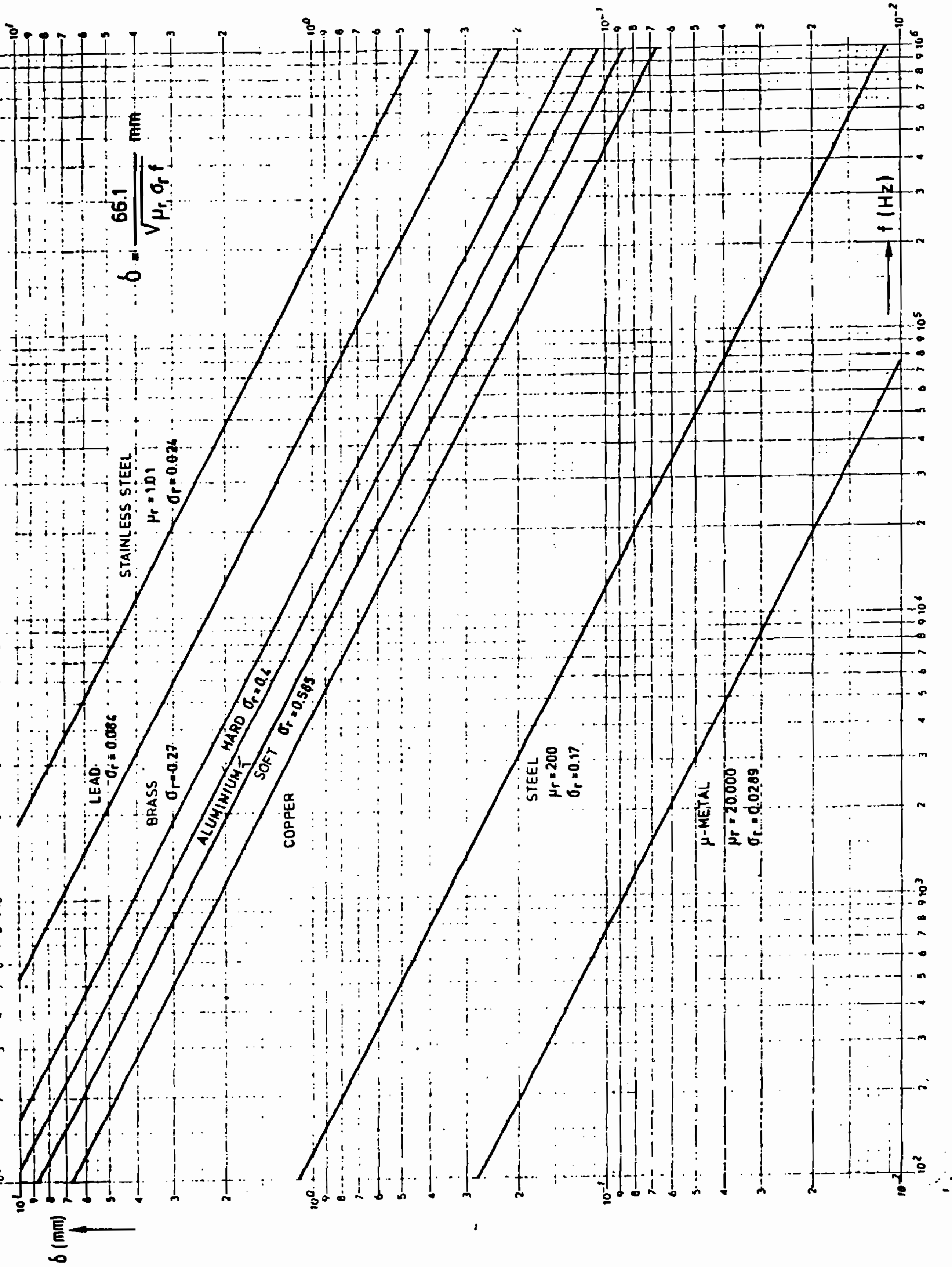


FIG.3 SKINDEPTH δ VERSUS FREQUENCY f FOR SOME METALS (SEE TABLE 3)

Fig. 3

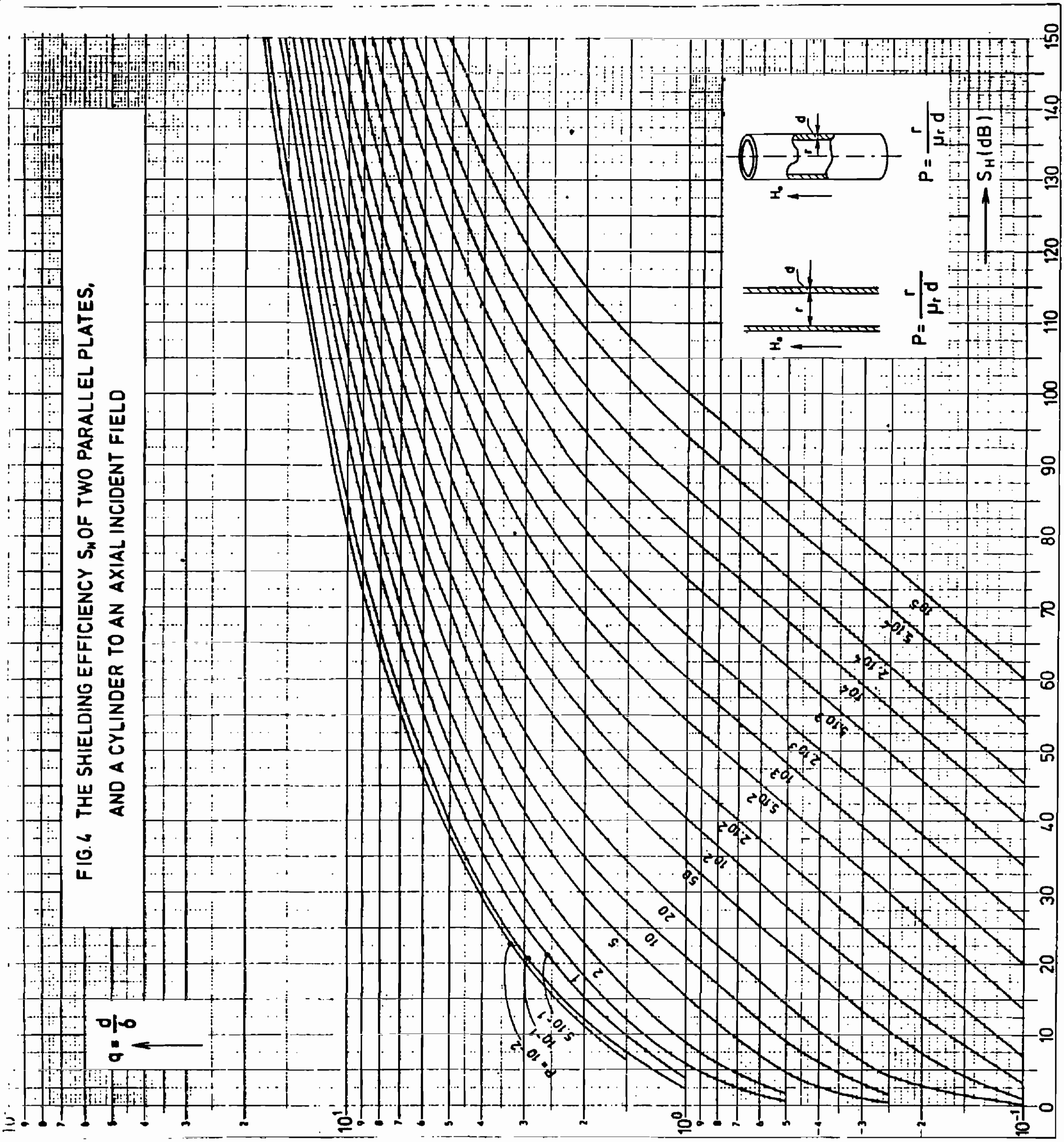


FIG.4 THE SHIELDING EFFICIENCY S_H OF TWO PARALLEL PLATES,
AND A CYLINDER TO AN AXIAL INCIDENT FIELD
q = d/δ
$P = \frac{r}{\mu_r d}$
$P = \frac{r}{\mu_r d}$
H_o
r
d
S_H (dB)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
10^{-1}
10^{0}
10^{1}
P = 10^{-2}
10^{-1}
5.10^{-1}
1
2
5
10
20
50
10^{2}
2.10^{2}
5.10^{2}
10^{3}
2.10^{3}
5.10^{3}
10^{4}
2.10^{4}
5.10^{4}
10^{5}

Fig. 4

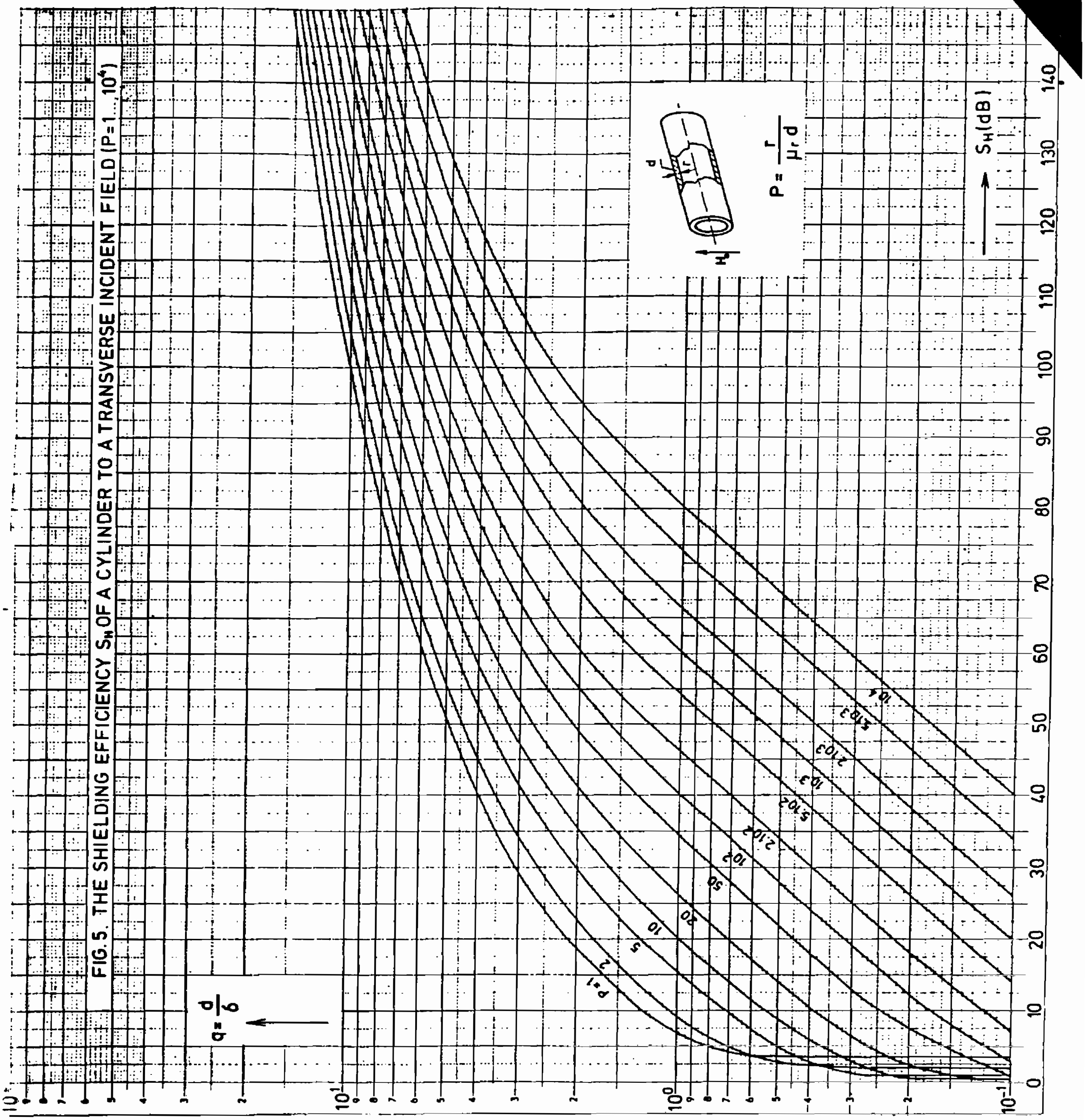


FIG.5. THE SHIELDING EFFICIENCY S_H OF A CYLINDER TO A TRANSVERSE INCIDENT FIELD (P=1...10^4)
$q = \frac{d}{\delta}$
S_H(dB)
$P = \frac{r}{\mu_r d}$
P=1
2
5
10
20
50
10^2
2.10^2
5.10^2
10^3
2.10^3
5.10^3
10^4

Fig. 5

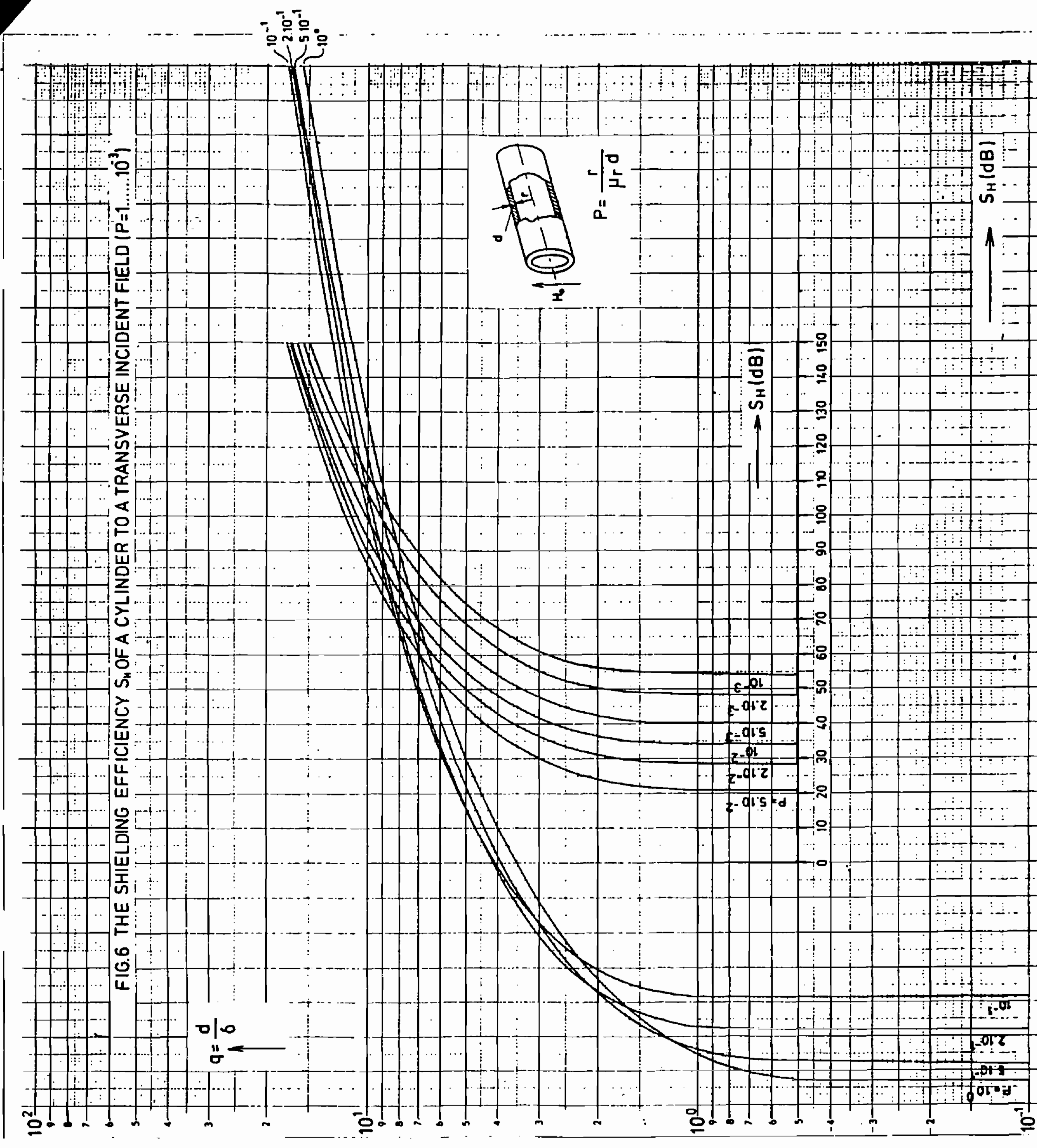


FIG.6 THE SHIELDING EFFICIENCY S_H OF A CYLINDER TO A TRANSVERSE INCIDENT FIELD (P=1.....10^-3)
P= r / μr d
S_H (dB)
q= d / δ

Fig. 6

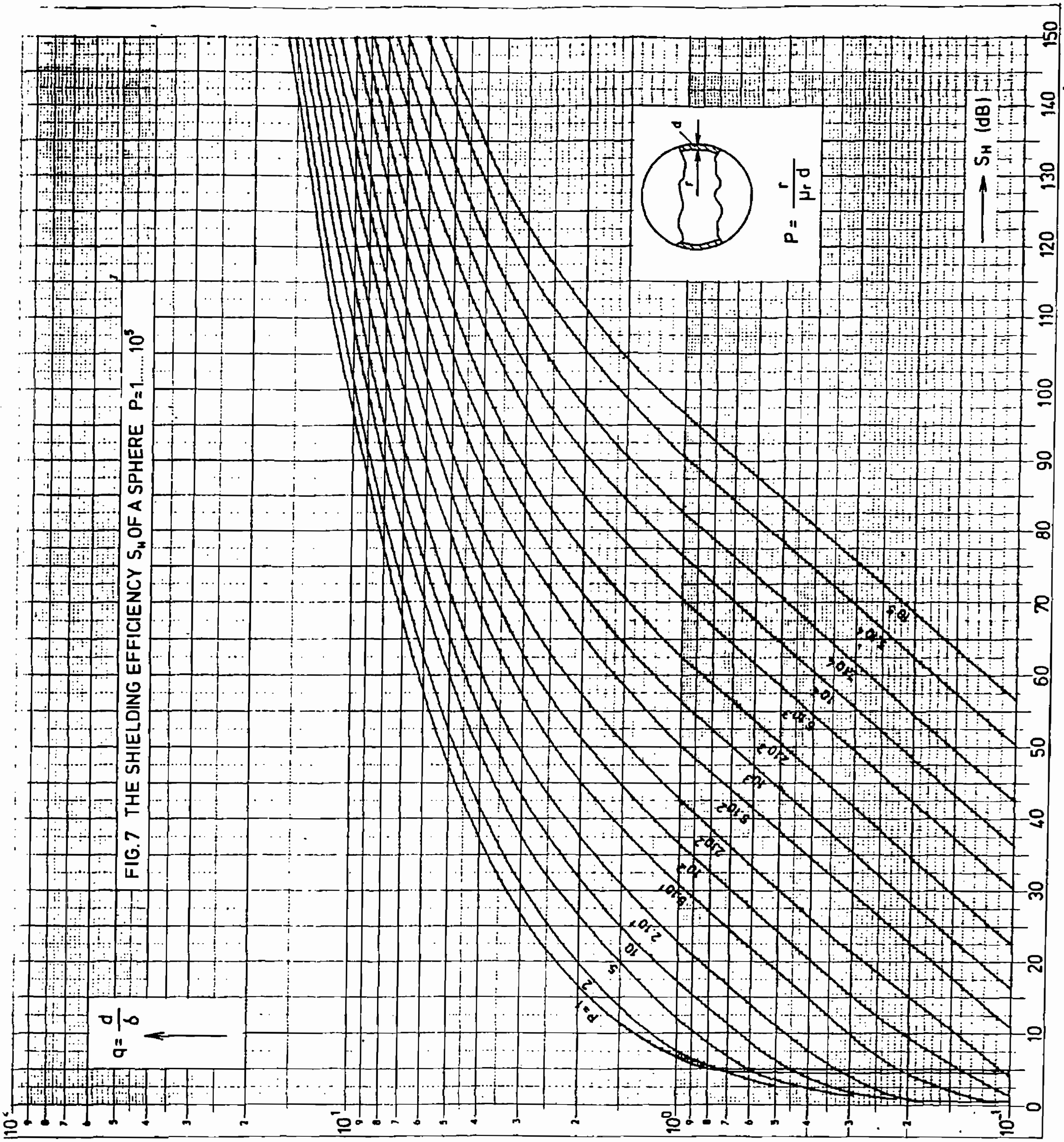


FIG.7 THE SHIELDING EFFICIENCY S_H OF A SPHERE P=1.....10^5
q = d/δ
P = r/(μr d)
S_H (dB)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
10^-1
10^0
10^1
10^2
P=1
2
5
10
2.10^1
5.10^1
10^2
2.10^2
5.10^2
10^3
2.10^3
5.10^3
10^4

Fig. 7

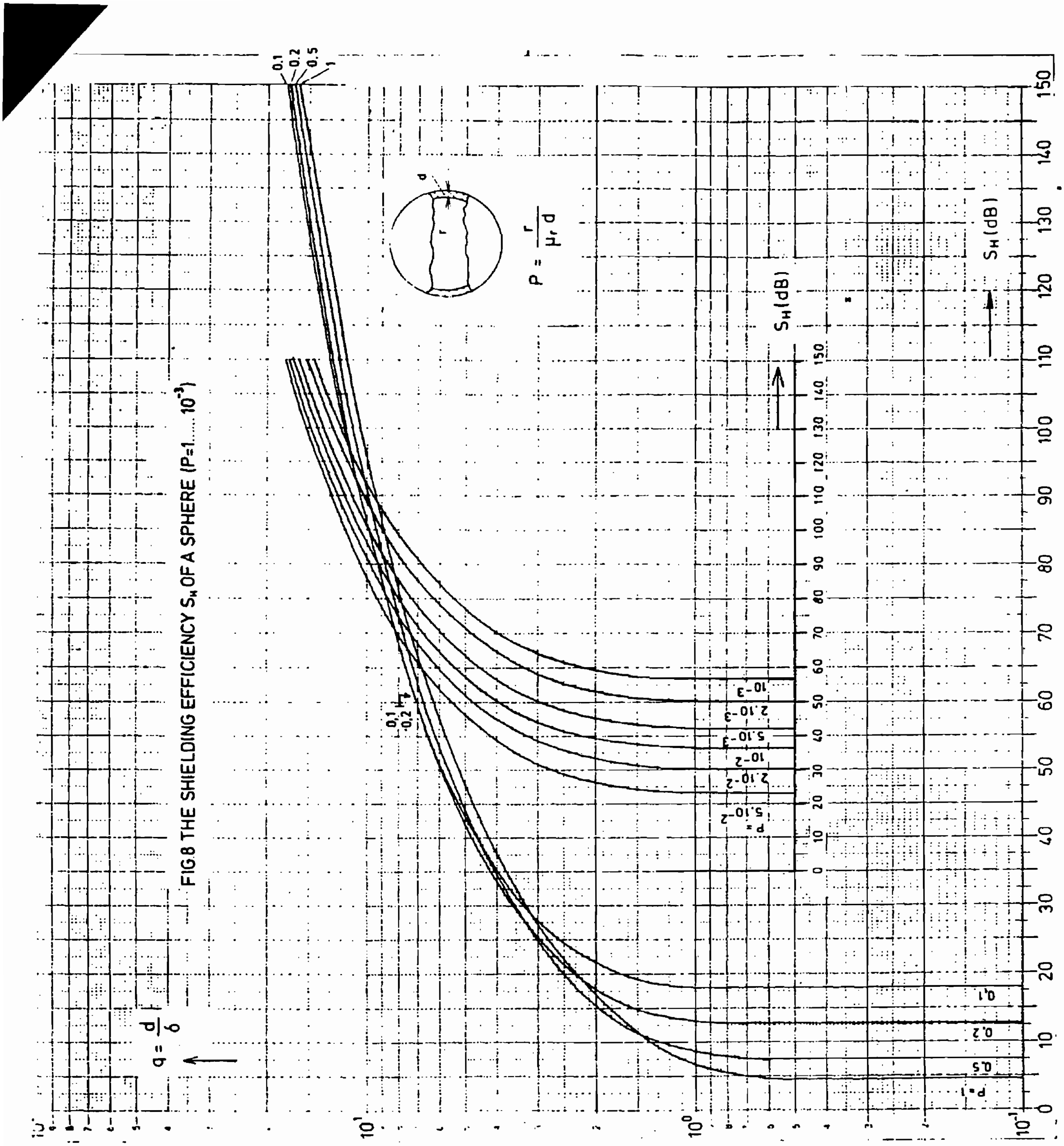


FIG.8 THE SHIELDING EFFICIENCY S_H OF A SPHERE (P=1.....10^-3)
q = d/δ
P = r/(μ_r d)
S_H (dB)
P = 1
0.5
0.2
0.1
P = 5.10^-2
2.10^-2
10^-2
5.10^-3
2.10^-3
10^-3
0.1
0.2
0.5
1
d
r

Fig. 8

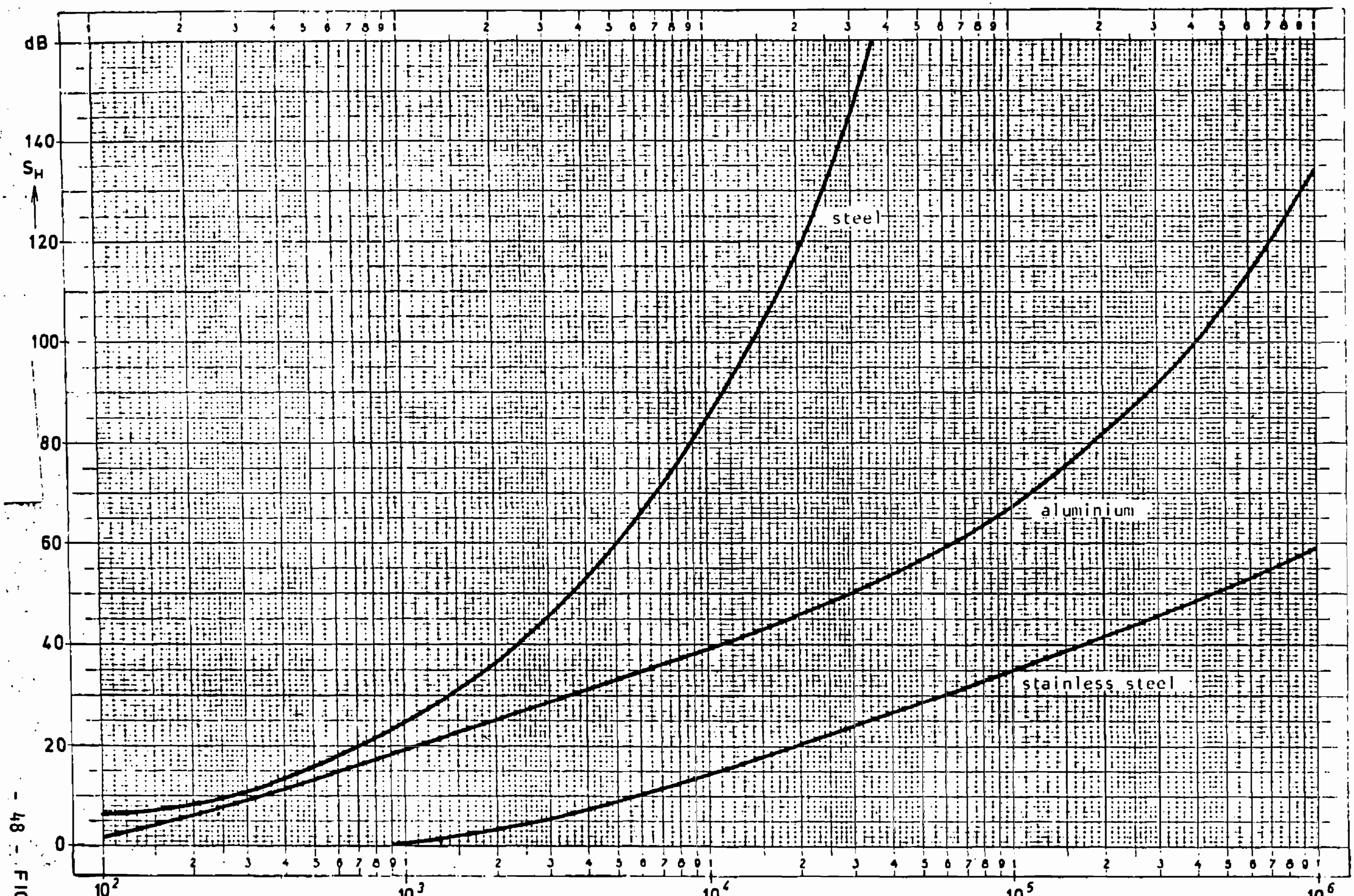


FIG.9 The shielding efficiency S_H of the cabinet in example 1

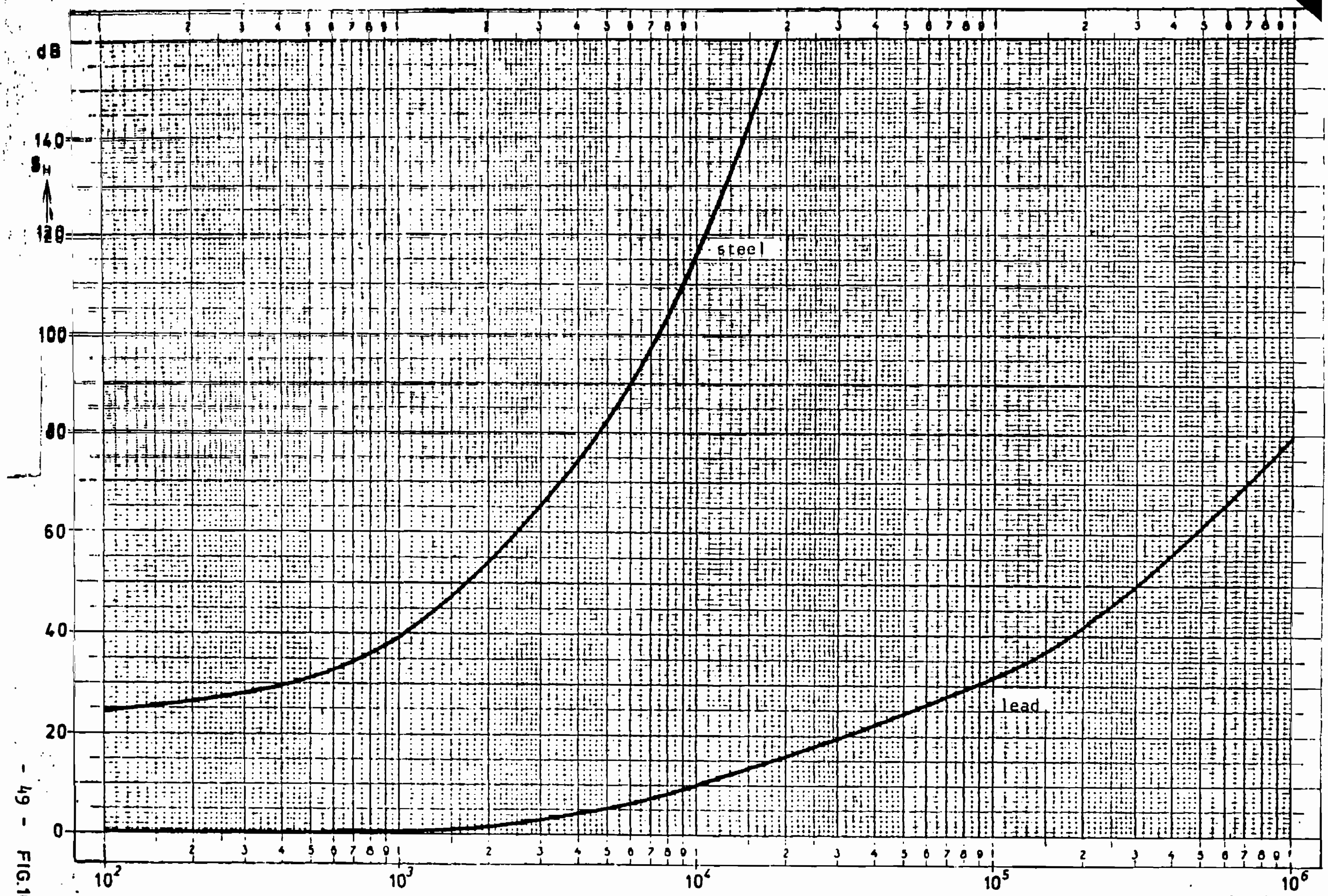


FIG.10 The shielding efficiency S_H of the cable in example 2.

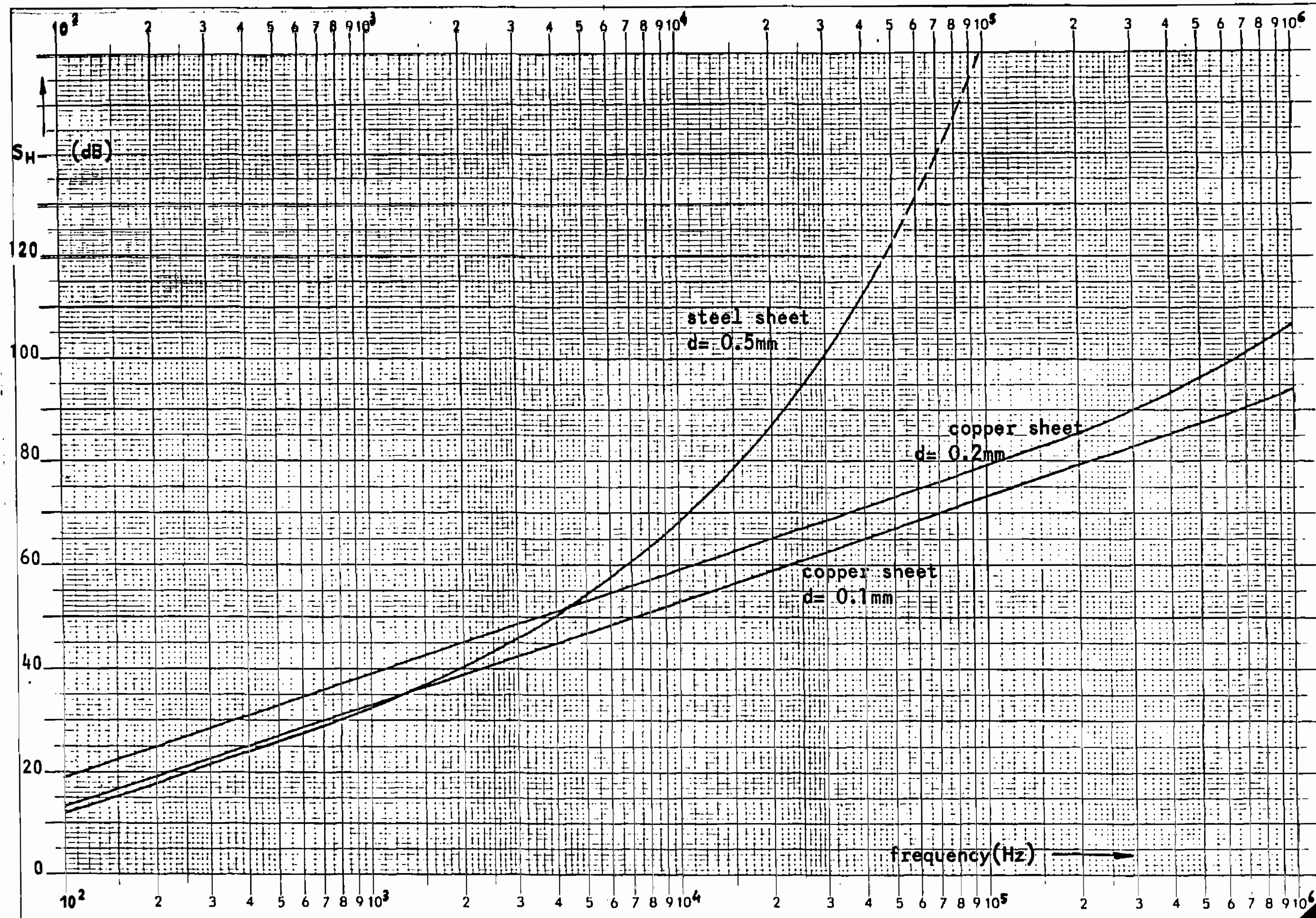


Fig.11 The shielding efficiency S_H of the shielded room in example 3.

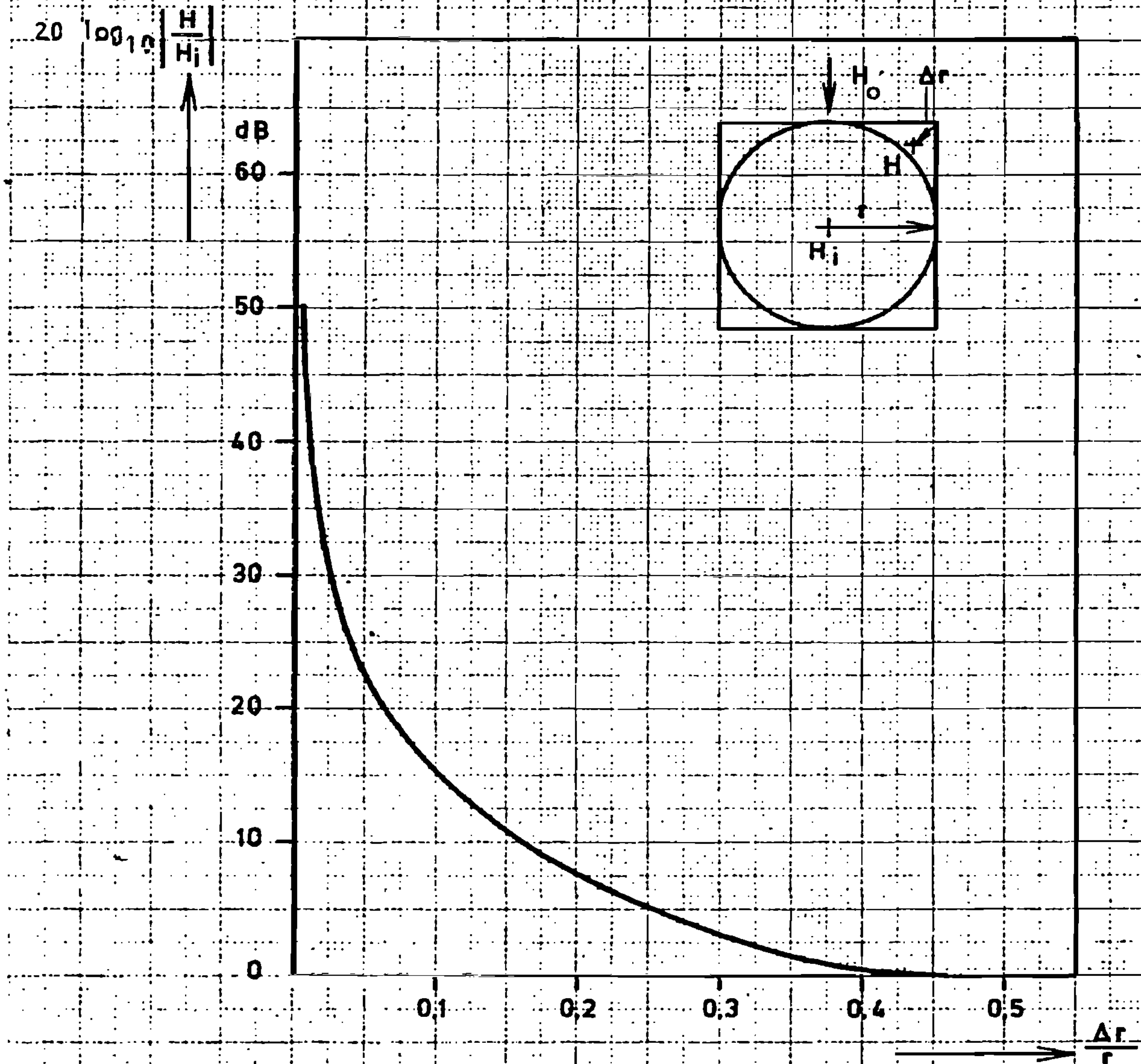
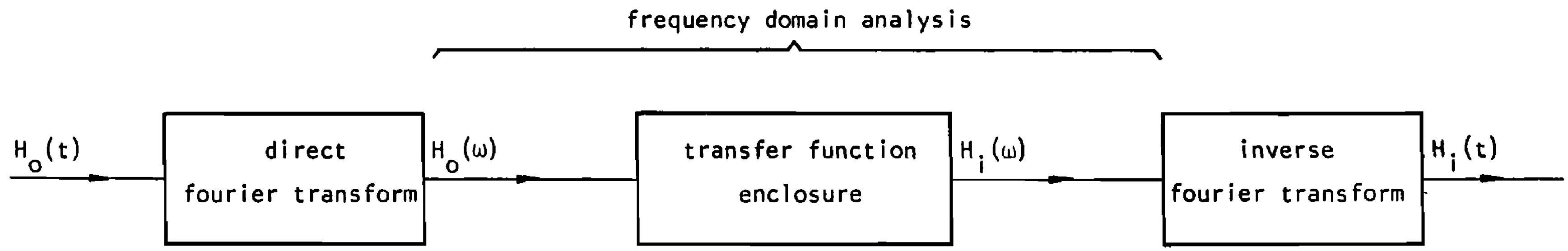


FIG.12 The reduction of S_H in the corners of a cubical enclosure

FIG. 12



$$H_o(\omega) = \int_{-\infty}^{+\infty} H_o(t) e^{-j\omega t} dt \qquad T_H(\omega) = \frac{H_i(\omega)}{H_o(\omega)} \qquad H_i(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} H_i(\omega) e^{j\omega t} d\omega$$

fourier transform integral

$$H_i(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} T_H(\omega)\ H_o(\omega) e^{j\omega t} d\omega$$

Fig.13 A schematic diagram of a frequency domain analysis

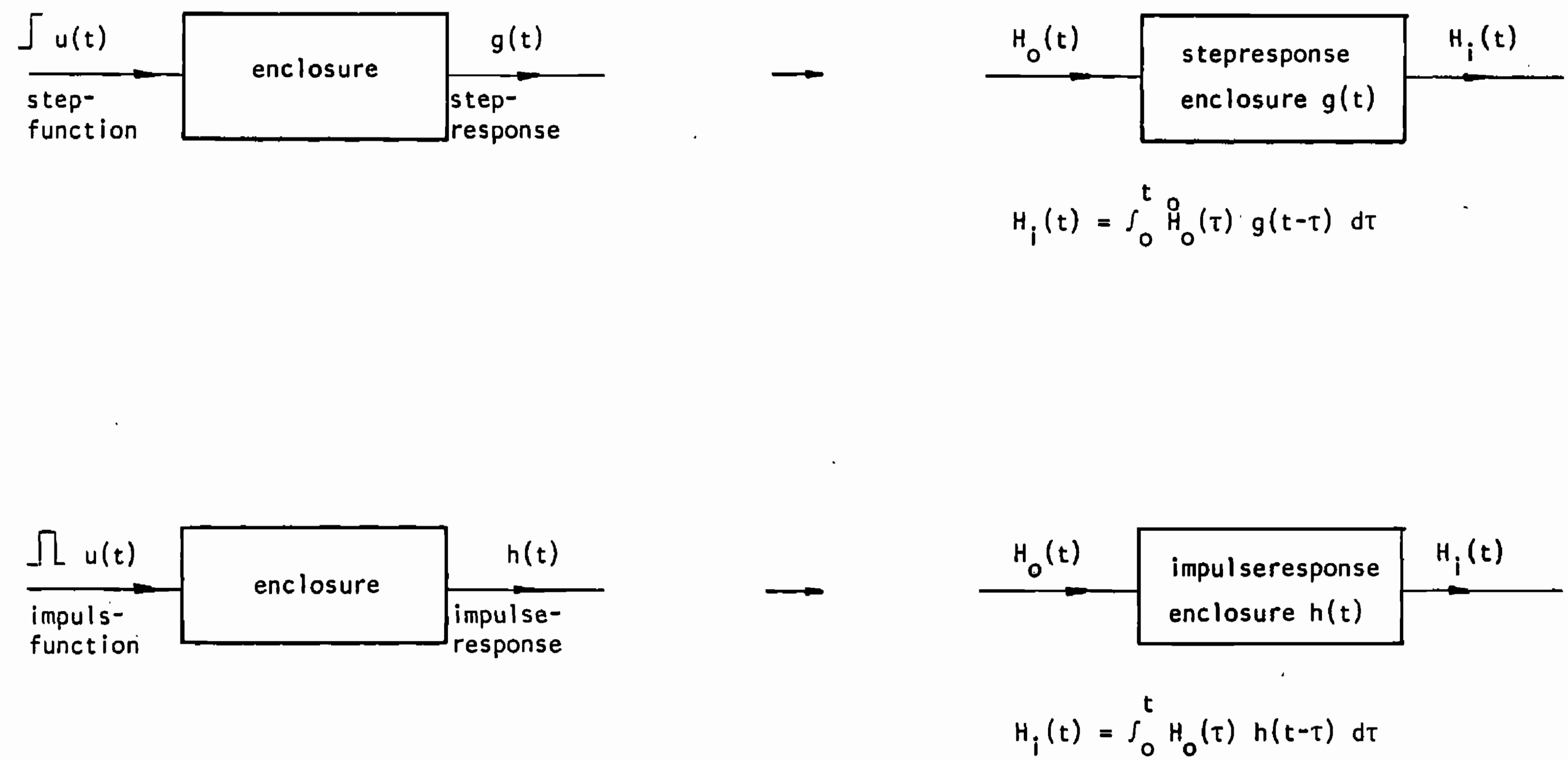
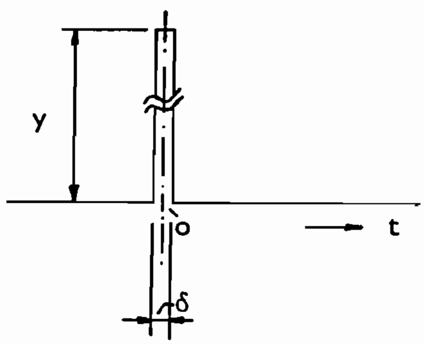
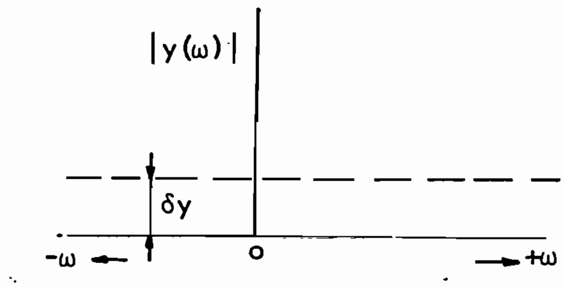


Fig.14 <u>A schematic diagram of a time domain analysis</u>
upper: with help of stepresponse of enclosure
lower: with help of impulseresponse of enclosure





time function y(t)

y → ∞

δ → o

area δy is finite

amplitude spectrum |y(ω)|

spectral amplitude |y(ω)| = δy,

from ω → +∞ to ω → -∞

Fig.15 Delta function with corresponding spectrum

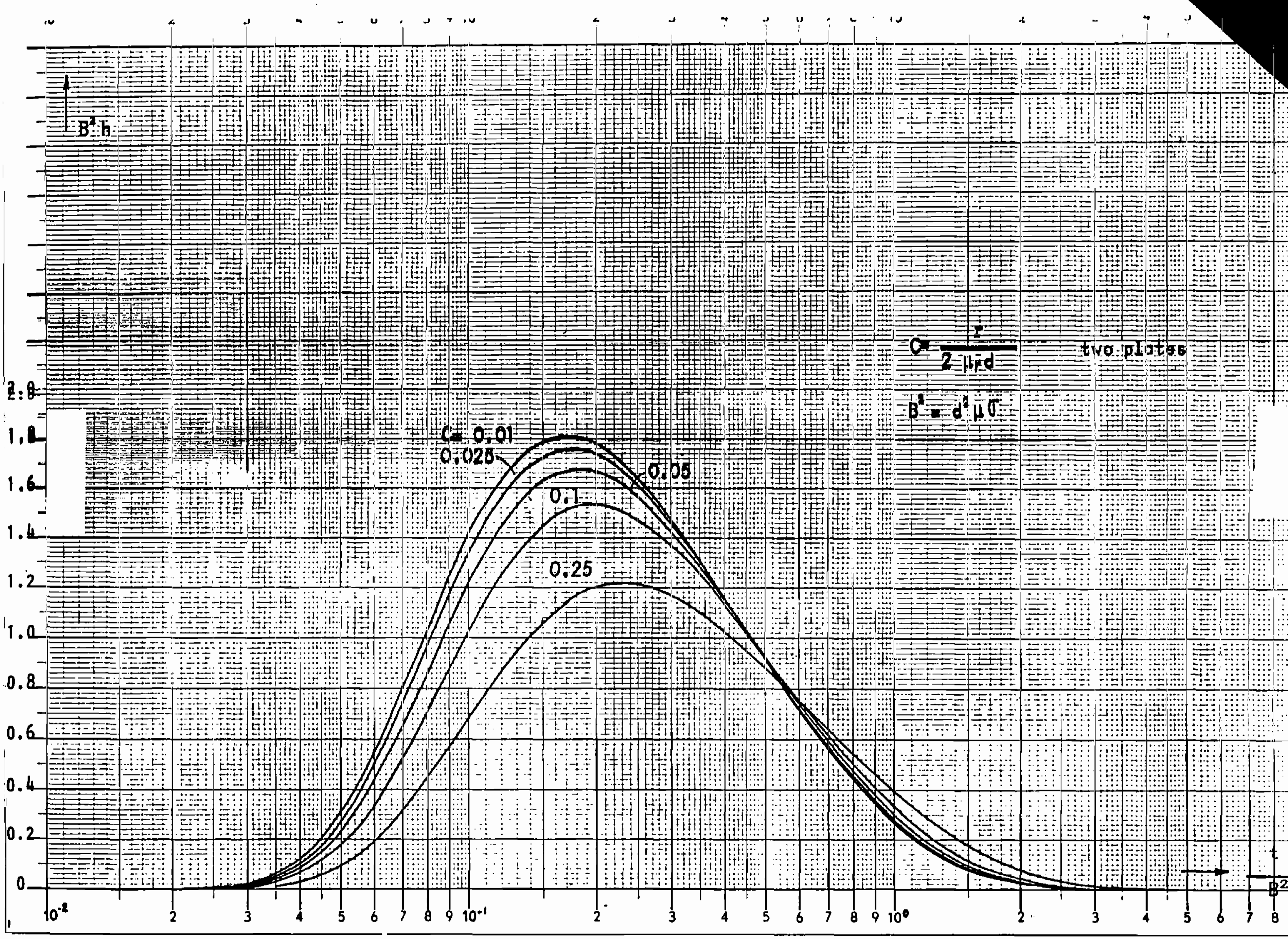


Fig.16 Curves to determine h(t). Two parallel plates C = 0.01 ...0.25.

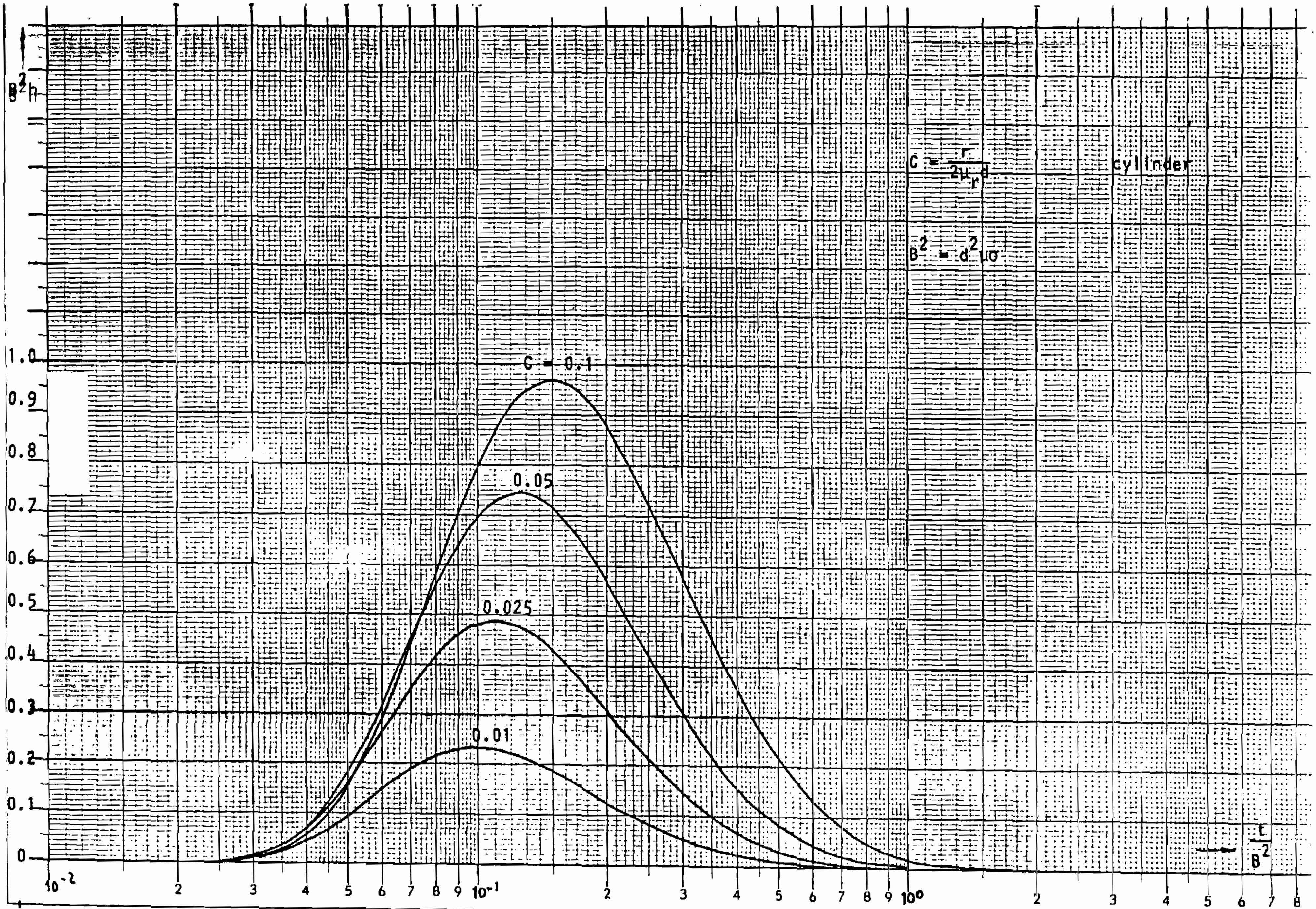


Fig.17 Curves to determine h(t). Cylinders, C = 0.01 ...0.1

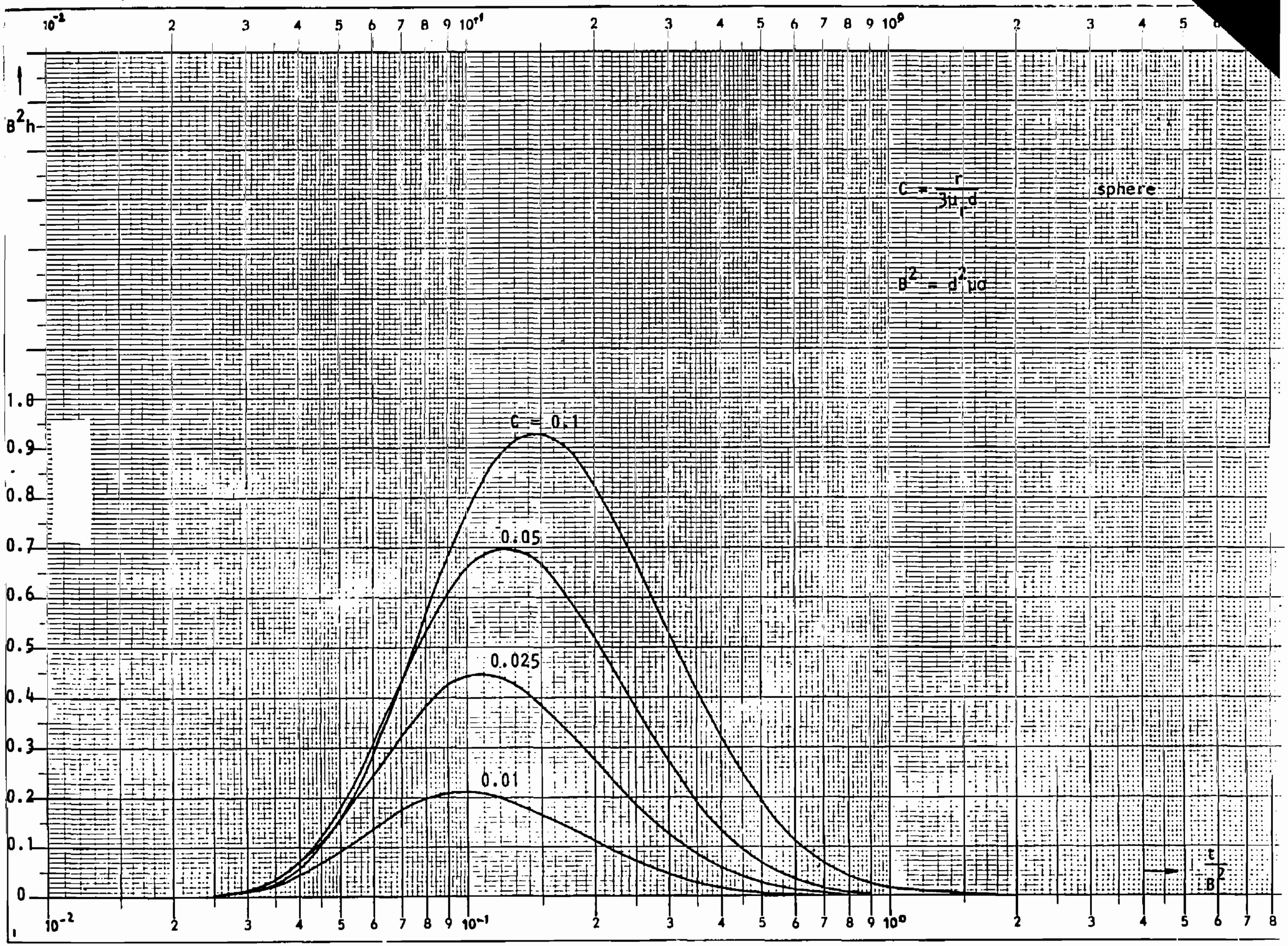


Fig.18 Curves to determine h(t). Spheres, C = 0.01...0.1

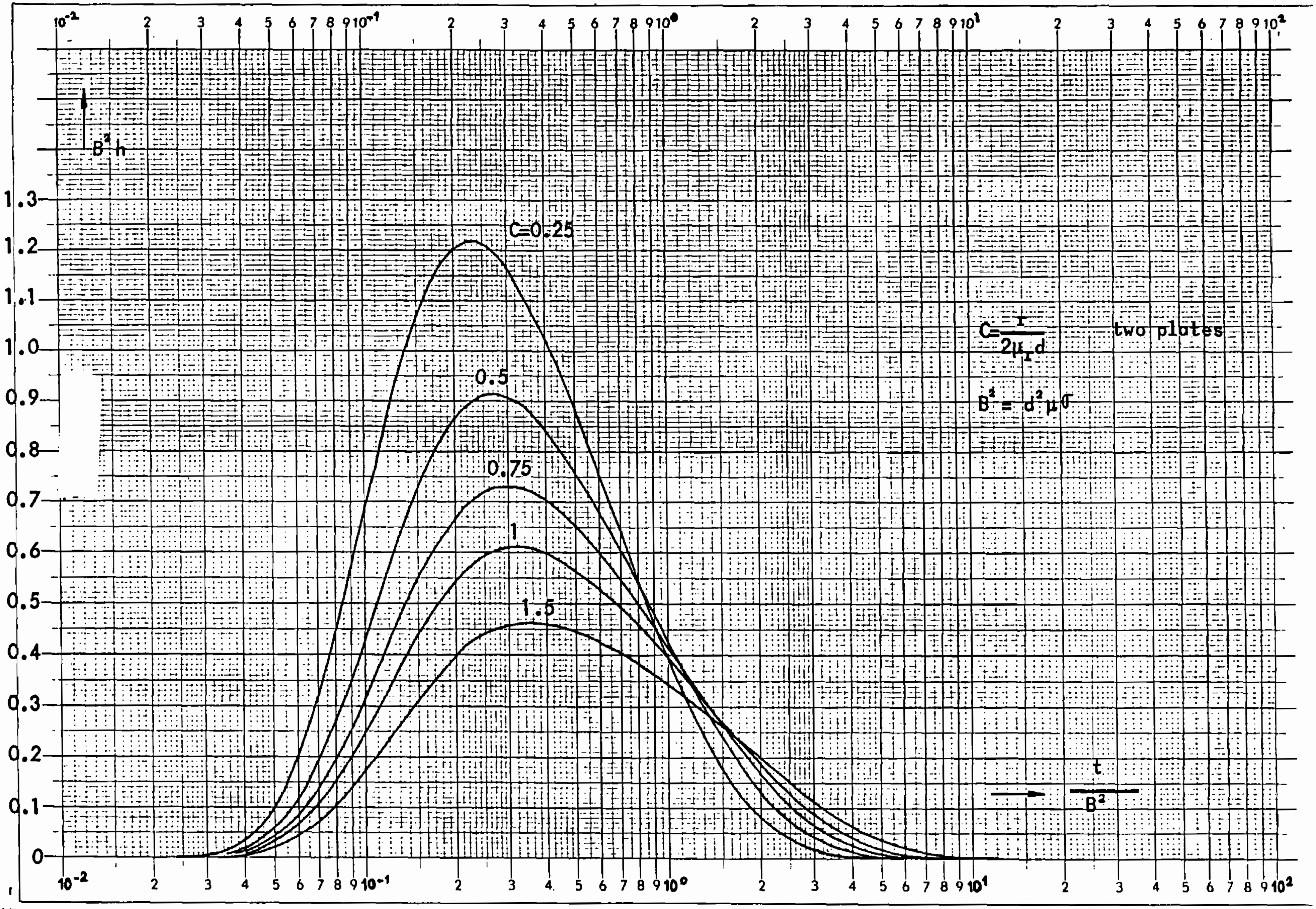


Fig.19 Curves to determine h(t). Two parallel plates, C = 0.25...1.5.

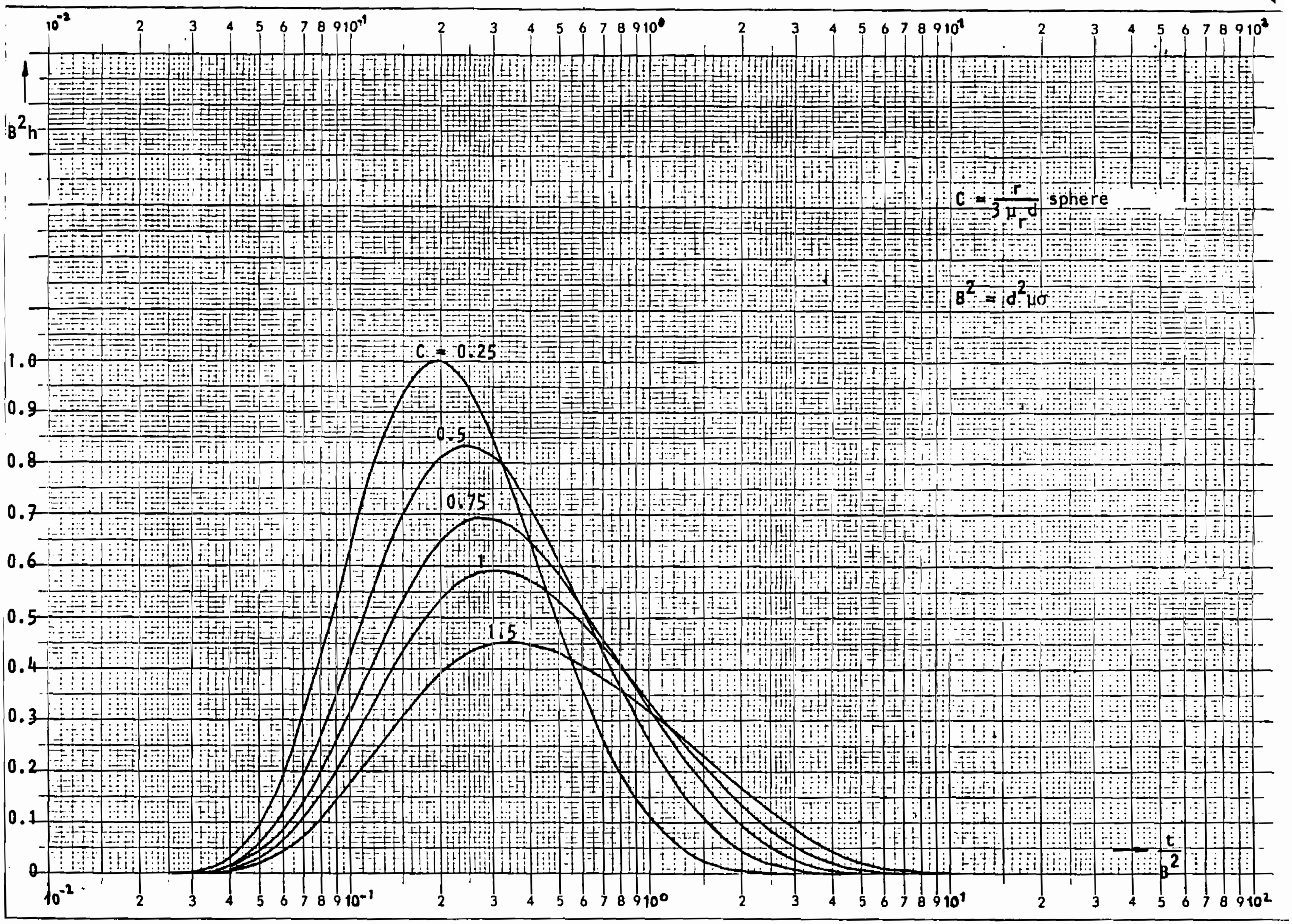


Fig.20 Curves to determine h(t). Spheres, C = 0.25...1.5.

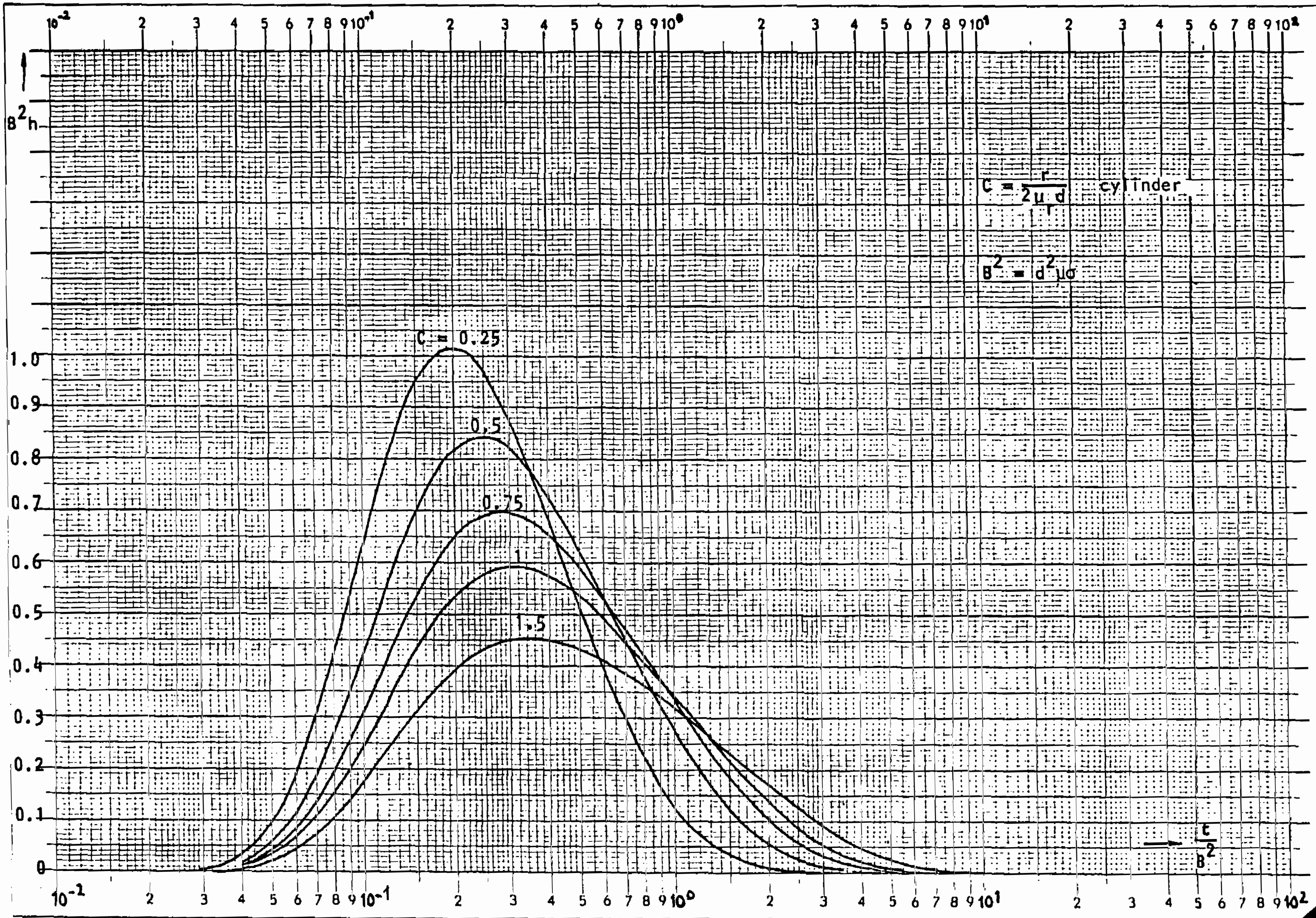


Fig.21 Curves to determine h(t). Cylinders C = 0.25...1.5.

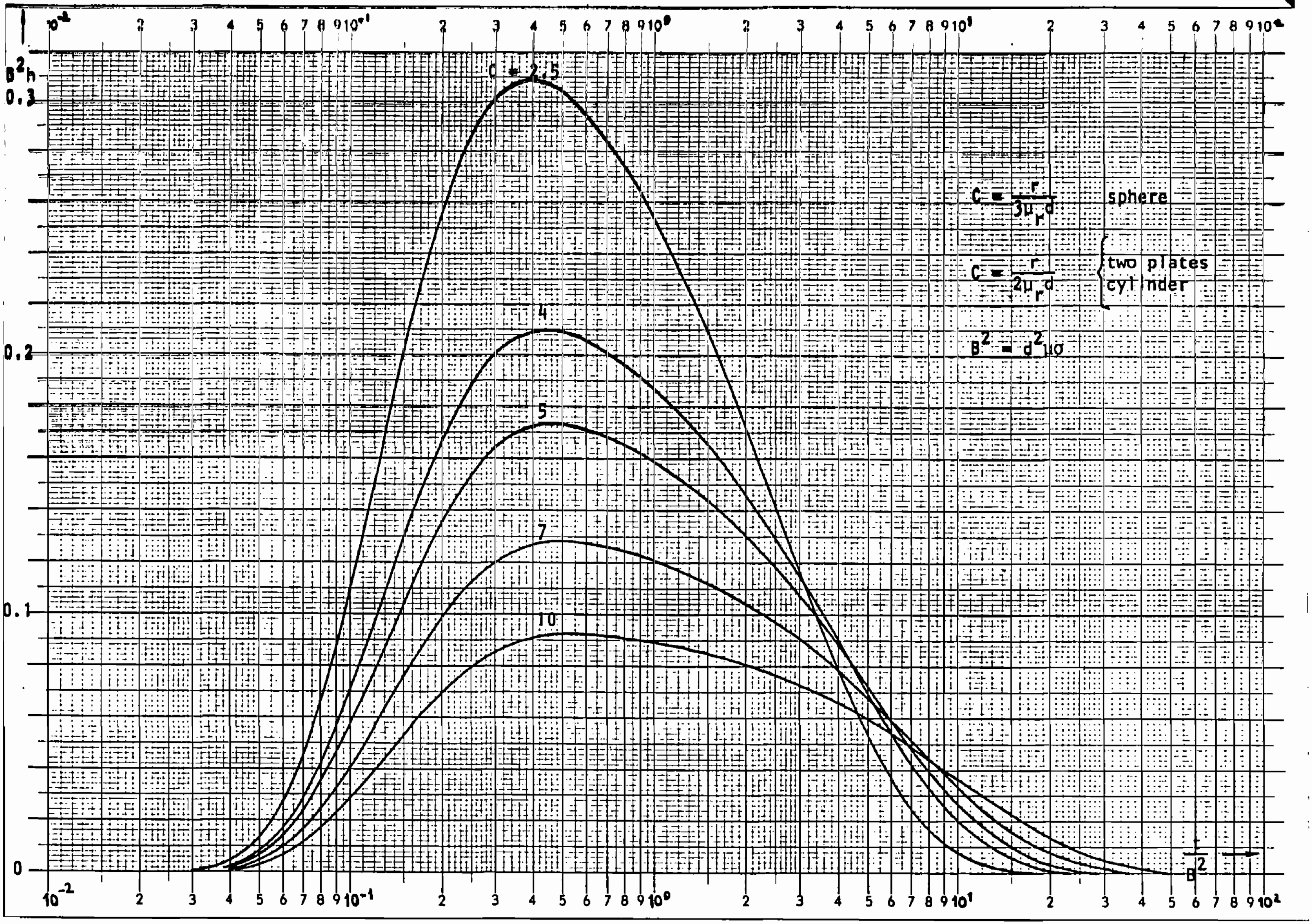


Fig.22 Curves to determine h(t). C = 2.5...10

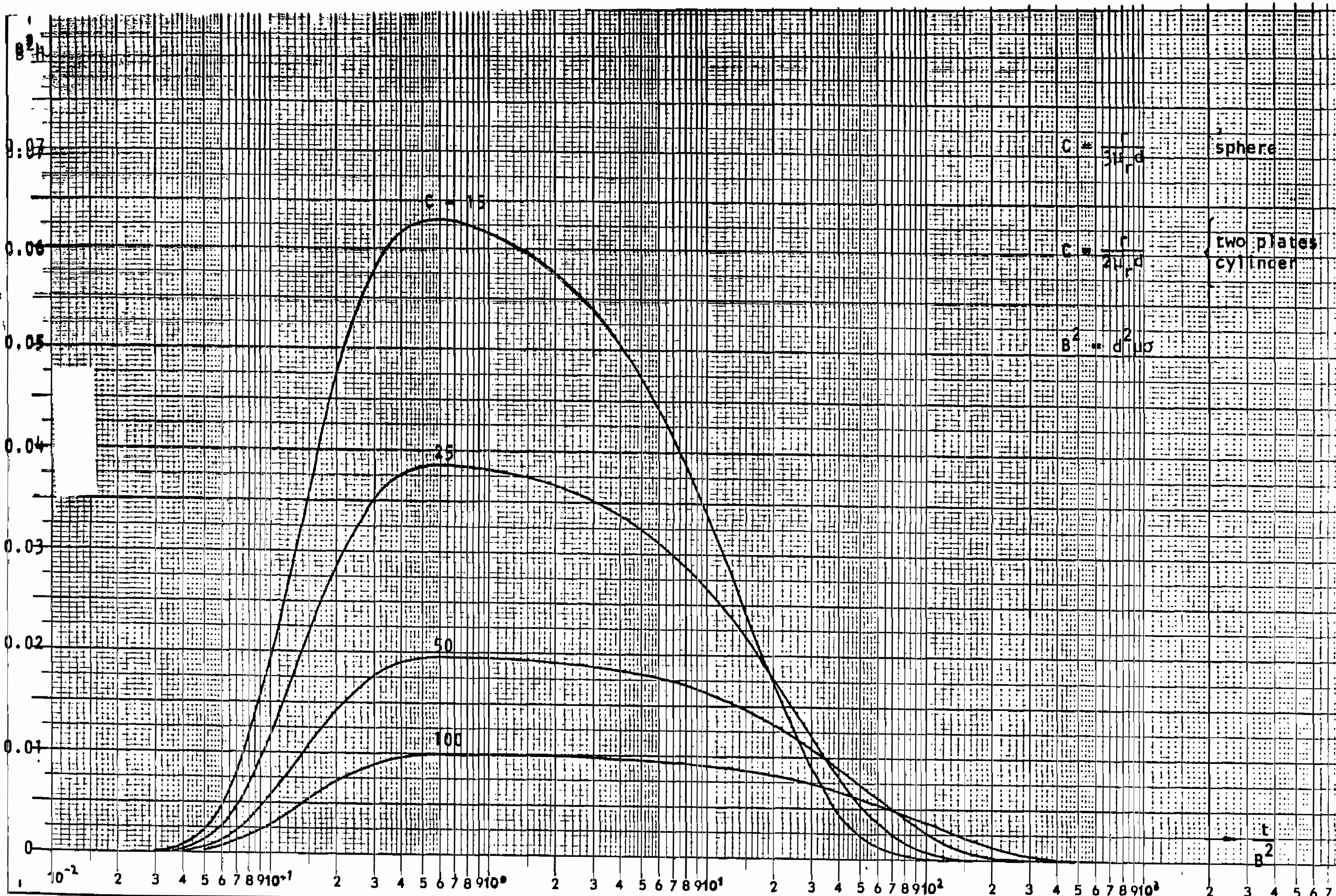


Fig.23 Curves to determine h(t). C = 15...100.

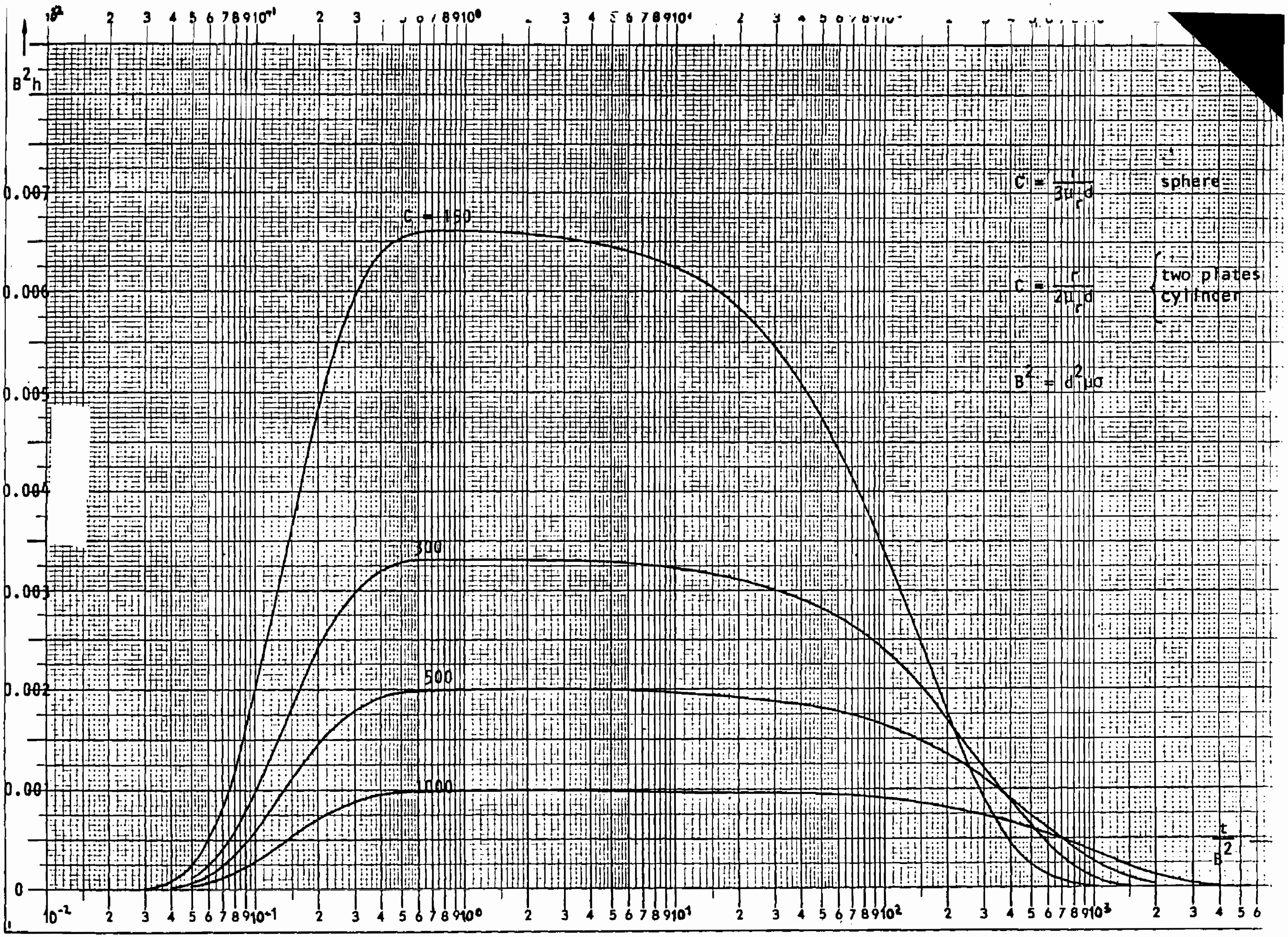


Fig.24 Curves to determine h(t). C = 150...1000

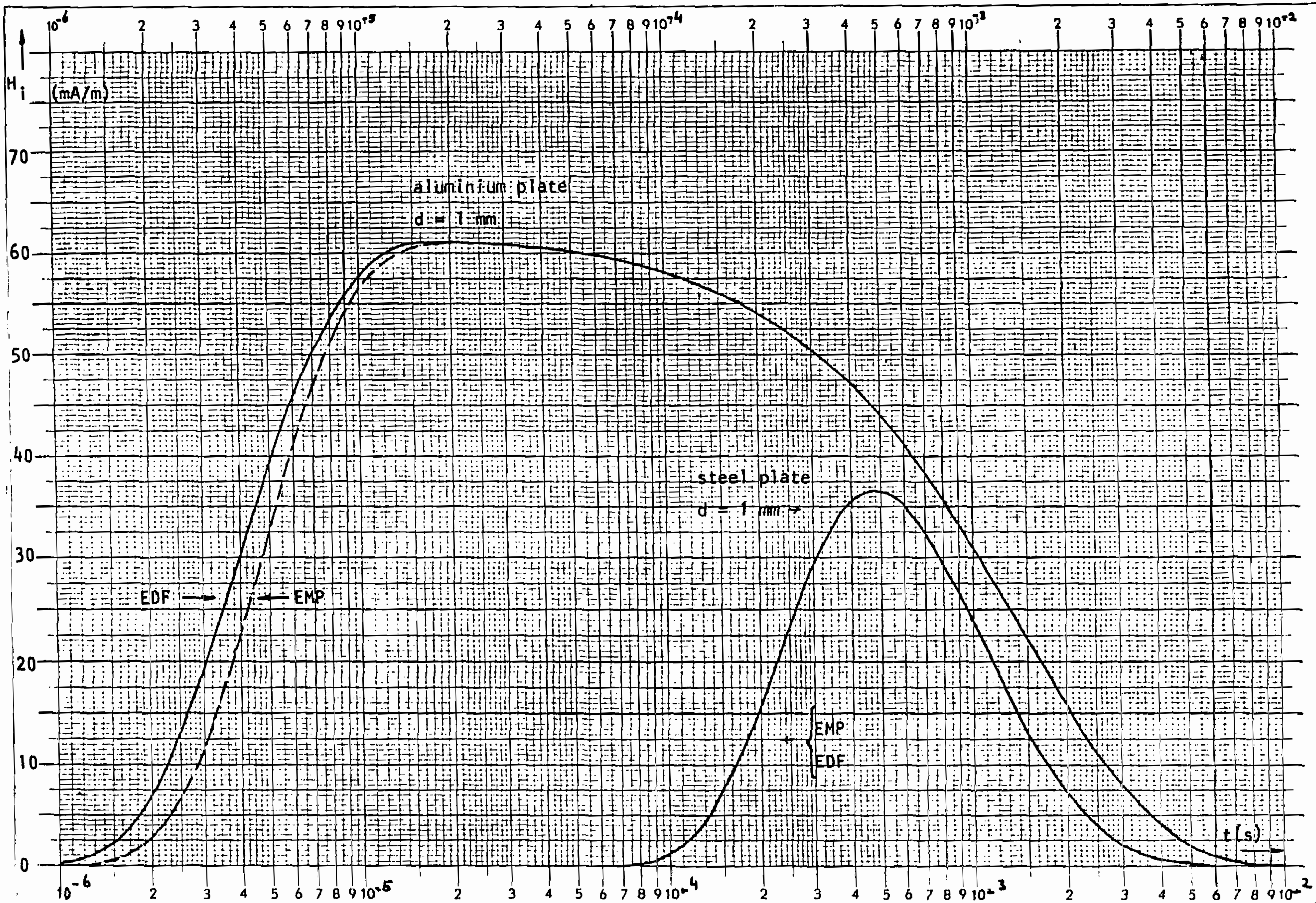


Fig.25 The response of the cabinet in example 4 to EMP model II (steel and aluminium).

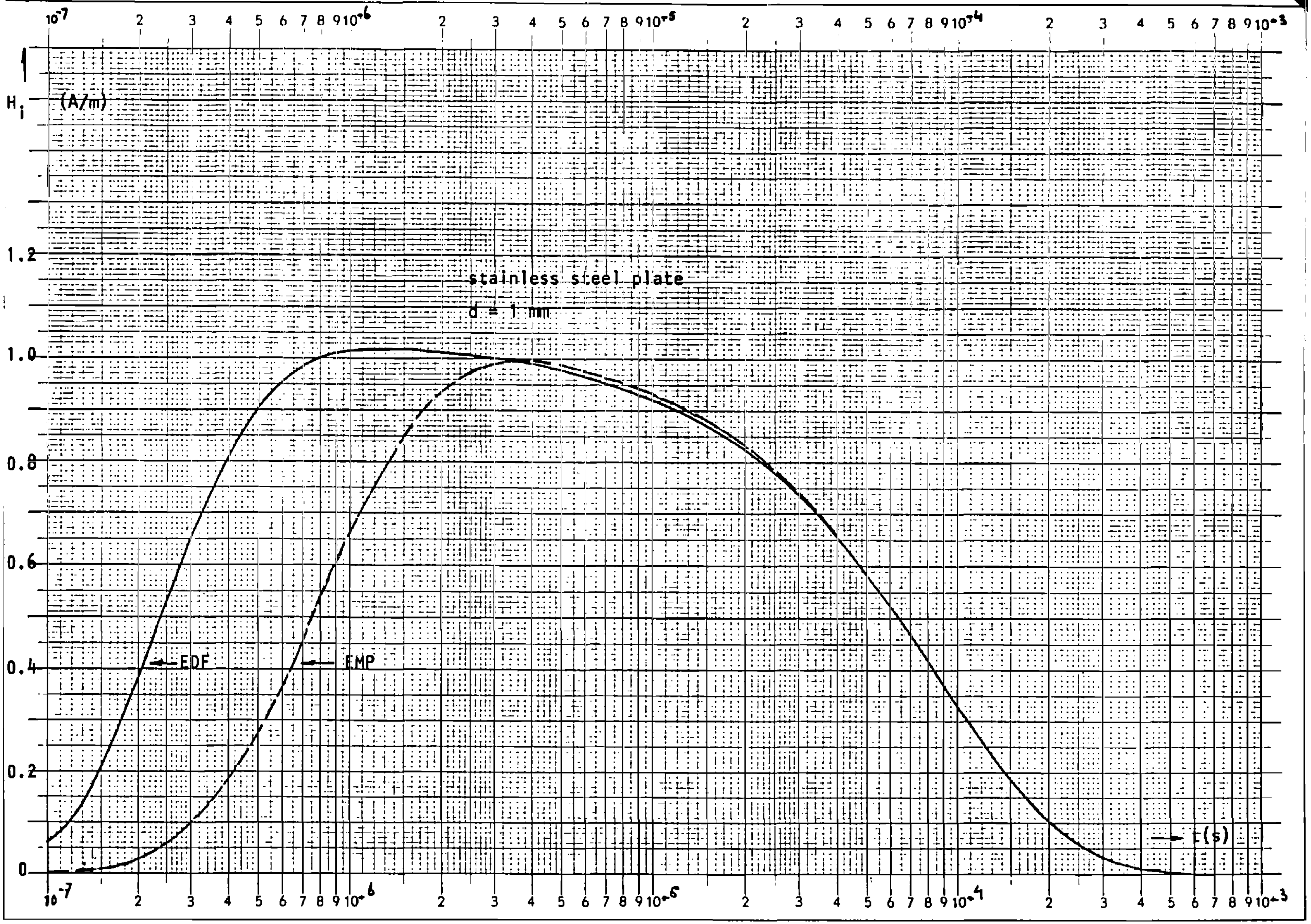


Fig.26 The response of the cabinet in example 4 to EMP model II (stainless steel)

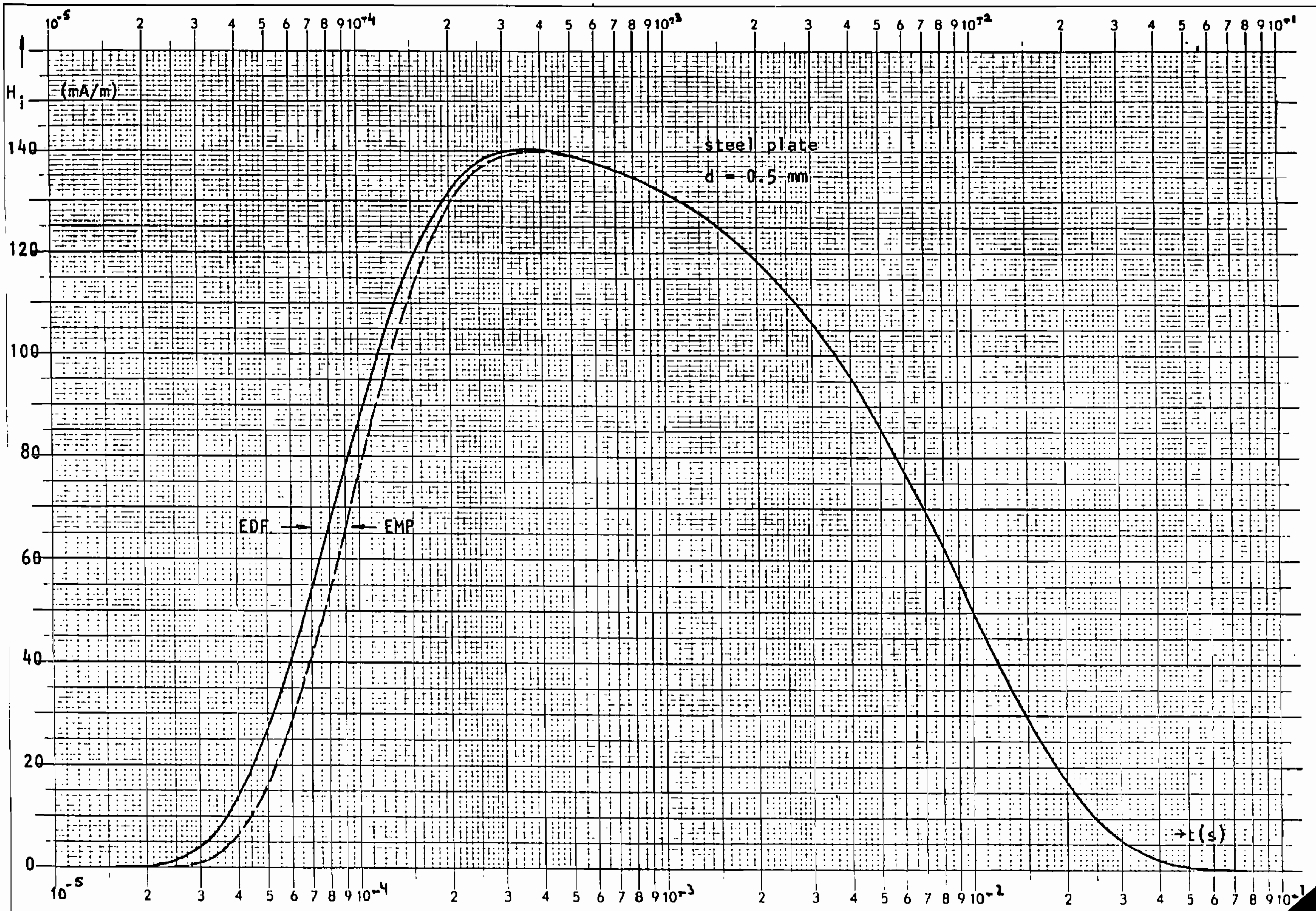


Fig.27 The response of the shielded room in example 5 to an arbitrarily chosen low altitude EMP.

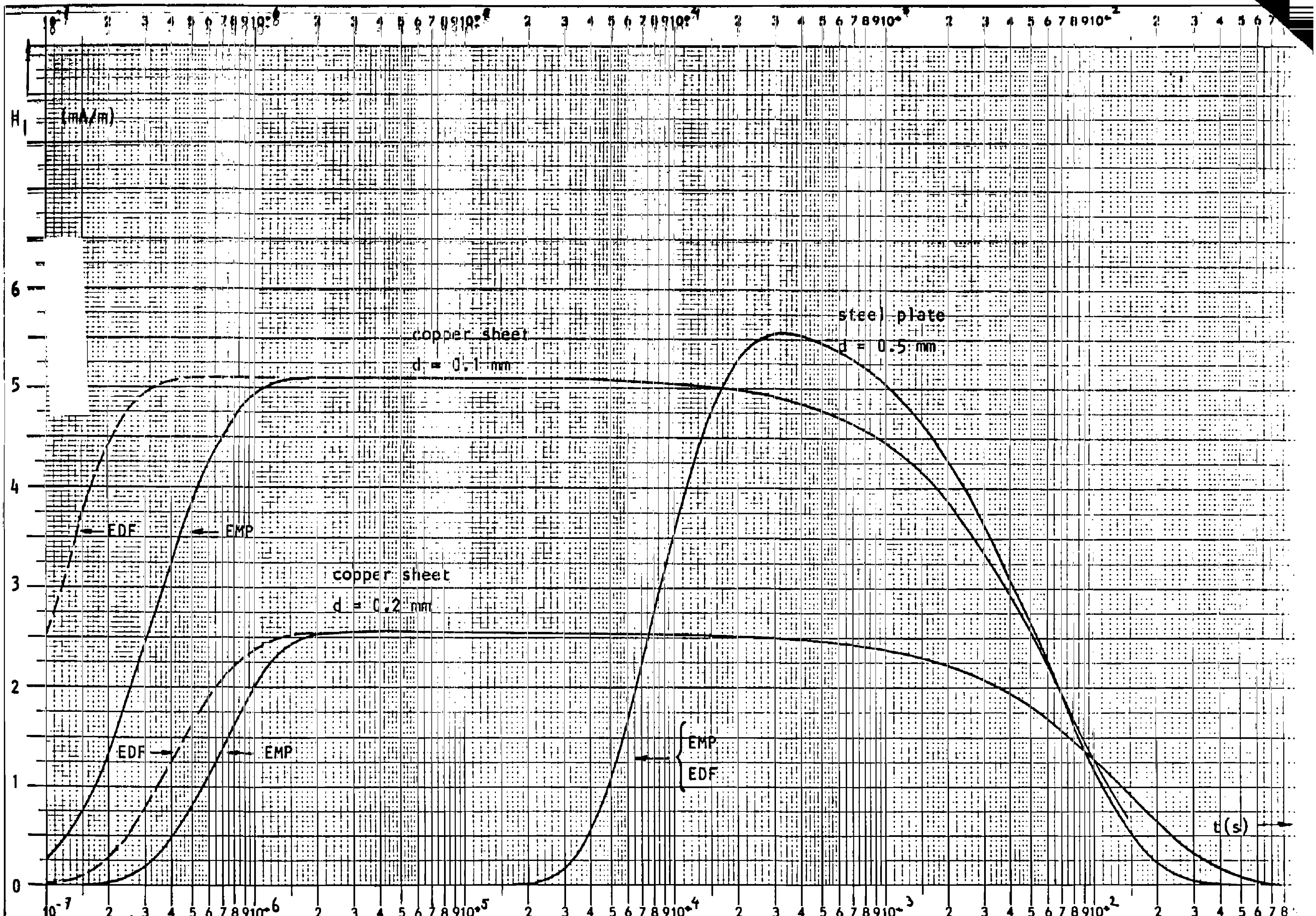


Fig.28 The response of the shielded room in example 6 to EMP model III.