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POPULATION EXPOSURE FROM HIGH-ENERGY ACCELERATORS

Lloyd D. Stephens, Ralph H. Thomas and Samuel B. Thomas

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POPULATION EXPOSURE FROM HIGH-ENERGY ACCELERATORS

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ABSTRACT

There is increasing interest in estimating the magnitudes of population exposure due to the operation of nuclear facilities. This paper discusses the population exposures that might result from high energy accelerators. External whole body radiation is the dominant type of radiation exposure, while exposure resulting from the leakage of radionuclides into the atmosphere or ground water is negligible. At large distances from operating accelerators, neutrons are the predominant form of radiation. The transport of high-energy neutrons through the atmosphere is not well understood at distances greater than about 1000 meters from the radiation source. Consequently, estimates of population exposure out to distances of 80 km from high energy accelerators may be quite inaccurate. It is extremely important that health physicists and administrators be aware of the limitations of estimates of population exposure. A model is described which facilitates the estimation of population exposure due to accelerators and its limitations are discussed. Suggestions are made for experimental investigations which would improve the model.

"On the bare earth expos'd he lies"
Alexander's Feast, John Dryden

1. Introduction

The International Commission on Radiological Protection has recommended[1] that: "As any exposure may involve some degree of risk, the Commission recommends that any unnecessary exposure be avoided, and that all doses be kept as low as is readily achievable, economic and social considerations being taken into account." This is particularly wise in view of man's increasing uses of ionizing radiation and the consequential possibility of the contamination of our environment to a small, but measurable degree.

In the past, most attention has been devoted to the quantification of radiation exposures. Until recently few attempts have been made to place the "social and economic factors" on a quantitative basis, which would enable rational judgments to be made as to both the benefits and detriments resulting from any particular application of activity which involves the use or production of ionizing radiation. Recently several papers have appeared in the literature discussing the techniques of "Risk-Benefit Analysis."[2]

In setting standards for radiation protection, it is assumed that biological effects are linearly related to the dose equivalent. Under these conditions an index of possible detriment to the population resulting from exposure to ionizing radiation, M, due to a given activity can be defined by the equation[3]

$$M = \int HN(H)dH \qquad (1)$$

where $N(H)dH$ is the number of people receiving a dose equivalent between H and $H + dH$, and the integration is carried out over the entire dose equivalent distribution and population exposed. M is usually expressed in the unit man-rem and is termed the population dose.

The concept of population dose equivalent may prove to be a useful qualitative (even semiquantitive) figure of merit in risk-benefit analysis, but some caution is to be recommended in its use for this purpose. Substantial errors are possible in estimates of man-rem and it is extremely important that health physicists should be aware of these limitations. Estimates of population exposure depend upon an accurate knowledge of both the number of people exposed and their dose equivalent. Several examples of population exposure estimates have appeared in the literature for a variety of nuclear installations.[4] The evaluation of the dose equivalent at large distances from nuclear installations may prove to be extremely difficult. In many cases the dose equivalent rate at their site boundaries are as low as a few millirem/year--smaller than the magnitude of the secular fluctuations in natural background dose rate. Under such conditions considerable extrapolation from measured data may be necessary in population exposure estimates. Such is the case for high-energy accelerators discussed in this paper.

For high-energy accelerators operating in populated areas, neutrons are the dominant source of radiation exposure. Exposure resulting from the leakage of radionuclides into the atmosphere or ground water is negligible. The transport of high-energy neutrons through the atmosphere has not been experimentally investigated at distances greater than about 1000 meters from the radiation source. Consequently, estimates of population dose out to distances of 80 kilometers from high energy accelerators may be quite inaccurate. A model is described in this paper which facilitates the estimation of population exposure due to accelerators and its limitations are discussed. Suggestions

are made for experimental investigations which would improve the model.

2. The Environmental Impact of High-Energy Accelerators

The environmental impact of high-energy accelerators is different in character from most types of nuclear installations. At accelerators the predominant source of population exposures is due to the radiation field produced during operation rather than due to the leakage of radionuclides into the environment.

Possible contamination of the ground water close to accelerator laboratories and consequent contamination of drinking water has been carefully studied at the Stanford Linear Accelerator 20-GeV electron linac,[5,6] the 24-GeV proton synchrotron at CERN,[7,8] the 400-GeV proton synchrotron at the National Accelerator Laboratory,[9] and elsewhere.[10-14]

General consideration of the total quantity of radionuclides produced in the earth shields of high-energy accelerators suggests no serious contamination problems in volumes of water comparable to rainfall on the accelerator site.[15] Such studies all conclude that no significant ground water contamination is likely due to accelerator operation. This conclusion has been supported to date by the absence of any reports in the literature of any significant elevation in the radioactivity in water supplies close to accelerator laboratories.

The experience with the operation of diverse types of particle accelerators over many years makes it possible to conclude that the exposure resulting from radioactive gases or aerosols produced by particle accelerators are usually significantly lower than those due to the external radiation field. Measurements of the production of radioactive gases have been reported[16-25] and show that in many cases in the immediate vicinity of high energy particle beams the air may be extremely radioactive. Most of the radionuclides are, however, extremely short-lived and do not survive in significant concentrations outside accelerator installations. ^{3}H and ^{7}Be are two examples of long-lived radionuclides of significance. Recent studies have been made at CERN as part of the design studies for a 300-GeV proton synchrotron[26] and the 600-MeV synchrocyclotron improvement program.[27] Calculations show that the concentration of ^{7}Be deposited on neighboring vegetation will be comparable to that produced by the interaction of cosmic radiation with the atmosphere, and will barely be detectable. Preliminary studies by Smith[28] of the ^{7}Be concentration on vegetation and gravel around the Lawrence Berkeley Laboratory and its vicinity do not indicate any measurable production of ^{7}Be that may be attributed to accelerator operation. Measurements of ^{3}H around high energy accelerators have not been reported but similar conclusions are to be expected. The CERN studies conclude that despite the high beam power of the new accelerators under construction, external radiation due to accelerator operation will continue to predominate.

3. The Radiation Environment of High-Energy Accelerators

The composition of the radiation field around high-energy accelerators has been studied for many years and is now well understood. Several reviews of these studies exist in the literature.[29]

Neutrons dominate the radiation field of high-energy, high-intensity electron and proton accelerators, particularly at large distances from the accelerators during actual operation.

The character of the shield-leakage neutron spectrum is controlled by the interaction of neutrons of energy greater than about 100 MeV. The nature of the equilibrium achieved between these high-energy neutrons and their interaction products is determined by the nuclear properties of the shield. The

nuclear properties of concrete, earth, and air do not differ greatly and the equilibrium spectra established in these media likewise do not differ greatly. Nevertheless at a shield-air interface small changes in the spectrum—most noticeably in the neutron resonance region—are initiated. An equilibrium determined by the nuclear properties of air will be reestablished after passage through two to three interaction mean free paths, corresponding to several hundred meters.

4. The Variation of Dose Equivalent with Distance from a High Energy Accelerator

Many measurements of dose equivalent around a variety of particle accelerators have been published. These measurements have recently been reviewed and critically evaluated.[30] No measurements have been reported beyond a distance of 1500 meters. At all accelerators the dose equivalent falls at least as fast as the inverse square of the distance. At distances beyond about 300 meters the variation of dose equivalent H(r), with distance, r, from shielded high energy accelerators is probably best expressed by:

$$H(r) = a \frac{e^{-r/\lambda}}{r^2} \quad r \geq 300 \text{ meters} \qquad (2)$$

where a is a constant.

The parameter $e^{-r/\lambda}$ is interpreted as due to air attenuation. The attenuation length, λ, depends upon the spectrum of neutrons entering the air from the accelerator shield. The experimental data published in the literature do not determine the value of λ with any great accuracy, as may be seen by inspecting Fig. 1 which summarizes neutron measurements made around several accelerators. Values of λ between about 240 and 1000 meters are reported. Despite the poor accuracy of the data, some consistent patterns are evident. To interpret Fig. 1 we first place some reasonable physical constraints on the value of attenuation length. A reasonable lower limit would be that measured for fission neutrons of $\approx$ 225 meters.[30] If the accelerator is capable of producing neutrons of energy greater than about 100 MeV, it is reasonable to assume that at large distances when an equilibrium spectrum has been established in air, λ will take on the value corresponding to high energy neutrons. The high-energy attenuation length in air may be calculated as $\sim$ 95 cm^{-2}. Cosmic ray studies have measured the attenuation of strongly interparticles, produced in Extensive Air Showers and obtained values in the range 100-120 gm cm^{-2}. It is reasonable therefore to take an upper limit of λ as $\approx$ 100 gm cm^{-2} (850 meters). To a large degree the measurements summarized in Fig. 1 are consistent with this interpretation. Measurements made at low-energy accelerators, or at high-energy accelerators whose leakage spectrum is rich in low energy neutrons tend to show values of λ in the region of $\sim$ 250 meters. At other high-energy accelerators values of λ between 600 and 1000 meters have been reported. There are anomalies in the literature, however. For example, Höfert and his colleagues[31,32] have described measurements around the CERN 24-GeV proton synchrotron (CPS) and reported values of λ in the range 244-290 meters. Since the CPS is well shielded one would have expected a much higher value, as is indeed suggested from data previously reported by CERN.[30] Further studies are needed to resolve some of these discrepancies.

5. Model for Estimating Population Dose Due to High-Energy Accelerator Operation

An operating high-energy accelerator is a source of neutrons irradiating its surroundings. This exposure may be modified by the topography around the accelerator, or by conditions of accelerator operation, but is not influenced by meteorological conditions such as wind direction or rainfall. Population

exposure is due only to the prompt radiation field produced by an accelerator during operation.

These facts suggest a simple model that may be used to calculate population dose. Imagine a high-energy accelerator located on a flat plane so that there is no shielding or shadowing due to hills, surrounded by a mixed urban population (Fig. 2) and the radiation field at large distances from a high-energy accelerator to a good approximation, isotropic in character and depending only on the intensity of and distance from the source. Equation (1) can then be transformed to:

$$M = \int_{t=0}^{1\,\text{year}} \int_{r_0}^{R} N(r,t)\, \dot{H}(r,t)\, dr\, dt. \tag{3}$$

where $N(r,t)\, dr\, dt$ is the number of people at a distance between r and $r + dr$ from the accelerator at time between t and $t + dt$, $\dot{H}(r,t)$ is the corresponding dose equivalent rate, and r_0, R, are the limits of radial integration at the closest and furthest distances of approach under consideration to the accelerator.

In principle the dose equivalent rate may be determined as a function of distance from the accelerator. $H(r)$ has the form

$$H(r) = \frac{aQ}{r^2}\, e^{-r/\lambda}$$

with $250\ \text{m} \leq \lambda \leq 900$ meters. (Section 4)

The form of $H(r)$ is independent of accelerator intensity and therefore of t in Eq. (3).

In a homogeneous urban area it is plausible that the population density may be considered constant when averaged over long periods of time. This should not result in serious error in the estimate of population exposure provided the intensity of accelerator operation is uncorrelated with fluctuations in population (e.g., high intensity operation is not restricted to times of known low population). If this assumption is made, Eq. (3) may be simplifed to:

$$M = \int_{r_0}^{R} H(r)\, N(r)\, dr \tag{4}$$

where $H(r)$ is the annual dose equivalent to a person at a distance from r to $r + dr$ from the accelerator.

$N(r)$ is the average number of people at this distance given by:

$$N(r)\, dr = 2\pi\, \sigma r\, dr \tag{5}$$

where σ is the average population density.

And we obtain finally:

$$M = 2\pi\sigma\, D_0\, r_0^2\, e^{r_0/\lambda} \int_{r_0}^{\infty} \frac{e^{-r/\lambda}}{r}\, dr \tag{6}$$

where D_0 is the annual dose equivalent at distance r_0 from the accelerator

(the fence post dose equilvalent) and the other parameters have previously been defined.

The integral of Eq. (6) does not have a convenient analytical solution but may readily be evaluated numerically. (See Table I and Fig. 3.)

Convergence of the Integral. The convergence of the integrand may be examined by inspecting integrals of the form

$$I(R, r_0, \lambda) = \int_{r_0}^{R} \frac{e^{-r/\lambda}}{r} \, dr \tag{7}$$

as a function of R for various values of r_0 and λ. Figure 4 shows values of the integral $I(R, 300, \lambda)$ as a function of R for values of λ = 100, 200, 500, 1000 meters.

The convergence of the integral $I(R, r_0, \lambda)$ may be more generally understood by plotting the parameter $F(r_0, R)$, defined by

$$F(r_0, r) = \frac{\int_{r_0}^{R} \frac{e^{-r/\lambda}}{r} \, dr}{\int_{r_0}^{\infty} \frac{e^{-r/\lambda}}{r} \, dr}, \tag{8}$$

as a function of R. Figure 5 shows the parameter $F(300, r)$ for values of λ between 100 meters and 1000 meters. The integral is seen to converge quite rapidly, and as a rule of thumb, under the conditions of the model, it is only necessary to extend integration out to distances $\sim (r_0 + 3\lambda)$ from the accelerator for an accurate evaluation. This knowledge could save extensive efforts in the evaluation of so called "80 kilometer man-rem dose," required in some environmental monitoring reports, for high-energy accelerators.

6. Influence of the Parameters λ and r_0 on Estimates of Population Exposure

From the data given in Table I it is now possible to investigate the influence of the parameters λ and r_0 on estimates of population exposures. For this purpose it is convenient to define a parameter $\mu(r_0, \lambda)$, (proportional to population dose) given by:

$$\mu(r_0, \lambda) = \frac{M}{2\pi\sigma D_0} = r_0^2 \, e^{r_0/\lambda} \int_{r_0}^{\infty} \frac{e^{-r/\lambda}}{r} \, dr. \tag{9}$$

Table II summarizes values of $\mu_0(r_0, \lambda)$ in the range of r_0 from 300 meters to 1000 meters and λ from 100 meters to 1000 meters. Figures 6 and 7 show $\mu(r_0, \lambda)$ as of function λ and r_0 respectively.

It is convenient to summarize these calculations in an empirical formula of the form

$$M = k \, r_0^n \, \lambda^m. \tag{10}$$

The values of k, n, m will vary somewhat but inspection of Figs. 6 and 7 show that over the range of r_0 and λ discussed here, n has values in the range 1.1 to 1.4. Similarly, m has values ranging from 0.60 to 0.80.

A convenient and suitably accurate empirical formula for $r_0 \approx 300$ meters, $\lambda \approx 900$ meters is:

$$\frac{M}{\sigma D_0} = 3.5\, r_0^{4/3}\, \lambda^{2/3} \tag{11}$$

with σ in people m^{-2}, and r_0, λ in meters.

We have already seen that published values of λ range from about 250 meters to 1000 meters. Such an uncertainty in λ leads to an uncertainty in population dose estimates of nearly a factor of three, even for the simple model described here. In order to improve the accuracy of population dose estimates at accelerators, it is important therefore first to improve our knowledge of λ.

The annual dose equivalent at the site boundary of a nuclear facility is limited by law to 500 mrem.[33] At most high energy accelerators the actual fence post dose is a small fraction of this limit.[34,35] If these radiation levels are maintained at existing accelerators, it is probably not feasible to significantly improve our present knowledge of high energy neutron transport in air. It is easy to show that in order to measure neutrons produced by accelerator operation at a distance of 3 km a neutron source strength close to $\sim 10^{12}$ n sec^{-1} would be required. Measurements using such an intense source would have to be made carefully and only in fairly remote locations. Unless such measurements are made, however, we must accept the fundamental inaccuracy of population dose estimates around high energy accelerators. Until λ is well determined, there is little point, for example, in greater efforts being expended to evaluate the population distribution with great accuracy. An upper limit to population dose may be obtained using a value of $\lambda = 850$ meters. If and when the day arrives when both λ and population density distribution are well known, it will then be necessary to improve the model described here to take into account the perturbations caused by topographical variations.

REFERENCES

1. International Commission on Radiological Protection, Publication 9. Para. 52, Pergamon Press, Oxford (1966).

2. For example see:
   L. A. Sagan, Human Costs of Nuclear Power, Science 177, 487 (1972).
   H. J. Dunster, Costs and Benefits of Nuclear Power, New Scientist, 18 October 1973, p. 192.

3. International Commission on Radiological Protection. "Implications of Commission recommendations that doses be kept as low as readily achieveable," Para. 21, ICRP Publication 22, Pergamon Press, Oxford (1973).

4. For an example of the techniques used see, for example:
   J. A. Martin, Calculations of Environmental Radiation Exposures and Population Doses Due to Effluents from a Nuclear Fuel Reprocessing Plant, Radiation Data and Reports XIV, 59 (1973).

5. W. R. Nelson, "Radioactive Ground Water Produced in the Vicinity of Beam Dumps." Stanford Linear Accelerator Center Internal Report SLAC TN, July 1965 (unpublished).

6. D. Busick, A Three Year Summary of Environmental Radiation Measurement at SLAC. To be published.

7. F. Hoyer, Induced Radioactivity in the Earth Shielding on Top of High Energy Particle Accelerators. CERN 68-42, December 9, 1968.

8. R. H. Thomas, Possible Contamination of Ground Water System by High Energy Proton Accelerators, in Proceedings of the Symposium on Health Physics Aspects of Nuclear Facility Siting, Idaho Falls, November 3-6, 1970.

9. T. B. Borak, et al., The Underground Migration of Radionuclides Produced in Soil Near High Energy Proton Accelerators, Health Physics 23, 679 (1972).

10. G. B. Stapleton and R. H. Thomas, Estimation of the Induced Radioactivity of the Ground Water System in the Neighborhood of a Proposed 300-GeV High Energy Accelerator Situation on a Chalk Site. Health Physics 23, 689 (1972).

11. G. Stapleton and R. H. Thomas, The Production of ^{7}Be by 7-GeV Proton Interactions with Oxygen, Nucl. Phys. A175, 124 (1971).

12. G. Stapleton and R. H. Thomas, The Effect of Sorption on the Migration of ^{7}Be from a High Energy Accelerator Constructed on a Chalk Site. Water Research 7, 1259 (1973).

13. R. H. Thomas, Radioactivity in Earth Induced by High Energy Electrons, Nucl. Inst. Methods 102, 149 (1972).

14. C. A. Mawson, Consequences of Radioactive Disposal into the Ground in Health Physics, Vol. 2, Pt. I, Edited by A.M.F. Duhamel, Pergamon Press, Oxford (1969).

15. H. W. Patterson and R. H. Thomas, Accelerator Health Physics, Chapter 7, p. 539, Academic Press, New York (1973).

16. Brookhaven National Laboratory, Advanced Accelerator Department. Proposal for Increasing the Intensity of the AGS at the Brookhaven National Laboratory, Internal Report BNL-7956 (May, 1964).

17. A. G. George, A. J. Breslin, J. W. Hoskins and R. M. Ryan, Proc. First Symposium on Accelerator Radiation Dosimetry, Brookhaven National Laboratory, CONF-65119, 1969, pp. 513-555.

18. A. Rindi and S. Charalambus, Airborne Radioactivity Produced at High Energy Accelerators, Nucl. Inst. and Methods 47, 227 (1967).

19. S. Charalambus and A. Rindi, Aerosol and Dust Radioactivity in the Halls of High Energy Accelerators, Nucl. Inst. and Methods 56, 125 (1967).

20. K. B. Shaw and R. H. Thomas, Problems Associated with High Energy Proton Beams, Health Physics 13, 1127 (1967).

21. M. Ladu, M. Pellicioni and M. Roccella, Produzione e Scarcio di Gas Tossici e Radioattiviti nel Tunnel del Linac di Frascati, Giornale di Fisica Sanitaria - Minerva Fisico - Nucleare 11, No. 2, 112 (1967).

22. M. Awschalom, F. L. Larsen, and W. Schimmerling, Activation of Air Near a Target Bombarded by 3-GeV Protons, Princeton Report PPAD-661E, May 1969 (unpublished).

23. M. Höfert, Radiation Hazard of Induced Activity in Air as Produced by High Energy Accelerators in Proc. Second Int. Conf. on Accelerator Dosimetry, Stanford, November 1969, CONF-691101, p. 111.

24. H. Viallettes, Gas and Dust Activation in the Target Room of the Saclay Electron Linac, in Proc. Second Int. Conf. on Accelerator Dosimetry, Stanford, November 1969. CONF-691101, p. 121.

25. G. J. Warren, D. D. Busick and R. C. McCall, Radioactivity Produced and Released from Water at High Energies in Proc. Second Int. Conf. in Accelerator Dosimetry, Stanford, November 1969, CONF-691101, p. 99.

26. A. Rindi, "La Radioactivité induite dans l'air de l'accelerateur de protons de 300-GeV du CERN, "CERN Internal Note, CERN Lab II, RA-72/5 (1972).

27. A. Peetermans and J. Baarli, Radioactive Gas and Aerosol Production by the CERN High Energy Accelerators and the Evaluation of its Influence on the Environmental Problems, CERN Internal Note, DI/HP/174, October, 1973.

28. A. R. Smith, Lawrence Berkeley Laboratory, private communication, 1974.

29. See for example:
A. Rindi and R. H. Thomas, The Radiation Environment of High Energy Accelerators, Ann. Rev. Nucl. Sci. 23, 315 (1973). H. W. Patterson, and R. H. Thomas, op cit, Ref. 15, Chaps. 3 and 6.

30. A. Rindi, and R. H. Thomas, "Skyshine--A Paper Tiger?" Lawrence Berkeley Laboratory Report LBL-3322, (1974).

31. M. Höfert and J. M Hanon, The Influence of the PS Operation on Stray Radiation Levels at the CERN Site. CERN Health Physics Internal Report, HP-73-121, January 1973.

32. M. Höfert, F. Coninckx, J.M. Hanon and G. Roubaud, Environmental Implications of the Operation of the Present Neutrino Facility with Beam Intensities Exceeding 5×10^{12} per Pulse, CERN Health Physics Internal Report, HP-74-136, February, 1974.

33. 10 CFR, Part 20.

34. USAEC, Environmental Monitoring at Major U.S. Atomic Energy Commission Contractor Sites, CY 1972, WASH 1259 (1972).

35. USAEC, Environmental Monitoring at Major U.S. Atomic Energy Commission Contractor Sites, CY 1973, Vols. I and II, WASH 1259-73 (1973).

Table I. Values of the integrand: $\int_{r_0}^{\infty} \frac{e^{-r/\lambda}}{r} dr$

Perimeter radius r_0 (meters)	Attenuation length, λ (meters) 100	150	200	350	500	750	1000
300	1.39 E-2	5.12 E-2	1.04 E-1	2.88 E-1	4.64 E-1	7.14 E-1	9.18 E-1
500	1.08 E-3	8.22 E-3	2.41 E-2	1.09 E-1	2.16 E-1	3.93 E-1	5.54 E-1
700	1.09 E-4	1.63 E-3	6.75 E-3	4.79 E-2	1.14 E-1	2.43 E-1	3.70 E-1
1000	3.93 E-6	1.62 E-4	1.11 E-3	1.54 E-2	4.82 E-2	1.27 E-1	2.17 E-1

Table II. Values of the parameter $\frac{M}{2\pi\sigma D_0}$ for different values of λ and r_0.

Perimeter radius r_0 (meters)	Attenuation length, λ (meters) 100	150	200	350	500	750	1000
300	2.51 E+8	3.40 E+8	4.19 E+8	6.10 E+8	7.60 E+8	9.58 E+8	1.11 E+9
500	4.01 E+8	5.76 E+8	7.34 E+8	1.14 E+9	1.47 E+9	1.91 E+9	2.28 E+9
700	5.86 E+8	8.52 E+8	1.09 E+9	1.74 E+9	2.27 E+9	3.03 E+9	3.65 E+9
1000	8.65 E+8	1.27 E+9	1.65 E+9	2.68 E+9	3.56 E+9	4.83 E+9	5.91 E+9

FIGURE CAPTIONS

Fig. 1. The parameter $4\pi r^2 \phi/Q$ as a function of distance measured at several high-energy accelerators.

Fig. 2. Schematic diagram of model used to calculate population dose.

Fig. 3. $\int_{r_0}^{\infty} e^{-r/\lambda}/r \, dr$ as a function of λ for values of r_0 between 300 and 1000 meters.

Fig. 4. Diagram showing the convergence of the integral.

Fig. 5. The parameter $F(r_0, R)$ for $r_0 = 300$ meters with values of λ between 100 and 1000 meters.

Fig. 6. The parameter $M/2\pi\sigma D_0$ as a function of attenuation length.

Fig. 7. The parameter $M/2\pi\sigma D_0$ as a function of perimeter radius.

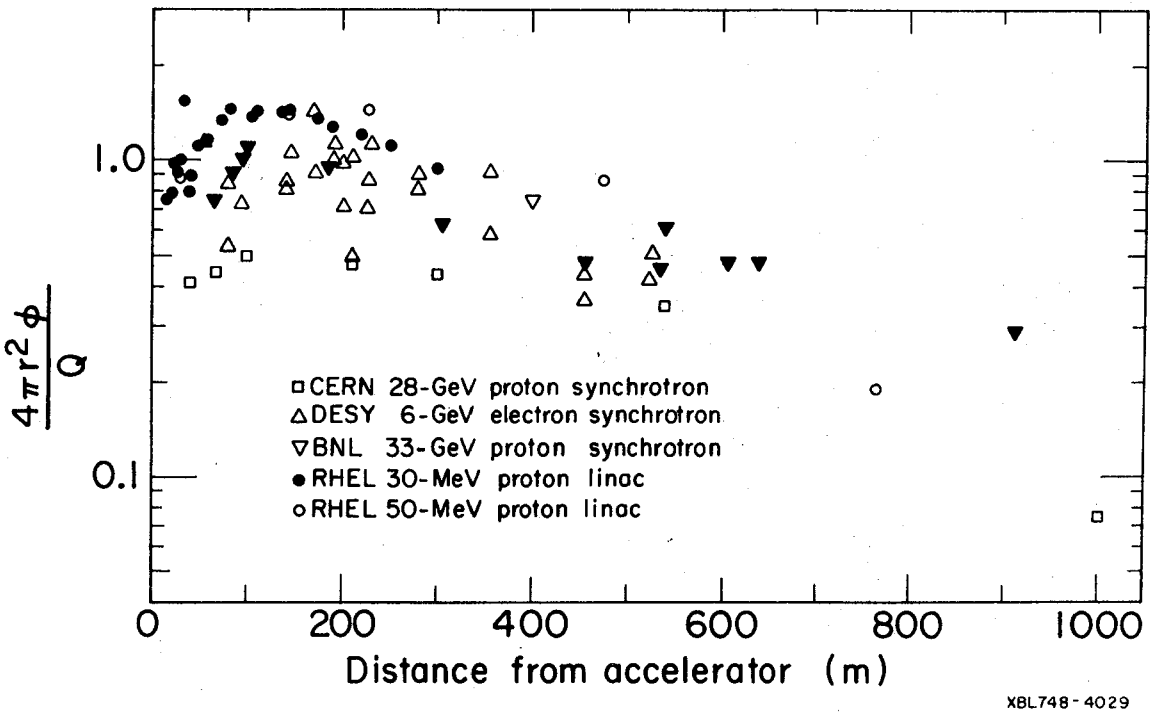
1.0
0.1
$\frac{4\pi r^2 \phi}{Q}$
□ CERN 28-GeV proton synchrotron
△ DESY 6-GeV electron synchrotron
▽ BNL 33-GeV proton synchrotron
● RHEL 30-MeV proton linac
○ RHEL 50-MeV proton linac
0
200
400
600
800
1000
Distance from accelerator (m)
XBL748-4029

Fig. 1

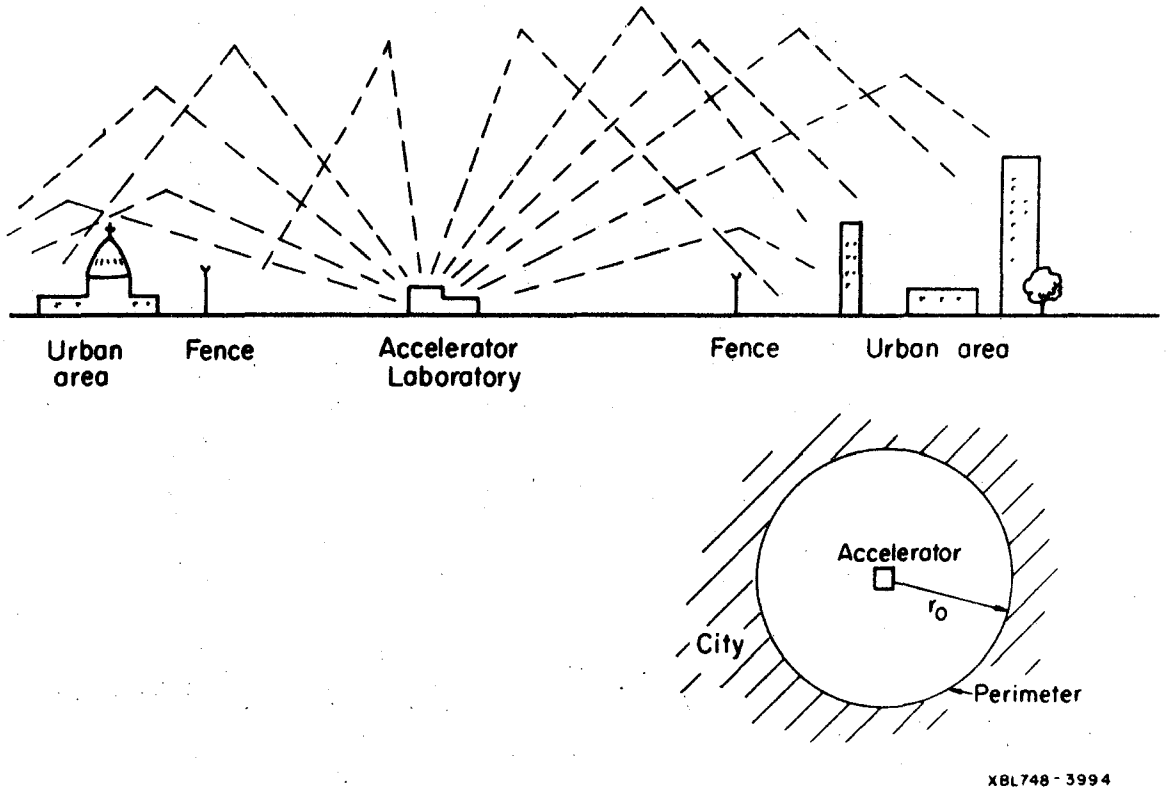
Urban area
Fence
Accelerator Laboratory
Fence
Urban area
Accelerator
r_o
City
Perimeter
XBL748-3994

Fig. 2

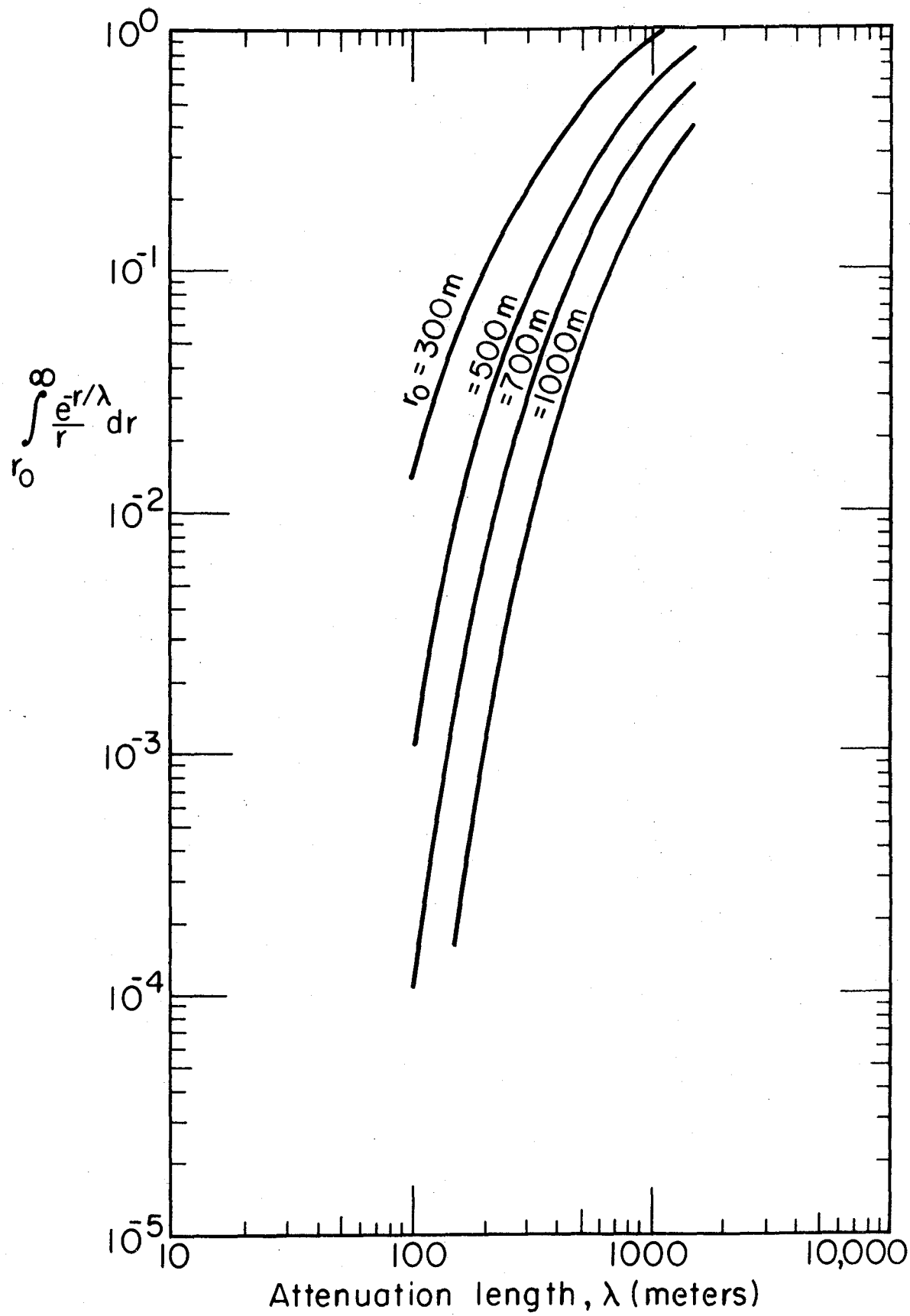

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Fig. 3

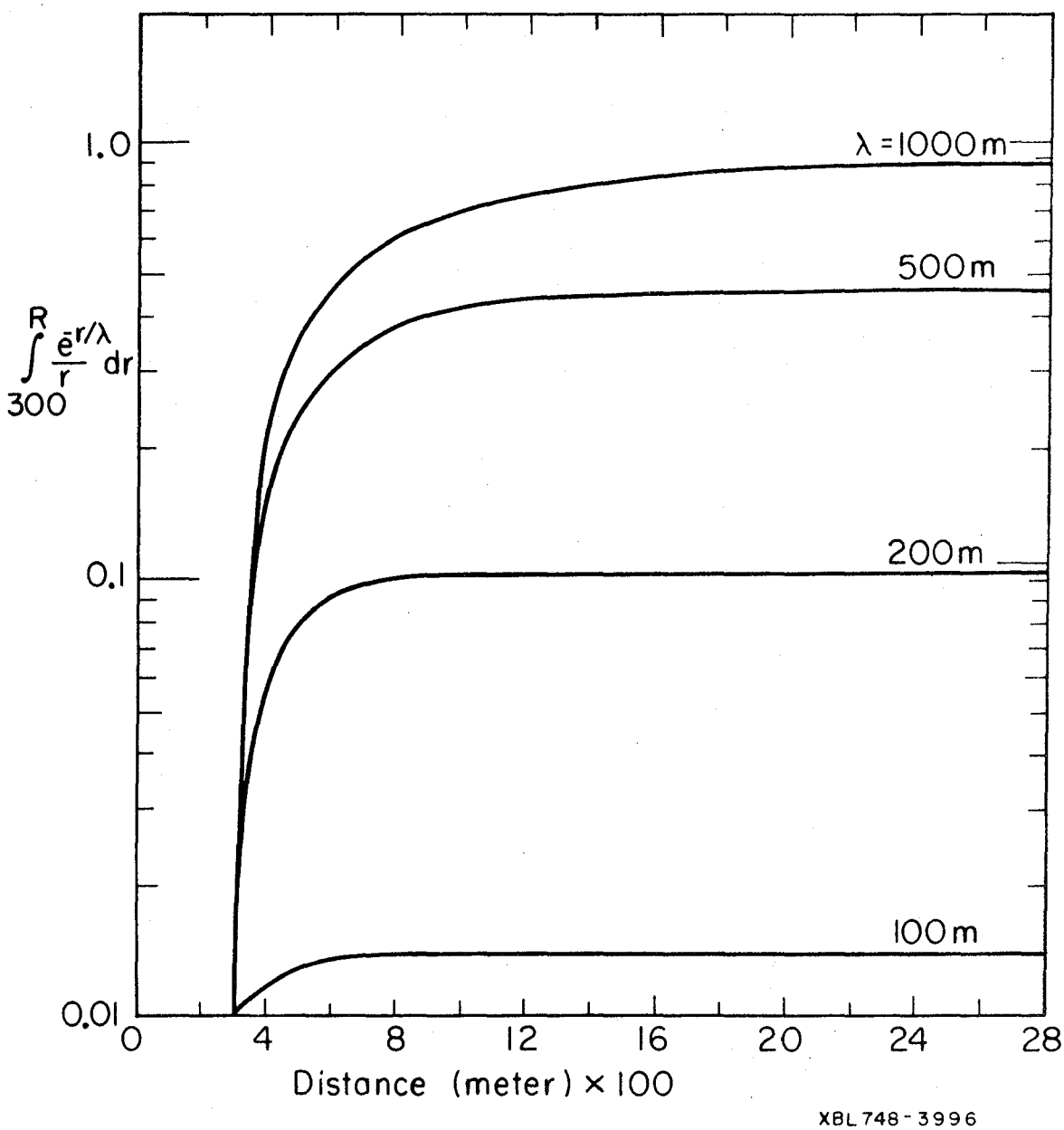
1.0
0.1
0.01
$\int_{300}^{R} \frac{e^{-r/\lambda}}{r} dr$
λ = 1000 m
500 m
200 m
100 m
0
4
8
12
16
20
24
28
Distance (meter) × 100
XBL 748-3996

Fig. 4

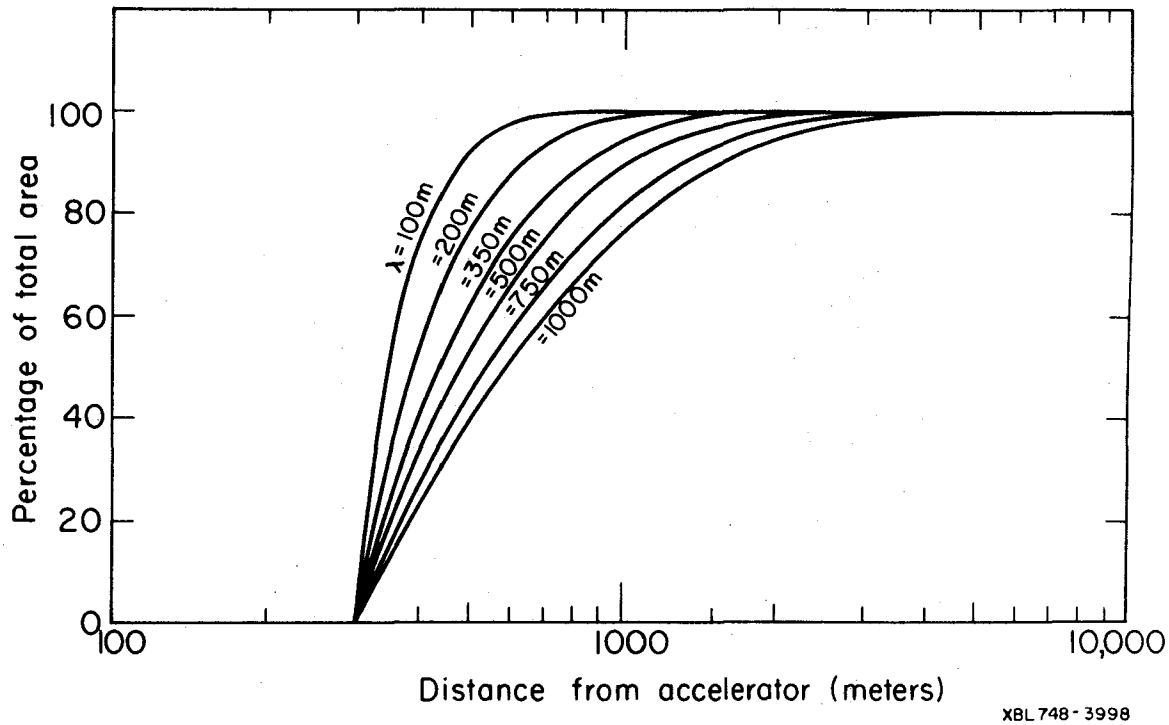
100
80
60
40
20
0
Percentage of total area
λ=100m
=200m
=350m
=500m
=750m
=1000m
100
1000
10,000
Distance from accelerator (meters)
XBL 748-3998

Fig. 5

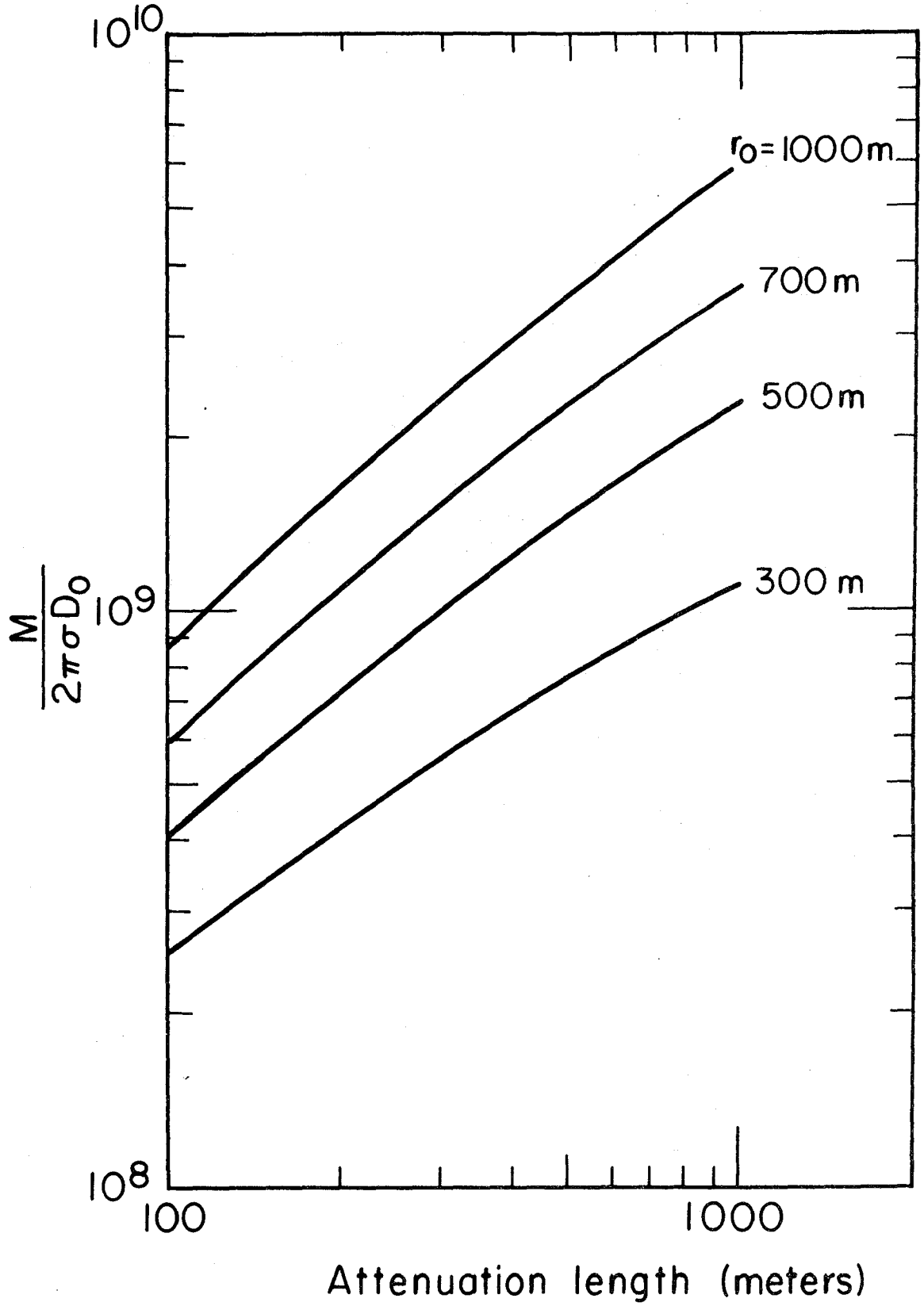

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Fig. 6

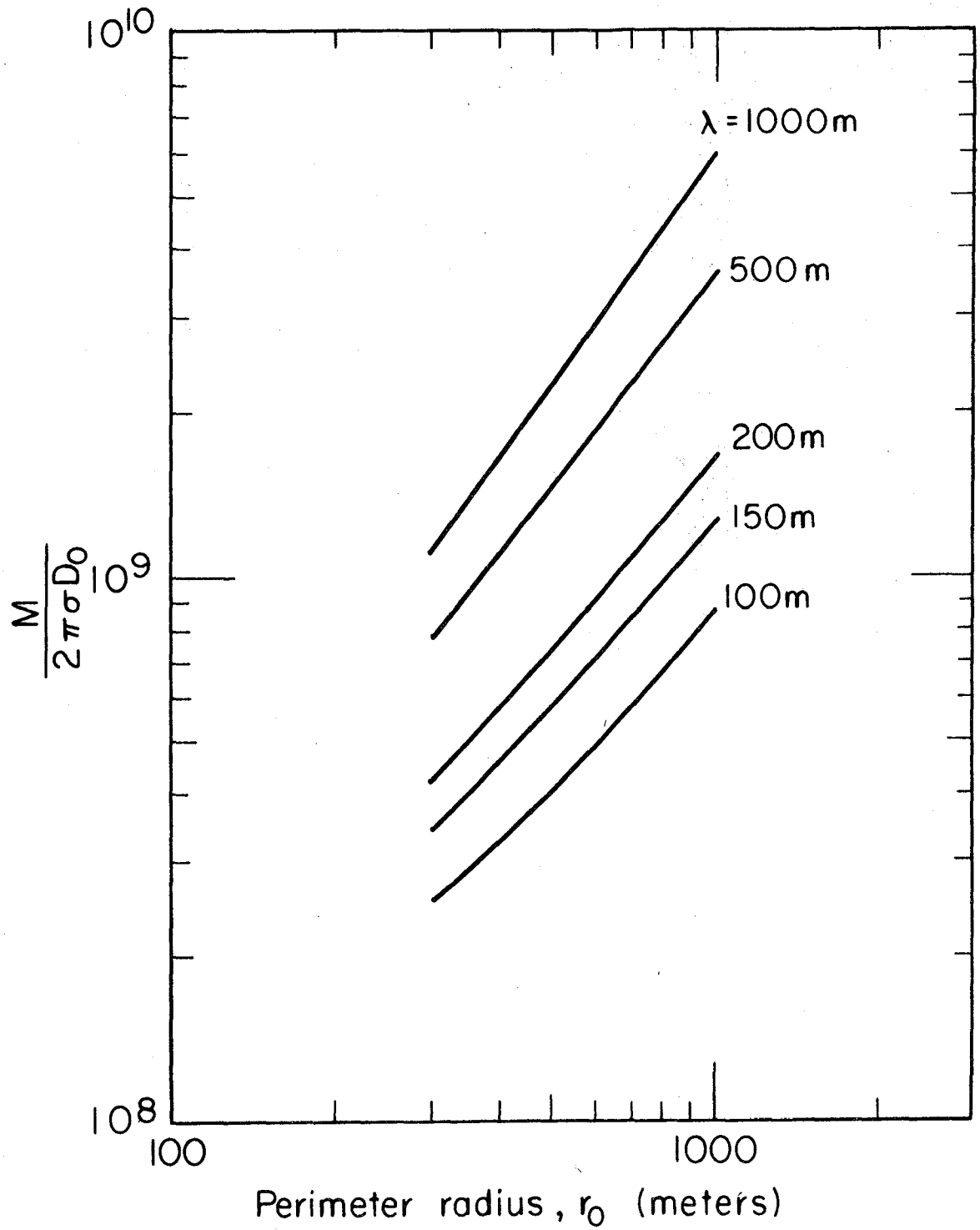

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Fig. 7