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MIGRATION OF RADIONUCLIDES IN FISSURED ROCK - RESULTS OBTAINED FROM A MODEL BASED ON THE CONCEPTS OF HYDRODYNAMIC DISPERSION AND MATRIX DIFFUSION

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A list of other reports published in this series during 1982, is attached at the end of this report. Information on KBS technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26) and 1981 (TR 81-17) is available through SKBF/KBS.

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SUMMARY

The migration of individual radionuclides in a porous medium where hydrodynamic dispersion takes place and where the radionuclides migrate in the matrix of solid medium by diffusion has been calculated for a variety of cases. The cases center around the main case in the second KBS study on spent fuel. The main differences from the KBS study is the inclusion of matrix diffusion and the use of large dispersivities.

The effluent rates of 23 important nuclides are presented as functions of distance and time for various values of important parameters such as rock permeability, diffusion coefficients, release rates, time of first release, fissure spacing and longitudinal dispersion coefficients.

CONTENTS

1 INTRODUCTION

In the Swedish concept, the final repository for high level waste is to be in crystalline rock at 500 m depth (KBS 1978). To this end moderately fissured crystalline rocks such as Swedish granite and gneiss were investigated. The bedrock has a low hydraulic conductivity. Water flow occurs in fractures in the rock. Radionuclides may interact in several ways with the bedrock. Radionuclides may migrate into the micropores of the rock through the mechanism of molecular diffusion (Neretnieks, 1980). Many nuclides will sorb (e.g. adsorption, ion exchange) on the pore surfaces.

A one-dimensional transport model of this process was presented in Rasmuson and Neretnieks (1981). The model considers diffusion of nuclides into microfissures of the rock, linear sorption, and flow and longitudinal dispersion in the bedrock. Using this model, a number of simulations have been performed for estimated ranges of input parameters. The results of these calculations are presented in this report.

2 MATHEMATICAL MODEL

The mathematical model and its analytical solution are presented in detail in Rasmuson and Neretnieks (1980, 1981). A summary is given below.

In the analysis the rock is regarded as a double-porosity medium, consisting of porous blocks separated by fissures. Since the permeability of solid rock is very low, water flow is assumed to take place only in fissures. However, transport of dissolved constituents to the interior of the rock blocks takes place via the mechanism of molecular diffusion.

In mathematical terms, the process is governed by two coupled transport equations, one for the fissures and one for the blocks.

For flow and sorption from the water in the fissures we have:

$$\frac{\partial C_f}{\partial t} + U_f \frac{\partial C_f}{\partial z} - D_L \frac{\partial^2 C_f}{\partial z^2} = - \frac{1-\varepsilon_f}{\varepsilon_f} \left(\frac{\partial \bar{q}}{\partial t} \right) - \lambda_d C_f \qquad (1)$$

The terms in this equation represent accumulation in water in the fissures, convective transport, transport by axial dispersion, accumulation in the blocks, and radioactive decay.

Diffusion into the matrix (assuming spherical blocks) is given by:

$$K \frac{\partial C_p}{\partial t} = \varepsilon_p D_p \left(\frac{\partial^2 C_p}{\partial r^2} + \frac{2}{r} \frac{\partial C_p}{\partial r} \right) - K\lambda_d C_p \qquad (2)$$

In this equation, the terms give sorption on the interior surfaces + accumulation in the pore fluid, radial diffusion in the pore fluid, and radioactive decay.

In a system which is initially free of nuclides, and in which the inlet (z=o) nuclide concentration suddenly is increased to C_o at time t_o, and then decreased to 0 again at $t_o + \Delta t$, the initial and boundary conditions are:

$$C_f(0,t) = \begin{cases} C_o e^{-\lambda_d t} & t_o \leq t \leq t_o + \Delta t \\ 0 & t < t_o,\ t_o + \Delta t < t \end{cases} \qquad (3)$$

$$C_f(\infty,t) = 0 \qquad (4)$$

$$C_f(z,0) = 0 \qquad (5)$$

$$\frac{\partial C_p}{\partial r}(0,z,t) = 0 \qquad (6)$$

$$C_p(r_o,z,t) = C_p|_{r=r_o} \quad \text{given by} \quad \frac{\partial \bar{q}}{\partial t} = \frac{3k_f}{r_o}(C_f - C_p|_{r=r_o}) \qquad (7)$$

$$C_p(r,z,0) = 0 \qquad (8)$$

The simultaneous solution for equations (1) and (2), with the boundary conditions indicated, has been obtained by the Laplace transform method and inversion in the complex plane (Rasmuson and Neretnieks, 1980).

In terms of the following dimensionless parameters:

$$\delta = \frac{3D_p \varepsilon_p}{r_o^2} \frac{z}{mU_f}$$ bed length parameter

$$R = \frac{K}{m}$$ distribution ratio

$$Pe = \frac{zU_f}{D_L}$$ Peclet number

$$y = \frac{2D_p \varepsilon_p}{Kr_o^2} t$$ contact time parameter

$$\nu = \frac{D_p \varepsilon_p}{k_f r_o}$$ film resistance parameter

the concentration in the fissures C_f is obtained as:

$$\frac{C_f}{C_o} = e^{-\lambda_d t}\Big[u(z,t - t_o)\ H(t - t_o) - u(z,t - (t_o + \Delta t))\ H(t - (t_o + \Delta t))\Big] \qquad (9)$$

where:

$$u(z,t) = \frac{1}{2} + \frac{2}{\pi}\int_0^\infty \exp\left(\frac{1}{2}\,Pe - \sqrt{\frac{\sqrt{(z^2x')^2 + (z^2y')^2} + z^2x'}{2}}\right)$$

$$\sin\left(y\,\lambda^2 - \sqrt{\frac{\sqrt{(z^2x')^2 + (z^2y')^2} - z^2x'}{2}}\right)\frac{d\lambda}{\lambda} \qquad (10)$$

and:

$$z^2x' = Pe\,\left(\frac{1}{4}\,Pe + \delta H_1\right) \qquad (11)$$

$$z^2y' = \delta Pe\left(\frac{2}{3}\,\frac{\lambda^2}{R} + H_2\right) \qquad (12)$$

$$H_1(\lambda,\nu) = \frac{H_{D_1} + \nu(H_{D_1}^2 + H_{D_2}^2)}{(1 + \nu H_{D_1})^2 + (\nu H_{D_2})^2} \qquad (13)$$

$$H_2(\lambda,\nu) = \frac{H_{D_2}}{(1 + \nu H_{D_1})^2 + (\nu H_{D_2})^2} \qquad (14)$$

$$H_{D_1}(\lambda) = \lambda\left(\frac{\sinh 2\lambda + \sin 2\lambda}{\cosh 2\lambda - \cos 2\lambda}\right) - 1 \qquad (15)$$

$$H_{D_2}(\lambda) = \lambda\left(\frac{\sinh 2\lambda - \sin 2\lambda}{\cosh 2\lambda - \cos 2\lambda}\right) \qquad (16)$$

It was shown by Rasmuson and Neretnieks (1981) that the film resistance may be neglected ($\nu \sim 0$). Then the functions H_1 and H_2 may be simplified to:

$$H_1(\lambda,\nu) = H_{D_1}(\lambda) \qquad (17)$$

$$H_2(\lambda,\nu) = H_{D_2}(\lambda) \qquad (18)$$

Furthermore, for all radionuclides (except the non-sorbing I-129), the value of the capacity quotient R is so large that its influence is neglible. This is true, except for very short contact times, and is a consequence of the fact that accumulation in the fluid in the fissures may be neglected.

Thus the expression for z^2y' may be simplified to:

$$z^2y' = \delta PeH_2 \qquad (19)$$

Assuming known values of hydraulic conductivity, hydraulic gradient and fissure spacing, fissure width, fissure porosity and average fracture velocity are calculated according to a model proposed by Snow (1968):

$$(2b)^3 = \frac{1}{2}\ \frac{12\mu}{\rho g} \cdot SK_p \qquad (20)$$

$$\varepsilon_f = 3\ (2b/S) \qquad (21)$$

$$U_f\varepsilon_f = K_p i \qquad (22)$$

To model internal diffusion, the cubic blocks used in the hydraulic model (Snow, 1968) are approximated by spheres having the same surface-to-volume ratio as a cubic block. Then:

$$r_o = 0.5\ S \qquad (23)$$

A method for evaluating the infinite integral in equation (10) is given by Rasmuson and Neretnieks (1981).

3 INPUT PARAMETERS

Calculations were made for the 23 nuclides listed in Table 1.

The input parameters in the model are:

Hydraulic conductivity	K_p	L/T
Hydraulic gradient	i	L/L
Constant in equation (20)	$12\mu/\rho g$	LT
Effective diffusivity in pores	$D_p\varepsilon_p$	L^2/T
Fissure spacing	S	L
Half Life	$T_{1/2}$	T
Volume equilibrium constant	K	L^3/L^3
Distance	z	L
Peclet number	Pe	-
Time of canister penetration	t_o	T
Time for dissolution of waste	Δt	T

L = length
T = time

Halflives and mass sorption coefficients were taken from the Nuclear Fuel Safety Project study (KBS, 1978). Mass sorption coefficients are converted to volume sorption coefficients K by multiplying by the rock density $\rho_p = 2700$ kg/m^3.

D_p is the diffusivity in the water in the pores and is related to the diffusivity in pure water by $D_p = D_v\delta_D/\tau^2$. Here δ_D/τ^2 is a geometric factor. The diffusivity of strong electrolytes in water at ambient temperature is $D_v \approx 1\text{-}3\cdot10^{-9}$ m^2/s. The ratio δ_D/τ^2 is expected to be somewhere in the interval 0.15 to 0.6 (Neretnieks, 1980) and the porosity ε_p has been found to be 0.003-0.005 for the granites in this study. Expected values for the effective pore diffusivity $D_p\varepsilon_p$ would then be from $4\cdot10^{-13}$m^2/s to $10\cdot10^{-12}$m^2/s. This was experimentally confirmed by Skagius et. al (1981). In the present study we used $D_p\varepsilon_p = 10^{-12}$ m^2/s.

The hydraulic conductivity used was in the range 10^{-7}-10^{-9} m/s. The low permeability value was observed in several boreholes in granite and gneiss in south Sweden (KBS, 1979). The fissure spacing was taken as 1-50 m. This is substantiated by the bore-hole investigations. In the calculations we used a hydraulic gradient of 0.001 - 0.01 m/m.

The Peclet numbers used in the examples were based on a recent compilation of about 50 field measurements by Lallemand - Barrès and Peaudecerf (1978). The data of Lallemand - Barrès and Peaudecerf have Peclet numbers ranging from 0.5 to 50, with most of the data around 5.

Times for canister penetration of 40, 5000 and 100,000 years have been used. The dissolution times were 30,000 and 500,000 year

Using these data $\sigma = \frac{2D_p\varepsilon_p}{Kr_o^2}$ (coefficient in y) and the dimensionless quantities δ and R may be computed.

The influence of R is in most cases negligible. (See discussion under "Mathematical model".) In these cases, there is no need to determine U_f and ε_f separately, since $mU_f \approx K_p i$, giving:

$$\delta = \frac{3D_p\varepsilon_p}{r_o^2} \frac{z}{K_p i} \qquad (24)$$

It is in the nature of a dimensionless quantity that infinitely many combinations of the individual variables correspond to a specific value of e.g. δ. All combinations of variables which result in a given value of δ yield the same mathematical solution. For example, z = 100 m and $K_p = 10^{-9}$ m/s give the same solution as z = 1000 m and $K_p = 10^{-8}$ m/s. Dimensionless breakthrough curves for the approximate range of variation of δ, R and Pe are given in Rasmuson and Neretnieks (1981).

The time for canister penetration t_o is counted from an arbitrary starting time, for example, the time at which the fuel is taken from the reactor. At that time, the waste contains N_i^o Curies of nuclide i/ton of waste. Since this initial inventory decays with time, the inventory of this nuclide at time t is:

$$N^i = N_o^i \, e^{-\lambda_d^i t} \qquad [Ci/ton] \qquad (25)$$

In this single nuclide migration study, only the part of the nuclide inventory originally present in the waste is considered. The release of nuclides is taken to be proportional to the dissolution rate of the waste. The dissolution rate is assumed to be constant over the whole dissolution time Δt. Accordingly, the release of a nuclide during this dissolution time is:

$$n^i = \frac{N^i}{\Delta t} \qquad [{}^{Ci}/ton,\ year] \qquad (26)$$

or, using equation (25),

$$n^i = \frac{N_o^i \, e^{-\lambda_d^i t}}{\Delta t} \qquad (27)$$

This amount of nuclide corresponds to an initial concentration $C_o^i \, e^{-\lambda_d^i t}$ (boundary condition (3)) in the water flowing through the bedrock. The nuclide transported with the water will be retarded by diffusion into the microfissures of the rock and by subsequent sorption on the intrapore surfaces.

The concentration in the flowing water is observed at a distance z downstream. This concentration is obtained from equation (9). The discharge rate of nuclide i at distance z is:

$$n_z^i = n^i \frac{C_f^i}{C_o^i e^{-\lambda_d^i t}} = \frac{N_o^i}{\Delta t} \cdot \frac{C_f^i}{C_o^i} \left[\frac{\text{Ci}}{\text{ton, year}}\right] \tag{28}$$

The fraction of the original inventory of nuclide i arriving each year at distance z is:

$$\frac{n_z^i}{N_o^i} = \frac{C_f^i}{\Delta t C_o^i} \left[\frac{\text{fraction}}{\text{year}}\right] \tag{29}$$

4 COMPUTED CASES

Data for the different cases are given in Table 2. All (432) possible combinations of the parameters are treated. Actually, computations were made for $t_o = 0$ only. Breakthrough curves for different times of canister penetration are then obtained by multiplying by $\exp(-\lambda_d t_o)$ and plotting the results as a function of $t + t_o$. Since the breakthrough calculations are done for 23 nuclides with 2 curves each (up at t_o and down at $t_o + \Delta t$) but for $t_o = 0$ only, this corresponds to 6 624 breakthrough curves.

The computer program for the model is presented in Appendix. The purpose of each SUBROUTINE is given,as well as a listing of INPUT parameters. A SOURCE listing is also provided.

5 RESULTS

In each case, breakthrough curves for the 23 nuclides at a given distance were calculated versus time. The results for z = 1000 m were plotted (72 diagrams). Figures 1-10 give some typical examples. The resulting curves are shown for all nuclides which have C_f/C_o larger than 10^{-9} at any time.

In Figures 11-34, the maximum points on the breakthrough curves are plotted versus distance. To limit the number of figures, the time of canister penetration is set to 0. The curves for other t_o are then obtained by multiplication by $\exp(-\lambda_d^i t_o)$. These factors are given in Table 3 for t_o = 40, 5000 and 100 000 years. It may be inferred from the Table that some nuclides will decay to insignificant levels within the lifetime of the canister shielding. This is the case for

t_o	Nuclides
40	Cm-242
5000	+ Cs-137, Sr-90, Pu-241, Cm-244, Am-242m, Pu-238
100 000	+ Am-241, Ra-226

On the other hand, some radionuclides, notably Pu-242, Tc-99, Np-237, Cs-135, I-129, and U-238, will not decay to any substantial degree within even 100 000 years.

For these nuclides,the retardation capacity of the bedrock is essential.

Table 4 gives an overview of the cases computed and a reference to figures.

6 DISCUSSION AND CONCLUSIONS

The input parameters may be divided into two categories;

I. Nuclide - independent

K_p, i, $12\mu/\rho g$, S, z, Pe, t_o, Δt

(the last two terms affect only the source boundary condition)

II. Nuclide - dependent

$D_p \varepsilon_p$(?), $T_{1/2}$, K

In most situations, the only significant term is the product $K_p i$ (see discussion in the section "Input parameters Furthermore, the constant $12\mu/\rho g$ (dependent on temperature) affects only the capacity ratio R. It was shown that (except for I-129) R may be taken as ∞. The influence of the input parameters are illustrated in Figures 1-10.

<u>The influence of K_p (or i)</u>. Calculations were made with K_p at two values 10^{-9} and 10^{-7} m/s. The latter case corresponds to a higher water velocity, and thus a shorter time for interaction with the solid rock. Except for I-129, K_p will affect only the dimensionless parameter δ (equation (24)). An increase in K_p

by two orders of magnitude will cause a decrease in δ of the same order. The effect on the breakthrough curve is shown in diagrams given by Rasmuson and Neretnieks (1981). Since, for most cases, only the product $K_p i$ is important, the same results are obtained for a variation in the hydraulic gradient i.

Different values of δ produce breakthrough curves for various degrees of saturation of the solid rock. Low values of δ imply that only the outer surface of the rock is utilized for sorption. For this situation ($\delta \lesssim 10^{-2}$), it was shown that C_f/C_o is a function o y/δ^2, and not of y and δ independently. High values of δ, on the other hand, indicate full penetration of the blocks and, C_f/C_o is a function of y/δ ($\delta \gtrsim 10^2$) (Rasmuson and Neretnieks, 1981).

Figures 3 and 10 differ only in the value used for the hydraulic conductivity K_p. We get $\delta = 1.2 \cdot 10^3$ and $1.2 \cdot 10^1$ respectively. The high value of δ implies almost complete penetration of the rock matrix. The low value is an intermediate case. From the breakthrough calculations, referred to above, it may be inferred that the time scale for the highly sorbing nuclides will change by a factor of ≈ 5000. For Cs-135 and U-238, the first arrival is roughly that much earlier in Figure 10. Note that the same reasoning does not hold for the non-sorbing I-129. Because of the earlier breakthrough, a large number of nuclides will not have time to decay for $K_p = 10^{-7}$ m/s.

The influence of S

Two values of S were used S = 1 and 50 m. The fracture spacing primarily affects the size of the rock blocks (equation (23)). In principal, it will also have an effect on the water velocity and the fracture porosity. From equations (20) - (22), we get $U_f \propto S^{2/3}$ and $\varepsilon_f \propto S^{-2/3}$. However, from equation (24), we see again that only the product $U_f \varepsilon_f = K_p i$ (independent of S) is important.

Thus a higher value of r_o gives less surface for contact with the moving water. In terms of the dimensionless quantities, we find that both δ and y are proportional to r_o^{-2}.

In Figures 1-3 and 4-6, the cases differ only in values of S, 1 and 50 m. We have:

Figures 1-3: $\delta = 1.2 \cdot 10^3$, $\sigma = 8 \cdot 10^{-12}$/K

Figures 4-6: $\delta = 0.48$, $\sigma = 3.2 \cdot 10^{-15}$/K

The influence of Pe

As shown in Rasmuson and Neretnieks (1981), the impact of longitudinal dispersion is severe. This is further illustrated in Figures 1-3 and Figures 4-6, in which the Peclet number in each group decreases as ∞, 5.0 and 0.5.

The influence of t_o is shown in Figures 6-8, which are for the same case with three different values of canister penetration time: 40, 5000 and 100 000 years. The figures again illustrate that, for many radionuclides, the proposed engineering barriers are ineffective in preventing the arrival of significant concentrations at the site boundaries. Comparing Figure 6 and Figure 8, we find that only the Pu-240 peak has disappeared below the base-line.

The influence of Δt is illustrated in Figures 5 and 9. As Δt increases the breakthrough concentration usually decreases. This is not always true, since $u(z,t) - u(z,t - \Delta t)\ H(t - \Delta t)$ (a function of Δt) may increase faster than Δt.

For example, consider the curve for I-129 at $t = 2.83 \cdot 10^5$ years. We have

Figure 5 ($\Delta t = 3 \cdot 10^4$ years): $2.13 \cdot 10^{-11}$ fraction of inventory/year

Figure 9 ($\Delta t = 5 \cdot 10^5$ years): $1.98 \cdot 10^{-6}$ fraction of inventory/year

However, as shown in Figures 11-34, the peak concentrations for all the calculated cases are lower for $\Delta t = 5 \cdot 10^5$ years.

The points discussed above are further illustrated in Figures 11-34, in which the peak heights versus distance are given. The impacts of the nuclide-dependent quantities $T_{1/2}$ and K are clearly shown. A good example of the influence of $T_{1/2}$ for constant K is given by the isotopes of Pu: Pu-238, Pu-239, Pu-240, Pu-241 and Pu-242. For an example of the influence of K when $T_{1/2}$ is (approximately) constant see Tc-99 and U-234.

Nuclide	Half life, years	K, m^3/m^3
Sr-90	28.1	43
Tc-99	2.12×10^5	135
I-129	1.7×10^7	0.005
Cs-135	3.0×10^6	170
Cs-137	30.2	170
Ra-226	1,600	1,350
Th-229	7,340	6,480
Th-230	80,000	6,480
U-233	1.62×10^5	3,240
U-234	2.47×10^5	3.240
U-238	4.51×10^9	3,240
Np-237	2.14×10^6	3,240
Pu-238	86	810
Pu-239	24,400	810
Pu-240	6,580	810
Pu-241	13.2	810
Pu-242	3.79×10^5	810
Am-241	458	86,000
Am-242m	152	86,000
Am-243	7,370	86,000
Cm-242	0.5	43,000
Cm-244	17.6	43,000
Cm-245	9,300	43,000

Table 1: Nuclides considered in this study. No decay chains are accounted for.

hydraulic conductivity	K_p	10^{-9}; 10^{-7}	m/s
hydraulic gradient	i	0.01	m/m
constant (kinematic viscosity 10^{-6} m^2/s)	$12\mu/\rho g$	1.223242×10^{-6}	ms
$D_p \varepsilon_p$		10^{-12}	m^2/s
fissure spacing	S	1; 50	m
Peclet number	Pe	∞; 5.0; 0.5	–
distance from repository	z	30; 100; 300; 1000; 3000; 10,000	m
leach time	Δt	30,000; 500,000	years
time of canister breakdown	t_o	40; 5000; 100,000	years

Table 2: Values of the input parameters

Nuclide	Half life years	Time of canister breakdown (years)		
		40	5000	100,000
Sr-90	28.1	$3.7281 \cdot 10^{-1}$	0	
Tc-99	$2.12 \cdot 10^{5}$	$9.9987 \cdot 10^{-1}$	$9.8379 \cdot 10^{-1}$	$7.2112 \cdot 10^{-1}$
I-129	$1.7 \cdot 10^{7}$	1.0	$9.9980 \cdot 10^{-1}$	$9.9593 \cdot 10^{-1}$
Cs-135	$3.0 \cdot 10^{6}$	$9.9999 \cdot 10^{-1}$	$9.9885 \cdot 10^{-1}$	$9.7716 \cdot 10^{-1}$
Cs-137	30.2	$3.9929 \cdot 10^{-1}$	0	
Ra-226	$1.6 \cdot 10^{3}$	$9.8282 \cdot 10^{-1}$	$1.1463 \cdot 10^{-1}$	0
Th-229	$7.34 \cdot 10^{3}$	$9.9623 \cdot 10^{-1}$	$6.2365 \cdot 10^{-1}$	$7.9209 \cdot 10^{-5}$
Th-230	$8.0 \cdot 10^{4}$	$9.9965 \cdot 10^{-1}$	$9.5760 \cdot 10^{-1}$	$4.2045 \cdot 10^{-1}$
U-233	$1.62 \cdot 10^{5}$	$9.9983 \cdot 10^{-1}$	$9.7883 \cdot 10^{-1}$	$6.5190 \cdot 10^{-1}$
U-234	$2.47 \cdot 10^{5}$	$9.9989 \cdot 10^{-1}$	$9.8607 \cdot 10^{-1}$	$7.5531 \cdot 10^{-1}$
U-238	$4.51 \cdot 10^{9}$	1.0	1.0	$9.9998 \cdot 10^{-1}$
Np-237	$2.14 \cdot 10^{6}$	$9.9999 \cdot 10^{-1}$	$9.9838 \cdot 10^{-1}$	$9.6813 \cdot 10^{-1}$
Pu-238	86	$7.2441 \cdot 10^{-1}$	0	
Pu-239	$2.44 \cdot 10^{4}$	$9.9886 \cdot 10^{-1}$	$8.6759 \cdot 10^{-1}$	$5.8381 \cdot 10^{-2}$
Pu-240	$6.58 \cdot 10^{3}$	$9.9580 \cdot 10^{-1}$	$5.9055 \cdot 10^{-1}$	$2.6612 \cdot 10^{-5}$
Pu-241	13.2	$1.2240 \cdot 10^{-1}$	0	
Pu-242	$3.79 \cdot 10^{5}$	$9.9993 \cdot 10^{-1}$	$9.9090 \cdot 10^{-1}$	$8.3286 \cdot 10^{-1}$
Am-241	$4.58 \cdot 10^{2}$	$9.4126 \cdot 10^{-1}$	$5.1719 \cdot 10^{-4}$	0
Am-242m	$1.52 \cdot 10^{2}$	$8.3326 \cdot 10^{-1}$	$1.2523 \cdot 10^{-10}$	0
Am-243	$7.37 \cdot 10^{3}$	$9.9625 \cdot 10^{-1}$	$6.2485 \cdot 10^{-1}$	$8.2913 \cdot 10^{-5}$
Cm-242	0.5	0		
Cm-244	17.6	$2.0694 \cdot 10^{-1}$	0	
Cm-245	$9.3 \cdot 10^{3}$	$9.9702 \cdot 10^{-1}$	$6.8890 \cdot 10^{-1}$	$5.7959 \cdot 10^{-4}$

Table 3: The decay of original nuclide content (=1.0) for three different times of first canister penetration.

t_o yrs	40	40	$5000/10^5$	40	40
Δt yrs	$3 \cdot 10^4$	$3 \cdot 10^4$	$3 \cdot 10^4$	$5 \cdot 10^5$	$3 \cdot 10^4$
K_p m/s	10^{-9}	10^{-9}	10^{-9}	10^{-9}	10^{-7}
S m	1	50	50	50	1
Pe –	∞/5/0.5	∞/5/0.5	0.5	5	5
Fig	1/2/3	4/5/6	7/8	9	10

t_o yrs	0	0	0	0	0	0	0	0
Δt yrs	$3 \cdot 10^4$	$5 \cdot 10^5$	$3 \cdot 10^4$	$5 \cdot 10^5$	$3 \cdot 10^4$	$5 \cdot 10^5$	$3 \cdot 10^4$	$5 \cdot 10^5$
K_p m/s	10^{-9}	10^{-9}	10^{-9}	10^{-9}	10^{-7}	10^{-7}	10^{-7}	10^{-7}
S m	1	1	50	50	1	1	50	50
Pe –	∞/5/0.5	∞/5/0.5	∞/5/0.5	∞/5/0.5	∞/5/0.5	∞/5/0.5	∞/5/0.5	∞/5/0.5
Fig	11/12/13	14/15/16	17/18/19	20/21/22	23/24/25	26/27/28	29/30/31	32/33/34

Table 4. Overview of the cases computed with reference to the figures.

NOTATION

b	half width of fissure	m
C	concentration in liquid	mol/m^3
C_f	concentration in liquid in fissures	mol/m^3
C_p	concentration in liquid in microfissures	mol/m^3
C_o	inlet concentration in the liquid	mol/m^3
D_L	longitudinal dispersion coefficient	m^2/s
D_p	diffusivity in water in pores	m^2/s
D_v	diffusivity in water	m^2/s
g	gravitational constant	m/s^2
H	Heaviside´s step function	
H_1	see equation (13)	
H_2	see equation (14)	
H_{D_1}	see equation (15)	
H_{D_2}	see equation (16)	
i	hydraulic gradient	m/m
K	volume equilibrium constant	m^3/m^3
K_p	hydraulic conductivity	m/s
k_f	mass transfer coefficient	m/s
m	$= \frac{\varepsilon_f}{1 - \varepsilon_f}$	
N	inventory of nuclide	Ci/ton
N_o	original inventory of nuclide	Ci/ton
n	release of nuclide	Ci/ton, year
n_z	discharge rate of nuclide at distance z	Ci/ton, year
Pe	$= \frac{zU_f}{D_L}$, Peclet number	
$\bar{q}$	volume averaged concentration in blocks	mol/m^3

R	$= \frac{K}{m}$, distribution ratio	
r	radial distance from center of spherical particle	m
r_o	effective spherical radius	m
S	fissure spacing	m
$T_{1/2}$	half life	s
t	time	s
t_o	time of canister penetration	s
Δt	time for dissolution of waste	s
U_f	average velocity of water in fissures	m/s
u	see equation (10)	
x'	see equation (11)	
y	$= \frac{2D_p \varepsilon_p}{K r_o^2} t$, contact time parameter	
y'	see equation (12)	
z	distance in flow direction	m

<u>Greek letters</u>

δ	$= \frac{3D_p \varepsilon_p}{r_o^2} \frac{z}{mU_f}$, bed length parameter	
δ_D	constrictivity for diffusion	
ε_f	porosity of fissures	
ε_p	porosity of rock matrix	
λ	variable of integration	
λ_d	decay constant of radionuclide	s^{-1}
μ	viscosity of water	Ns/m^2
ν	$= \frac{D_p \varepsilon_p}{k_f r_o}$	
ρ	density of water	kg/m^3
σ	$= \frac{2D_p \varepsilon_p}{K r_o^2}$	s^{-1}
τ	tortuosity	

Superscript

i	nuclide i

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APPENDIX

Computer program

PROGRAM NUCDIF1

FUNCTION F(LAM)

calculates the value of the integrand

$$f(\lambda) = \exp\ (\mathrm{arg1})\ \sin\ (\mathrm{arg2})/\lambda$$

$$\mathrm{arg1} = \tfrac{1}{2}\ Pe - \sqrt{\frac{\sqrt{(z^2\,x')^2 + (z^2y')^2} + z^2x'}{2}}$$

$$\mathrm{arg2} = y\lambda^2 - \sqrt{\frac{\sqrt{(z^2x') + (z^2y')^2} - z^2x'}{2}}$$

$$z^2x' = Pe\ (\tfrac{1}{4}\ Pe + \delta H_{D_1})$$

$$z^2y' = \delta Pe\ (2/3\ \frac{\lambda^2}{R} + H_{D_2})$$

LAM variable of integration

SUBROUTINE HBOL (LAM, HD1, HD2)

evaluates:

$$H_{D_1} = \lambda \left(\frac{\sinh 2\lambda + \sin 2\lambda}{\cosh 2\lambda - \cos 2\lambda}\right) - 1$$

$$H_{D_2} = \lambda \left(\frac{\sinh 2\lambda - \sin 2\lambda}{\cosh 2\lambda - \cos 2\lambda}\right)$$

LAM = variable of integration

HD1 = H_{D_1} ; HD2 = H_{D_2}

SUBROUTINE DHBOL (LAM, DHD1, DHD2)

evaluates the derivatives of H_{D_1} and H_{D_2}:

LAM = variable of integration

DHD1 = $dH_{D_1}/d\lambda$

DHD2 = $dH_{D_2}/d\lambda$

SUBROUTINE ROOT (LAMROT, NROT)

calculates the n:th zero of sin(arg2)

LAMROT = value of λ giving arg2 = $n \cdot \pi$

NROT = n

SUBROUTINE AVERAGE (LAMROT, NROT, SUM)

computation of integral by averaging of the partial sums.

LAMROT = value of λ giving arg2 = $n \cdot \pi$

NROT = n

SUM = value of integral

SUBROUTINE UPPER (B, TRUMAX)

calculates upper limit of infinite integral

B = upper limit

$e^{-TRUMAX}$ ~ truncation error

INPUT

PERM	hydraulic conductivity	m/s
GRADI	hydraulic gradient	m/m
CONST	constant 12μ/ρg	ms
DPORE	$D_p \varepsilon_p$	m^2/s
SPACNG	fissure spacing	m
TLEAK	leach time	years
NAME	name of radionuclide e.g.	Cs-137
TNUCL	half life	years
KVOL	volume equilibrium constant	m^3/m^3
Z	distance	m
PECL	Peclet number	

```
      PROGRAM NUCDIF1(INPUT,OUTPUT,TAPE10,TAPE5=INPUT,TAPE6=OUTPUT)
C     ************************************************************
C     THIS PROGRAM CALCULATES 1-D MIGRATION OF SINGLE RADIONUCLIDES
C     IN FISSURED ROCK INCLUDING LONGITUDINAL DISPERSION AND DIFFU-
C     SION INTO SPHERICAL ROCK BLOCKS.  AN ANALYTICAL SOLUTION BY
C     RASMUSON A.  AND I.  NERETNIEKS(J.  GEOPHYSICAL RESEARCH
C     86,3749-3758(1981))IS USED.
C
C     THE FILE TAPE10 IS CONCERNED WITH STORAGE OF OUTPUT DATA.
C     ACCORDINGLY ALL WRITE(10,X) STATEMENTS MAY BE OMITTED AS WELL
C     AS THE VECTORS UVEC,TVEC AND MAP.  IN THE INTEGRATION THE
C     ROUTINE QNC7 FROM THE SANDIA MATHEMATICAL PROGRAM LIBRARY IS
C     USED.  THIS LIBRARY ROUTINE MAY BE REPLACED BY ANY STANDARD
C     INTEGRATION ROUTINE.
C     ************************************************************
      COMMON/COM1/DELTA,PECL,R,Y
      DIMENSION UVEC(100),TVEC(100),MAP(2,30)
      REAL KVOL,M,LAMROT
      EXTERNAL F
      DATA MAP/30*(10H          ,0)/
      CALL ERXSET(50,0)
      IPRINT=-1
      READ(5,*)PERM,GRADI,CONST,DPORE,SPACNG,TLEAK
      READ(5,220)((MAP(I,J),I=1,2),J=1,23)
  220 FORMAT(1X,10(A10,I3))
      WRITE(10,200)PERM,GRADI,CONST,DPORE,SPACNG,TLEAK
      WRITE(10,220)((MAP(I,J),I=1,2),J=1,30)
      TLEAK=TLEAK*3.15E07
      B1=0.5*SPACNG
      B2=(0.5*CONST*SPACNG*PERM)**0.3333333333
      FI=3.*(B2/SPACNG)
      V=(PERM*GRADI)/FI
      M=FI/(1.-FI)
      DLPRIM=1.8*SPACNG*V
C
C
C     LOOP FOR DIFFERENT NUCLIDES
C
      DO 4000 I4=1,23
      READ(5,135)NAME
      READ(5,*)TNUCL,KVOL
      ALAM=0.69314718/TNUCL
      DS=DPORE/KVOL
      GAM=(3.*DS*KVOL)/(B1**2.)
      SIG=(2.*DS)/(B1**2.)
      R=KVOL/M
      WRITE(6,105)
      WRITE(6,105)
      WRITE(6,100)PERM,GRADI,CONST,DPORE,SPACNG,TLEAK/3.15E07
      WRITE(6,140)B1,V,FI,DS
      WRITE(6,145)NAME,TNUCL,KVOL
      WRITE(10,200)PERM,GRADI,CONST,DPORE,SPACNG,TLEAK/3.15E07
      WRITE(10,205)NAME,TNUCL,KVOL
  100 FORMAT(2X,*KP=*,E13.7,2X,*I=*,E13.7,2X,*CONST=*,
     1E13.7,2X,*DPORE=*,E13.7,2X,*SPACNG=*,E13.7,
     12X,*TLEAK=*,E13.7,2X,*YEARS*)
```

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```
  135 FORMAT(A1Ø)
  14Ø FORMAT(2X,*RADIUS=*,E13.7,2X,*FRACTURE VELOCITY=*,
     1E13.7,2X,*FRACTURE POROSITY=*,E13.7,2X,*APPARENT DIFFUSIVITY=*,
     1E13.7)
  145 FORMAT(2X,*NUCLIDE=*,A1Ø,2X,*HALFLIFE=*,E13.7,2X,*YEARS*,
     13X,*KVOL=*,E13.7)
  2ØØ FORMAT(6(1X,E13.7))
  2Ø5 FORMAT(1X,A1Ø,2(1X,E13.7))
C
C
C     LOOP FOR DIFFERENT DISTANCES
C
      DO 3ØØØ I1=1,6
      IF(I1.EQ.1)Z=3Ø.
      IF(I1.EQ.2)Z=1ØØ.
      IF(I1.EQ.3)Z=3ØØ.
      IF(I1.EQ.4)Z=1ØØØ.
      IF(I1.EQ.5)Z=3ØØØ.
      IF(I1.EQ.6)Z=1ØØØØ.
      DELTA=(GAM*Z)/(M*V)
      TW=Z/V
      PART=DS*KVOL**2.*TW/B2**2.
      RF=1.Ø+5.Ø*PART
      TMEAN=TW*RF
      R1PERC=1.Ø+PART/3.35
      T1PERC=TW*R1PERC
      WRITE(6,1Ø5)
      WRITE(6,1Ø5)
      WRITE(6,1Ø5)
  1Ø5 FORMAT(2X)
      WRITE(6,11Ø)TW/3.15EØ7,T1PERC/3.15EØ7,TMEAN/3.15EØ7
  11Ø FORMAT(2X,*TW=*,E13.7,2X,*T1PERC=*,E13.7,2X,*TMEAN=*,E13.7,
     13X,*YEARS*)
C
C
C     LOOP FOR DIFFERENT PECLET NUMBERS
C
C
      DO 2ØØØ I2=2,3
      NTIMES=Ø
      TRUMAX=4Ø.
      L=-1
      L1=-1
      IF(I2.EQ.1)PECL=1.ØE98
      IF(I2.EQ.2)PECL=5.Ø
      IF(I2.EQ.3)PECL=Ø.5
      IF(PECL.EQ.1.ØE98)GOTO 4Ø
      DL=(Z*V)/PECL
      GOTO 5Ø
   4Ø DL=Ø.Ø
   5Ø WRITE(6,1Ø5)
      WRITE(6,1Ø5)
      WRITE(6,115)Z,DL,DELTA,PECL,R
      WRITE(6,1Ø5)
  115 FORMAT(2X,*Z=*,E13.7,2X,*DL=*,E13.7,5X,*DELTA=*,E13.7,2X,
     1*PECL=*,E13.7,2X,*R=*,E13.7)
```

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```
      WRITE(6,120)
  120 FORMAT(1H ,8X,*U*,13X,*T(YEARS)*,14X,*T(SEC)*,13X,*Y*,17X,
     1*UPPER LIMIT*,6X,*ABS TRUNC ERR*,5X,*REL TRUNC ERR*)
C
C
C     LOOP FOR DIFFERENT TIMES
C
C
      DO 1000 I3=1,50
      ILEAK=-1
      T=1.8**(I3-26.)*TMEAN/20.
      IF(I3.GE.26)T=T+TW
      TREL=(T/3.15E07)*ALAM
      IF(TREL.GT.100.)GOTO 500
   35 Y=SIG*T
      IF(T.GT.TW)GOTO 60
      IF(DL.GT.0.)GOTO 60
      U=0.
      TRUNC=0.
      RELTRU=0.
      B=0.
      GOTO 20
   60 CONTINUE
C     ***********************************************************
C
C     INTEGRATION
C
C     ***********************************************************
      IF(L.EQ.1)GOTO 10
      IF(L1.EQ.1)GOTO 30
C     CALCULATION OF UPPER LIMIT OF INTEGRAL
      IF(DL.EQ.0.)GOTO 70
      AA1=0.5*PECL+TRUMAX
      AA2=DELTA*PECL
      B=(2.*AA1*(SQRT(2.*AA1**2.-0.25*PECL**2.+AA2)-AA1))/AA2
      GOTO 85
   70 B=(TRUMAX+DELTA)/DELTA
      GOTO 90
   85 IF(KVOL.GT.0.5)GOTO 90
      CALL UPPER(B,TRUMAX)
      GOTO 95
   90 IF(B.LT.4.5)CALL UPPER(B,TRUMAX)
C     CALCULATION OF TRUNCATION ERROR
   95 TRUNC=(2.*EXP(-TRUMAX))/3.1415926536
      L1=1
   30 ERR=1.0E-10
      CALL QNC7(F,0.,B,ERR,ANS,IERR)
      U=0.5+(2./3.1415926536)*ANS
      IF(U.NE.0.)GOTO 5
      RELTRU=0.
      GOTO 15
    5 RELTRU=TRUNC/U
   15 CONTINUE
      IF(IERR.EQ.1)GOTO 20
C
C
```

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```
C      INTEGRATION BY SPECIAL TECHNIQUE
C
C
   10 NROT=10
      CALL ROOT(LAMROT,NROT)
      B=LAMROT
      ERR=1.0E-08
C     EVALUATION OF INTEGRAL
      CALL QNC7(F,0.,B,ERR,ANS,IERR)
      IF(IPRINT.EQ.1)WRITE(6,130)ANS
  130 FORMAT(2X,*ANS=*,E13.7)
      CALL AVERAGE(LAMROT,NROT,SUM)
      U=0.5+(2./3.1415926536)*(ANS+SUM)
      L=1
C     CALCULATION OF TRUNCATION ERROR
      TRUNC=(2./3.1415926536)*1.0E-08
      RELTRU=TRUNC/U
C     ******************************************************
C
C     FINITE LEACHING TIME
C
   20 IF(ILEAK.EQ.1)GOTO 45
      IF(T.LT.TLEAK)GOTO 25
      U1=U
      T1=T
      Y1=Y
      B11=B
      TRUNC1=TRUNC
      RELTRU1=RELTRU
      T=T-TLEAK
      ILEAK=1
      GOTO 35
   45 U=U1-U
      T=T1
      Y=Y1
      B=B11
      TRUNC=TRUNC1
      RELTRU=RELTRU1
C
C
C     OUTPUT
C
   25 U=U*EXP(-TREL)
      UVEC(I3)=U
      TVEC(I3)=T/3.15E07
      NTIMES=I3
      WRITE(6,125)U,T/3.15E07,T,Y,B,TRUNC,RELTRU
  125 FORMAT(2X,E13.7,5X,E13.7,8X,E13.7,5X,E13.7,
     18X,E13.7,5X,E13.7,5X,E13.7)
 1000 CONTINUE
  500 WRITE(10,210)Z,PECL,NTIMES
      IF(NTIMES.EQ.0)GOTO 2000
      WRITE(10,215)(UVEC(I),TVEC(I),I=1,NTIMES)
  210 FORMAT(2(1X,E13.7),1X,I5)
  215 FORMAT(9(1X,E13.7))
 2000 CONTINUE
```

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```
3000 CONTINUE
     ENDFILE 10
4000 CONTINUE
     END
```

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```
      FUNCTION F(LAM)
      COMMON/COM1/DELTA,PECL,R,Y
      REAL LAM
      IF(LAM.EQ.Ø.)GOTO 1Ø
      CALL HBOL(LAM,HD1,HD2)
      IF(PECL.EQ.1.ØE+98)GOTO 5Ø
      AA1=PECL*(Ø.25*PECL+DELTA*HD1)
      AA2=DELTA*PECL*((2.*LAM**2.)/(3.*R)+HD2)
      AA5=AA2/AA1
      IF(AA5.LT.1.ØE-Ø3)GOTO 3Ø
      RR=SQRT(AA1**2.+AA2**2.)
      AA3=RR+AA1
      AA4=RR-AA1
      GOTO 4Ø
   3Ø AA3=AA1*(2.+Ø.5*AA5**2.-Ø.125*AA5**4.)
      AA4=AA1*(Ø.5*AA5**2.-Ø.125*AA5**4.)
   4Ø ARG1=Ø.5*PECL-SQRT((AA3)/2.)
      ARG2=Y*LAM**2.-SQRT((AA4)/2.)
      GOTO 6Ø
   5Ø ARG1=-DELTA*HD1
      ARG2=(Y-(2.*DELTA)/(3.*R))*LAM**2.-DELTA*HD2
   6Ø F=(EXP(ARG1)*SIN(ARG2))/LAM
      GOTO 2Ø
   1Ø F=Ø.Ø
   2Ø RETURN
      END
```

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```
      SUBROUTINE HBOL(LAM,HD1,HD2)
      REAL LAM
      IF(LAM.LT.Ø.Ø1)GOTO 1Ø
      IF(LAM.GT.15.)GOTO 2Ø
      HN=LAM/(COSH(2.*LAM)-COS(2.*LAM))
      HD1=HN*(SINH(2.*LAM)+SIN(2.*LAM))-1.
      HD2=HN*(SINH(2.*LAM)-SIN(2.*LAM))
      GOTO 3Ø
   1Ø HD1=(4.*LAM**4.)/45.
      HD2=(2.*LAM**2.)/3.
      GOTO 3Ø
   2Ø HD1=LAM-1.
      HD2=LAM
   3Ø RETURN
      END
```

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```
      SUBROUTINE DHBOL(LAM,DHD1,DHD2)
      REAL LAM
      IF(LAM.LT.Ø.Ø1)GOTO 1Ø
      IF(LAM.GT.15.)GOTO 2Ø
      HN=LAM/(COSH(2.*LAM)-COS(2.*LAM))
      HD1=HN*(SINH(2.*LAM)+SIN(2.*LAM))-1.
      HD2=HN*(SINH(2.*LAM)-SIN(2.*LAM))
      DHD1=(HD1+1.-4.*HN**2.*SINH(2.*LAM)*SIN(2.*LAM))/LAM
      DHD2=(HD2+4.*HN**2.*(1.-COSH(2.*LAM)*COS(2.*LAM)))/LAM
      GOTO 3Ø
   1Ø DHD1=(16.*LAM**3.)/45.
      DHD2=(4.*LAM)/3.
      GOTO 3Ø
   2Ø DHD1=1.
      DHD2=1.
   3Ø RETURN
      END
```

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```
      SUBROUTINE ROOT(LAMROT,NROT)
      COMMON/COM1/DELTA,PECL,R,Y
      REAL LAMROT
      IPRINT=-1
C     INITIAL VALUE OF ITERATION
      IF(PECL.EQ.1.ØE+98)Y=Y-(2.*DELTA)/(3.*R)
      AA1=DELTA/(2.*Y)
      AA2=3.1415926536/Y
      XØ=AA1+SQRT(AA1**2.+NROT*AA2)
      IF(XØ.LT.4.5)XØ=1.Ø
      IF(XØ.EQ.1.)GOTO 4Ø
      IF(PECL.NE.1.ØE+98)GOTO 4Ø
      X1=XØ
      GOTO 3Ø
   4Ø CONTINUE
C     NEWTON RAPHSON ITERATION
      DO 1ØØØ I=1,2Ø
      CALL HBOL(XØ,HD1,HD2)
      CALL DHBOL(XØ,DHD1,DHD2)
      IF(PECL.EQ.1.ØE+98)GOTO 5Ø
      AA3=PECL*(Ø.25*PECL+DELTA*HD1)
      AA4=DELTA*PECL*((2.*XØ**2.)/(3.*R)+HD2)
      AA5=AA4/AA3
      RR=SQRT(AA3**2.+AA4**2.)
      IF(AA5.LT.1.ØE-Ø3)GOTO 1Ø
      AA6=RR-AA3
      GOTO 2Ø
   1Ø AA6=AA3*(Ø.5*AA5**2.-Ø.125*AA5**4.)
   2Ø F=Y*XØ**2.-SQRT(AA6/2.)-NROT*3.1415926536
      DAA3=DELTA*PECL*DHD1
      DAA4=DELTA*PECL*((4.*XØ)/(3.*R)+DHD2)
      FPRIM=2.*Y*XØ-((AA3*DAA3+AA4*DAA4)/RR-DAA3)/(4.*SQRT(AA6/2.))
      GOTO 6Ø
   5Ø F=Y*XØ**2.-DELTA*HD2-NROT*3.1415926536
      FPRIM=2.*Y*XØ-DELTA*DHD2
   6Ø DELTA1=F/FPRIM
      X1=XØ-DELTA1
      IF(IPRINT.EQ.1)WRITE(6,1ØØ)I,XØ
  1ØØ FORMAT(2X,I2,3X,E13.7)
      IF(ABS(X1-XØ).LT.1.ØE-Ø5)GOTO 3Ø
      IF(I.EQ.2Ø)WRITE(6,1Ø5)
  1Ø5 FORMAT(2X,*THE ACCURACY OF LAMROT WAS NOT ACHIEVED*)
      XØ=X1
 1ØØØ CONTINUE
   3Ø LAMROT=X1
      IF(PECL.EQ.1.ØE+98)Y=Y+(2.*DELTA)/(3.*R)
      RETURN
      END
```

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```
      SUBROUTINE AVERAGE(LAMROT,NROT,SUM)
      REAL LAMROT
      EXTERNAL F
      DIMENSION S(100)
      IPRINT=-1
      ERR=1.0E-08
      IMAX=20
C     CALCULATION OF PARTIAL SUMS
      A=LAMROT
      NROT=NROT+1
      CALL ROOT(LAMROT,NROT)
      B=LAMROT
      IF(IPRINT.EQ.1)WRITE(6,100)A,B
  100 FORMAT(2X,*A=*,E13.7,*B=*,E13.7)
      CALL QNC7(F,A,B,ERR,ANS,IERR)
      S(1)=ANS
      DO 1000 I=2,IMAX
      NROT=NROT+1
      A=B
      CALL ROOT(LAMROT,NROT)
      B=LAMROT
      ANS1=ANS
      CALL QNC7(F,A,B,ERR,ANS,IERR)
      S(I)=S(I-1)+ANS
      IF(ANS1*ANS.GT.0.)WRITE(6,125)
      IF(ABS(ANS)-ABS(ANS1).GT.0.)WRITE(6,130)
  125 FORMAT(2X,*AVERAGE  SUBSEQUENT TERMS IN SERIES *,
     1*ARE NOT OF DIFFERENT SIGN*)
  130 FORMAT(2X,*AVERAGE  ABSOLUTE VALUES OF TERMS IN *,
     1*SERIES ARE NOT DECREASING*)
      IF(IPRINT.EQ.1)WRITE(6,105)A,B,ANS
  105 FORMAT(2X,*A=*,E13.7,*B=*,E13.7,*ANS=*,E13.7)
 1000 CONTINUE
      IF(IPRINT.NE.1)GOTO 10
      DO 2000 I=1,IMAX
      WRITE(6,110)S(I)
  110 FORMAT(2X,E13.7)
 2000 CONTINUE
   10 CONTINUE
C     REPEATED AVERAGING
      K=IMAX-1
   50 DO 3000 I=1,K
      S(I)=(S(I)+S(I+1))/2.
      IF(ABS(S(I)-S(I+1)).LT.1.0E-08)GOTO 20
 3000 CONTINUE
      IF(IPRINT.NE.1)GOTO 30
      WRITE(6,115)IMAX-K
  115 FORMAT(2X,*ITER=*,I2)
      DO 4000 I=1,K
      WRITE(6,110)S(I)
 4000 CONTINUE
   30 K=K-1
      IF(K.EQ.0)GOTO 40
      GOTO 50
   40 WRITE(6,120)
  120 FORMAT(2X,*THE ACCURACY OF SUM WAS NOT ACHIEVED*)
```

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```
      GOTO 6Ø
   2Ø SUM=S(I)
   6Ø CONTINUE
      RETURN
      END
```

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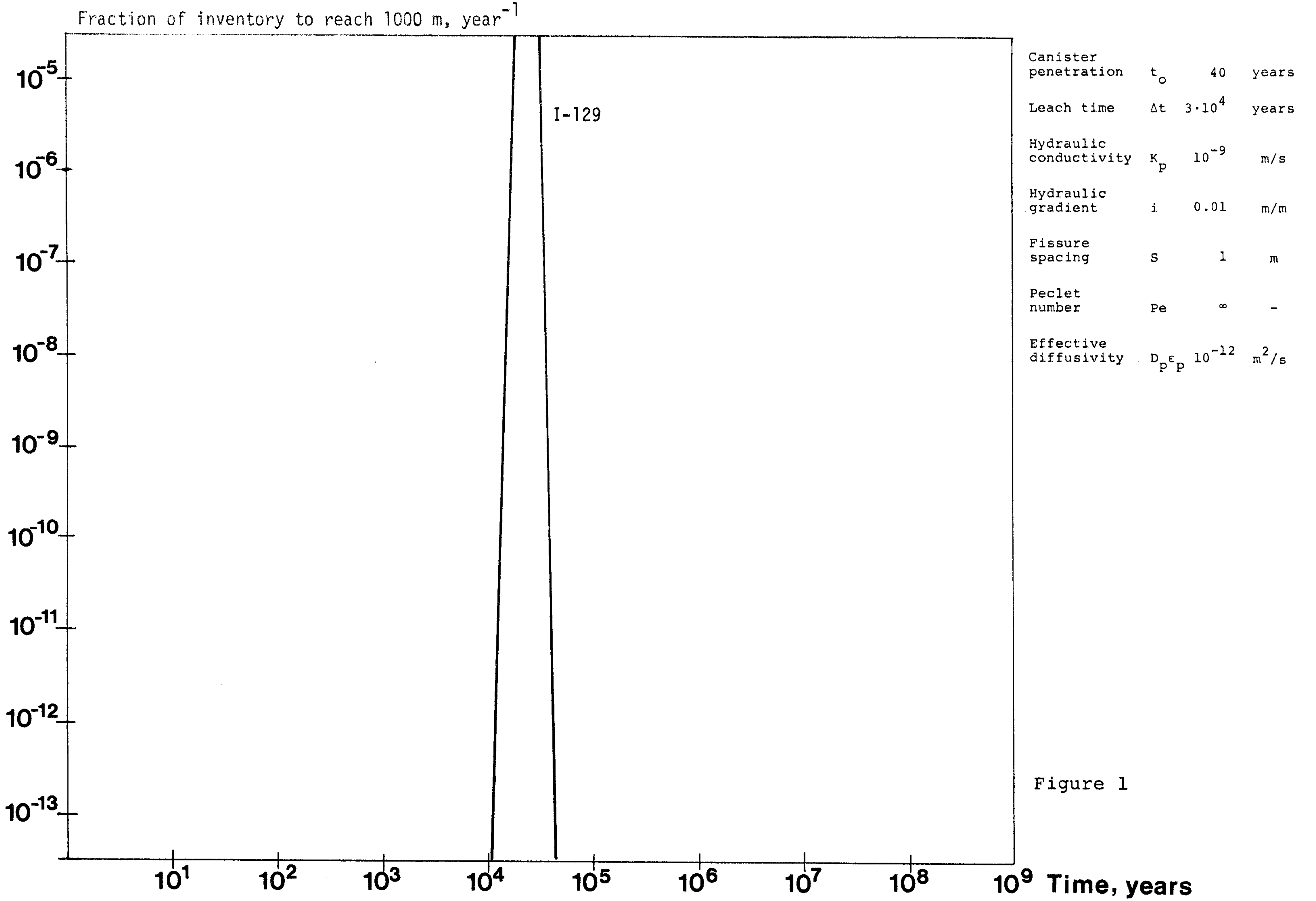
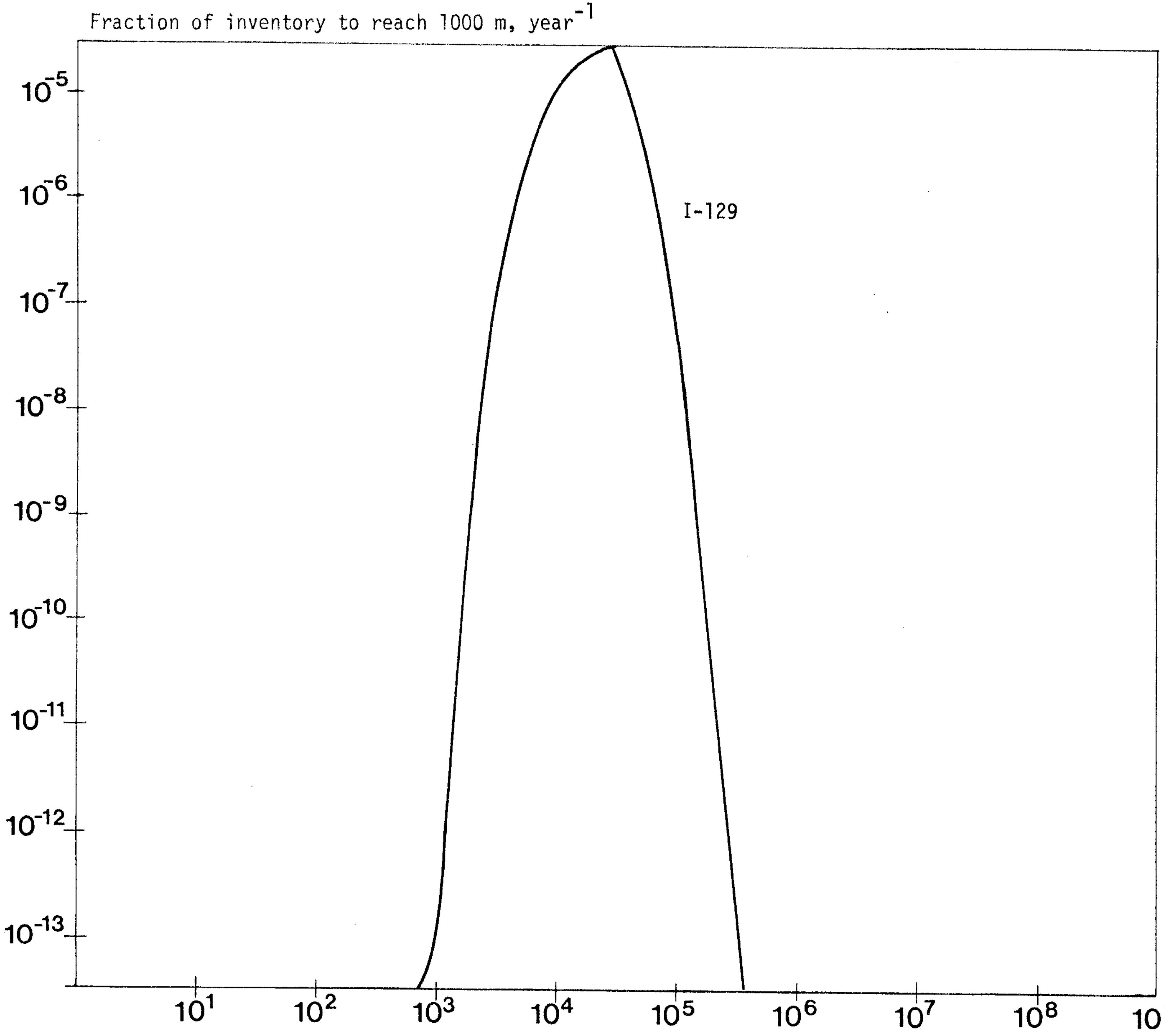
```
      SUBROUTINE UPPER(B,TRUMAX)
      COMMON/COM1/DELTA,PECL,R,Y
      XØ=B
C     NEWTON RAPHSON ITERATION
      DO 1ØØØ I=1,2Ø
      CALL HBOL(XØ,HD1,HD2)
      CALL DHBOL(XØ,DHD1,DHD2)
      IF(PECL.EQ.1.ØE+98)GOTO 2Ø
      AA1=PECL*(Ø.25*PECL+DELTA*HD1)
      AA2=DELTA*PECL*((2.*XØ**2.)/(3.*R)+HD2)
      RR=SQRT(AA1**2.+AA2**2.)
      AA3=RR+AA1
      F=Ø.5*PECL+TRUMAX-SQRT(AA3/2.)
      DAA1=DELTA*PECL*DHD1
      DAA2=DELTA*PECL*((4.*XØ)/(3.*R)+DHD2)
      FPRIM=-((AA1*DAA1+AA2*DAA2)/RR+DAA1)/(4.*SQRT(AA3/2.))
      GOTO 3Ø
   2Ø F=DELTA*HD1-TRUMAX
      FPRIM=DELTA*DHD1
   3Ø DELTA1=F/FPRIM
      X1=XØ-DELTA1
      IF(ABS(DELTA1/X1).LT.1.ØE-Ø5)GOTO 1Ø
      IF(I.EQ.2Ø)WRITE(6,1ØØ)
  1ØØ FORMAT(2X,
     1*THE ACCURACY OF UPPER INTEGRATION LIMIT WAS NOT ACHIEVED*)
      XØ=X1
 1ØØØ CONTINUE
   1Ø B=X1
      RETURN
      END
```



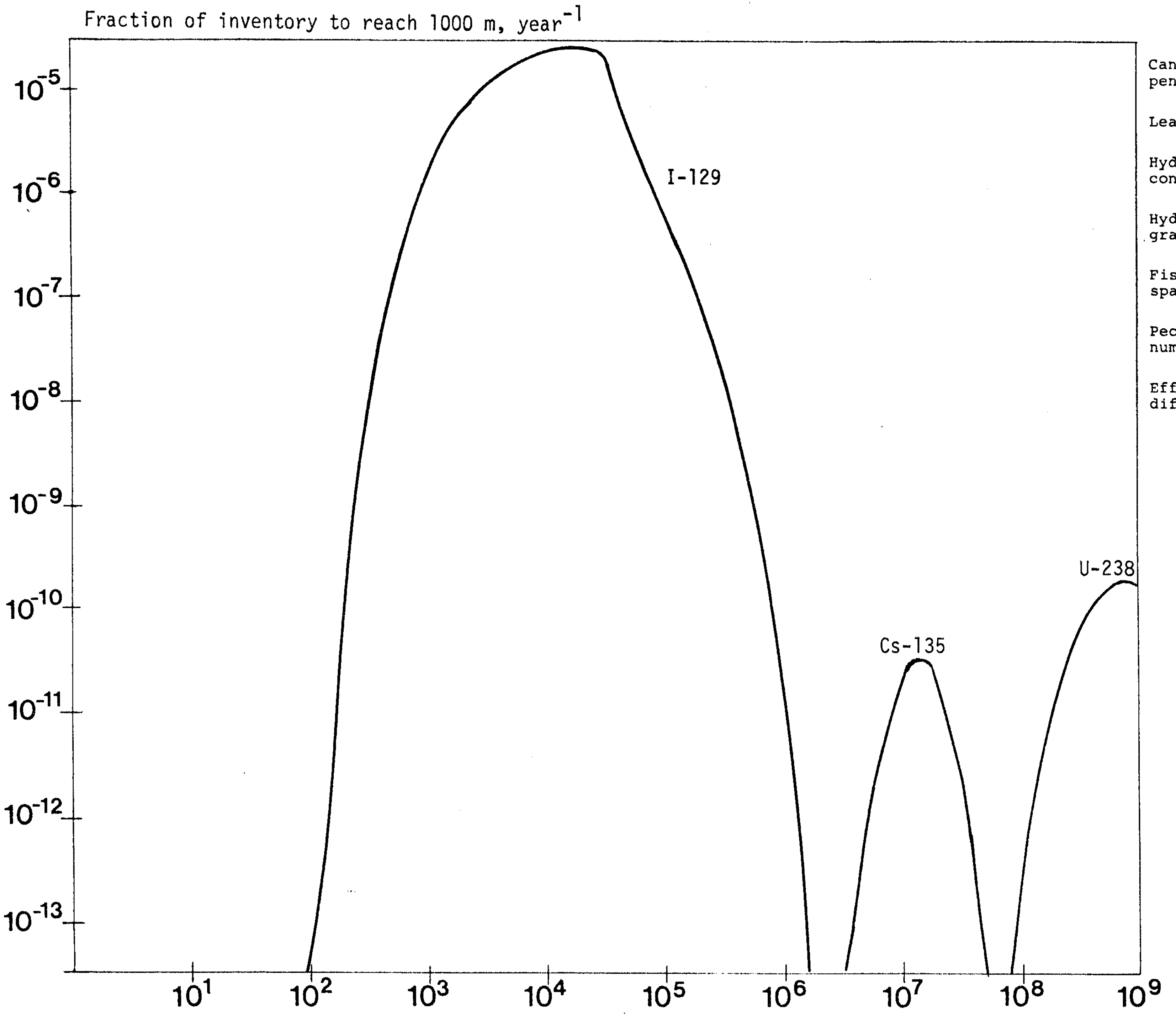
Fraction of inventory to reach 1000 m, year^{-1}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
I-129
10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9}
Time, years
Canister penetration t_o 40 years
Leach time Δt $3 \cdot 10^{4}$ years
Hydraulic conductivity K_p 10^{-9} m/s
Hydraulic gradient i 0.01 m/m
Fissure spacing S 1 m
Peclet number Pe ∞ -
Effective diffusivity $D_p \varepsilon_p$ 10^{-12} m^2/s

Figure 1



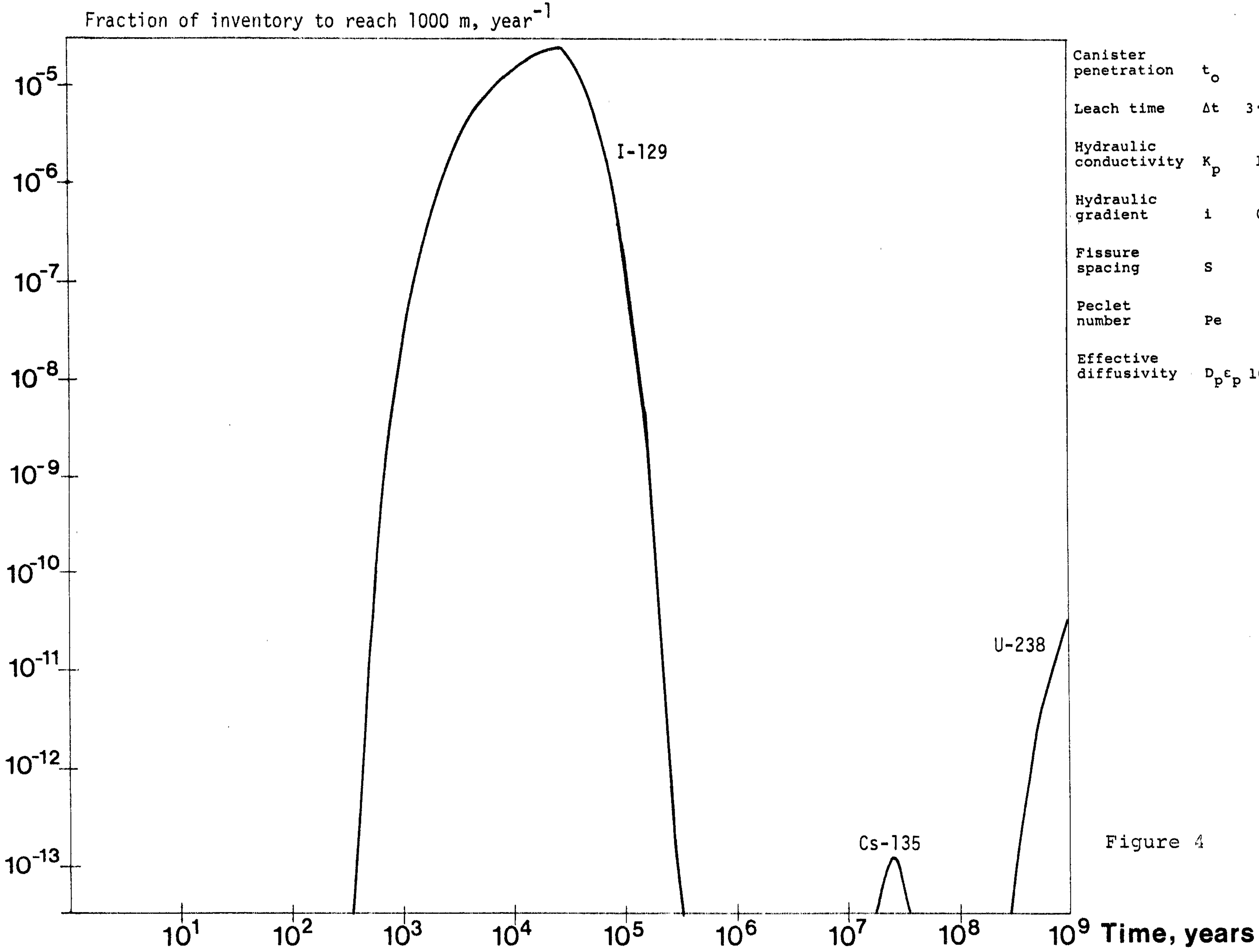
Canister penetration	t_o	40	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Peclet number	Pe	5.0	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 2



Canister penetration	t_o	40	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Peclet number	Pe	0.5	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 3



Canister penetration	t_o	40	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	50	m
Peclet number	Pe	∞	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 4

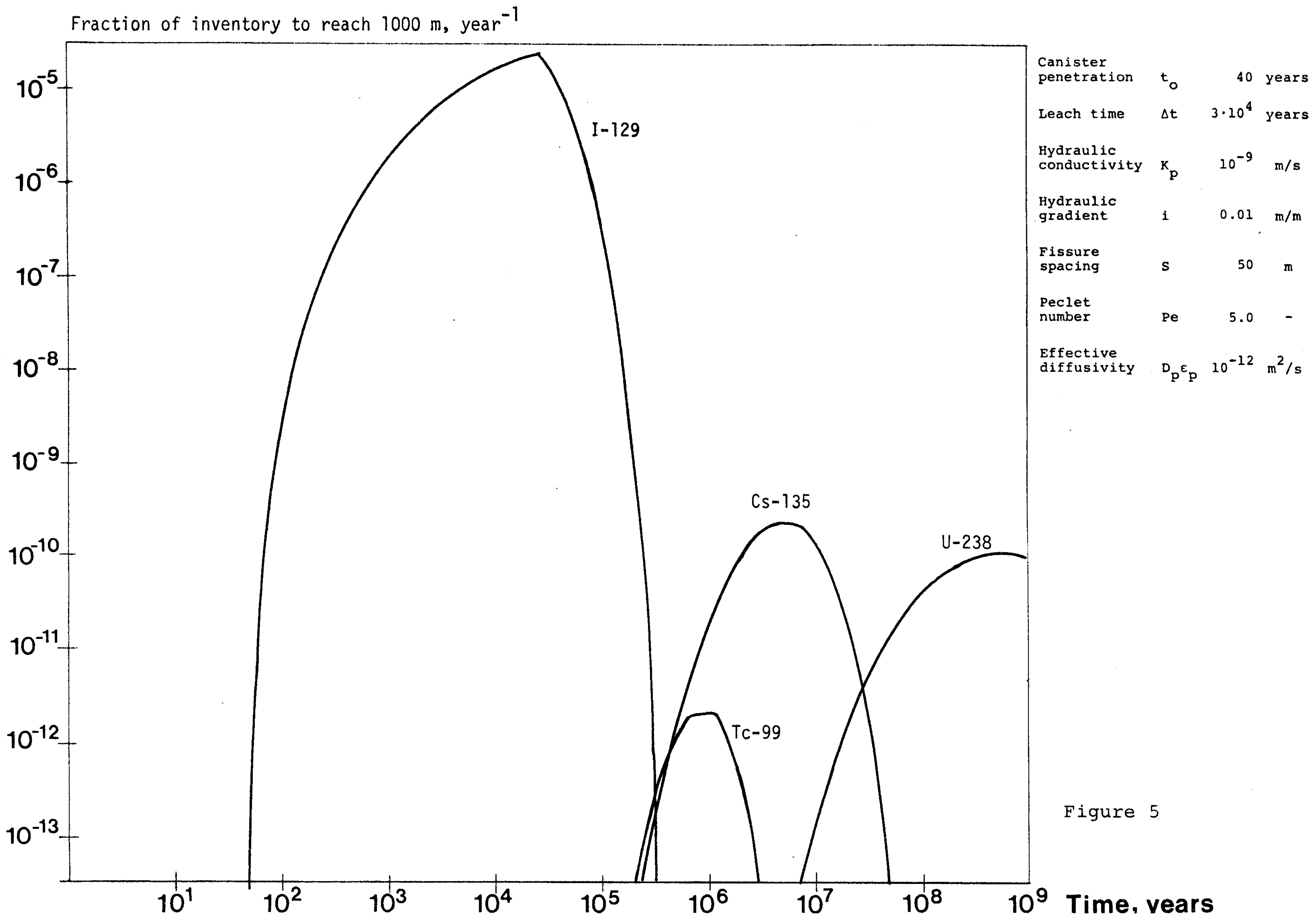
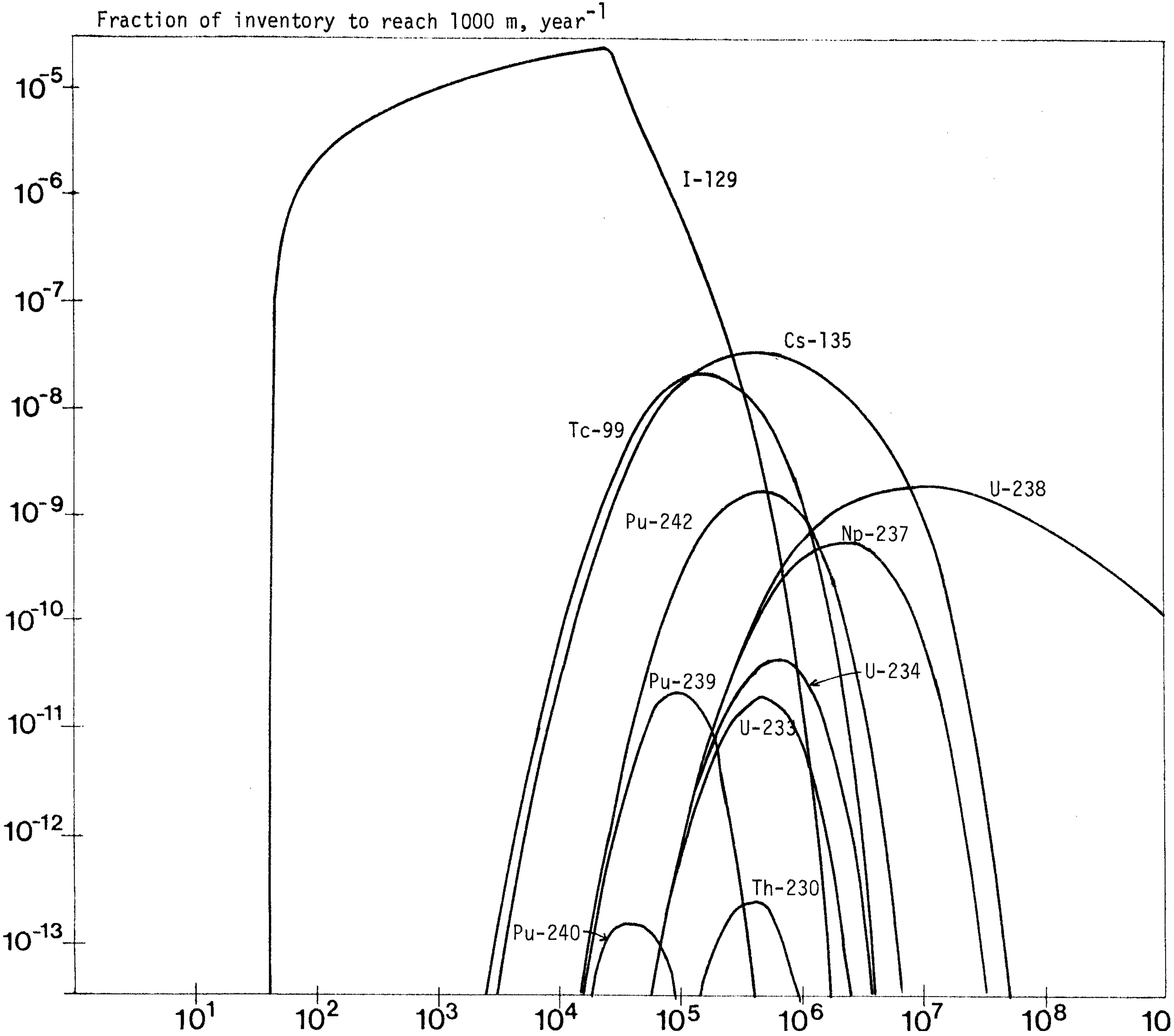
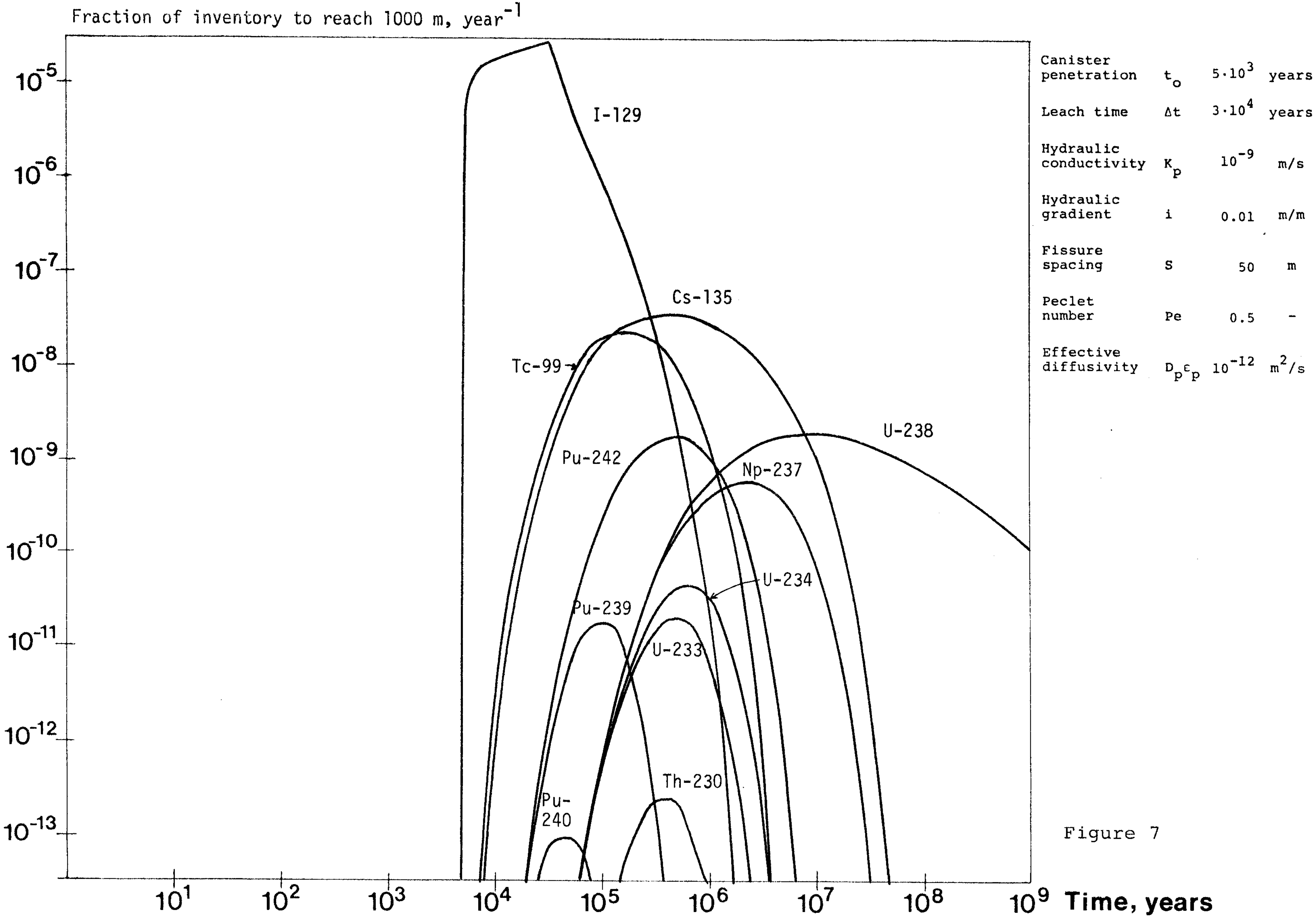

Fraction of inventory to reach 1000 m, year^{-1}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
I-129
Cs-135
U-238
Tc-99
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
Time, years
Canister penetration t_o 40 years
Leach time Δt $3 \cdot 10^{4}$ years
Hydraulic conductivity K_p 10^{-9} m/s
Hydraulic gradient i 0.01 m/m
Fissure spacing S 50 m
Peclet number Pe 5.0 -
Effective diffusivity $D_p \varepsilon_p$ 10^{-12} m^2/s

Figure 5



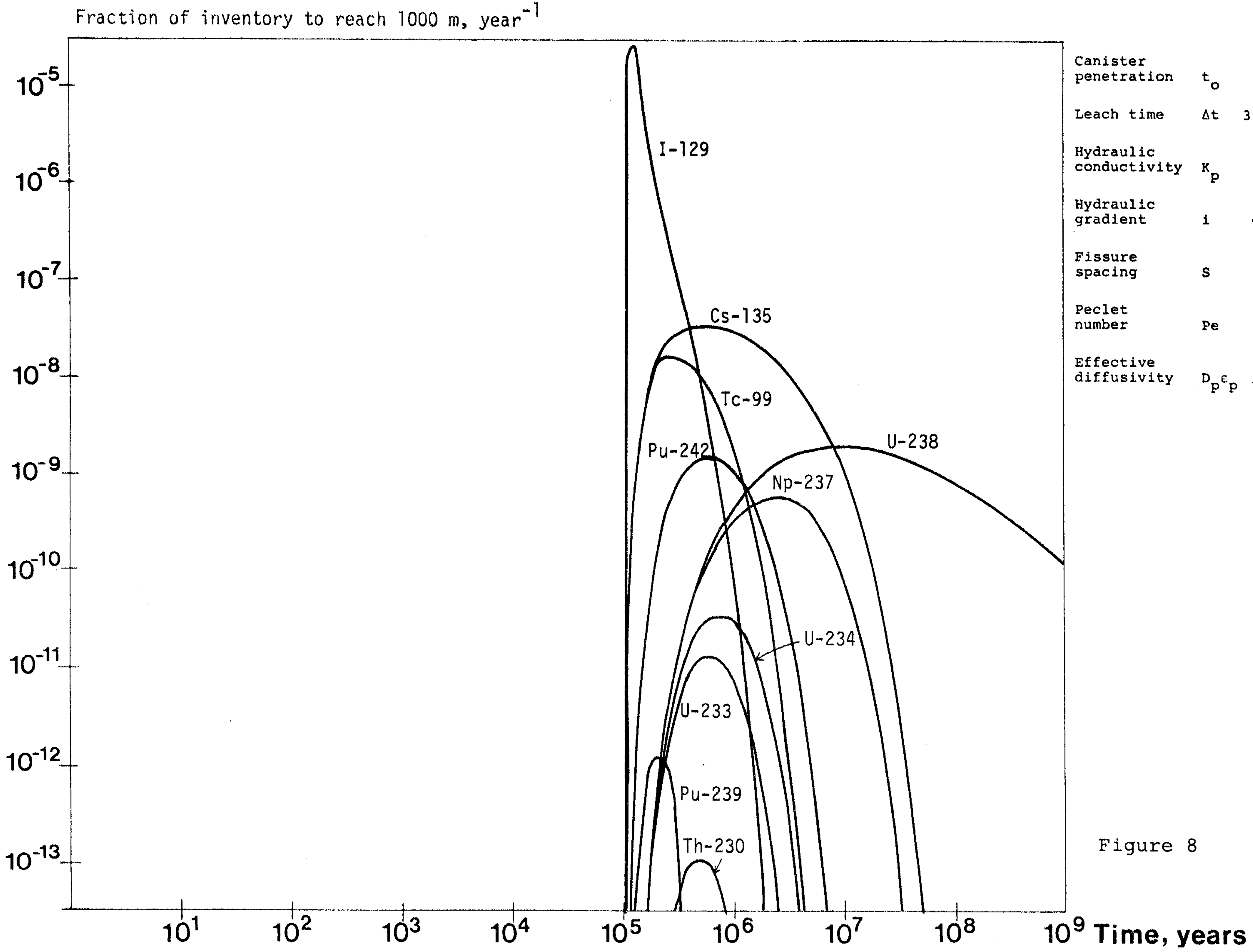
Canister penetration	t_o	40	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	50	m
Peclet number	Pe	0.5	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 6



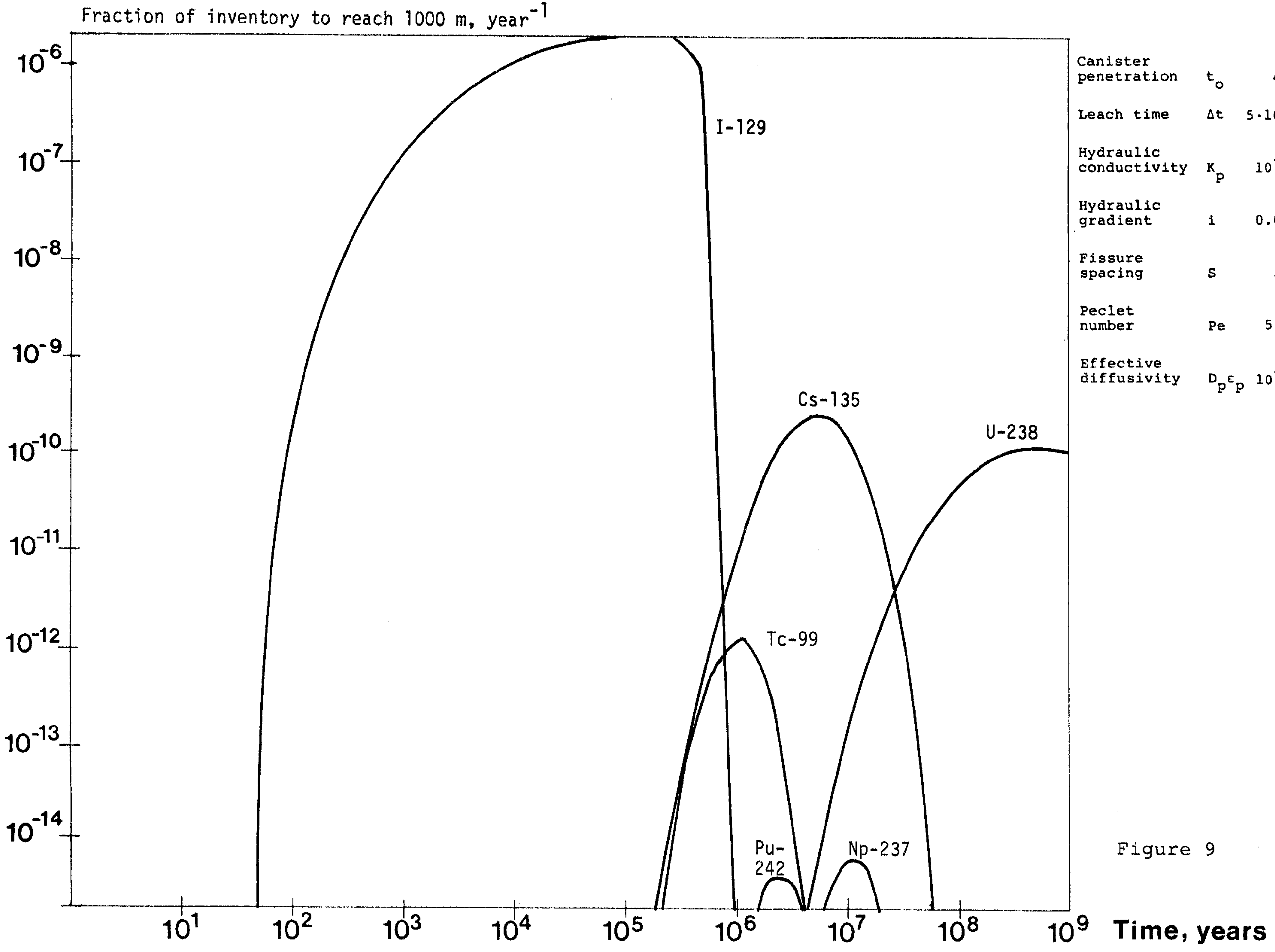
Fraction of inventory to reach 1000 m, year^{-1}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
I-129
Cs-135
Tc-99
U-238
Pu-242
Np-237
U-234
Pu-239
U-233
Th-230
Pu-240
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9
Time, years
Canister penetration t_o $5 \cdot 10^3$ years
Leach time Δt $3 \cdot 10^4$ years
Hydraulic conductivity K_p 10^{-9} m/s
Hydraulic gradient i 0.01 m/m
Fissure spacing S 50 m
Peclet number Pe 0.5 -
Effective diffusivity $D_p \varepsilon_p$ 10^{-12} m^2/s

Figure 7



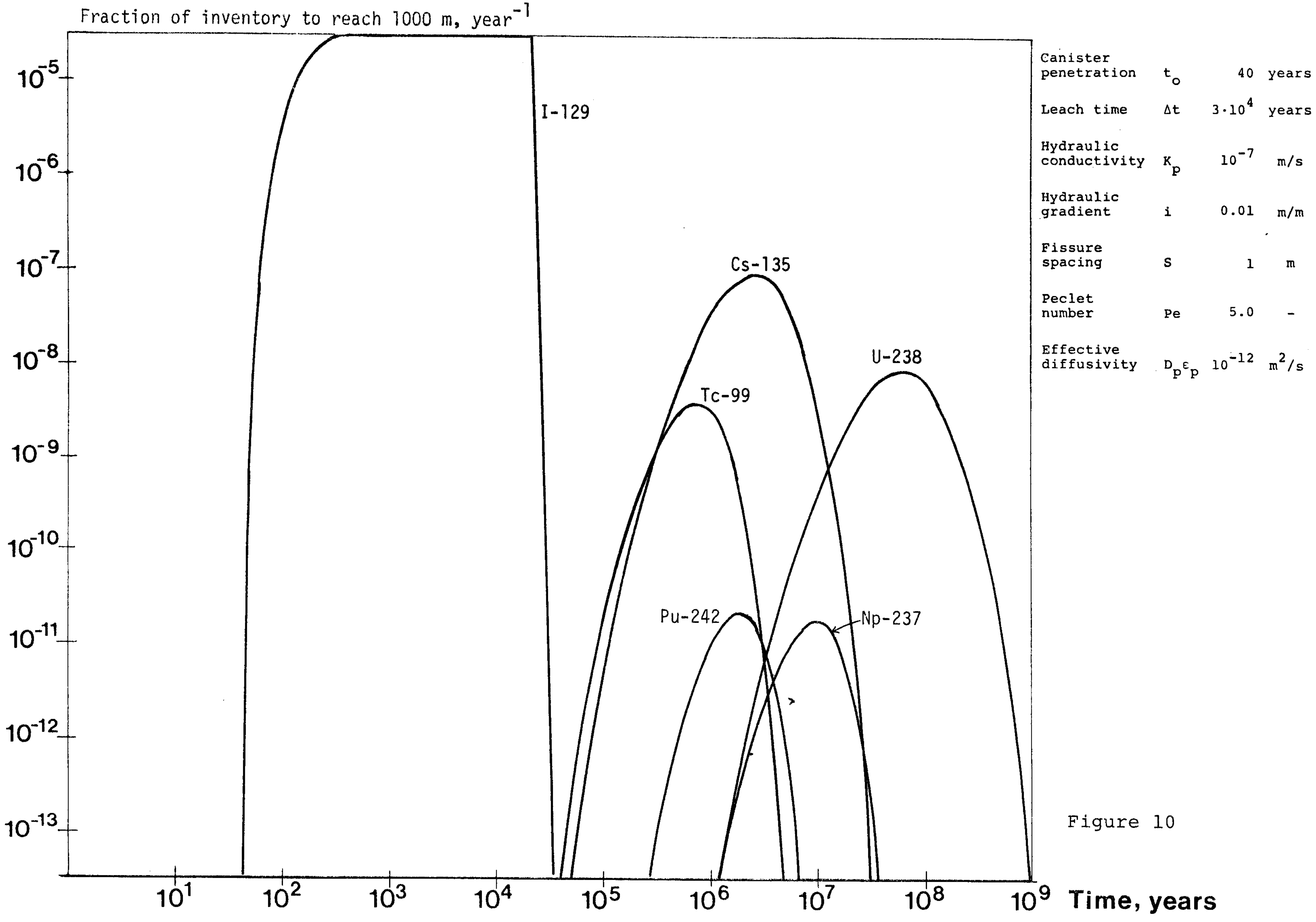
Canister penetration	t_o	10^5	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	50	m
Peclet number	Pe	0.5	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 8



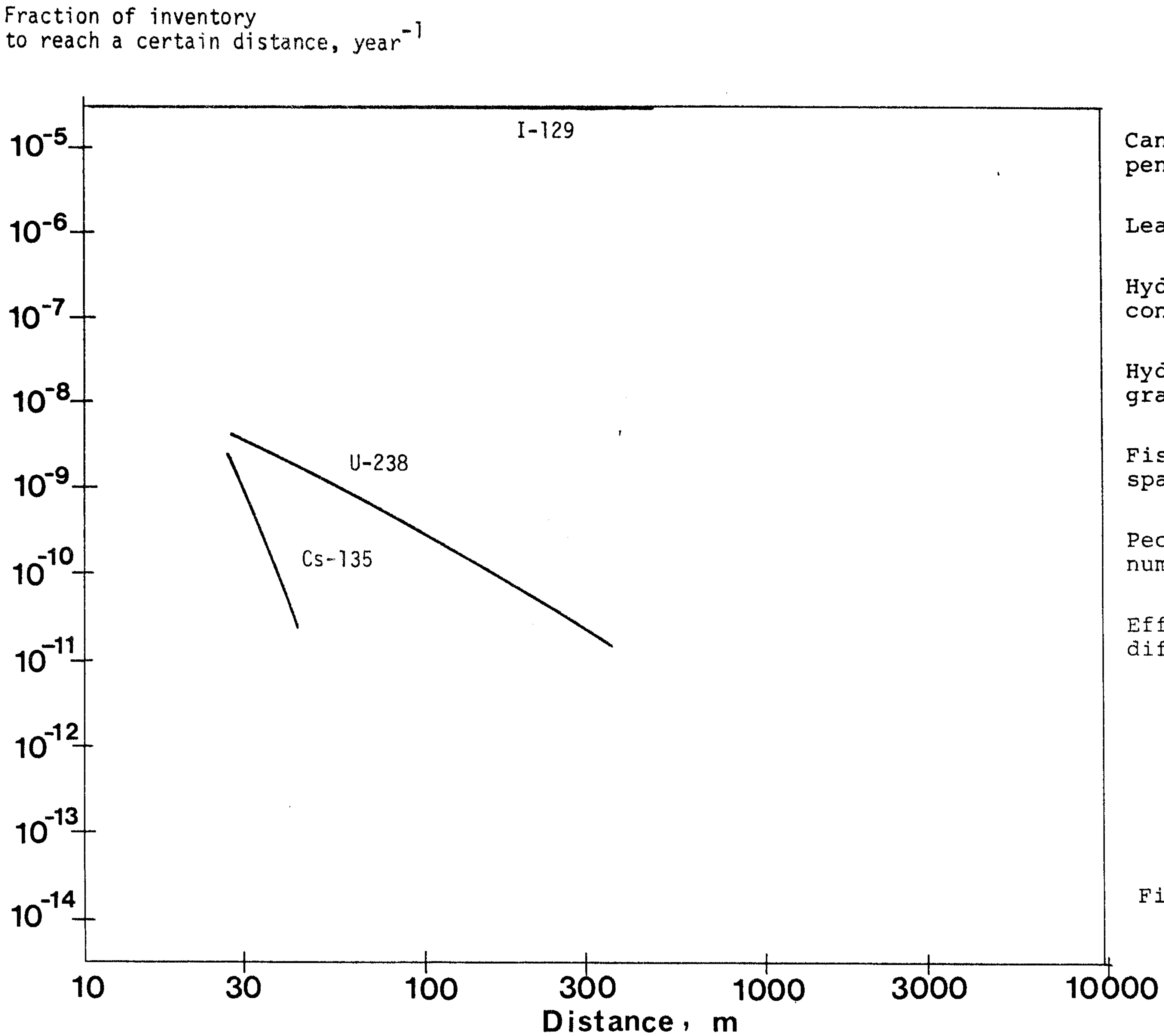
Canister penetration	t_o	40	years
Leach time	Δt	$5 \cdot 10^5$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	50	m
Peclet number	Pe	5.0	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 9



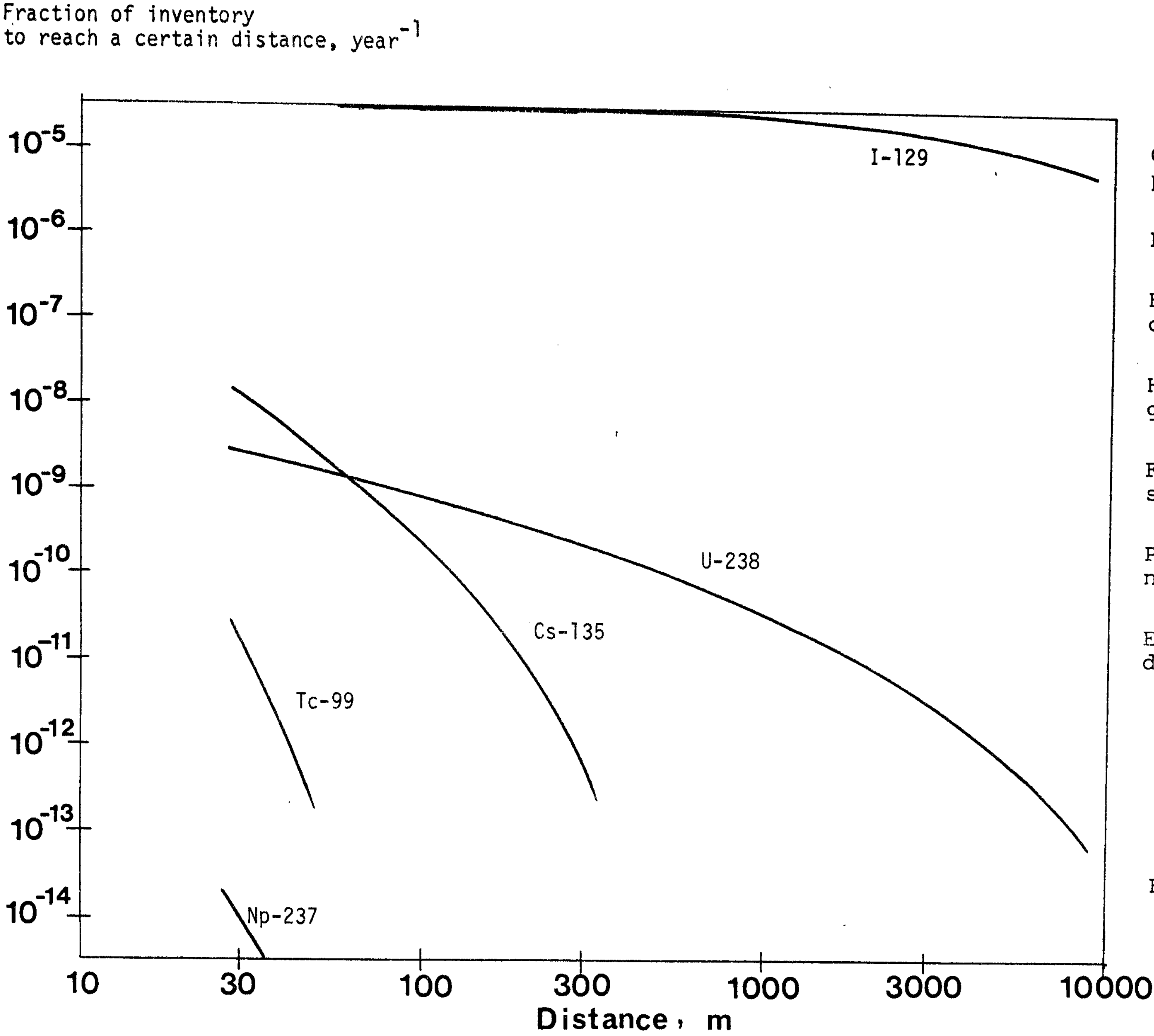
Fraction of inventory to reach 1000 m, year^{-1}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
I-129
Cs-135
Tc-99
U-238
Pu-242
Np-237
10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9
Time, years
Canister penetration t_o 40 years
Leach time Δt $3 \cdot 10^4$ years
Hydraulic conductivity K_p 10^{-7} m/s
Hydraulic gradient i 0.01 m/m
Fissure spacing S 1 m
Peclet number Pe 5.0 -
Effective diffusivity $D_p \varepsilon_p$ 10^{-12} m^2/s

Figure 10



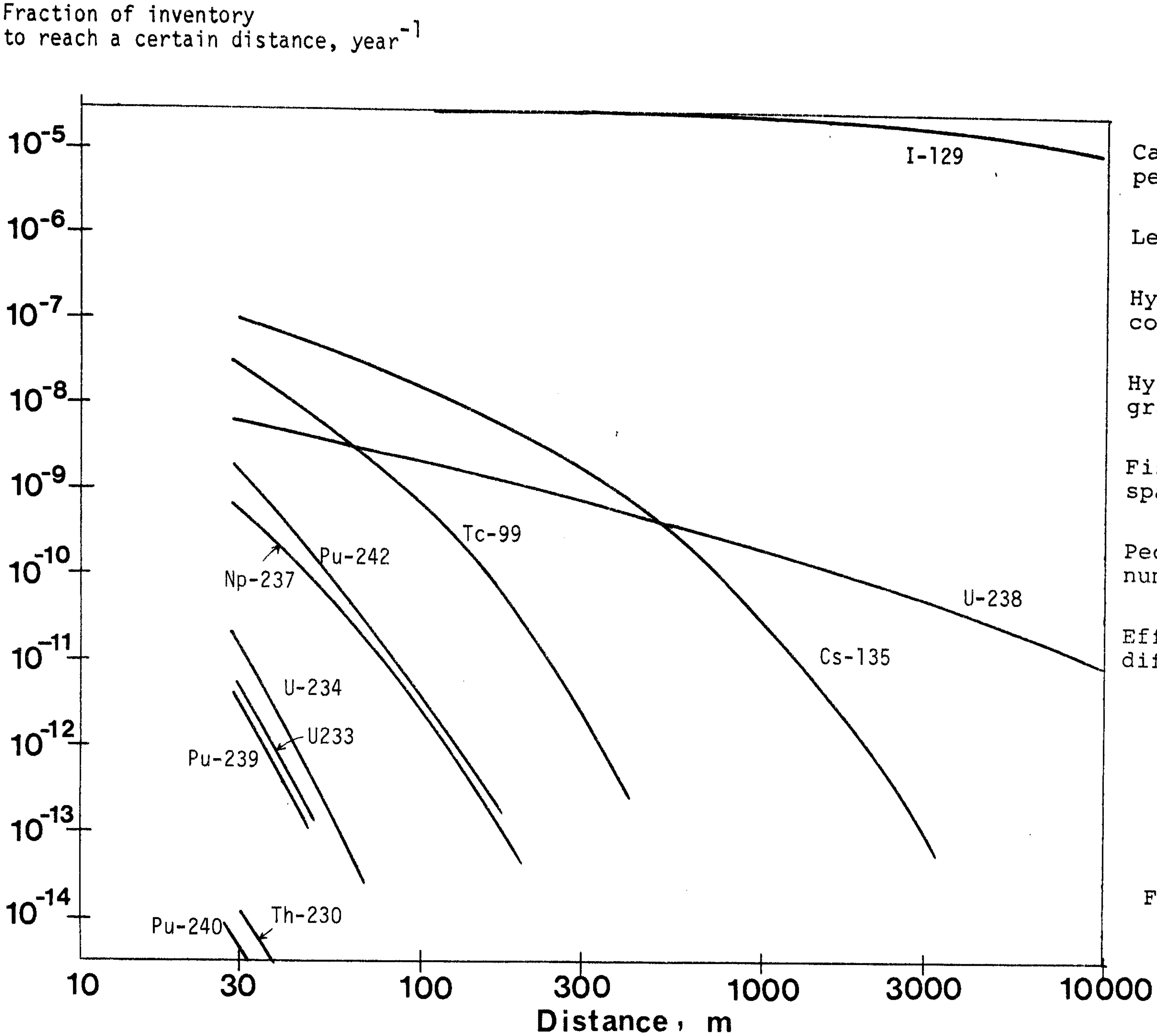
Canister penetration	t_o	0	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Peclet number	Pe	∞	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 11



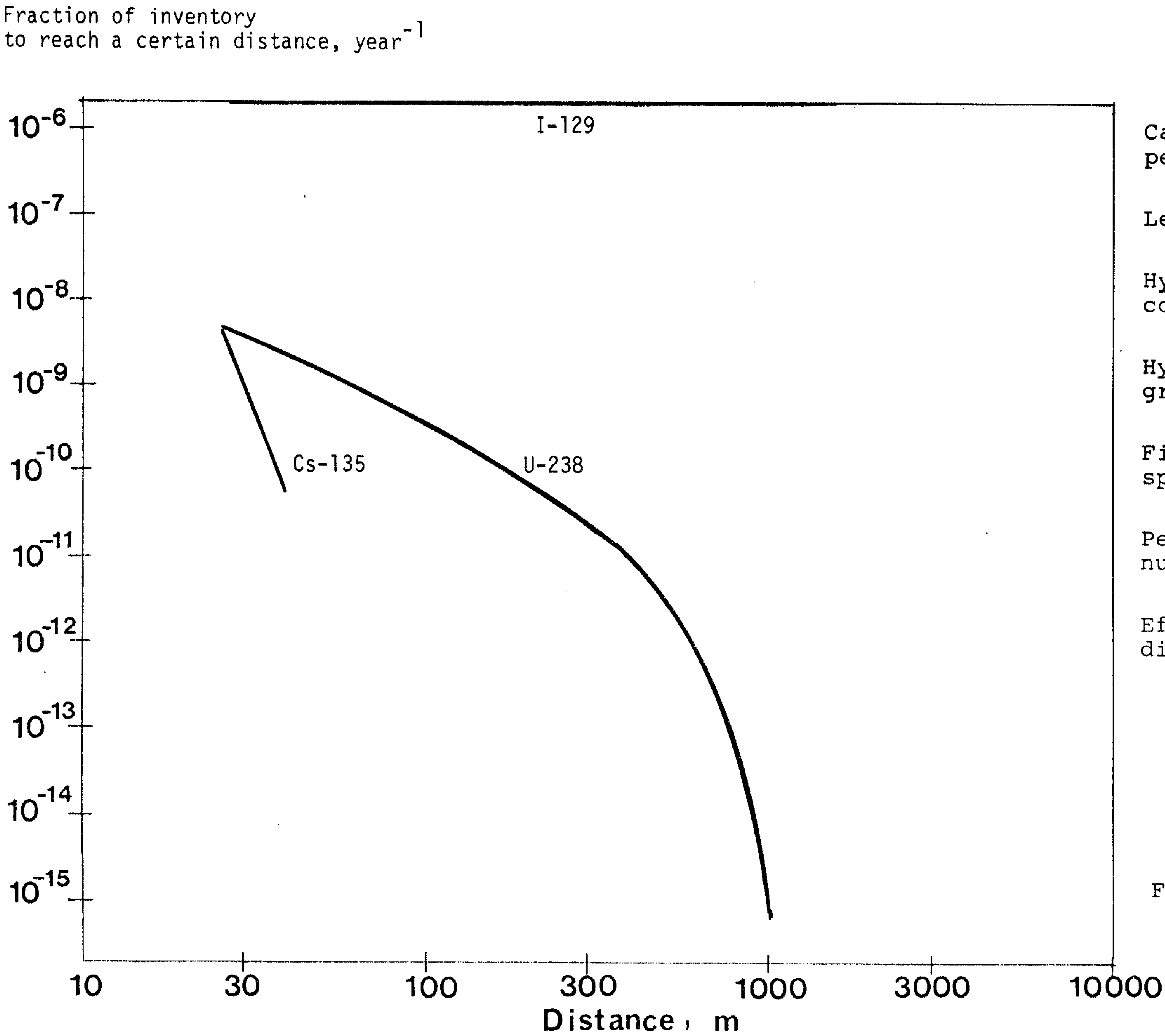
Canister penetration	t_o	0	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Peclet number	Pe	5.0	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 12



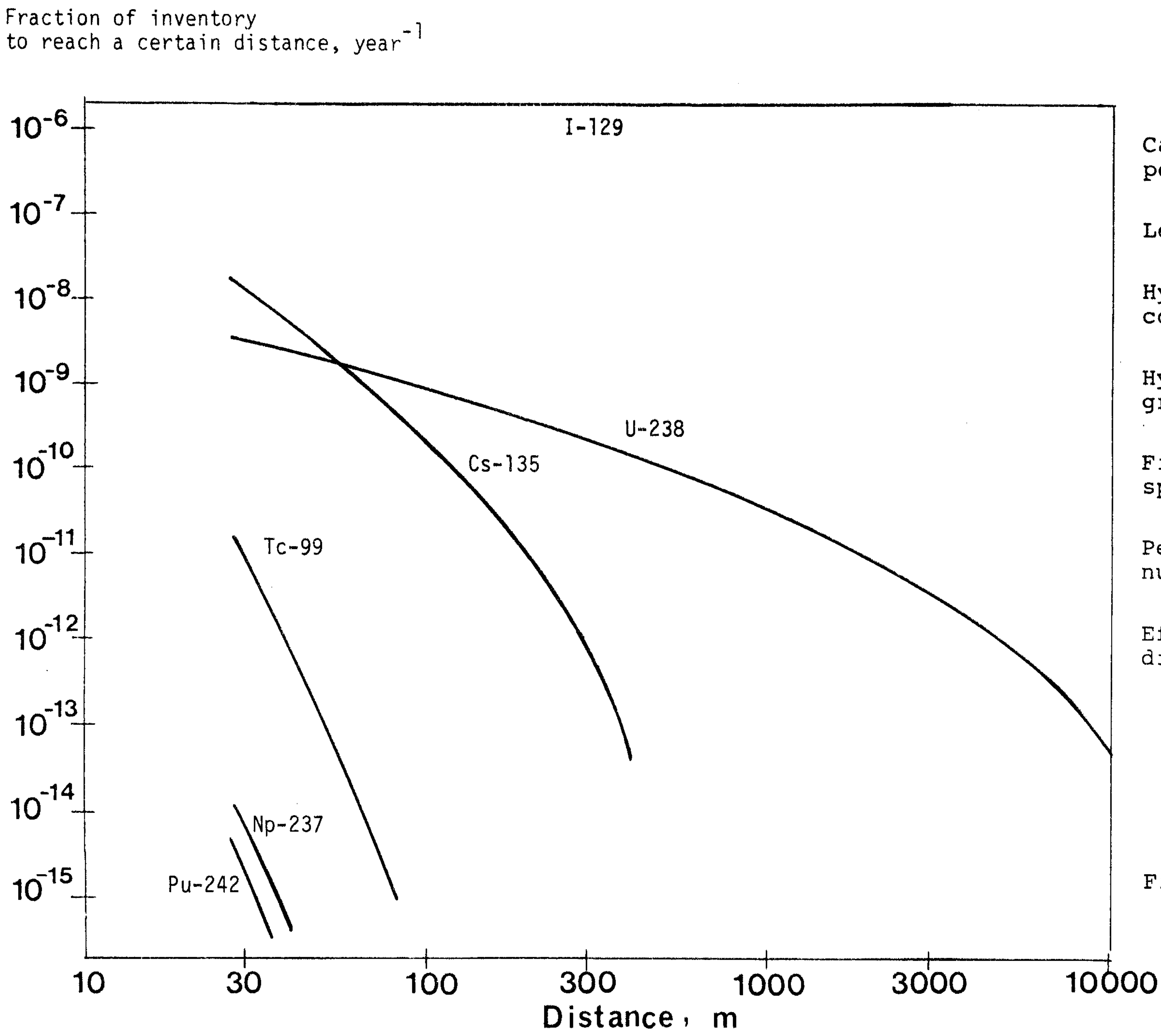
Canister penetration	t_o	0	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Peclet number	Pe	0.5	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 13



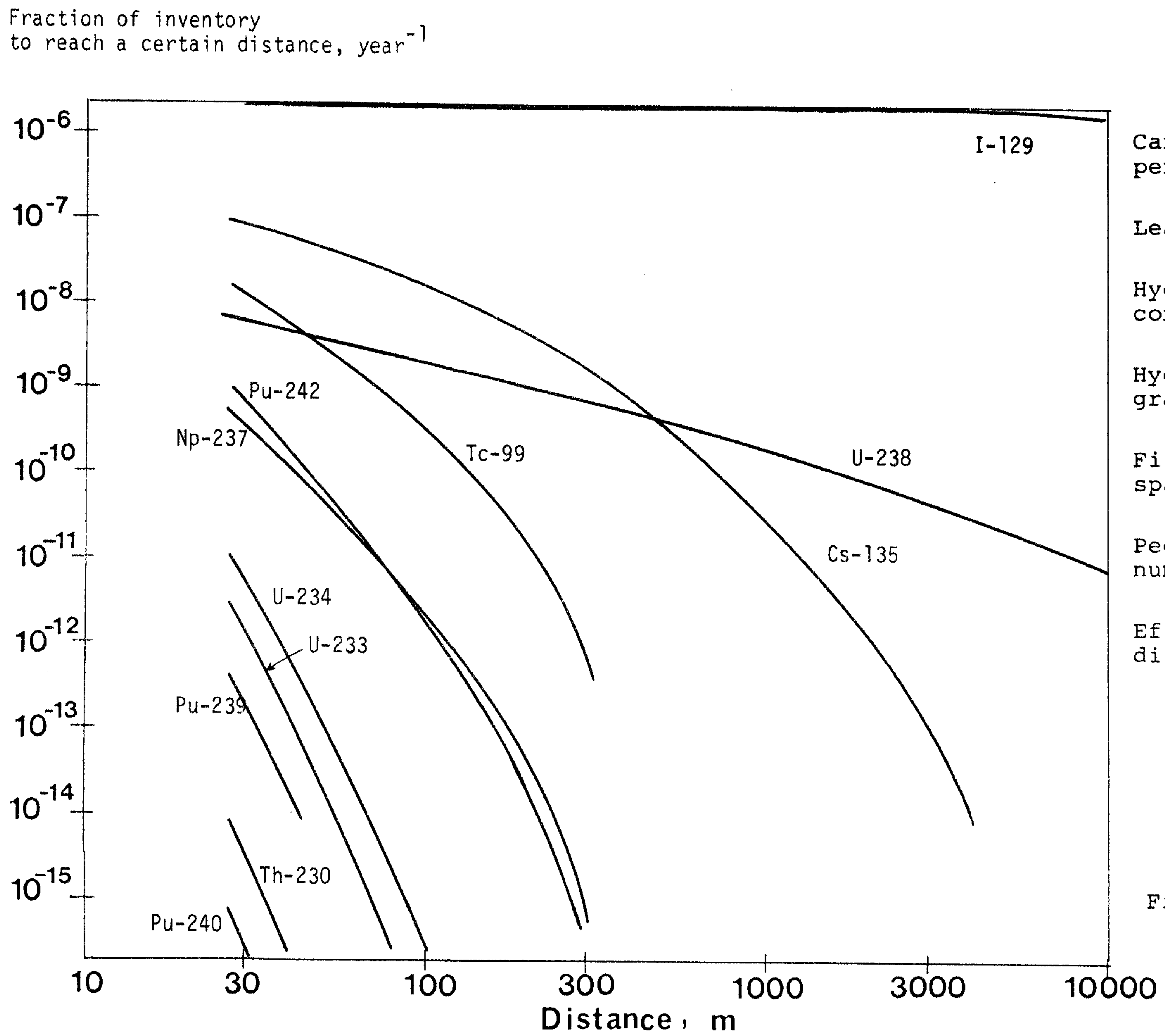
Canister penetration	t_o	0	years
Leach time	Δt	$5 \cdot 10^5$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Peclet number	Pe	∞	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 14



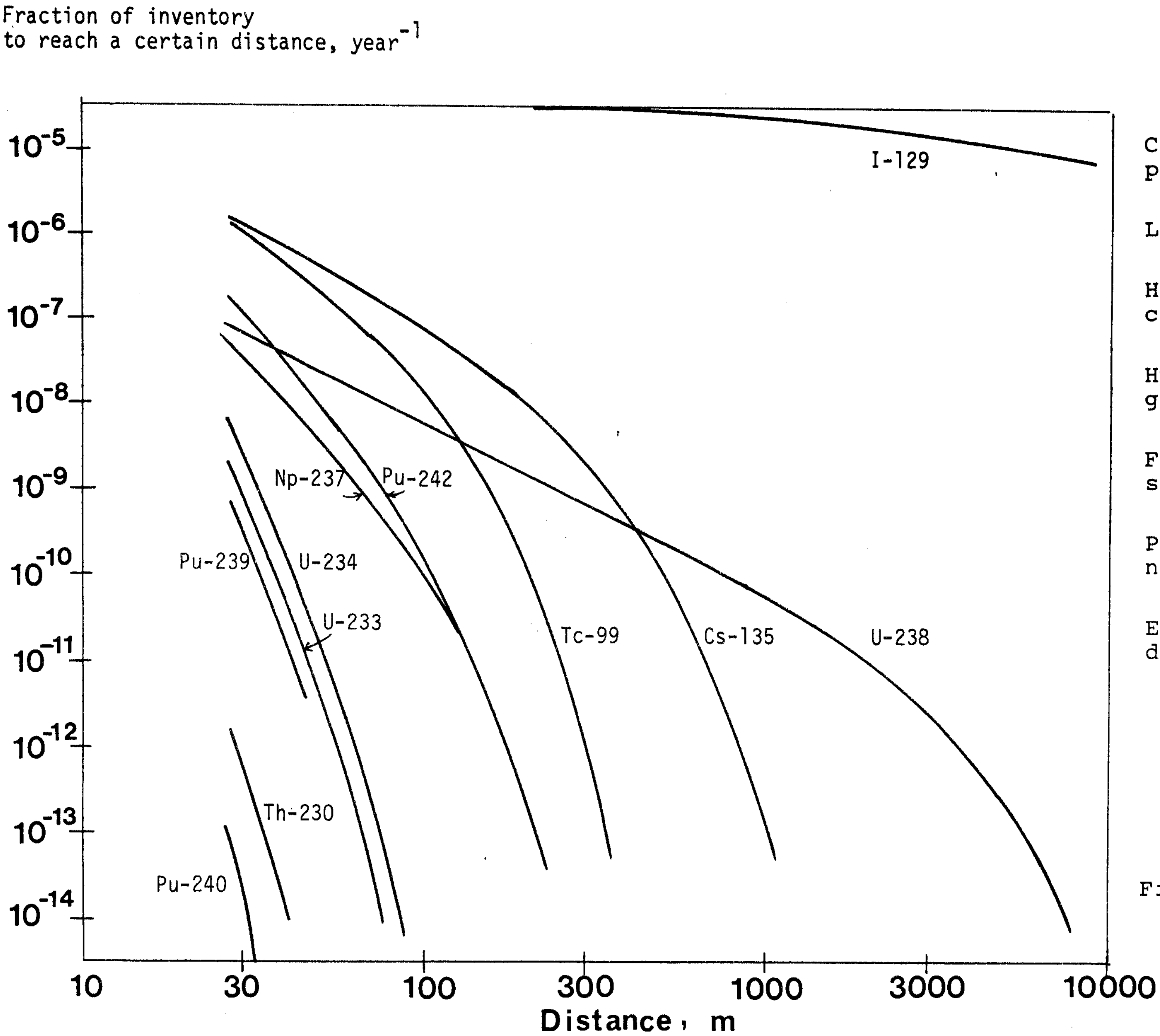
Canister penetration	t_o	0	years
Leach time	Δt	$5 \cdot 10^5$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Peclet number	Pe	5.0	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 15



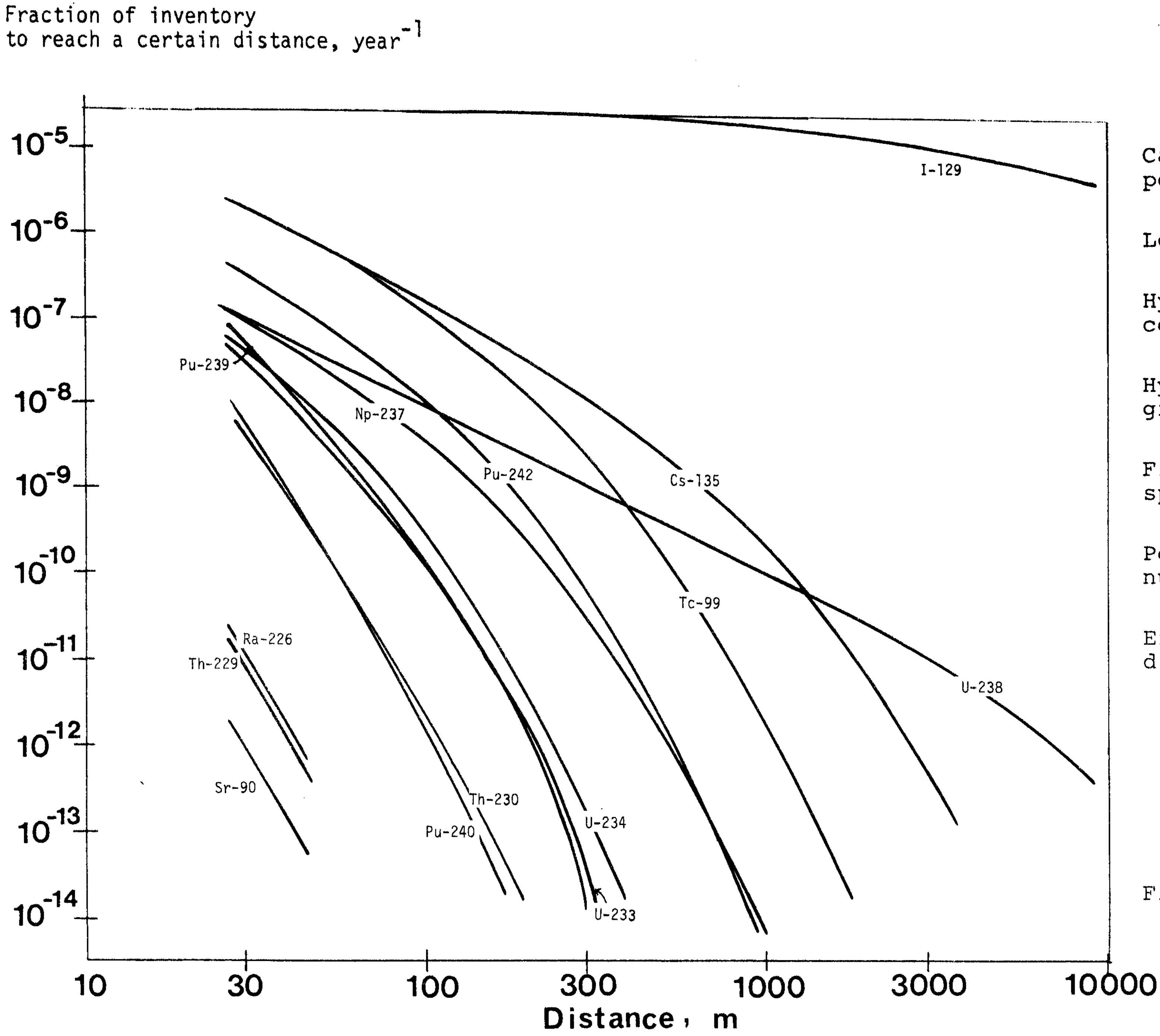
Canister penetration	t_o	0	years
Leach time	Δt	$5 \cdot 10^5$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Peclet number	Pe	0.5	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 16



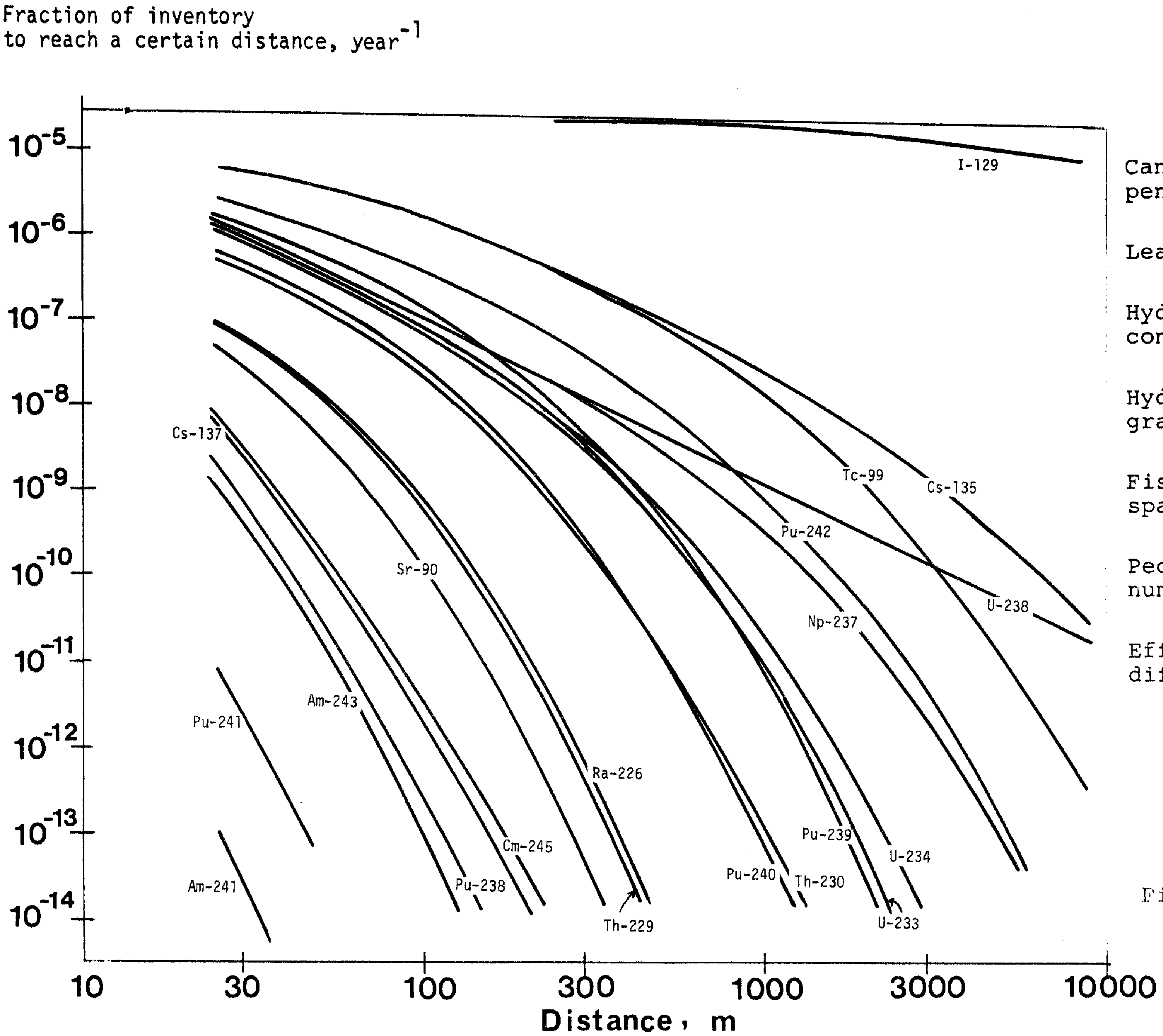
Canister penetration	t_o	0	year
Leach time	Δt	$3 \cdot 10^4$	year
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	50	m
Peclet number	Pe	∞	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 17



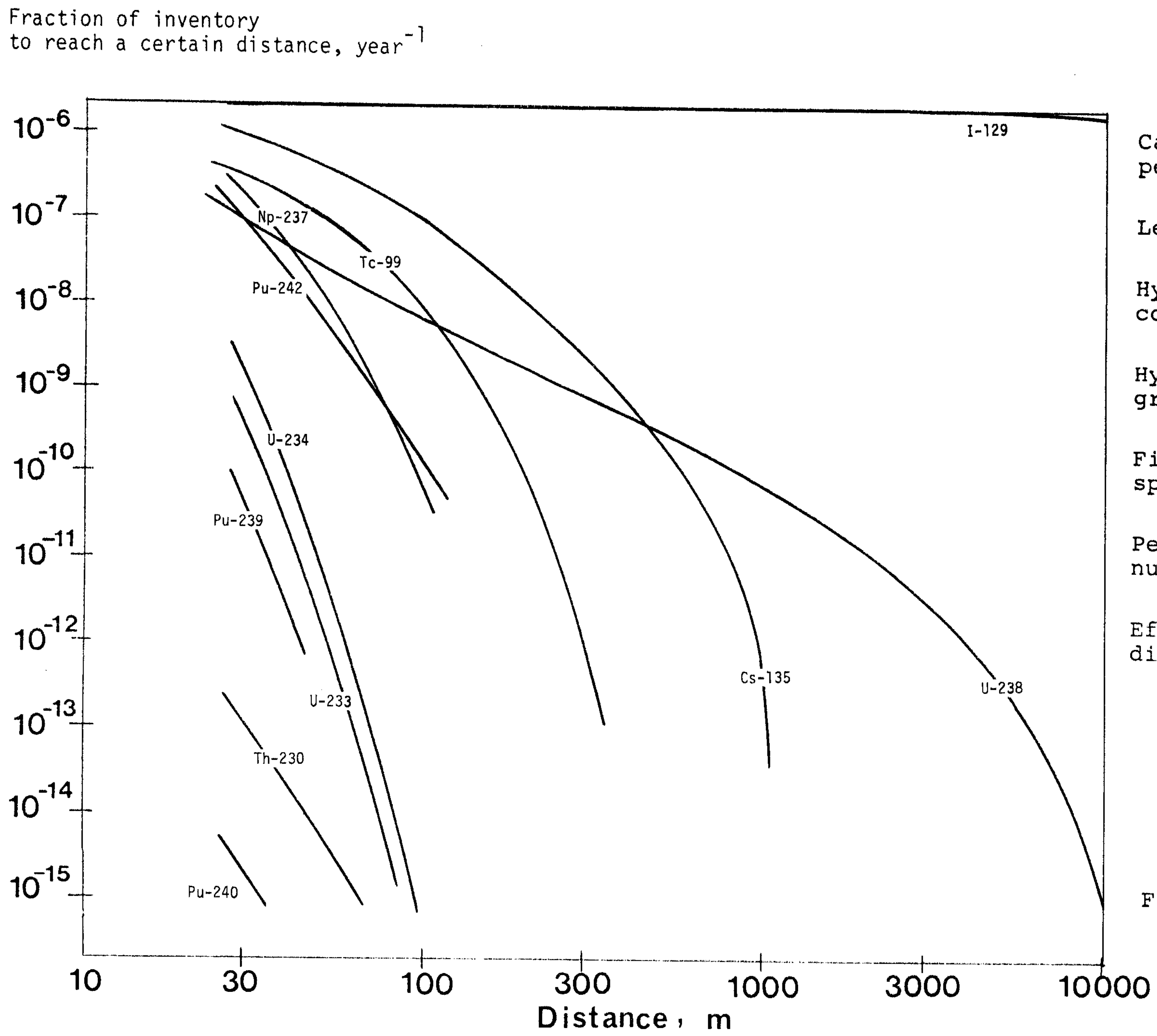
Canister penetration	t_o	0	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	50	m
Peclet number	Pe	5.0	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 18



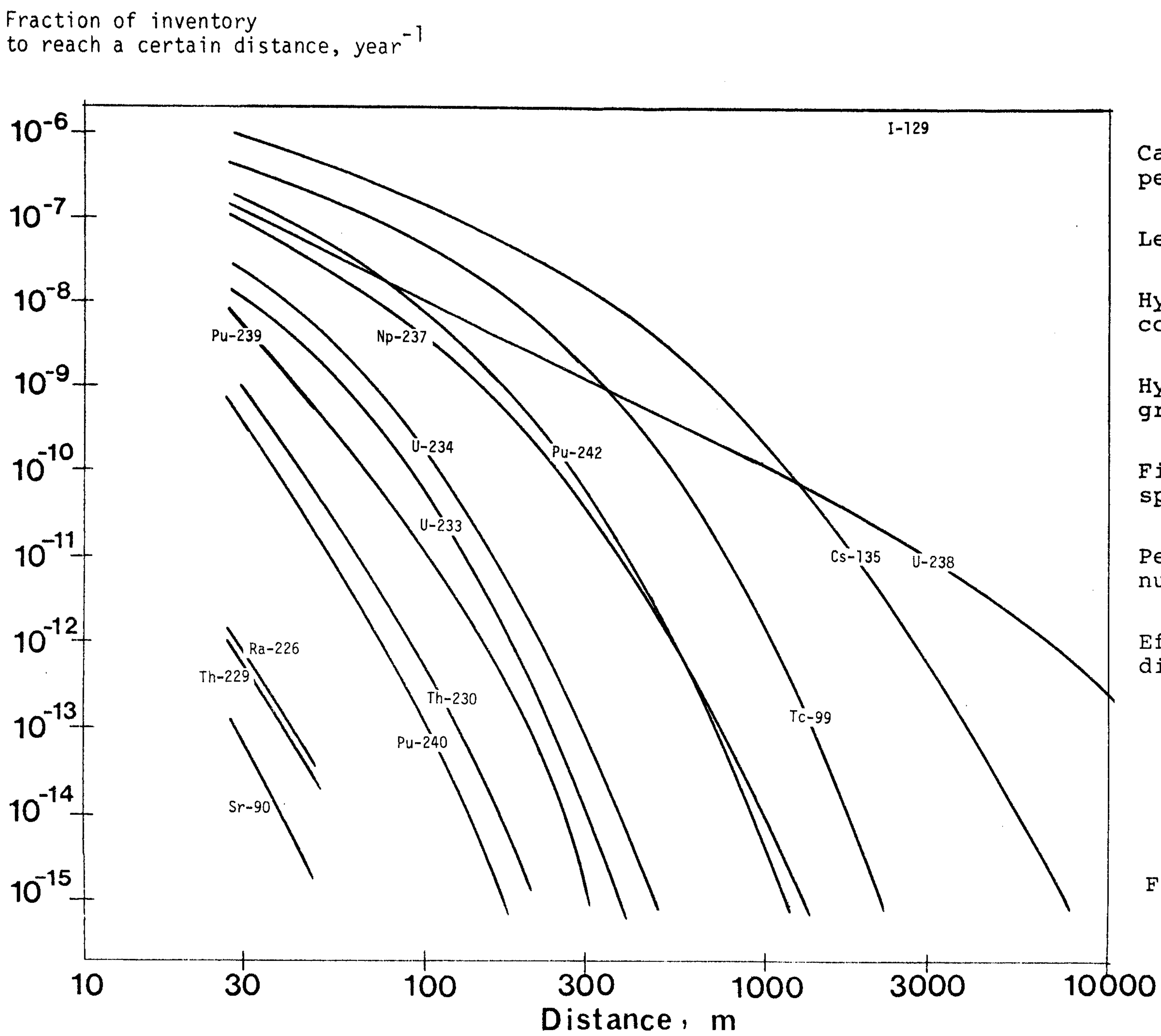
Canister penetration	t_o	0	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	50	m
Peclet number	Pe	0.5	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 19



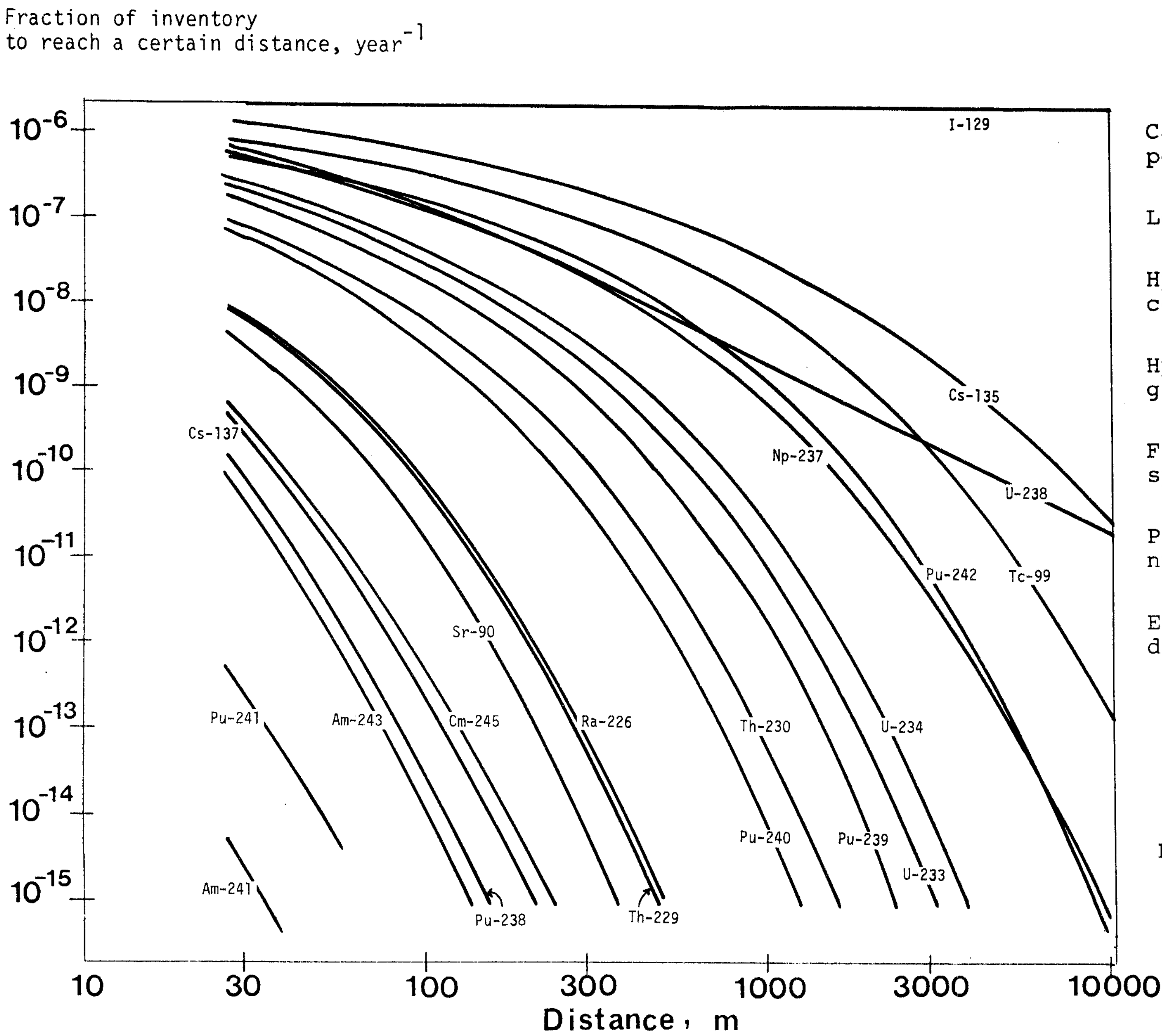
Canister penetration	t_o	0	years
Leach time	Δt	$5 \cdot 10^5$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	50	m
Peclet number	Pe	∞	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 20



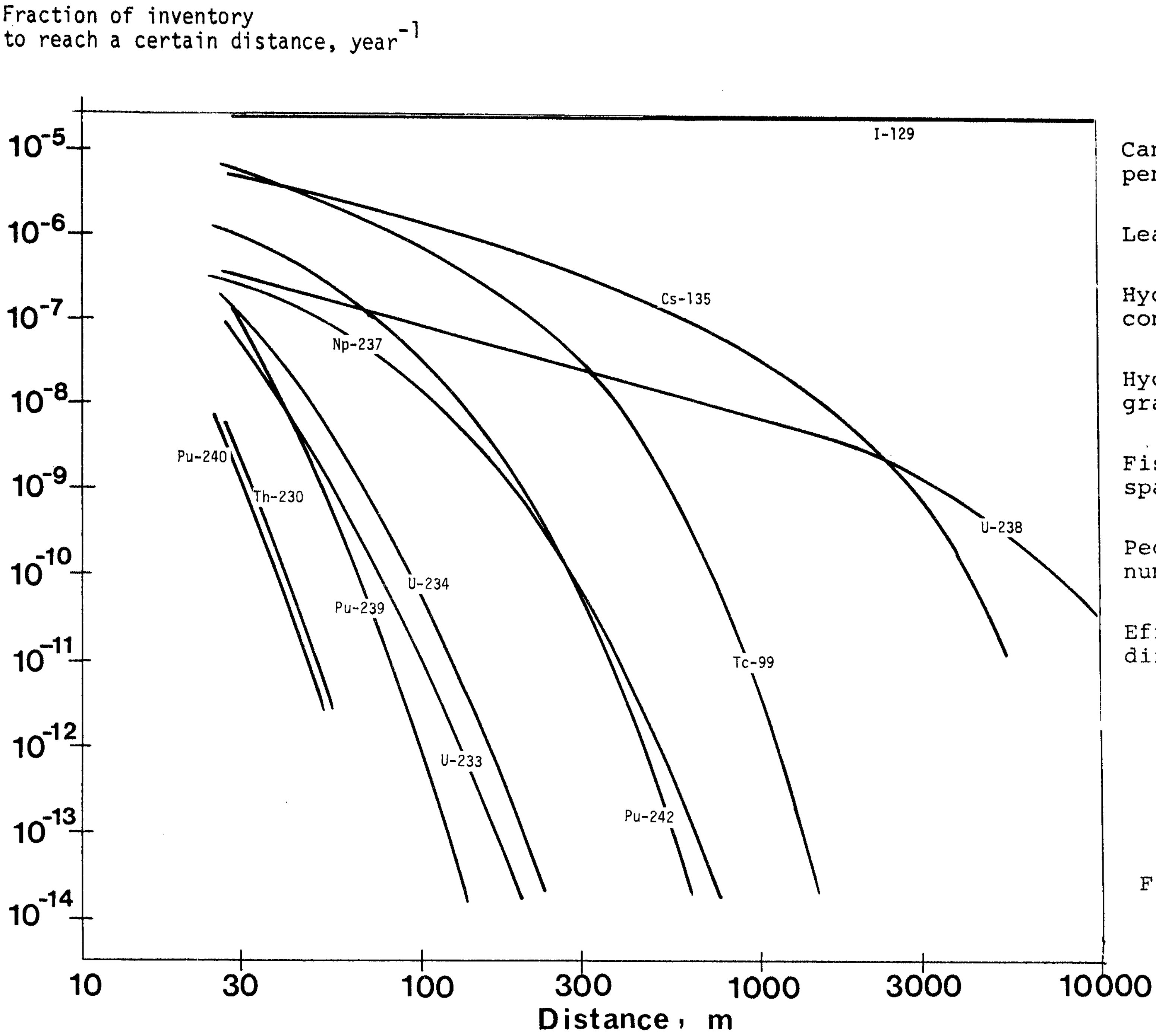
Canister penetration	t_o	0	years
Leach time	Δt	$5 \cdot 10^5$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	50	m
Peclet number	Pe	5.0	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 21



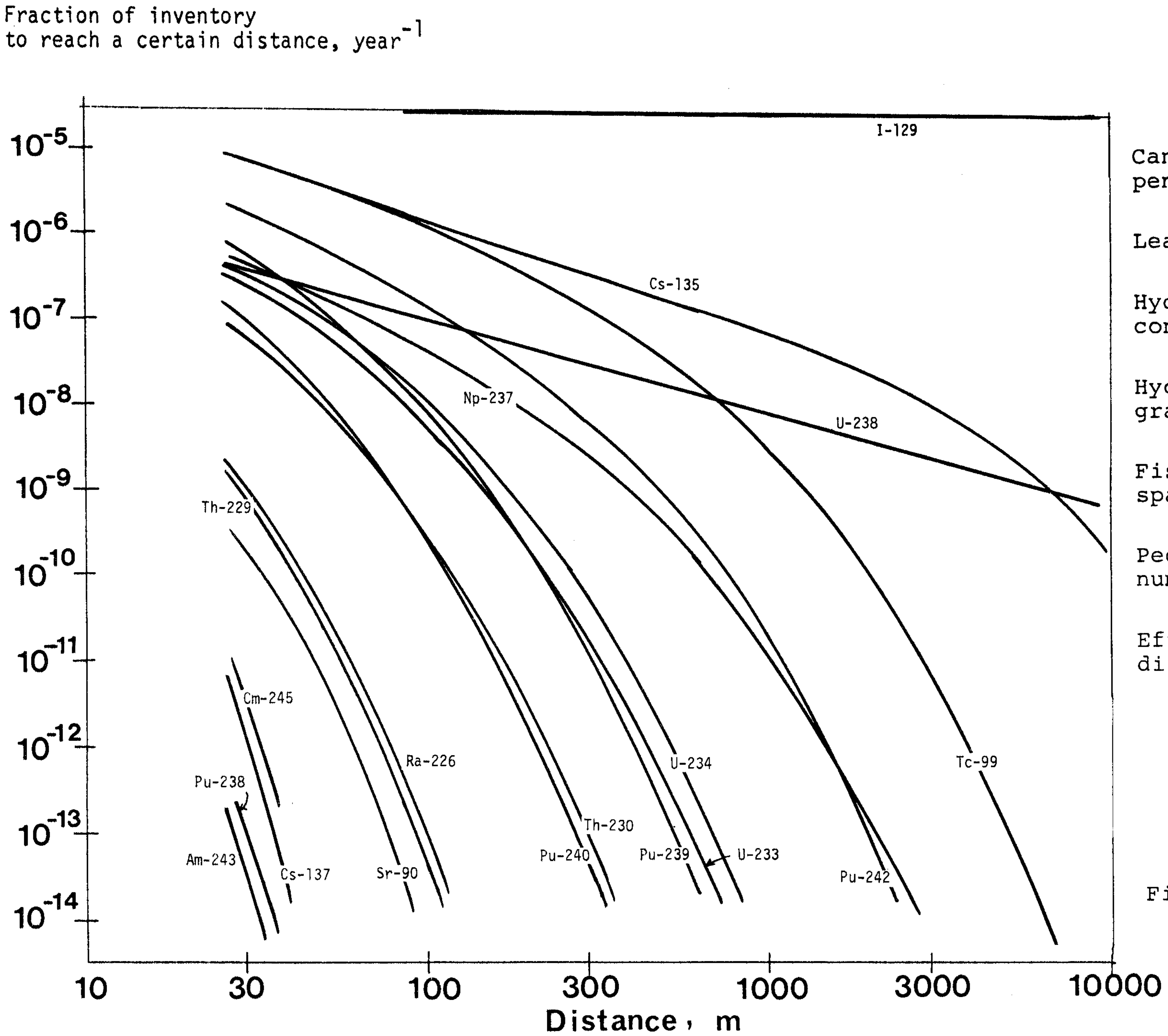
Canister penetration	t_o	0	years
Leach time	Δt	$5 \cdot 10^5$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	50	m
Peclet number	Pe	0.5	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 22



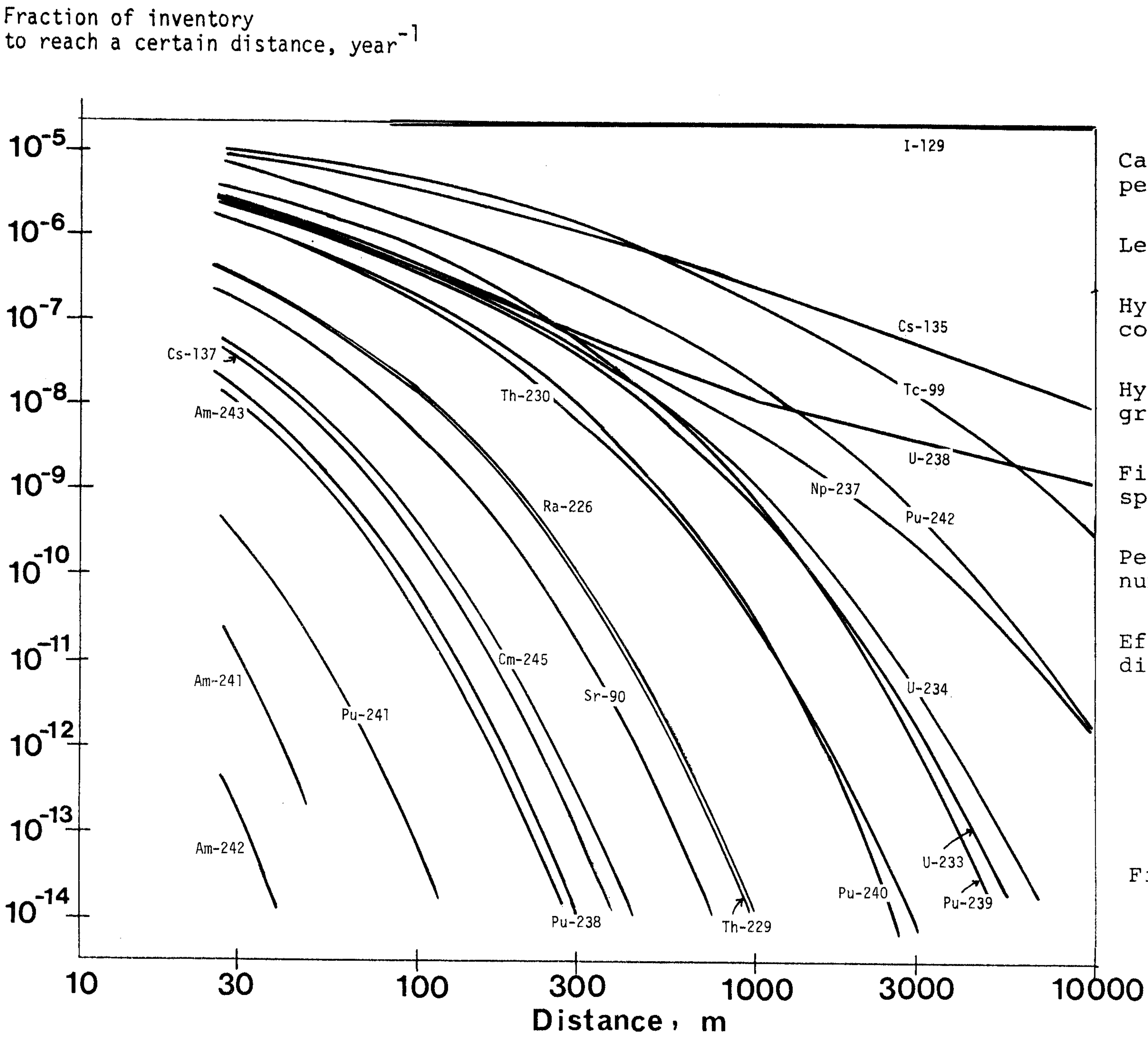
Canister penetration	t_o	0	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-7}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Peclet number	Pe	∞	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 23



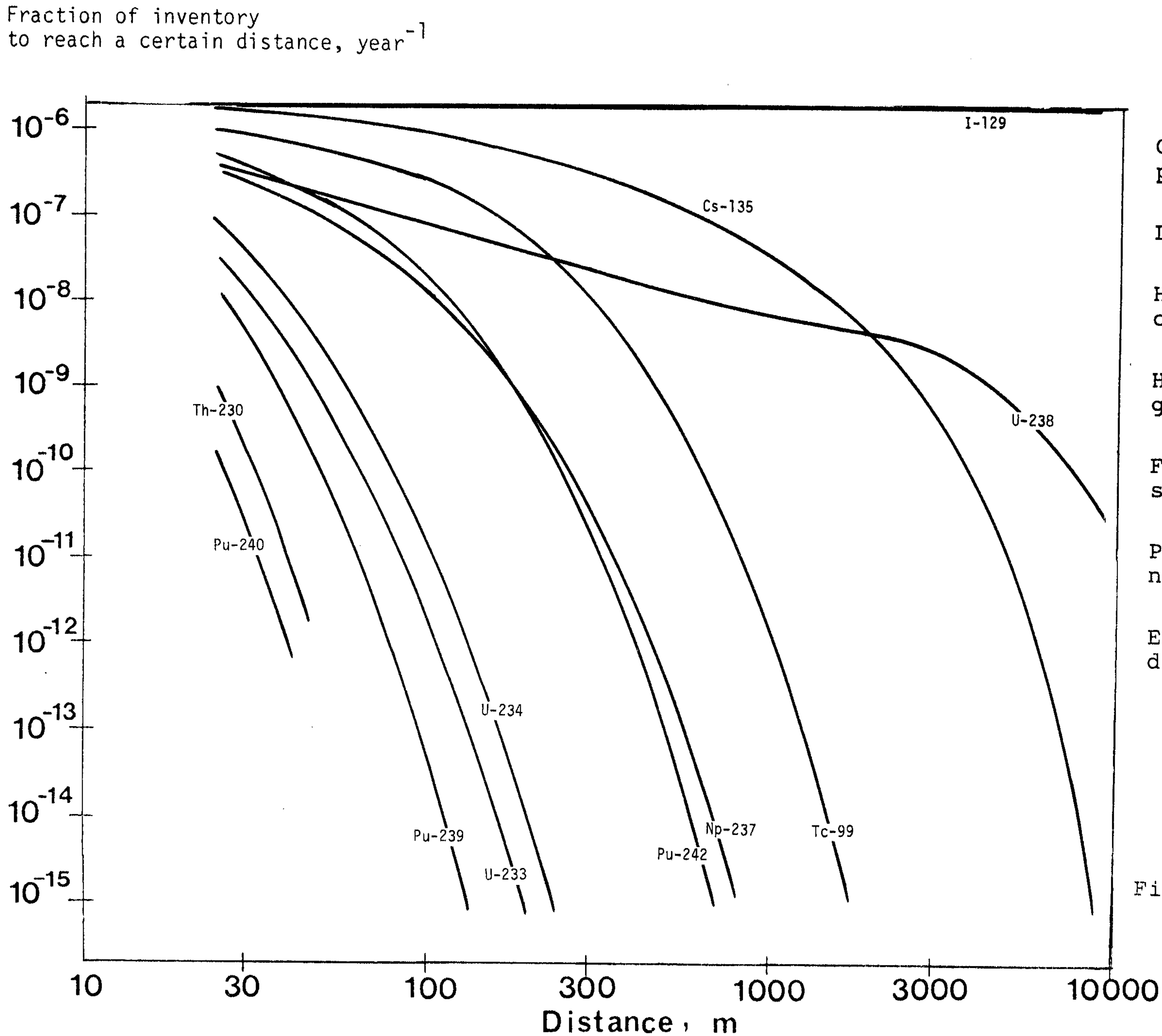
Canister penetration	t_o	0	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-7}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Peclet number	Pe	5.0	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 24



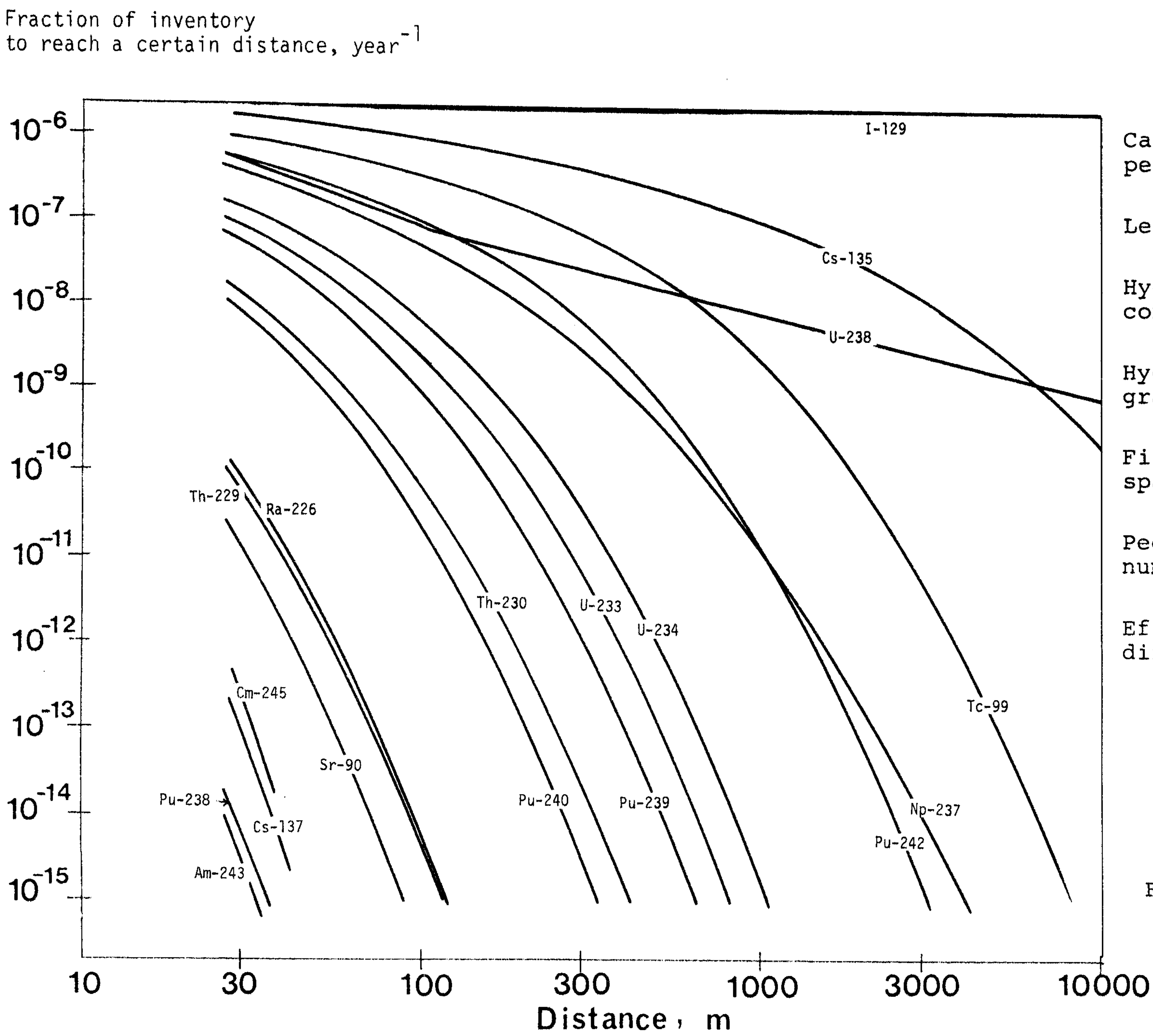
Canister penetration	t_o	0	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-7}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Peclet number	Pe	0.5	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 25



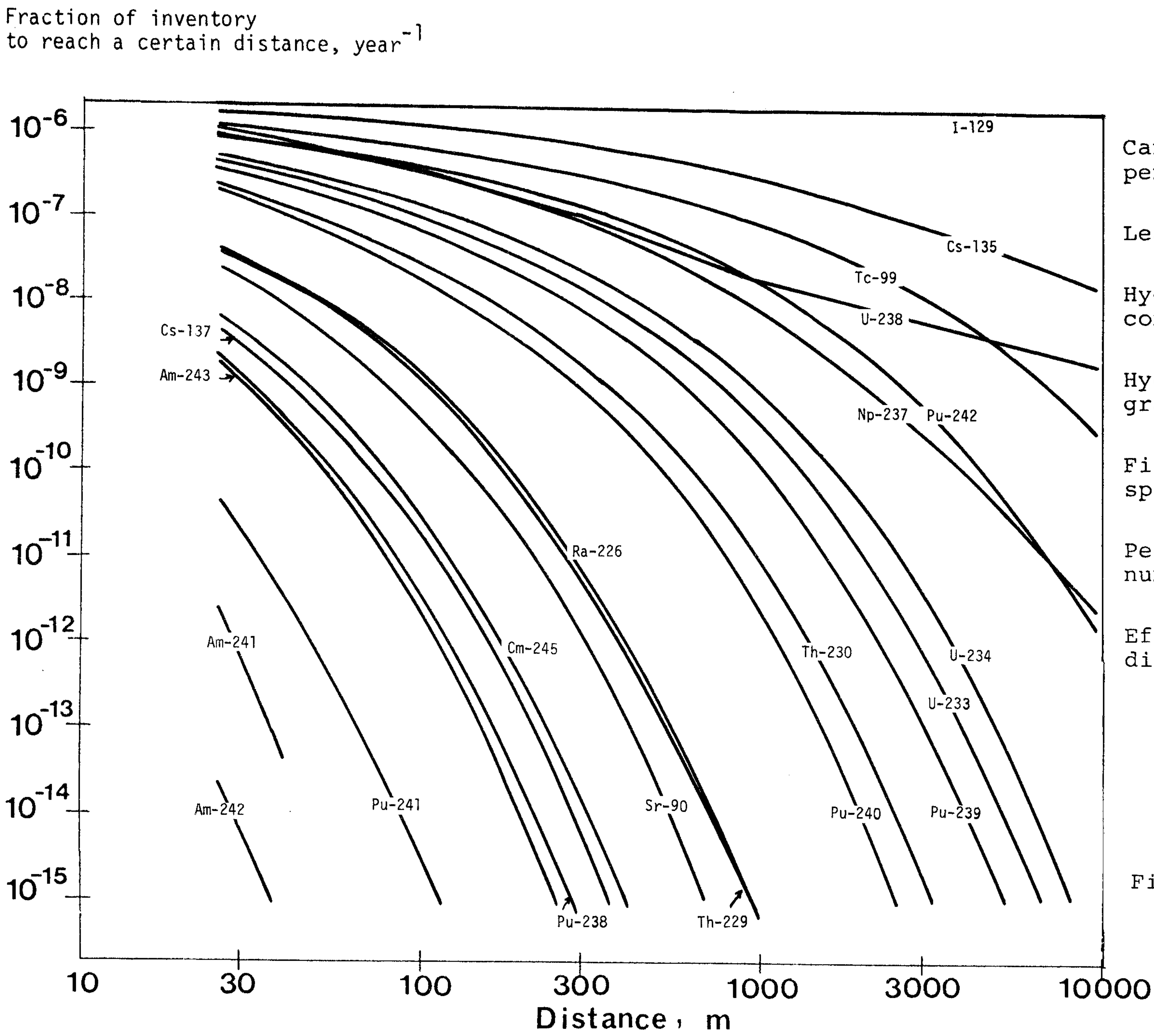
Canister penetration	t_o	0	year
Leach time	Δt	$5 \cdot 10^5$	year
Hydraulic conductivity	K_p	10^{-7}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Peclet number	Pe	∞	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 26



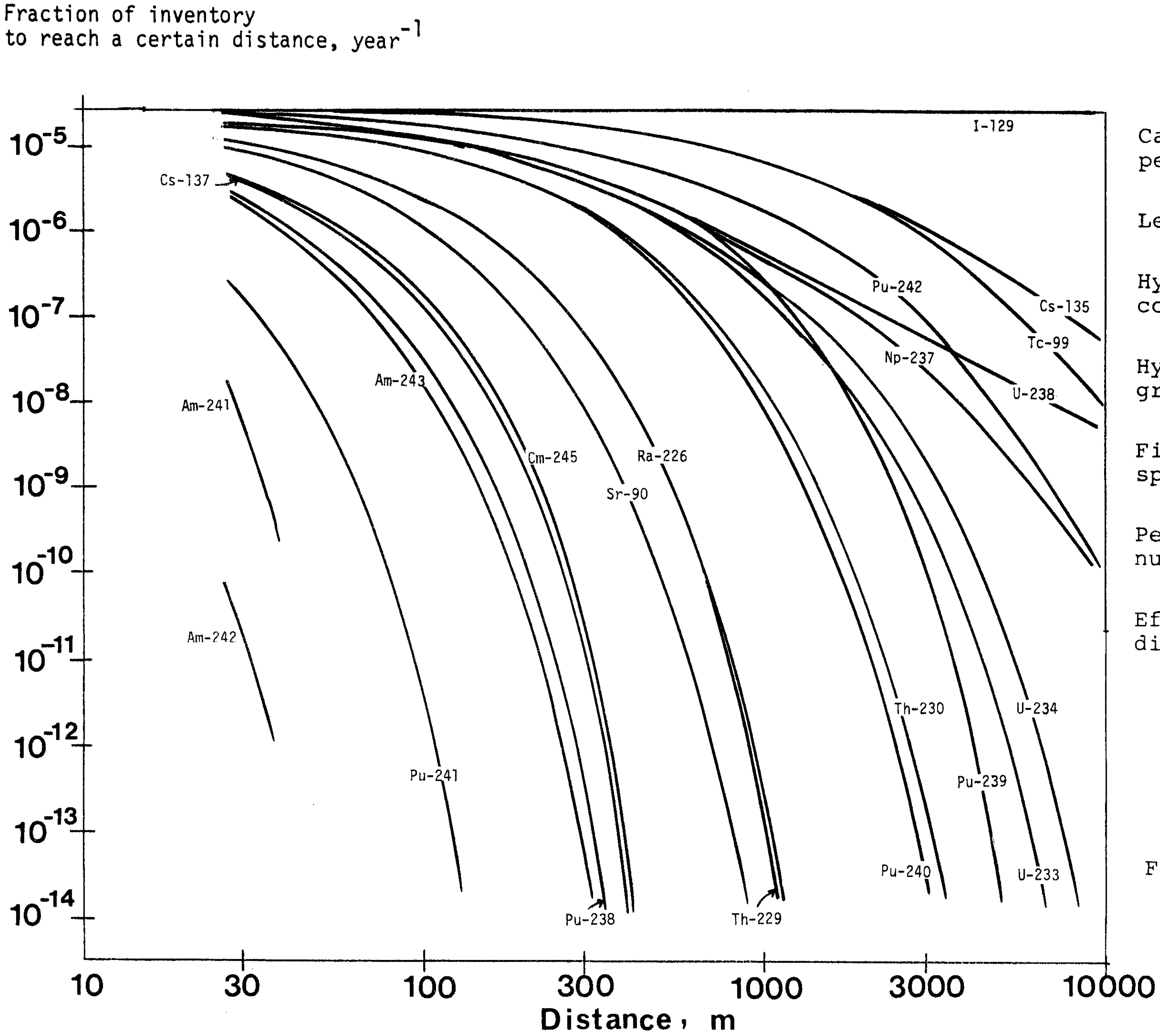
Canister penetration	t_o	0	years
Leach time	Δt	5.10^5	years
Hydraulic conductivity	K_p	10^{-7}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Peclet number	Pe	5.0	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 27



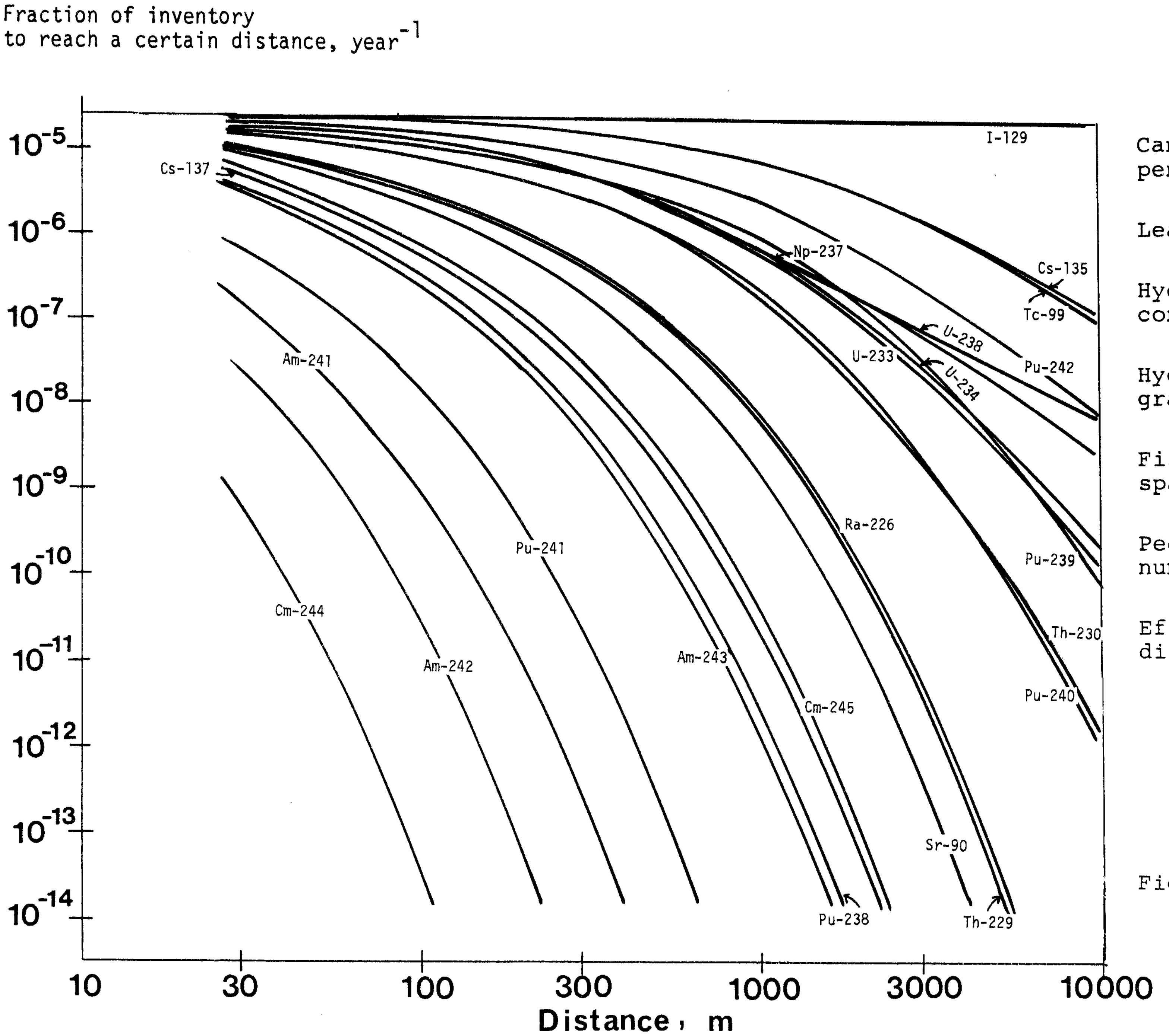
Canister penetration	t_o	0	years
Leach time	Δt	$5 \cdot 10^5$	years
Hydraulic conductivity	K_p	10^{-7}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Peclet number	Pe	0.5	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 28



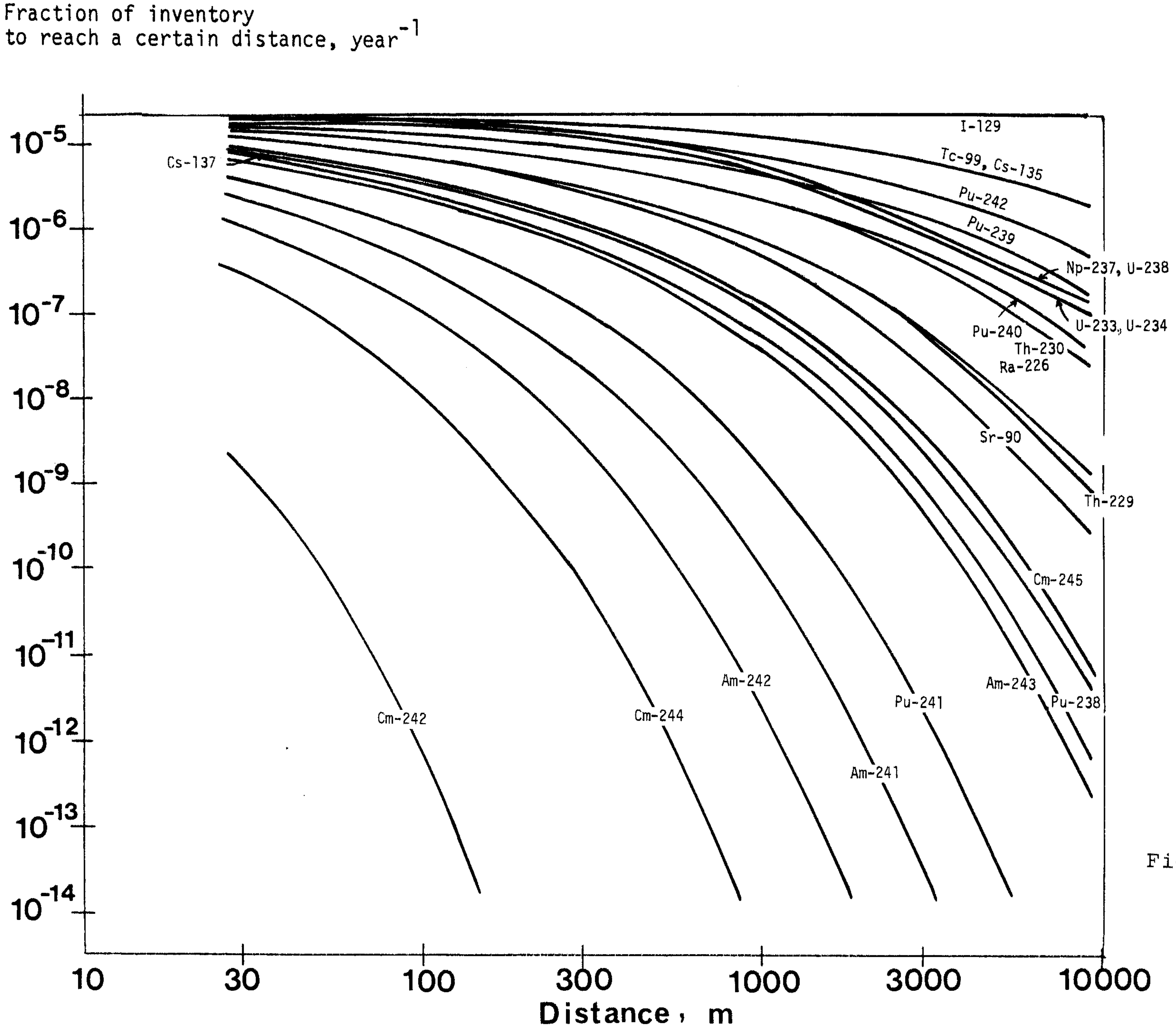
Canister penetration	t_o	0	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-7}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	50	m
Peclet number	Pe	∞	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 29



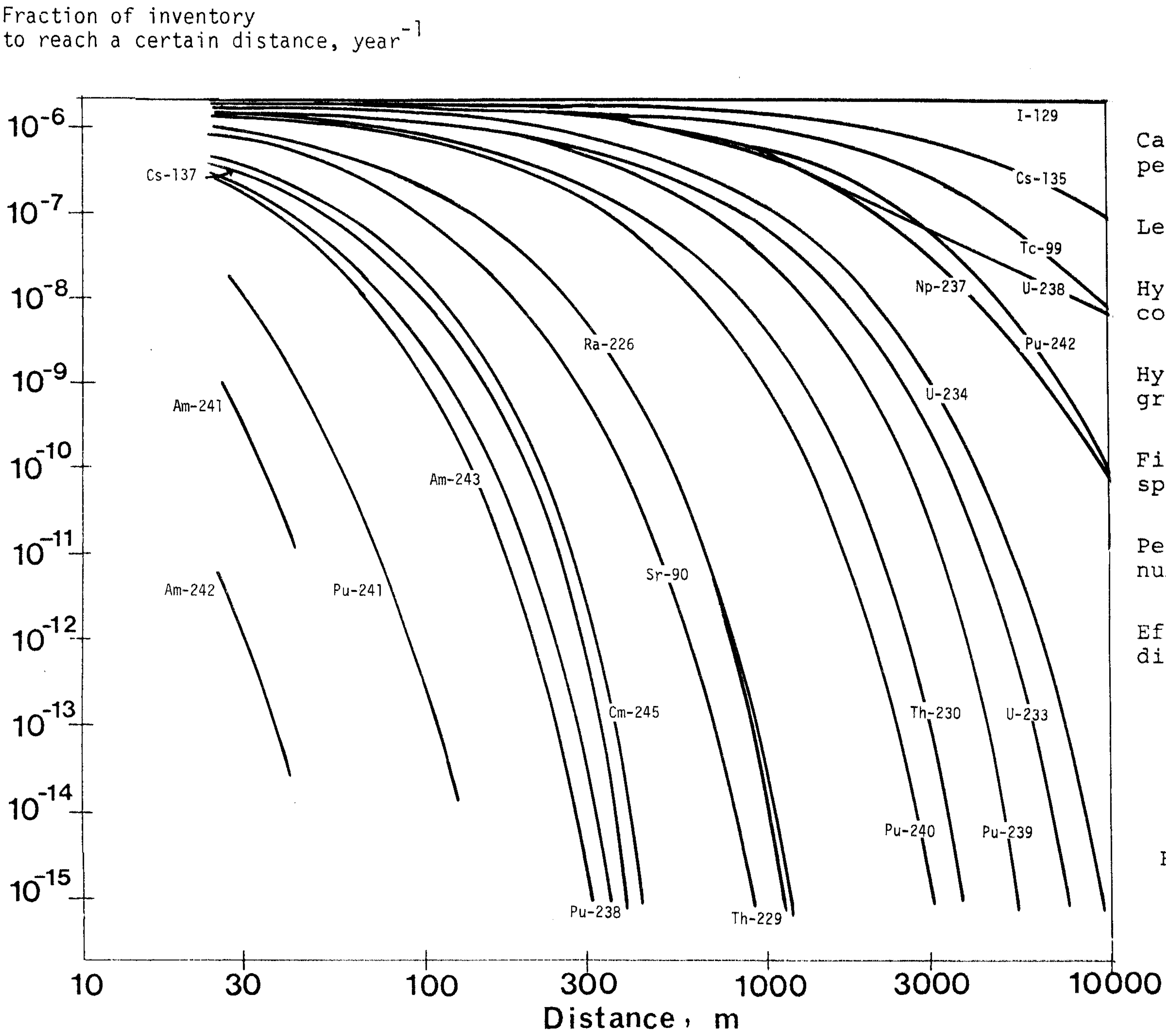
Canister penetration	t_o	0	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-7}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	50	m
Peclet number	Pe	5.0	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 30



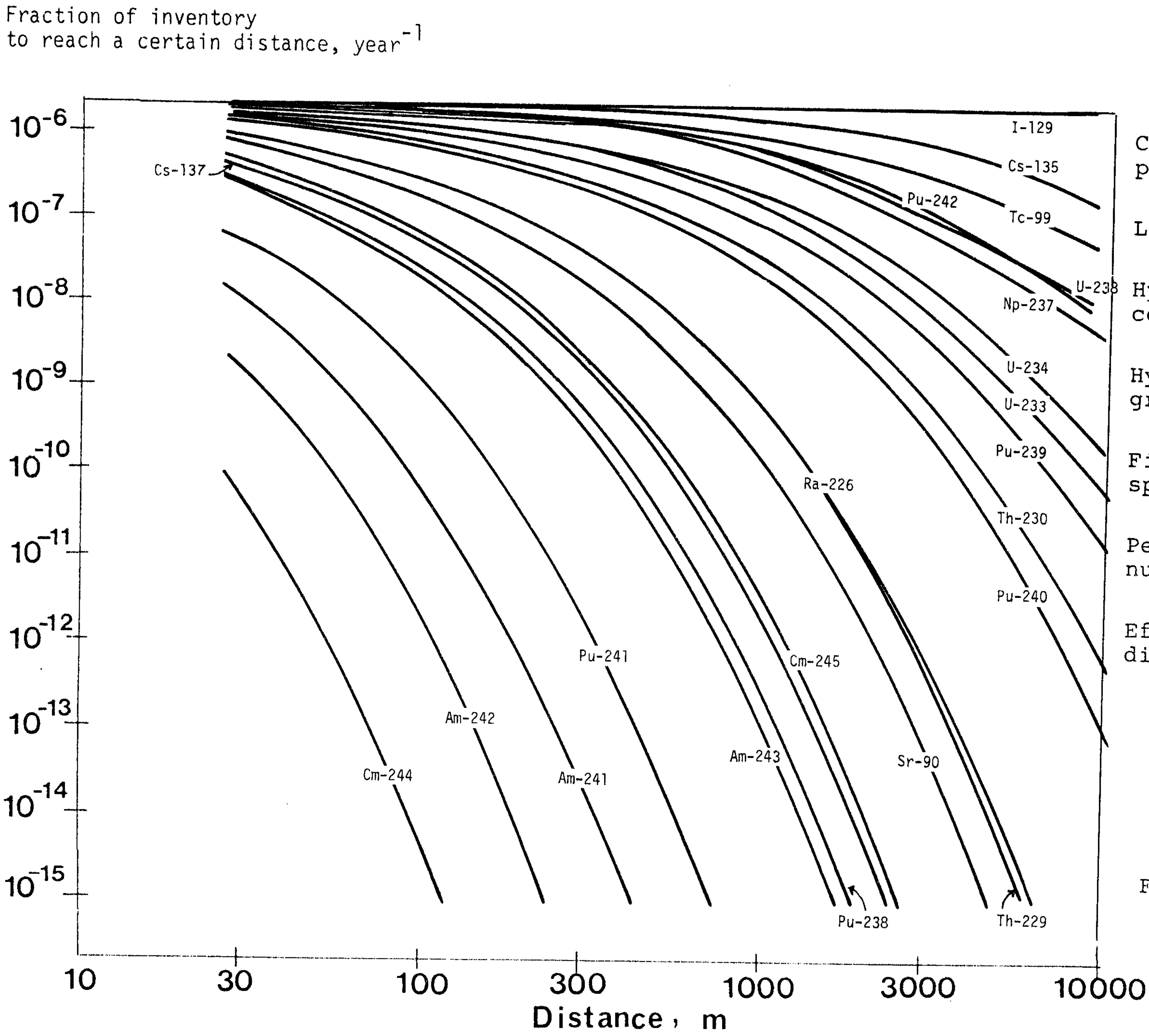
Canister penetration	t_o	0	year
Leach time	Δt	$3 \cdot 10^4$	year
Hydraulic conductivity	K_p	10^{-7}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	50	m
Peclet number	Pe	0.5	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 31



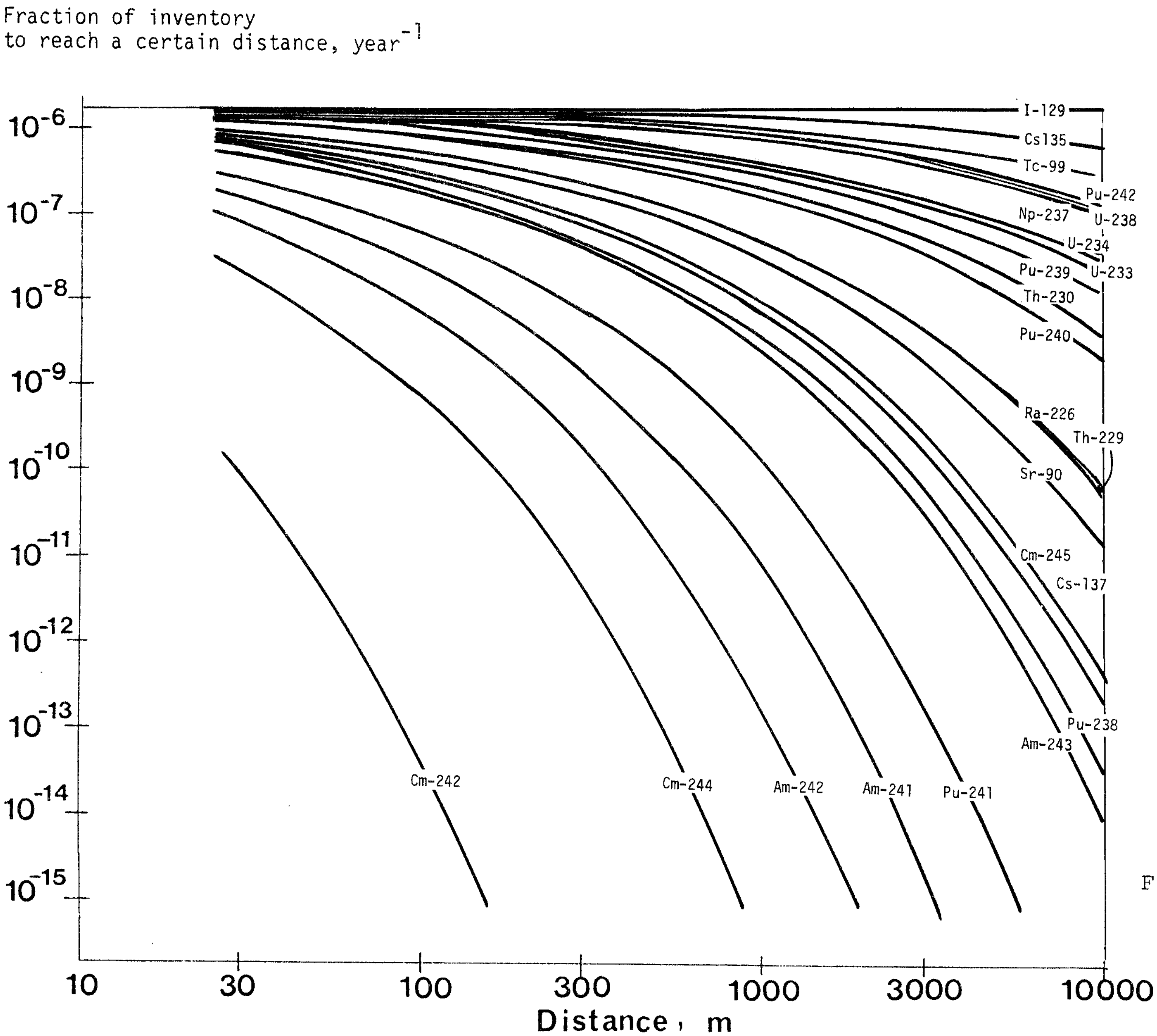
Canister penetration	t_o	0	years
Leach time	Δt	$5 \cdot 10^5$	years
Hydraulic conductivity	K_p	10^{-7}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	50	m
Peclet number	Pe	∞	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 32



Canister penetration	t_o	0	years
Leach time	Δt	$5 \cdot 10^5$	years
Hydraulic conductivity	K_p	10^{-7}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	50	m
Peclet number	Pe	5.0	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 33



Canister penetration	t_o	0	yea
Leach time	Δt	$5 \cdot 10^5$	yea
Hydraulic conductivity	K_p	10^{-7}	m/
Hydraulic gradient	i	0.01	m/ɪ
Fissure spacing	S	50	m
Peclet number	Pe	0.5	-
Effective diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/ɪ

Figure 34

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