F. Lucci, M. Pelliccioni and M. Roccella : MEASUREMENTS ON 1 GeV ELECTROMAGNETIC CASCADE AND CASCADE-PRODUCED NEUTRONS IN SHIELDING MATERIALS. -

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ABSTRACT. -

Some properties of electromagnetic showers induced by
600 MeV to 1 GeV bremsstrahlung $\gamma$-rays have been studied in ordina
ry concrete by thermoluminescent $CaF_2$ dosimeters. The experimental
results have been compared with measurements performed elsewhere
in several materials.

The attenuation of $\gamma$-rays and cascade-produced neutrons in
ordinary concrete and in lead and concrete heterogeneous absorbers
has been also measured to obtain useful data for problems of shielding.

1. - INTRODUCTION. -

Many experimental investigations on electromagnetic showers
induced by high energy electrons and photons were carried out in the
past years. For these measurements a variety of detectors was used:
ionization chambers[1], scintillators[2], nuclear emulsions[3], spark
chambers[4], cloud chambers[5], Cerenkov counters[6] and bubble cham
bers[7]. However, each of these detection techniques has some disad-

vantages, mainly in measurements intended to study the radial development of the showers.

Recent measurements were performed by thermoluminescent LiF powders[8], which proved very versatile owing to the small physical size of the detectors, the sufficiently flat energy response and the linearity over a wide dose range.

Owing to the lack of experimental information on the electro magnetic showers in shielding materials, especially light materials, we used thermoluminescent $CaF_2$ dosimeters to study the development of showers produced by bremsstrahlung beams of maximum energy up to 1 GeV in ordinary concrete.

At the same time we also studied the attenuation of a 1 GeV bremsstrahlung beam and of the cascade-produced neutrons in heterogeneous absorbers.

Moreover measurements of $\gamma$-ray doses and neutron dose rates were performed at several depths in heterogeneous absorbers made of lead and concrete slabs. The $\gamma$-ray doses were measured by thermoluminescent $CaF_2$ dosimeters, while for neutron measurements we used a rem-counter type detector and the activation of aluminium foils.

Since a little experimental information on neutron production and attenuation near high energy electron accelerators is available[9, 10], and because there are few studies on neutron attenuation in heterogeneous materials[11], it seems that the results obtained may be useful for solving some problems in shielding design.


## 2. - EXPERIMENTAL ARRANGEMENT. -

Our measurements were carried out using the bremsstrahlung beam produced in the Frascati electron synchrotron.

The beam, after a suitable collimation, was monitored by a thin-walled ionization chamber, which had been in turn intercalibrated with a Wilson quantameter.

For shower measurements the absorber was made of ordinary concrete blocks (density 2.3 $g/cm^3$), each one 25 cm thick. For attenuation measurements we put a lead slab of a thickness up to 30 cm in front of the concrete blocks. Detectors were inserted among the blocks.

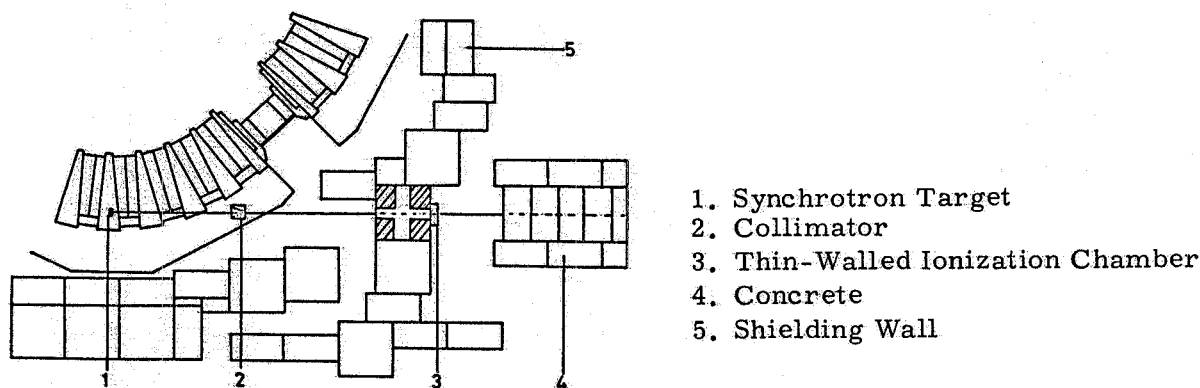The diagram of the experimental area is shown in Fig. 1.

1. Synchrotron Target
2. Collimator
3. Thin-Walled Ionization Chamber
4. Concrete
5. Shielding Wall

FIG. 1 - Experimental arrangement.

## 3. - SHOWER IN CONCRETE. -

For studying the development of the shower in ordinary concrete, thermoluminescent $CaF_2$ dosimeters were used. To obtain a better energy response they were surrounded by a 0.5 cm thick lead shield with holes over 13% of the surface. In the system we used, $CaF_2$ powders are deposited on a hollow cylinder surrounding a heating element and everything is enclosed in a vacuum tube. After the exposure the $CaF_2$ powders are heated and the light emitted may be measured by a photomultiplier.

The dosimeters were put at several depths and several distances from the beam axis.

The measurements were carried out at three maximum energies of the bremsstrahlung beam: 1000 MeV, 800 MeV and 600 MeV, and the diameter of the beam on the concrete absorber was 3.5 cm.

Results are shown in Fig. 2, 3 and 4 where the radiation exposure in mR[x] is reported versus the radial distance from the beam axis in radiation lengths. Every curve refers to a different concrete depth, as is shown in the tables attached to the graphs. For clearness' sake

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(x) - We expressed our results in terms of "radiation exposure" measured in roengtens, because our instrumentation was calibrated in these units. We remark that this calibration was performed for energies up to about 1 MeV. Because we reasonably are quite off this energy range, and because thermoluminescent powders measure the "absorbed energy", it is preferable to think our results as measurements of "absorbed energy" expressed in arbitrary units.
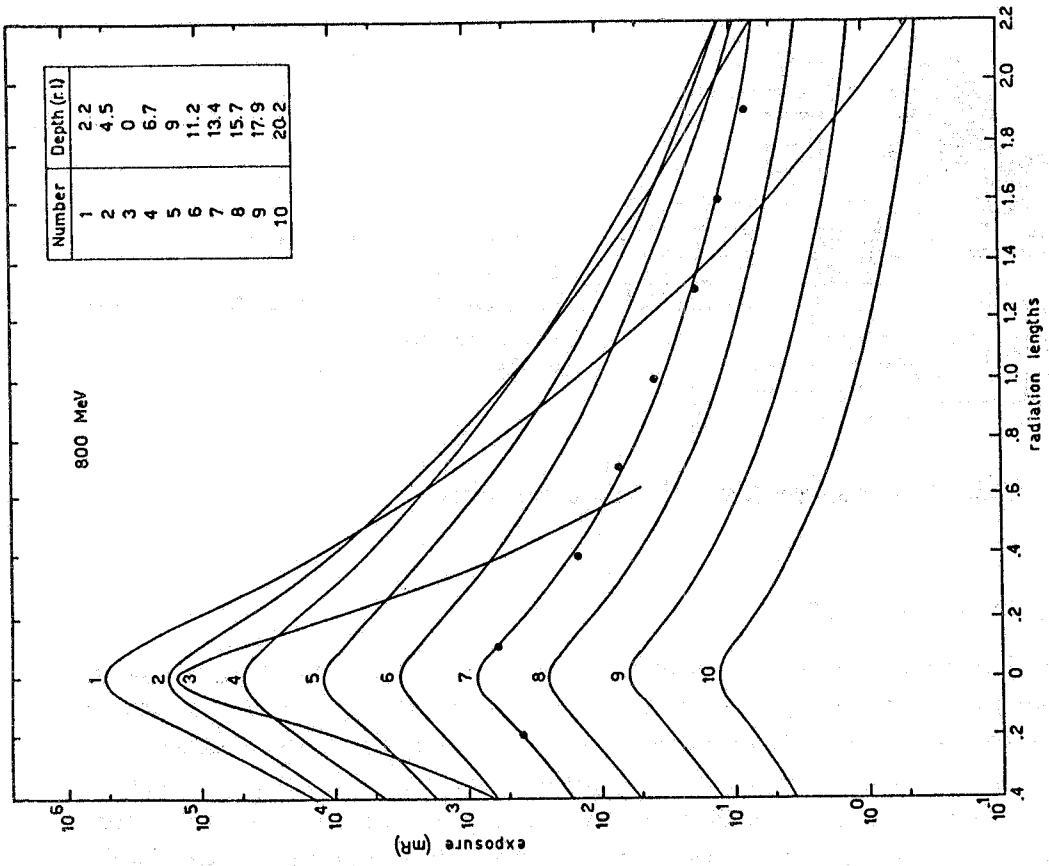
4.



| Number | Depth (r.l) |
|--------|-------------|
| 1 | 2.2 |
| 2 | 4.5 |
| 3 | 0 |
| 4 | 6.7 |
| 5 | 9 |
| 6 | 11.2 |
| 7 | 13.4 |
| 8 | 15.7 |
| 9 | 17.9 |
| 10 | 20.2 |

800 MeV

exposure (mR)

radiation lengths

FIG. 3 - Energy deposition profile curve for electro magnetic cascade produced by 800 MeV bremsstrah lung in ordinary concrete. Measured points are sho wn for a representative depth.
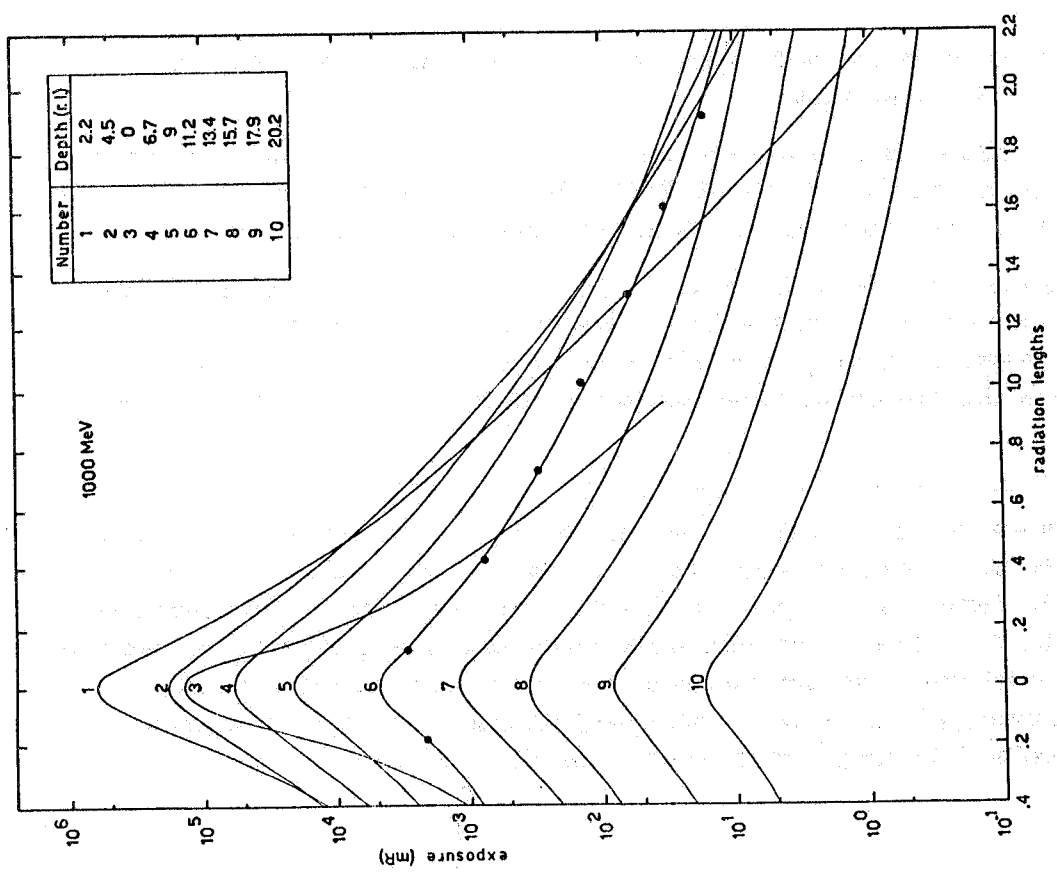


| Number | Depth (r.l) |
|--------|-------------|
| 1 | 2.2 |
| 2 | 4.5 |
| 3 | 0 |
| 4 | 6.7 |
| 5 | 9 |
| 6 | 11.2 |
| 7 | 13.4 |
| 8 | 15.7 |
| 9 | 17.9 |
| 10 | 20.2 |

1000 MeV

exposure (mR)

radiation lengths

FIG. 2 - Energy deposition profile curve for electro magnetic cascade produced by 1000 MeV bremsstrah lung in ordinary concrete. Measured points are shown for a representative depth.

experimental points have been reported only for one of the curves in every figure. All the data have been normalized to about $4.5 \times 10^{10}$ equi_valent quanta striking the absorber.

The longitudinal development of the cascade is shown in Fig. 5, where the fraction of energy deposited per radiation length is plotted versus concrete depth.

While no precise observation on the position of the shower's maximum can be made on account of the few experimental points obtained in the transition zone, some comments can be made on the asymptotic behaviour of the curves, for which we can take the form $D=Ae^{-\lambda t}$, where D is the radiation exposure, t is the depth of concrete and A and $\lambda$ are constants.

It is possible to make an attempt to justify this behaviour by this simple model: that the shower propagates principally by means of the most penetrating $\gamma$-rays in the material which is the object of study. And so, some authors[8] think it would be suitable to compare the experimental $\lambda$ value with the minimum energy absorption coefficient. However this fact seems not to completely agree with the experimental results[8,12].

In our case, for the graphs presented in Fig. 5, $\lambda$ may be re_garded as substantially independent of the maximum beam energy and its value is $0.020$ cm$^2$/g, at least within the limits of experimental error. This value is substantially coincident with the mass attenuation coefficient of 20-30 MeV $\gamma$-rays, which are the most penetrating in concrete and for which $\lambda = \lambda_{min} = 0.021$ cm$^2$/g.

This fact agrees with the results of other experiments performed with several different materials as can be seen in Table I, where experimental $\lambda$ values are compared with the mass energy absorption coefficient and the mass attenuation coefficient of the most penetrating $\gamma$-rays.

It follows from the comparison that the experimental $\lambda$ value differs very little, and usually is lower, from the minimum mass attenuation coefficient. This fact may be explained if it is admitted that the shower propagates principally by means of the minimum attenuation $\gamma$-rays and that, in equilibrium with these $\gamma$-rays, there are lower energy secondaries which are attenuated more quickly. In that case, it would explain why the transition curve decreases exponentially at a rate which is a little less than the minimum attenuation coefficient[12].

It is clear, that for a complete solution of the problem it would be opportune to measure the energy spectrum of the photons at several depths of concrete.
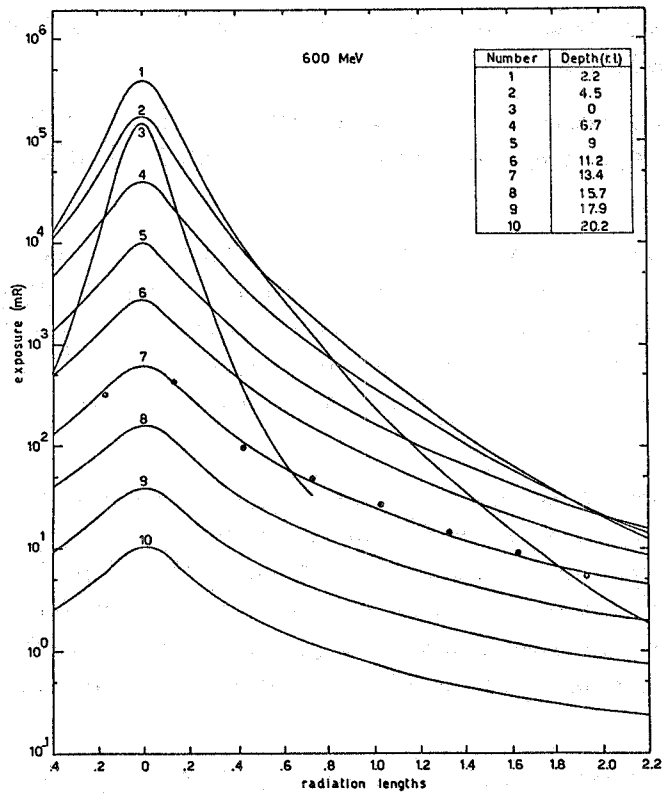
6.



FIG. 4 - Energy deposition
profile curve for electro-
magnetic cascade produced
by 600 MeV bremsstrahlung
in ordinary concrete. Mea-
sured points are shown for
a representative depth.

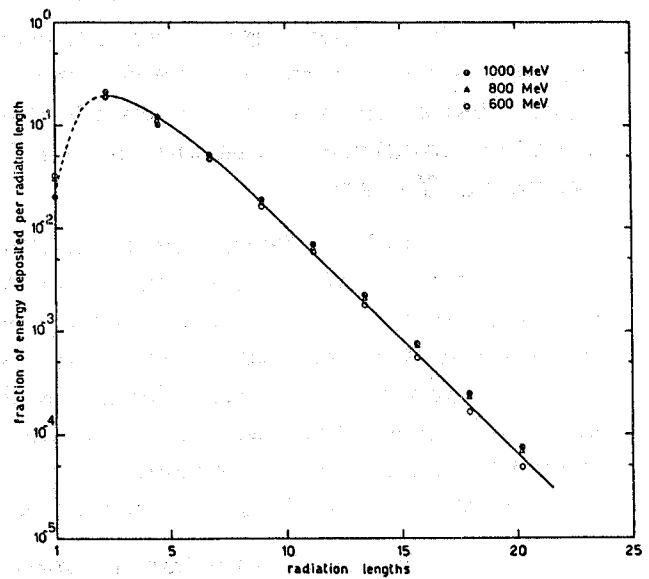FIG. 5 - Longitudinal energy
deposition in ordinary con-
crete.

## TABLE I

Comparison of the experimental $\lambda$ values with the theoretical coefficients for $\gamma$-rays.

| Material | $\lambda_{min}^{(E)\,(13)}$ cm$^2$/g | $\lambda_{min}^{(13)}$ cm$^2$/g | $\lambda$ this exp. cm$^2$/g | $\lambda^{(12)}$ cm$^2$/g | $\lambda^{(8)}$ cm$^2$/g | $\lambda^{(9,\,10)}$ cm$^2$/g | $\lambda^{(2)}$ cm$^2$/g |
|---|---|---|---|---|---|---|---|
| Lead | 0.028 | 0.0420 | – | 0.0435 | 0.045 | 0.043 | 0.0408 |
| Copper | 0.020 | 0.0303 | – | 0.029 | 0.024 | 0.028 | 0.0292 |
| Tin | 0.022 | 0.0355 | – | 0.033 | – | – | 0.0344 |
| Concrete | 0.017 | 0.0209 | 0.020 | – | – | – | – |

$\lambda_{min}^{(E)}$ = Minimum mass energy absorption coefficient.

$\lambda_{min}$ = Minimum mass attenuation coefficient.

Furthermore, we have tried to verify if the results of our measurements satisfy a property of the shower curves, which was discussed in some recent papers[8,12] on experiments carried out with high energy electrons in copper, lead and tin.

It has been, in fact suggested[8], that if the fraction of energy escaping from an infinitely long cylinder is plotted versus the radius of the cylinder measured in Molière units, a curve should be obtained which is independent of the choice of the absorber and of the energy of the incident particles. This curve is called radial escaping curve. In effect, from the analysis of the results of the measurements of various authors, while there seems to be agreement about the independence of the energy of the electrons, there is not such agreement in regard to the choice of the absorber. In fact, they have noted differences the more notable the lower is the atomic number of the material in question. Furthermore, it seems that the behaviour of the radial escaping curves, as found in the experiments, depends on the detector used, perhaps because of the different energy response of the detectors[12].

Our experimental points, plotted in the manner described above, are shown in Fig. 6. The solid curve presents the results of a Montecarlo in lead for electrons of 1000 MeV[14]. To calculate the value in concrete of the Molière length $r_M$, defined by $r_M = X_0 E_s / \mathcal{E}_0$, where $X_0$ is the radiation length, and $\mathcal{E}_0$ is the critical energy and $E_s = 21.2$ MeV, it has been necessary to first find the values of $X_0$ and $\mathcal{E}_0$. And so, we have calculated the value of the radiation length and

of the critical energy in ordinary concrete using the values presented in a recent paper[15], and using the composition in weight of concrete indicated in Table II[16].

And so we found $X_O$ = $= 26.2$ g. $cm^{-2}$, $\mathcal{E}_O = 46.8$ MeV and thus $r_M = 11.9$ g. $cm^{-2}$.

TABLE II

| PER CENT COMPOSITION IN WEIGHT OF ORDINARY CONCRETE | |
|---|---|
| H = 0.63 | Al = 2 |
| C = 0.4 | Si = 35.8 |
| O = 51.1 | Ca = 8.6 |
| Na = 0.33 | Fe = 1.2 |

The data presented in Fig. 6 seem to be in satisfactory agreement with each other and with the expectations of the Montecarlo, especially if it is taken into account that the values of the constants that serve to define the Molière unit are known with an uncertainty of about 20%.

It seems, therefore, that the proposed property can be verified even with bremsstrahlung beams and - which is even more interesting - with a light material like ordinary concrete.
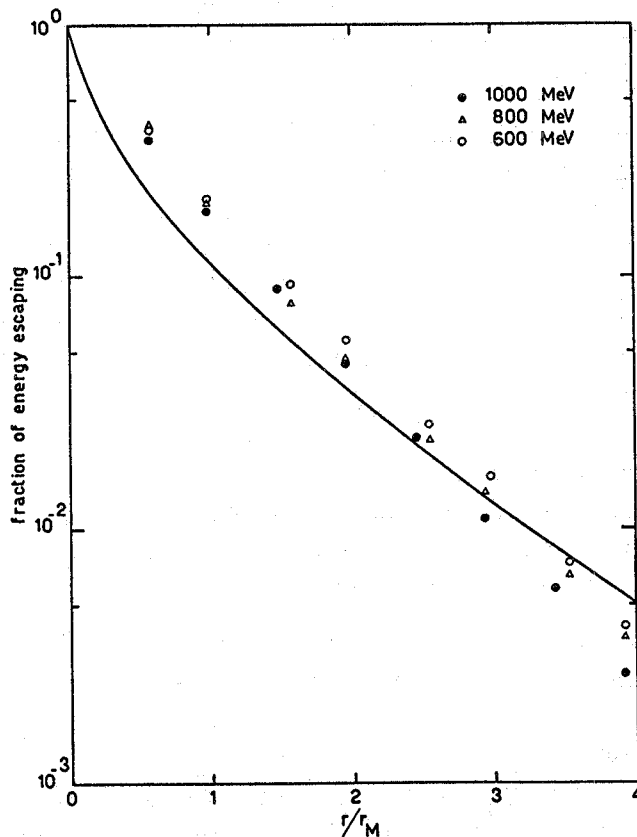


FIG. 6 - The fraction of the incident energy escaping from a infinitely long cylinder of radius r vs $r/r_M$, where $r_M$ is the Molière length. The data are compared with the predictions of the MonteCarlo calculations by Nagel in lead.

## 4. - ATTENUATION IN LEAD AND CONCRETE. -

We have also studied the attenuation of the $\mathcal{Y}$-rays and of the cascade-produced neutrons in heterogeneous lead and concrete absorbers. The experimental arrangement is the same as shown in Fig. 1, but, in this case, lead slabs of thickness up to 30 cm were inserted in front of the concrete blocks. All the measurements were carried out with the 1000 MeV bremsstrahlung beam.
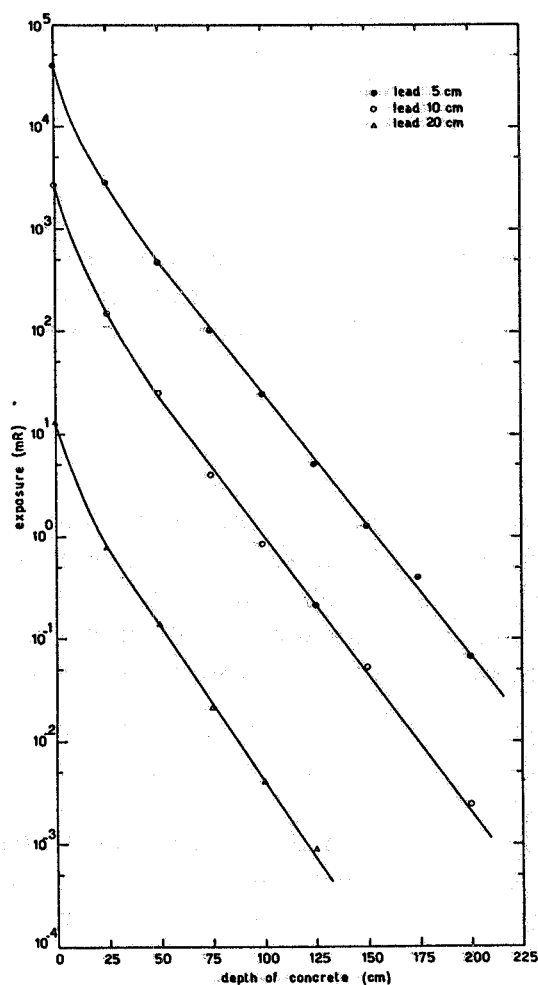
a) - $\mathcal{Y}$rays. -

Also for these measurements we have used thermoluminescent dosimeters. The results found with dosimeters placed near the beam axis are shown in Fig. 7, where the radiation exposure in mR is reported on the ordinate axis and the depth of concrete in cm on the abscissa axis. Each curve refers to a different depth of lead placed in front of the concrete blocks.

In this case too, we found that the radiation exposure tends to decrease exponentially with the concrete depth. However, the fractional rate of decrease depends on the thickness of the lead slab in front of the concrete. The $\lambda$ values for the curves in Fig. 7 are reported in Table III.

From the analysis of the results we think that in this case the propagation comes about by means of the minimum attenuation gamma rays in lead, the energy of which is about 4 MeV. In fact, the $\lambda$ values shown in Table III correspond to those of the mass attenuation coefficients in concrete for gamma rays



FIG. 7 - $\mathcal{Y}$-ray exposure vs depth of concrete measured in the beam direction in heterogeneous shields of lead and concrete.

of energy between 5 MeV ( $\lambda = 0.0287 \ cm^2/g$ )[13] and about 8 MeV ( $\lambda = 0.0243 \ cm^2/g$ )[13]; that is, the energy is very close to that of the minimum attenuation gamma rays in lead.

<div align="center">TABLE III</div>

| EXPERIMENTAL $\lambda$ VALUES IN CONCRETE WITH SEVERAL LEAD SLABS PLACED IN FRONT OF IT | |
| --- | --- |
| Thickness of lead (cm) | $\lambda \ (cm^2/g)$ |
| 5 | 0.024 |
| 10 | 0.026 |
| 20 | 0.029 |

Therefore, granted that these results seem to confirm the hypothesis that the propagation comes about by means of the minimum attenuation $\gamma$-rays, still they suggest the suitability of a spectrometry of $\gamma$-rays in order to completely clarify the question.

b) - Neutrons. -

We have also measured, at several depths in concrete, the dose rate due to the neutrons produced by 1 GeV bremsstrahlung beam in absorbers made either of concrete or of concrete and lead. For a detector we used a rem-counter. Further information on the propagation of the neutrons has been obtained by the activation of aluminum foils.

The use of the rem-counter presents the advantage of a direct response in dose units for neutrons of energy in the range between 7 keV and 14 MeV[17]. In our case, a great part of the neutrons are produced in this energy range, given that they are photoneutrons of the giant resonance. However, the use of the rem-counter cannot be considered completely free from criticism especially because of its great physical size.

The results of the measurements are shown in Fig. 8, where the dose rate in mrem.h$^{-1}$ is reported against the depth of the concrete. Each curve refers to a different thickness of lead placed in front of the concrete. The data are normalized to an intensity of about $5 \times 10^{12}$ equivalent quanta per minute, which is the maximum intensity we used in this series of measurements.
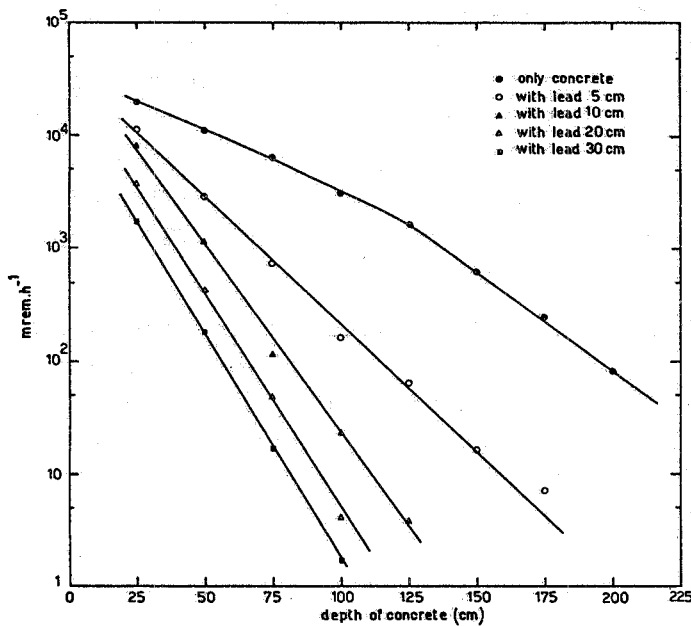
FIG. 8 - Neutron dose rate vs depth of concrete measured in the beam direction in heterogeneous shields of lead and concrete.

Although it is not altogether obvious theoretically to expect it, the curves shown in Fig. 8 seem to decrease exponentially, at least from a certain thickness of concrete on. In practice, some points have been measured in transition region only for the curve without the lead slab.

Curves that behave like ours have also been found at Desy, in heavy concrete with the 6.3 GeV bremsstrahlung beam[10] and with the 4 GeV and 6 GeV electron beams[9], using a detector made by an indium foil in a paraffin moderator.

In this case too, therefore, for the part of the curve that decreases exponentially with the depth we can assume a formula of the type $D_n = B e^{-\lambda_n t}$, where $D_n$ is the dose rate, $t$ is the depth of concrete, B and $\lambda_n$ are constants whose value depends on the thickness of the lead put in front of the concrete. In Table IV the values of $\lambda_n$ for the curves of Fig. 8 are reported.

TABLE IV

| EXPERIMENTAL $\lambda_n$ VALUES IN CONCRETE WITH SEVERAL LEAD SLABS PLACED IN FRONT OF IT | |
|---|---|
| Thickness of lead (cm) | $\lambda_n (cm^2/g)$ |
| 0 | 0.017 |
| 5 | 0.023 |
| 10 | 0.032 |
| 20 | 0.037 |
| 30 | 0.038 |

It must be observed that the values of $\lambda_n$ found in this way cannot be considered as attenuation coefficients of the neutrons in the material in question, especially for the curve relative to concrete alone. In fact, as we have seen, the energy of the most penetrating $\gamma$-rays in concrete is about 20-30 MeV, and at this energy the photoproduction cross sections are very high. And so, neutrons may by photoproduced even after notable depths of concrete the greater the rate the lesser the thickness of lead placed in front of the concrete.

From an examination of the results it seems opportune to note that the use of suitable thicknesses of lead in front of the concrete is very advantageous, both for favoring the development of the electroma- gnetic shower, and also for the more rapid absorption of the photoneu- trons produced. In fact, the lead slab not only attenuates the spectrum of the neutrons before they enter the concrete shield, but also strongly reduces the energy of the $\gamma$-rays, that, as we have seen in the above section, enter the concrete with a lower energy than the threshold for the photoproduction of other neutrons.

Further information about the distribution of neutrons in con- crete has been obtained using the reaction $Al^{27}(n, \alpha)Na^{24}$ in aluminum disks of a diameter of 5 cm and a thickness of 1.5 mm. The considered reaction has a threshold of about 6 MeV, and has been studied detecting the 1.39 MeV $\beta^-$ from the decay of the $Na^{24}$, the half life of which is 15 h. To distinguish the reaction in which we are interested from others produced in aluminum, we have made use of the differences of the half lives. However, this procedure introduces notable errors for the expe rimental points.

The measurements have been taken, placing three series of foils respectively on the beam axis, and at radial distances of 10 cm and 25 cm from it. All the foils have been exposed to an intensity of about $2.25 \times 10^{11}$ equivalent quanta per minute for about 12 hours. The maxi- mum energy of the bremsstrahlung beam was 1 GeV. In Fig. 9 the activi ties extrapolated at the time t=0 expressed in disintegrations per second have been shown against the concrete depth. These curves seem to us indicative of the distribution of the neutrons of a greater energy than 6 MeV in a concrete absorber exposed to a 1 GeV bremsstrahlung beam. However, due to the notable experimental errors introduced by this pro cedure, we prefer to abstain from any quantitative consideration.
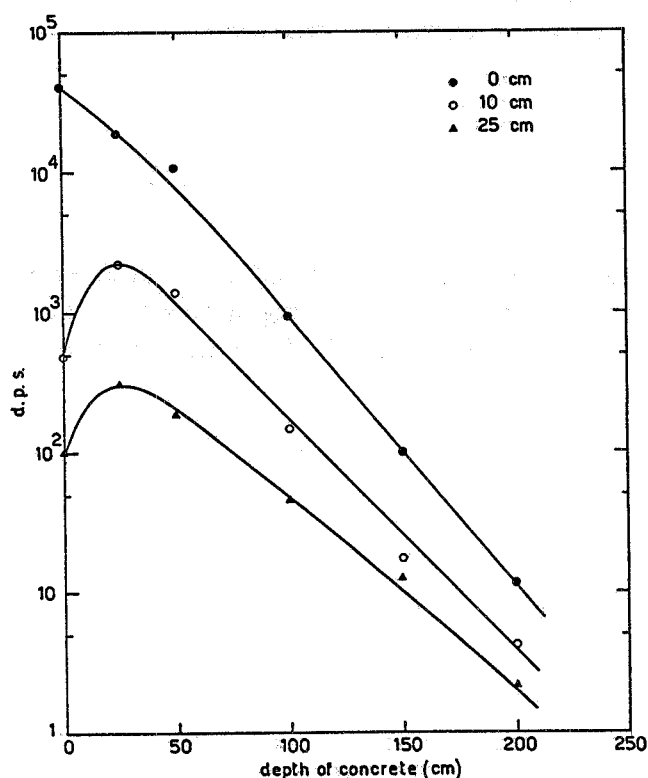
FIG. 9 - Initial activity for the reaction $Al^{27}(n, \alpha)Na^{24}$ induced by neutrons produced by 1.000 MeV bremsstrahlung vs depth of concrete for some distance from beam axis.

## CONCLUSIONS. -

In conclusion, it seems to us that we can affirm that the use of the thermoluminescent dosimeters is very advantageous for studying the longitudinal and radial development of the electromagnetic showers.

Insofar as regards the properties of the curves of showers in concrete, our results seem to be in agreement with the theory that the shower propagates principally by means of the minimum attenuation $\gamma$-rays. They also seem to satisfy the property for which the fraction of incident energy escaping from an infinitely long cylinder, when plotted against the radius of the cylinder measured in Molière units, might form a curve independent of the beam energy and of the target material. However, since this property does not seem to be verified by all the existing experimental data, especially when the target material is light, further experiments are to be carried out with lighter material than concrete.

The results of the attenuation measurements in heterogeneous shields seem to us to be useful for resolving shielding problems near high energy electron accelerators. We hold, however, that it is opportune to extend the experimentation to other combinations of different materials,

14.

and furthermore, to examine more thouroughly the propagation of the nucleonic cascade induced by the electromagnetic shower.

ACKNOWLEDGEMENTS. -

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