DRAFT
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A SURVEY OF SOME SHIELDING ASPECTS

1. Introduction

The professional Engineer-in-Charge of the MPS, being on duty, has been confronted in the past with the need to carry out rearrangements of the shielding in the experimental areas. The changes in the shielding were detailed to him by a member of the MPS Division. It has been difficult sometimes for the E.i.C. to understand the properties of the erected shielding. An attempt is made in this report to give some general information on shielding against nuclear particles.

The E.i.C. would then be able to understand better any given situation and play possibly a more active role when the need of simple rearrangements of an experimental layout occurs.

More frequently the E.i.C. has to face the problems arising from the handling of radio-active objects. Sufficient information has been given to the E.i.C. to enable him to take appropriate actions when active objects have to be handled. Some aspects concerning radiation hazards are compiled in this report for the sake of convenience.

As has been explained above, the first aim of this report is to supply the professional Engineer-in-Charge with a survey of some important shielding and radiation aspects.

When other members of the MPS Division think it is worthwhile extending the scope of this report, the author is quite willing to investigate the possibilities to incorporate them in a revised report.

2. Radiation dose and levels

2.1 Definitions

- The rad is the unit of absorbed dose.
  The rad is 100 ergs/gram tissue absorption.
- The RBE - the relative biological effect - is a factor expressing the magnitude of the biological effect of an absorbed dose of one rad.

  By definition : RBE = 1 for X-rays
- The rem - the roentgen equivalent man - is the unit of radiation dosage. One rem is the dose of radiation which has the same estimated biological effect as one rad of X-rays.

  Dose in rem = RBE x dose in rad

RBE	Radiations
1	X-, γ rays, electrons and β part. of all energies
5 - 10	protons up to 10 MeV
10	α - part.
20	heavy recoil nuclei
2,5 - 10,5	neutrons (see 2.3)

For the sake of completeness some other definitions are given below as well.

- The roentgen is the unit of X- or gamma radiation.
  One roentgen is the quantity of X- or gamma radiation which will release one electrostatic unit (esu) of electric charge per cm^3 air of 0^o C and 760 mm Hg pressure.
- The intensity or the flux of radiation is the amount traversing a unit area in unit time and is given in photons / cm^2 sec, n / cm^2 sec, etc..
- The curie is the unit of radioactive source strength.
  One curie is the amount of radioactivity which gives $3{,}7.10^{10}$ atom desintegrations per second.

2.2 Maximum permissible radiation dose (mpd)

The International Commission on Radiological Protection has made recommendations on the maximum permissible dose. The latest recommendations of the Commission are used as maximum permissible dose for the workers at CERN.

Maximum permissible dose of the whole body :

- 5 rem/year
- 3 rem/quarter
- 0,1 rem/week or for a 40-hour week
- 2,5 mrem/hour

Maximum permissible doses exist for specific parts of the body and for organs. However, the specialist only (The Health Physics) should apply those detailed recommendations. As an example : the mpd for hands and feet is about 6,6 times higher than for the body, so :

0,66 rem/week

Restricting the working time, jobs may be performed in a radiation field which exceeds the 2,5 mrem/hour limit. This type of work should be carefully controlled and information is needed on the radiation history of the man involved. A dose of 100 mrem/week corresponds to :

2,5	mrem/hour	during	40 hours
10	"	"	10 "
100	"	"	1 hour
1	rem/hour	"	6 minutes

2.3 Levels

For shielding calculations it is necessary to convert the mpd into terms of maximum permissible fluxes. This conversion depends largely on the value of RBE

Outside the shielding of PS experimental areas, the radiation is in general dominated by the neutrons flux and therefore the table below is of interest (ref. 1 : p 503 ; ref. 2 : p 152).

neutron energy in MeV	RBE	flux in neutrons /cm^2 sec for 2,5 mrem/hour
Thermal	3	670
0,02	5	280
0,1	8	85
0,5	10	30
1,0	10,5	18
2,5	8	20
5,0	7	18
10,0	6,5	18

There is a lack of information of figures at higer neutron energies but it is believed that the flux for 2,5 mrem/hour decreases with energy and amounts to several n/cm^2 sec only above 1 GeV (ref. 3). The energy of the main part of the neutrons outside the shielding in the PS Experimental Area is a few MeV.

- So, <u>the limiting flux outside the shielding, uncontrolled area</u> is 20 n/cm^2 sec when the neutrons form the only source of radiation.
- For muons and electrons the relation between flux and dose is (ref. 4, p 516)
  2,5 mrem/hour = 23 part./cm^2 sec
- For gammas above 0,1 MeV, a good approximation can be obtained with
  $$2{,}5 \text{ mrem/hour} = \frac{1{,}5 \,.\, 10^3}{E} \text{ photons/cm}^2 \text{ sec}$$
  E being the photon energy in MeV (see also ref. 5, p 9).

Shielding survey measurements in the PS Experimental Areas are performed with tissue-equivalent ionisation chambers which give the absorbed dose in rad. A RBE of 10 is then applied unless the type of radiation is exactly known.

3. Shielding against gamma rays

3.1 Beam of mono-energetic gamma rays

$I = B \; I_o e^{-\mu x}$

I = flux in photons/cm^2 sec after traversing absorber

I_o = initial flux

B = build-up factor

μ = linear absorption coefficient in cm^{-1}

x = thickness absorber in cm

In the literature, instead of μ, one uses also : $\mu_m = \mu/p$, the mass absorption coefficient in cm^2/gr, p being the density of the absorber, or one uses :

$L \frac{1}{2}$, the halfthickness, $L \frac{1}{2} = (\ln 2)/\mu = 0{,}693/\mu$

μ is a function of the energy of the gamma rays. When not known, one may assume that the energy of the gamma radiated from materials activated in the PS amounts to 1 MeV (for detailed information see ref. 5, p 37).

material	μ for 1 MeV in cm^{-1}
lead	0,78
steel	0,46
concrete, p = 3,1	0,18
concrete p = 2,35	0,15

The build-up factor B is a function of the energy of the gamma ray, the shield thickness, the form of the incident beam and the shielding material (ref. 5, p 43).

A conservative value of B, independent of shield thickness, for 1 MeV gamma on lead :

- for a monodirectional gamma source = 5
- for a point gamma source = 7

A photon whose energy is greater than the binding energy of a neutron in the nucleus can liberate a neutron (γ, n reaction). The photoneutron threshold energy varies with the material but is for the common shielding materials above 10 MeV. Photoneutrons can present a problem in the shielding as materials as lead and iron are good gamma but very poor low energy neutron absorber. In such cases the addition of low Z-materials is necessary, as concrete, wood or plastics.

3.2 A point source of gamma rays

Many sources of gamma activity in the PS ring can be treated as a point source.

The cheapest reduction in gamma intensity can be achieved by respecting distance (r) from the source.

$$I = B\, I_o \frac{e^{-\mu x}}{4 \pi r^2} \quad \text{(see fig. 1)}$$

3.3 Source strength and dose

When material has been irradiated in the PS by chemists, the source strength expressed in millicurie (mc) is probably known.

The dose at 1 metre from the source can be found approximately by the relation :

$\frac{1}{2}$ CE = dose in mrem/hour at 1 m from the source

C = source strength in mC

E = energy of emitted gammas

4. Shielding against nuclear particles

4.1 Shielding in forward direction for high energy nuclear particles

After a beam of high energy nuclear particles has traversed a shielding material over a distance of several mean free paths, the resulting beam will consist mainly of neutrons and the neutron flux behind the shield can be approximately found by :

$$\text{flux behind shield} \approx \frac{N_o \, BF_1 \, e^{-x/\lambda r}}{10 \, A} \qquad \text{(see fig. 2)}$$

where N_o is the number of primary particles per sec, being neutrons, protons or pions

BF_1 is the build-up factor

X is the thickness of the shielding in cm

λr is the mean removal free path in cm

A is the cross-section of incident beam in cm^2

Rule : take $10 \, A = 10^3$ for $A < 10^2 \; cm^2$ and

take proper product 10 A for $A \geqslant 10^2 \; cm^2$

BF_1 : at 3 GeV incident energy $BF_1 = 30$ and calculate BF_1 at other energies by assuming BF_1 proportional to $E^{\frac{1}{2}}$ (E : energy part.) See ref. 6.

λr : 150 g/cm^2 for concrete
170 g/cm^2 for steel

material	λr in cm
normal concrete, p = 2,4 g/cm^3	63
baryte concrete, p = 3,6 g/cm^3	42
steel p = 7,8 g/cm^3	22

The tolerable flux behind the shield due to the incident beam depends on the background due to other sources of radiation. When the background is negligible, the tolerable flux is 10 n/cm^2 sec, assuming that the shield thickness (x) is at least 4 λ r.

4.2 Side shielding for high energy particles (ref. 6).

The side shielding specifies the dimensions of the shield in the plane perpendicular to the axis of the incident beam.

The flux in the side direction can be approximately found by :

$$\text{flux} \quad \frac{N_o \, BF_2 \, e^{-x/\lambda r}}{2 \pi r^2} \qquad \text{(see fig. 3)}$$

where same indications are used as in 4.1 and r is the distance from the point where the axis incident beam strikes the shielding wall to the position where the flux is found, in cm ; at first take r = 300 cm in calculations

BF_2 : at 3 GeV incident energy $BF_2 = 4$; BF_2 proportional to E $\frac{1}{2}$

The thickness x is calculated again by taking the tolerable flux equal to 10 n/cm^2 sec (background considerations as above).
Add to the thickness calculated in this manner : three times the half width of the incident beam.

4.3 Shielding against muons

When the incident particle flux contains muons, an estimate of the muon flux behind the shield should be made.

Muons have a negligible small cross section for nuclear interactions and they lose their energy by ionization process only (ref. 1, p 583).

material	length to reduce energy muon by 1 GeV (in general : for single charged part.
normal concrete	210 cm
baryte concrete	145 cm
steel	75 cm
lead	63 cm

The spread of the muon beam in the shield depends largely on the incident energy of the muons and the shield thickness. When the shield thickness is sufficient to thermalise the muons, one can assume that the muon beam has been stopped. Are the muons not thermalised on leaving the shield, assume that the cross-section of the beam has not changed (take a cross-section of 100 cm^2 as a minimum). The tolerable flux in $muons/cm^2$ sec should be set taking into account the other sources of radiation as well (2.5 mrem/hour eq. 23 $muons/cm^2$ sec or 2300 incident muons).

In an exceptional case the pion flux will be known at a certain distance away from the shielding. The muon flux resulting from the decay of the pions can then be estimated by using the graphs M2, page 21 of the CPS User's Handbook.

4.4 Skyshine

Radiation which at first is directed upward and then scattered back towards the earth by collisions with air nuclei is called "skyshine". Neutrons in the range of 1-20 MeV appear to be the main radiation component in the skyshine present in the PS Experimental Areas and they are the main contributors to the background also. The skyshine is due to insufficient shielding on top of the targets and of the ring in general.

Information about standard PS shielding blocks can be found in section U of the CPS User's Handbook.

5. Acknowledgment

I would like to thank B. de Raad and J.Y. Freeman for many helpful discussions.

6. References

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7. R.G. Alsmiller et al. Nucleon-meson cascade calculations transverse shielding for a 45 GeV electron accelerator ORNL-3289

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7. Annex

7.1 Nuclear star process and attenuation of nuclonic shower

A very high energy neutron, proton or pion hitting a heavy nucleus induces a fission process which results in the production of a number of high-energy protons, neutrons, pions, and mesons. The residual heavy nuclei, being in a state of excitation, may emit low energy nucleons. The process described is called the nuclear star process. Some properties of this process.

Threshold energy : there is not a well defined threshold, above 100 MeV star processes can occur but above 300 MeV complete stars can be produced.

Cross-section : the cross-section for the star process are known only approximately, but the cross-sections can be assumed to be equal to n, p and pion, independent of the energy (see ref. 7, fig. 1).

Number of star part. (secon.) : the number depends on the energy of the star producing part. (build-up factor in formula in section 4.1 is proportional to $E^{\frac{1}{2}}$), the number of secondary neutrons and protons is roughly equal, the number of sec. pions is about half of that (see ref. 7, fig. 2)

Angular distribution sec. : high energy secondaries are peaked forward, peaking increases with increasing energy ; low energy secondaries are approximately distributed isotropically.

Properties sec. : the high energy secondaries will create other star processes resulting in tertiaries etc,, until they have lost sufficient energy to arrive below the threshold energy

<u>Properties sec.</u> (cont,) : Neutrons are not loosing energy by ionisation processes and this is one of the causes that the neutron flux is superior to the other fluxes inside the shield (see ref. 8). The range of protons in the low energy range is short, in the other of a few cm in concrete.

π^- : being slowed down sufficiently (star and ionisation processes) the pion is captured by a nucleus producing a low energy gamma and neutron which can be absorbed over a short distance.

π^+ : slowed down as π^- but there is no capture process ; decay $\pi^+ \longrightarrow \mu^+ + \nu$; $T \frac{1}{2} = 2,54 \, . \, 10^{-8}$ sec, as the main part of the π^+ decays at low energy, the resulting μ^+ has a low energy as well and is distributed in all directions ; the e^+ releases by decay of μ^+ is absorbed in the shield.

π^0 : essentially no interaction with nuclei, decay into 2 gammas (68 MeV each), $T \frac{1}{2} = 10^{-15}$ sec ; the low energy gammas are absorbed in the shield.

<u>7.2 Discussion</u> on denominator in formula of 4.1 :

$$\text{flux behind shield} \approx \frac{N_o \, BF_1 \, . \, e^{-x/\lambda \; r}}{10 \, A}$$

The formula is meant to be used in shielding calculations where minimum thickness is not an important requirement. For this reason BF_1 is taken proportional to $E \frac{1}{2}$ and not to $E \frac{1}{4}$ as some experimental data justify. The denominator takes into account the spread of the beam after passing through the shield.

An experiment in Brookhaven with a 3 GeV proton beam (incident cross-section 15 x 15 cm) showed an increase in the beam cross-section by a factor 40 after about 4 mean free paths (ref. 2, p 35).

Livingston (ref. 1, p 569) suggests to assume that the nucleonic shower in the forward direction is spread over an area of 10^4 cm^2, so in excess of the denomination in the proposed formula.

It should be worthwhile testing the proposed formula by erecting the shielding wall at the end of a secondary beam in several steps measuring the radiation behind the shield after each additional layer.

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Attenuation of a point gamma source 1MeV

FIG. 1

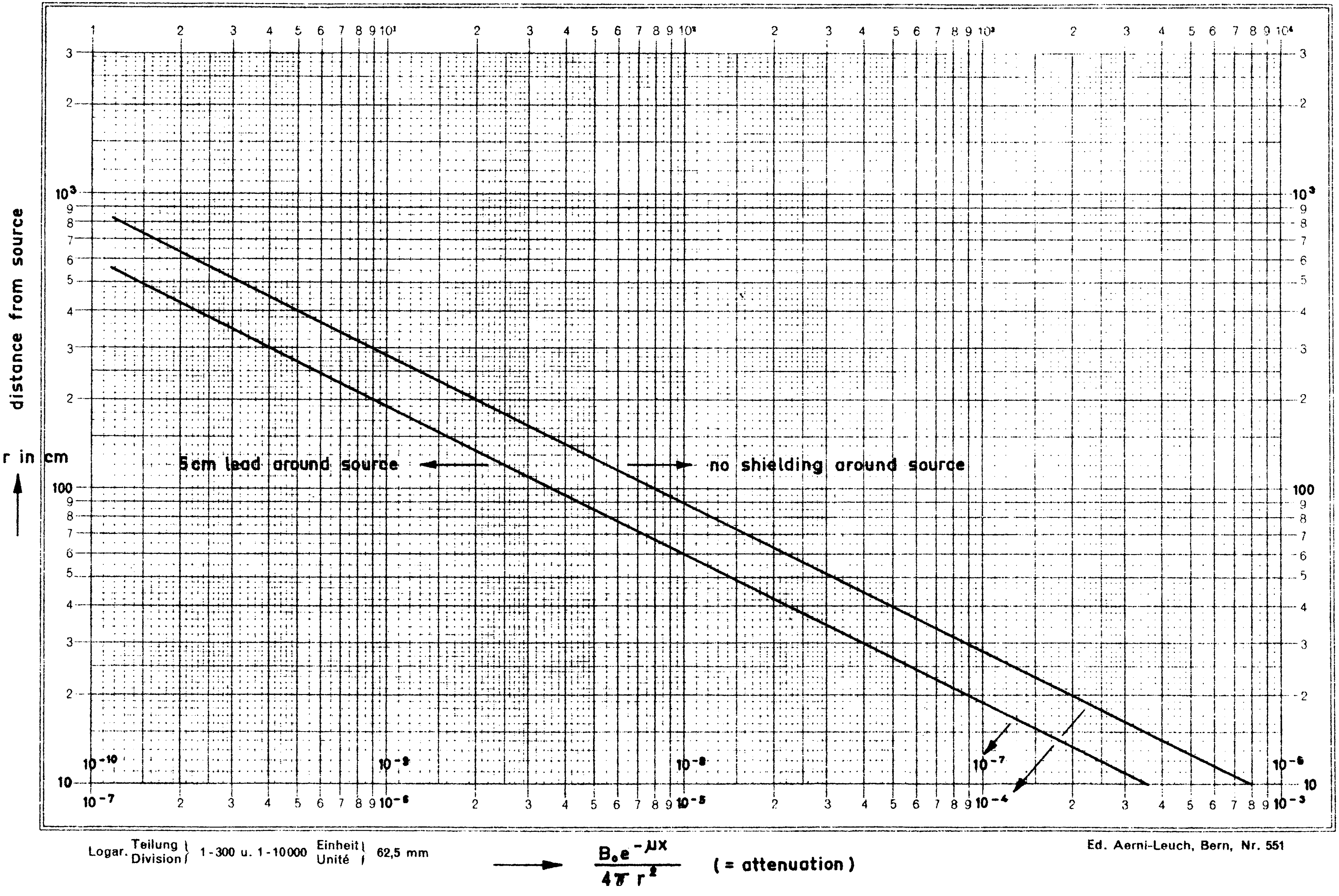
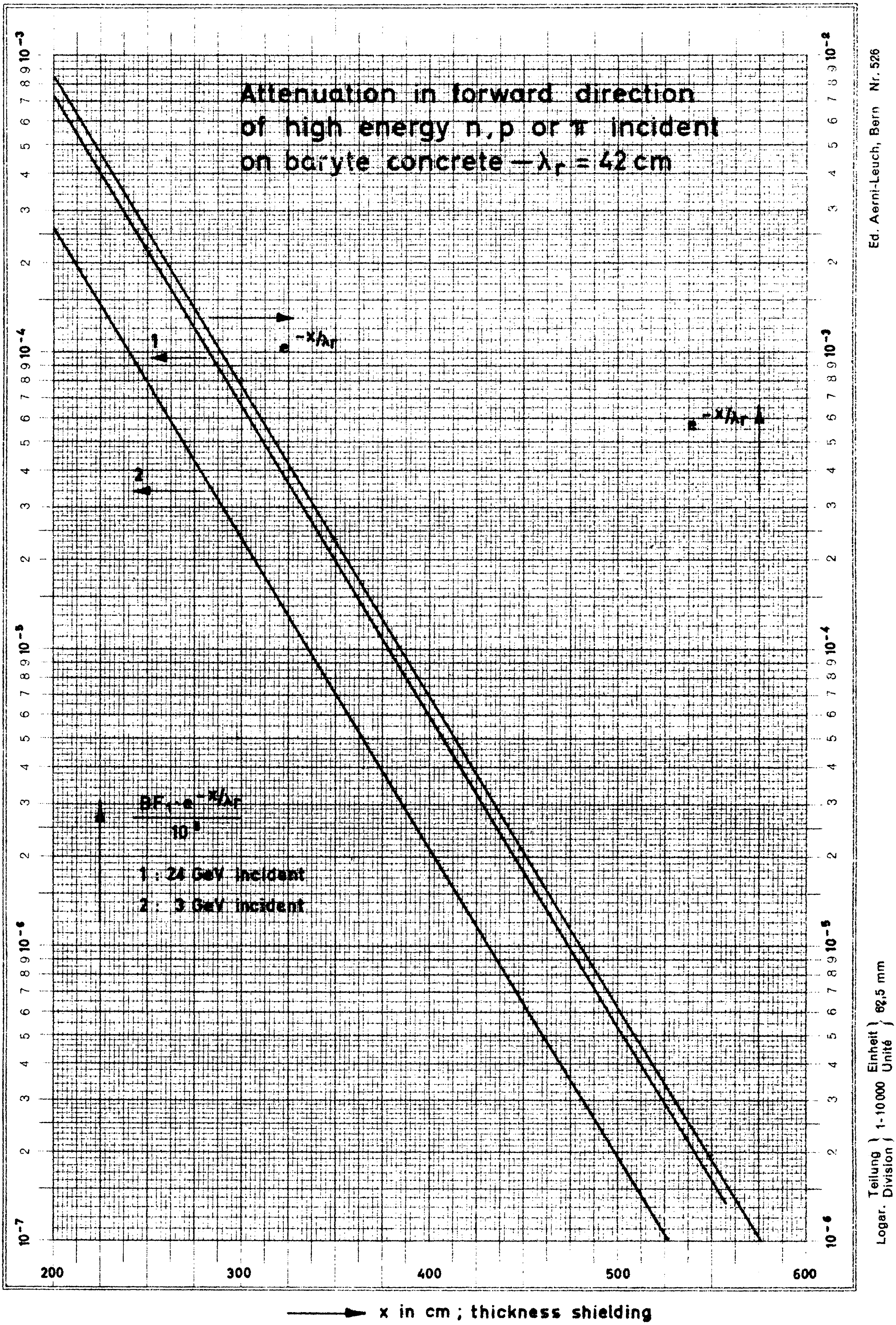


FIG. 2



Attenuation in forward direction of high energy n, p or π incident on baryte concrete — λ_r = 42 cm
1
2
e^{-x/λ_r}
e^{-x/λ_r}
$\frac{BF_1 \cdot e^{-x/\lambda_r}}{10^x}$
1 : 24 GeV incident
2 : 3 GeV incident
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
2
3
4
5
6
7
8
9
200
300
400
500
600
x in cm ; thickness shielding
Ed. Aerni-Leuch, Bern Nr. 526
Logar. Teilung / Division 1-10000 Einheit / Unité 62,5 mm

Attenuation in side direction

FIG. 3