LEP Note 507

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SHIELDING MATERIAL EQUIVALENCE IN LEP EXPERIMENTAL AREAS

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1. INTRODUCTION

The shielding requirements around the LEP experimental areas were discussed in HS-RP/IR/81-05 and defined in LEP Note 341 [Hoe81, Din81]. Figure 1 taken from the latter reference shows that beyond a concrete thickness of 1 m the high-energy hadron component dominates the radiation situation behind a lateral concrete shielding in an experimental area. Thus it was stated that "the minimum shielding requirements of 1 m of concrete (or the equivalent of iron) combined with a closest approach of 4 m can be used parallelling the PETRA shielding philosophy".

Because of space problems around the future experimental areas of LEP the question came up whether concrete (nominal density assumed to be 2.35 g/cm^3) could be replaced by other possibly denser materials. Hence the problem of material equivalence for shielding arose and will be discussed below.

2. ATTENUATION LENGTHS FOR HIGH-ENERGY HADRONS

In the following the focus will first be on the attenuation of the high-energy component, although the problem of fast neutrons and bremsstrahlung penetration cannot be neglected if the actual shield becomes thinner and is of different material than concrete.

In the case of lateral shielding the attenuation of the high-energy hadron component is characterized by an attenuation length

λ_a, generally expressed in units of g/cm^2, which is either determined experimentally or obtained by Monte Carlo calculations following an exponential decrease of dose within the depth of the shield. After removing the geometrical term (the dependence on distance according to the model of the source chosen), λ_a for concrete has been taken as 115 g/cm^2, taking into account the spread in experimentally determined values [Par82].

In the case of iron the results of measurements are however not as conclusive as for concrete owing to the fact that the inelastic cross-section for neutrons drops from 1500 mb at 5 MeV to values of less than 90 mb below 1 MeV. This so-called neutron window leads to a relative enrichment of neutron fluence in the intermediate energy range and increases the dose equivalent outside the shield accordingly (Fig. 2). Measurements of λ_a depend on the component for which the attenuation was determined. Clean measurements taking only the high-energy component into account tend to give attenuation lengths of around 140 g/cm^2, while attempts to measure total dose equivalent as a function of shielding thickness have led to considerably higher figures ($\approx$170 g/cm^2). This only confirms that iron is a material unsuited for shielding against intermediate energy neutrons and should not be used alone but in a sandwiched form together with concrete, a practice followed for the shielding of high-energy proton accelerators.

3. NUCLEAR INTERACTION LENGTH

If a narrow hadron beam of GeV energy hits a material of thickness x in g/cm^2 the attenuation of such a beam can be described by an exponential where a parameter λ_T in g/cm^2, the nuclear collision length, is a parameter of the material under consideration. The nuclear collision length can be calculated from the total nuclear cross-section σ_T, where the following relation holds:

$$\lambda_T = \frac{M}{N\ \sigma_T}$$

where M is the molar or atomic mass in g/mole, N Avogadro's number (6.023×10^{23} atoms per mole) and σ_T the total (asymtotic) nuclear cross-section in cm^2. The total nuclear cross-section is composed of a scattering contribution and an inelastic term. In the case of broad beam attenuation particles are not removed by scattering but by inelastic interactions. When subtracting the elastic scattering cross-section from the total nuclear cross-section, σ_i will result, for which with the help of a similar equation as above a macrogeometric quantity, the so-called nuclear interaction length λ_i can be defined. The value of this quantity is numerically rather close to the shielding parameter attenuation length λ_a.

In Table 1 the molar mass M, the inelastic cross-section σ_i, and the nuclear interaction length λ_i are given for several common construction and shielding materials. Data for elements were copied from [Par82]. For those not given in the reference the curve in Fig. 3 was used. In the case of composed materials the molar mass M^C was calculated according to the formula

$$M^C = \Sigma f_j^W A_j$$

where f_i^W is the fraction of weight of atomic component A_j. The inelastic cross-section σ_i^C of the compound is calculated by

$$\sigma_i^C = M^C \Sigma \frac{f_j^W \sigma_{ij}}{A_j}$$

where $\frac{M^C f_j^W}{A_j}$ is the fraction of element A_j per unit volume.

The nuclear interaction length λ_i^C is then given by

$\lambda_i^C = \frac{M^C}{N \sigma_i^C}$, with N being Avogadro's number.

The nuclear interaction lengths thus calculated agree well with those tabulated in [Par82].

In the fifth column, recommended attenuation lengths λ_a are given. Following the frequently used figures of 115 g/cm^2 for concrete and 144 g/cm^2 for iron, the recommended values were determined by essentially increasing the λ_i's by 10%. The rounded figures for λ_a should be sufficient to provide a good estimate for lateral shielding requirements in the case of high-energy hadrons.

Since shielding thicknesses are often used, the shielding length is likewise given in the last column of Table 1, taking conservative values for the density of the materials into consideration.

Hence it appears that iron is nearly as efficient as lead for the same thickness of material. Greater attenuations per unit length can only be achieved with tungsten or uranium. The gain in thickness for baryte concrete compared with the normal one does not usually justify the additional cost for the former. All organic material and water show about double the attenuation lengths of the normal concrete for hadrons.

4. ATTENUATION LENGTHS FOR GIANT RESONANCE NEUTRONS

The attenuation of giant resonance neutrons cannot be deducted in the same straightforward manner from material constants as for high-energy particles. Although the so-called removal cross-section makes it possible to introduce a removal length via a similar formula to the one quoted above (combining molar mass and cross-section), such a parameter is of only limited value. It describes the removal of neutrons from a specific energy group but does not really give their attenuation with respect to dose equivalent. Neutrons of a given energy are removed but find their way into a lower energy group for which the radiological quality factor is higher, thus leading to a build-up of dose equivalent. Hence there is little relation between the removal lengths (calculated for a neutron energy of 3.5 MeV as representative for the energy of giant resonance neutrons) and attenuation lengths as reported in the literature. Most of the measured data were determined for hydrogenous material which is more efficient for lower than for higher energy neutrons, while for material of higher molar mass inelastic cross-sections become more important for the attenuation process. Therefore concrete seems to be slightly more efficient as a shield for 14 MeV neutrons than for radioactive source neutrons (Table 2).

The classical shielding materials against photons (lead) and high-energy hadrons (iron) are easily penetrated by neutrons and cannot fully replace relatively efficient concrete shielding.

5. DISCUSSION

Starting from the source terms [Hoe81] for the high-energy component and the giant resonance neutrons, dose equivalent values given in Table 3 were calculated for LEP shielding taking various shielding configurations into account*. For a shielding of 1 m of concrete the high-energy particle component is clearly predominant outside the shield, whereas for a shielding sandwich built of 20 cm of iron and 40 cm of concrete giant resonance neutrons will penetrate the shield, increasing the dose rate by about a factor of three. A somewhat better solution for a thinner shield could be realized by using 20 cm of steel followed by 40 cm of polyethylene, decreasing the giant resonance neutron component considerably but allowing for a greater penetration of the high-energy particle component. Thus it seems that any deviation in the direction of reduced thicknesses replacing concrete by a combination of other materials will lead to a reduction in shielding efficiency and may possibly involve an increase in cost.

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* It is assumed that the electromagnetic component will always see enough shielding material (metals) to be of no problem in LEP.

REFERENCES

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FIGURE CAPTIONS

Fig. 1. Source terms and attenuation in concrete.

Fig. 2. Neutron leakage spectra outside a shielding of a GeV proton accelerator at a radius of 220 g/cm^2 for iron, and iron followed by heavy concrete.

Fig. 3. Inelastic nuclear cross-section σ_i as a function of atomic mass A.

Table 1

Attenuation parameters of various materials for high-energy particles

Material	Molar mass M g/mole	Inelastic cross-sec. σ_i barn	Nuclear interaction length λ_i g/cm^2	Attenuation length λ_a g/cm^2	Density ϱ g/cm^2	Shielding length Λ cm
Al	26.98	0.421	106.4	117	2.7	43.3
Fe	55.85	0.703	131.9	144	7.5	19.2
Cu	63.54	0.782	134.9	148	8.9	16.6
W	183.85	1.649	185.1	204	19.3	10.6
Pb	207.19	1.776	193.7	213	11.3	18.8
U	238.03	1.983	199.3	220	18.8	11.7
Concrete I [1]	22.25	0.361	102.4	115	2.35	48.9
Concrete II [2]	23.02	0.384	99.6			
Baryte [3]	64.16	0.904	111.7	123	3.2	38.4
Marble $CaCO_3$	25.15	0.416	100.4	110	2.5	44.0
Water H_2O	14.32	0.280	85.0	94	1	94.0
Polysterene $(CH)_n$	11.15	0.225	82.2	91	1.02	91.0
Polyethylene $(CH_2)_n$ [4]	10.43	0.219	79.0	87	0.92	94.4

1) Composition by weight: O: 0.52, Si: 0.32, Ca: 0.06, Al: 0.04, Fe: 0.02, Na: 0.015 [Par82]

2) Composition by weight: O: 0.511, Si: 0.358, Ca: 0.086, Al: 0.02, Fe: 0.012, H: 0.0063, C: 0.04, Na: 0.0033 [Pri57]

3) Composition by weight: Ba: 0.358, O: 0.354, Ca: 0.074, S: 0.09, Si: 0.089, Fe: 0.015, C: 0.011, H: 0.0044 [Pri57]

4) Paraffin has the same composition but a density of 0.88 g/cm^3.

Table 2

Attenuation parameters of various materials for fast neutrons

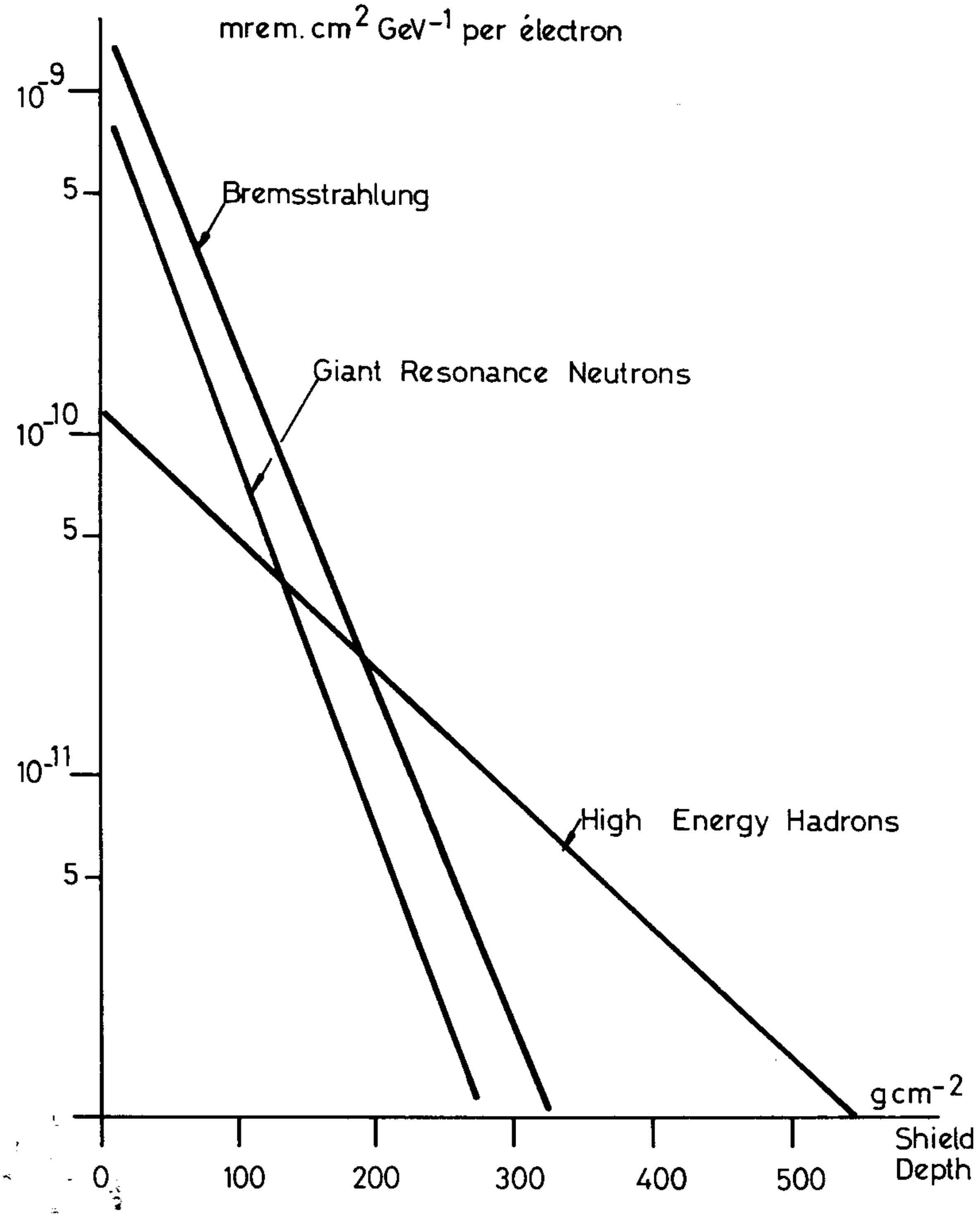
Materials[1]	Removal length[2] λ_r g/cm^2	Attenuation length λ_a in g/cm^2: Radioactive source neutrons $E_{mean} \approx 4$ MeV	14 MeV neutrons	Recommended	Shielding length Λ in cm
Fe	47.3	127 [5]	131 [3]	135	18.0
Pb	86.4	265 [3] 238 [5]		270	23.9
Concrete I Concrete II	20.1 17.2	39.2 [4]	33 [3] 35.1 [4]	40	17.0
Baryte	23.5	50.0 [5]		50	15.6
Marble	18.6			45	18.0
Water	6.8	9.5 [3] 10 [4]	16.5 [3] 18.9 [4]	12	12.0
Polysterene	6.1			12	12.0
Polyethylene	4.2	7.6 [3] 6.5 [4]	15 [3] 14 [4]	10	10.9

1) Composition as in Table 1.
2) For neutrons of 3.5 MeV [Ave60]
3) ICR71
4) Jae74
5) Tes79

Table 3

Dose rates per electron lost at 1 m distance in sievert per GeV from the high-energy particle component and the giant resonance neutrons

Shielding	HEP	GRN	Total
None	1.2×10^{-16}	1.0×10^{-15}	1.1×10^{-15}
1 m of concrete	1.6×10^{-17}	2.8×10^{-18}	1.9×10^{-17}
20 cm of iron followed by 40 cm of concrete	1.9×10^{-17}	3.1×10^{-17}	5.0×10^{-17}
20 cm of iron followed by 40 cm of polyethylene	2.8×10^{-17}	8.3×10^{-18}	3.6×10^{-17}



Source terms and attenuation in concrete

FIG. 1

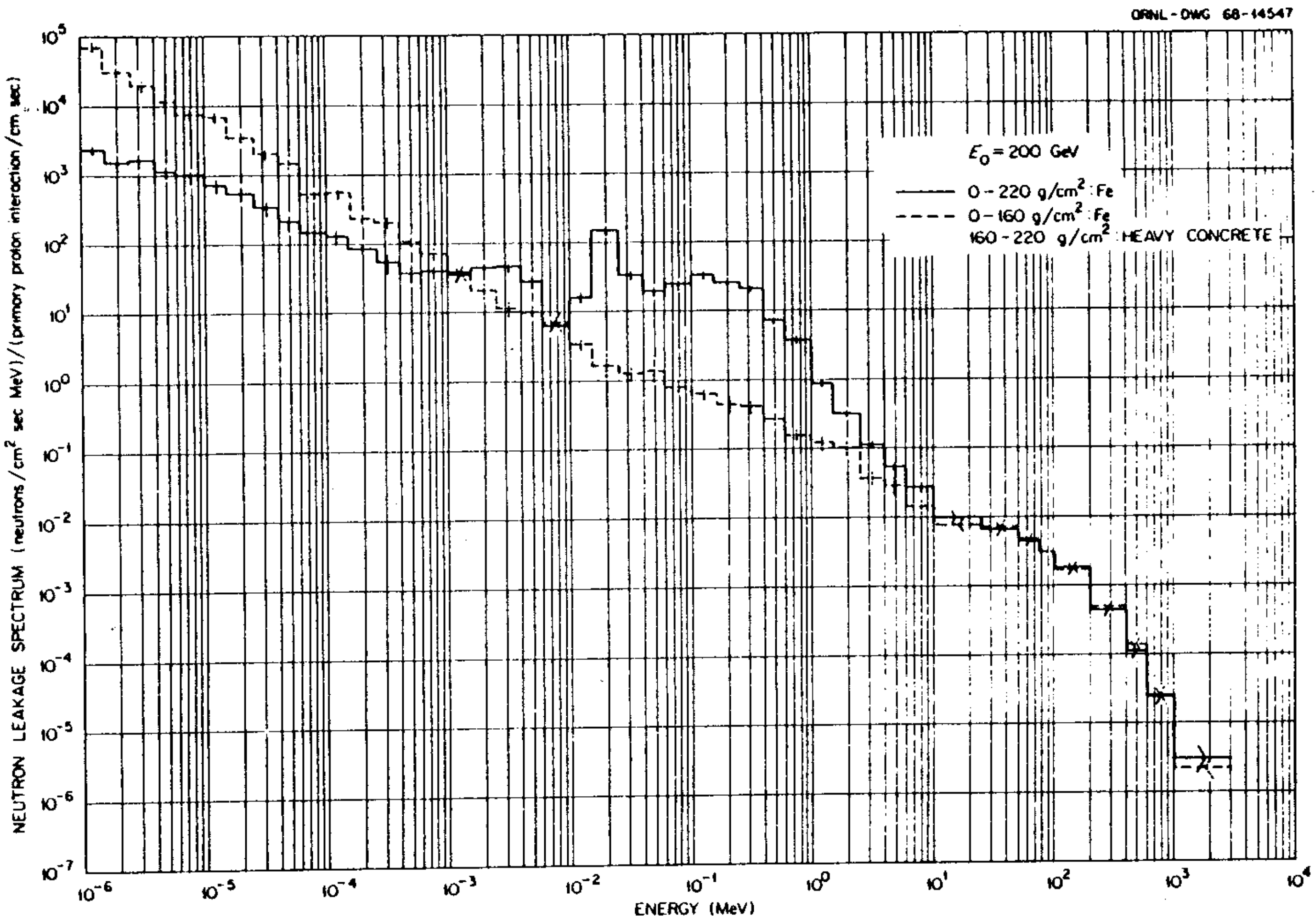
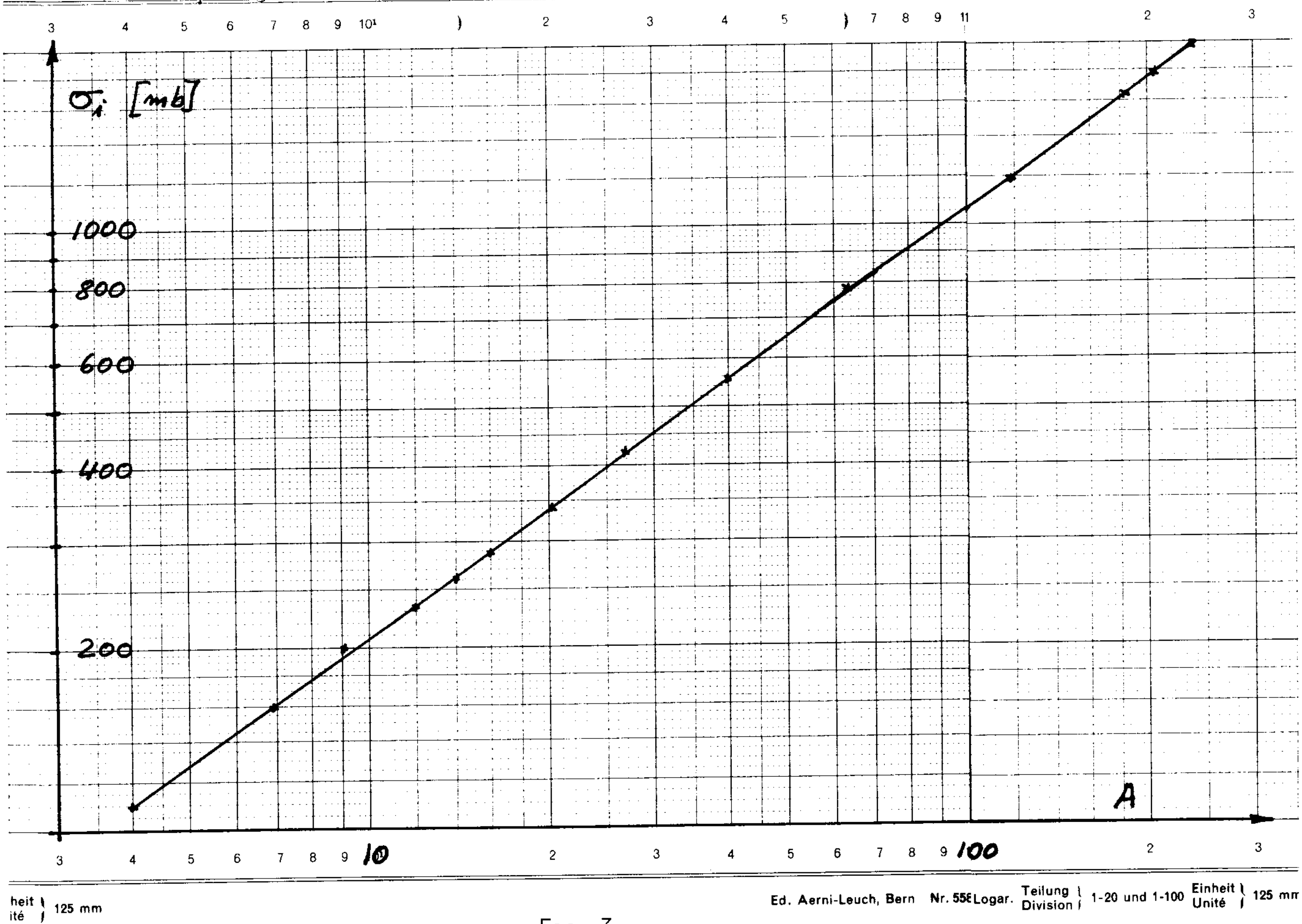

ORNL-DWG 68-14547
E_0 = 200 GeV
0 - 220 g/cm² : Fe
0 - 160 g/cm² : Fe
160 - 220 g/cm² : HEAVY CONCRETE
NEUTRON LEAKAGE SPECTRUM (neutrons/cm² sec MeV)/(primary proton interaction/cm sec)
ENERGY (MeV)
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰
10¹
10²
10³
10⁴
10⁵
10⁻⁷

FIG. 2



σi [mb]
1000
800
600
400
200
10
100
A
Ed. Aerni-Leuch, Bern Nr. 55ℇ Logar. Teilung / Division 1-20 und 1-100 Einheit / Unité 125 mm

FIG. 3