Migration of radionuclides in fissured rock: Some calculated results obtained from a model based on the concept of stratified flow 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

Some computed results of radionuclide migration in fissured rock are presented. The computations are based on a model which describes flow as occurring in a multitude of independent fissures (stratified flow). This gives rise to strong "dispersion" or channeling. The radionuclide migration in the individual fissures is modelled by the advection equation in a parallel walled channel with porous walls. The nuclides may diffuse into the pores and sorb reversibly on the pore surfaces.

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 fissure width distribution.

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1. BACKGROUND

Radionuclides which escape from a final repository for high level waste in deep geologic media, will have to migrate through the bedrock to reach the biosphere. In the Swedish concept (KBS 1978) the repository will be in crystalline rock at 500 m depth. The bedrock has a low hydraulic conductivity. Flow of water occurs in fissures in the rock. The radionuclides may interact in several ways with the bedrock. The rock has a low connected porosity of 0.1 - 1 % (Brace 1965, Skagius 1981). The radionuclides may migrate into these pores by diffusion (Neretnieks 1980, Skagius 1981) and may sorb on the pore surfaces. Nonsorbing species may utilize the micropore volume for retardation also, as this pore volume will give an additional residence time, where the radionuclide will have more time to decay.

The water conducting fissures in the bedrock may have fissure coating material e.g. chlorite, calcite (Larson et al. 1981) and fissure filling material, e.g. montmorillonite clay. These substances may also add to the retardation of the sorbing nuclides.

In an individual fissure a nuclide will thus be retarded in relation to the flow velocity of the water by the following mechanisms:

- Sorption on fissure filling and coating material. This is summarily called surface sorption and is quantified by a surface sorption coefficient K_a |m| . K_a indicates the sorption capacity of a nuclide per surface area of fissure.

- Migration into the micropores of the rock by diffusion. The diffusivity in the micropores D_p determines the rate of migration into the pore volume, and the porosity ε_p determines the volume which may be accessed.

- Sorption on the inner surfaces of the rock (microfissure surfaces). This is summarily called volume sorption and is quantified by a volume sorption coefficient $K_d\rho_p$ m^3/m^3.

As a first approximation and due to the lack of better data for most radionuclides, the sorption coefficients K_a, $K_d\rho_p$ and the diffusivity D_p for every nuclide is assumed to be constant, independent of concentration and time.

Different fissures may have different flow velocities, and the set of individual pathways from the repository to the biosphere which are made up of individual connected fissures, may also have considerable variations in travel times. In porous media such variations are described by the term hydrodynamic dispersion. In sparsely fissured rock individual channels may be poorly connected to others. In extreme cases the bedrock might be seen as consisting of a series of independent channels which all have different water velocities and flowrates. Such cases exhibit a "dispersion" behaviour entirely different from "normal" hydrodynamic dispersion as the fast channels do not dilute their nuclides in the water of the slower channels. If such channeling occurs, the fast channels may carry the nuclides much faster than the average water velocity of the bedrock. The time for decay might in some cases be so much less as to make a significant difference in the effluent concentrations. (Neretnieks 1981)

The model used in this study includes the effects of channeling (or stratified flow), surface sorption, matrix diffusion and volume sorption.

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2. MODEL USED FOR COMPUTATIONS

The derivation of the model is given in extenso in (Neretnieks 1980 and Neretnieks et al. 1981). A summary is given below.

Individual fissure

In an individual fissure of width δ where the fissure walls are porous, the tracer concentration c_f in the fluid in the fissure is determined by

$$\frac{\partial c_f}{\partial t} \cdot R + U_f \frac{\partial c_f}{\partial x} = \frac{2D_e}{\delta} \cdot \left.\frac{\partial c_p}{\partial z}\right|_{z=0} \tag{1}$$

$$R = 1 + \frac{2K_a}{\delta} \tag{2}$$

R is the retardation factor due to surface sorption.

U_f is the water velocity in the fissure.

D_e is the effective diffusivity in the micropores.

z is the depth into the wall.

x is the distance along the fissure.

The last term describes the loss of tracer from the fluid flowing in the fissure due to diffusion into the porous matrix of the wall. In this model hydrodynamic dispersion is neglected. The diffusion into the matrix is given by

$$\frac{\partial c_p}{\partial t} = D_a \frac{\partial^2 c_p}{\partial z^2} \tag{3}$$

where

$$D_a = D_e / K_d \rho_p$$

and c_p is the concentration in the fluid in the pores.

The initial and boundary conditions are: Decaying step input at the inlet (x=0) starting at time t_o and ending at time $t_o + \Delta t$. The bedrock is initially free of nuclide. This can be written

Initial condition

$$c_p = c_f = 0 \qquad t < t_o \quad \text{all } x \text{ and } z \tag{4}$$

Boundary condition 1

$$c_p = c_f = 0 \qquad \text{when} \quad t > 0 \quad \text{for } z \to \infty \tag{5}$$

Boundary condition 2

$$c_f = c_o e^{-\lambda t} \quad \text{for} \quad t_o < t < t_o + \Delta t \quad \text{at} \quad x = 0 \tag{6}$$

$$c_f = 0 \quad \text{for} \quad t > \Delta t \quad \text{at} \quad x = 0$$

The solution to these equations have been obtained by the Laplace transform method (Neretnieks 1980). The solution is

$$c_p / c_c = e^{-\lambda t} \quad \text{erfc}\left[\frac{G}{(t - t_o - Rt_w)^{\frac{1}{2}}}\right] - \text{erfc}\left[\frac{G}{(t - t_o - \Delta t - Rt_w)^{\frac{1}{2}}}\right] \tag{7}$$

where

$$G = \left\{\left[D_e + \frac{1}{2}\frac{U_f \delta z}{x}\right] / \delta D_a^{\frac{1}{2}}\right\} t_w \tag{8}$$

The solution applies for $z > 0$ and $x > 0$ and for $t > Rt_w + t_o$ for the first erfc expression and for $t > Rt_w + t_o + \Delta t$ for the second erfc expression. Otherwise these expressions are 0 .

The concentration in the fissure c_f is obtained for $z = 0$ and becomes

$$c_f/c_o = e^{-\lambda t}\left\{\mathrm{erfc}\left[\frac{1}{H^{\frac{1}{2}}(t - t_o - Rt_w)^{\frac{1}{2}}}\right] - \mathrm{erfc}\left[\frac{1}{H^{\frac{1}{2}}(t - t_o - \Delta t - Rt_w)^{\frac{1}{2}}}\right]\right\} \quad (9)$$

where

$$H = \frac{\delta^2}{t_w^2 D_e K_d \rho_p} \quad (10)$$

as

$$D_a = D_e/K_d\rho_p \quad (11)$$

The entities δ and t_w in equation 10 are difficult to measure in the field. They may be determined from other entities which are more amenable to observations.

With

$$t_w = x/U_f, \quad U_f = U_o/\varepsilon_f$$

and

$\varepsilon_f = \delta/S$ where U_o is the water flux m^3/m^2 of bedrock $\cdot$ s

S is fissure spacing

we obtain

$$\frac{\delta}{t_w} = \frac{\delta U_f}{x} = \frac{\delta U_o}{\varepsilon_f x} = \frac{SU_o}{x} \quad (12)$$

With this H becomes

$$H = \frac{S^2U_o^2}{x^2 D_e K_d \rho_p} \quad (13)$$

It is interesting to note that it is not necessary to know the actual fissure width, nor the actual water velocity for strongly volume sorbing nuclides. For the applications of interest in this study the time t is very much larger than Rt_w. For such cases the entity H is sufficient to describe the fissure.

Equation 9 is used to determine the concentration as it evolves with time in a single fissure.

Channeling model

The bedrock is assumed to consist of independent channels where the water flows with different velocities and flowrates. The model is based on the following concepts.

Derivation of model

At the inlet end of the channels a tracer is introduced. This is done simultaneously in all channels. At some distance downstream, the fluid from all channels is collected and mixed. The concentration of the mixture is measured over time. As some fissures carry the tracer faster than others, a step at the inlet will have spread when observed at the outlet. The fissure width distribution is $f(\delta)$. In a parallel walled fissure of width δ_i with laminar flow, the flow rate $Q(\delta_i)$ is proportional to the fissure width to the third power

$$Q(\delta_i) = k_1 \delta_i^3 \ell \qquad (14)$$

where ℓ is the breadth of the fissure. The velocity is proportional to the fissure width squared.

$$U_i = k_1 \delta_i^2 \qquad (15)$$

The residence time in fissures with width δ_i over a given distance x is:

$$t_i = \frac{x}{k_1 \delta_i^2} \qquad (16)$$

If a step with concentration c_o is introduced at the inlet of the set of fissures, it will travel the distance x in time t_i in fissures of width δ_i. The fissures with residence times less than t will carry tracer, a fissure with residence time longer than t will carry no tracer.

The concentration obtained at the outlet end, at a time t when the effluent from all fissures is collected and mixed, is the sum of the flow from all fissures with tracer at the outlet, divided by the total flow.

$$\frac{c(t)}{c_o} = \frac{\int_{\delta^1}^{\infty} f(\delta)Q(\delta)\,d\delta}{\int_{0}^{\infty} f(\delta)Q(\delta)\,d\delta} = \frac{Q_t}{\overline{Q}} \tag{17}$$

t is the residence time in fissure $\delta^1(t)$ given by equation 16.

The above expression says that the flow Q_t from the tracer carrying fissures with widths $\delta^1(t) \leq \delta < \infty$ is diluted by the total flow of water $\overline{Q}$ from all fissures.

In general, for channels with a concentration break-through curve $c(\delta,t)$ at the outlet, the concentration of the mixed effluent from all channels is

$$\frac{c(t)}{c_o} = \frac{\int_{c}^{\infty} f(\delta)Q(\delta)c(\delta,t)\,d\delta}{\int_{0}^{\infty} f(\delta)Q(\delta)\,d\delta} \tag{18}$$

Snow (1970) obtained the fissure width frequencies $f(\delta)$ for various consolidated rocks including granites. Snow used data from water injection tests in boreholes and from direct measurements of fissure widths. He found the distribution to be log normal

$$f\left(\frac{\delta}{\mu}\right) = \frac{1}{A}\cdot e^{-\frac{1}{2}\left(\frac{\log\frac{\delta}{\mu}}{\sigma_\ell}\right)^2} \tag{19}$$

Snow (1970) found standard deviation varying between 0.057 and 0.394. His average value is 0.221. If a nonreacting and non-diffusing tracer were used to monitor the spreading of a tracer pulse in a system of fissures such as in the model above, an equivalent dispersion could be determined. This has been done by determining the second statistical moment (Neretnieks 1981).

For $\sigma_\ell = 0.22$ the Peclet number which is defined below, is 1.1

$$Pec = \frac{U_f x}{D_L} \tag{20}$$

This indicates a very large dispersion. Such large dispersivities have been found in field experiments.

The channeling model indicates that the dispersion coefficient should increase with observation distance. This is usually found in field experiments. (Lallemand-Barrès and Peaudecerf 1978)

3. NUCLIDE RELEASE RATE

The time for canister penetration t_o is counted from an arbitrary starting time. It may be the time when the fuel is taken out from the reactor. At that time the waste contains N_{oi} Curies of nuclide i/ton of waste. The inventory of this nuclide will decay.

At time t the waste contains

$$N_i = N_{oi} \cdot e^{-\lambda_i t} \qquad |Ci/ton| \tag{21}$$

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. The release of a nondecaying nuclide during the dissolution time then is

$$n_{oi} = \frac{N_{oi}}{\Delta t} \qquad \left|\frac{Ci}{\text{ton of original waste} \cdot \text{year}}\right| \tag{22}$$

At time t the release rate for a decaying nuclide then is

$$n_i = n_{oi} \cdot e^{-\lambda_i t} = \frac{N_{oi} \cdot e^{-\lambda_i t}}{\Delta t} \tag{23}$$

This amount of nuclide is diluted in a given stream of water which flows through the bedrock. Its initial concentration at $t = 0$ will be c_{oi} . The nuclide travelling with the water will be subject to decay and loss due to diffusion into the matrix where the nuclide will have additional time to decay.

The concentration in the flowing water is observed at a distance x downstream. This concentration is obtained from equation (9) for a single channel and from equations (9, 18, 19) for the multiple channel case. The flowrate of nuclide i at distance x is

$$n_i^x = n_{oi} \cdot c_{fi}/c_{oi} = \frac{N_{oi}}{\Delta t} \cdot \frac{c_{fi}}{c_{oi}} \quad \left|\frac{\text{Ci}}{\text{ton} \cdot \text{year}}\right| \tag{24}$$

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

$$\frac{n_i^x}{N_{oi}} = \frac{1}{\Delta t} \cdot \frac{c_{fi}}{c_{oi}} \quad \left|\frac{\text{fraction}}{\text{year}}\right| \tag{25}$$

4. DATA USED

The nuclides treated in this study are listed in table 1. Halflives and mass sorption coefficients are taken from the Nuclear Fuel Safety project study (KBS 1978). Mass sorption coefficients are converted to volume sorption coefficients by multiplying it with the rock density $\rho_p = 2700\ kg/m^3$.

The data needed for the present model are

Time of canister penetration	t_o	|year|
Time for dissolution of waste[a]	Δt	|year|
Standard deviation of fissure width (channel) distribution	σ_ℓ	—
Matrix penetration parameter eq (10) or (13) for nuclide i	H_i	$\|year^{-1}\|$

a) constant dissolution rate is assumed.

Times for canister penetration of 0.1, 40, 5000 and 10^5 years have been used. Dissolution times of 30 000, 300 000, 500 000, $3 \cdot 10^6$ and 10^9 have been used. The standard deviation of the fissure width distribution σ_ℓ has been given the values 0 (equal fissure widths) and 0.221 .

The matrix penetration parameter H includes many entities

$$H_i = \frac{S^2 U_o^2}{x^2 D_e K_d \rho_p} \qquad (13)$$

With $U_o = K_p\,i$ and with a hydraulic conductivity K_p of 10^{-9} m/s and hydraulic gradient $i = 0.01$ m/m $U_o = 10^{-11}\ m^3/m^2 \cdot s$ or approximately 0.3 $l/m^2 \cdot$ year. With a fissure spacing $S = 1$ m and an effective diffusivity $D_e = 10^{-12}\ m^2/s$, the group α

$$\alpha = \frac{S^2 \cdot K_p^2 \cdot i^2}{D_e} \tag{26}$$

has a value of $10^{-10}\ |m^2/s|$.

The same value of α could be obtained with another combination of values for the individual variables. The noted values of S, K_p, i and D_e are in the range of values expected for the Swedish bedrock. They are used as central case values.

The water velocity which gives the water residence time t_w is calculated from equation (16). The constant k_1 is obtained from laminar flow theory applied to flow between infinite parallel plates (Snow 1968).

$$k_1 = g/12\,\nu\,i$$

where the gravitational constant $g = 9.81\ m/s^2$ and the viscosity of water $\nu = 10^{-6}\ m^2/s$. The water residence time t_w per se has no influence of the results for all practival purposes. This applies also to non-interacting nuclides such as I-129 except for the earliest breakthrough times if the assumption (equation 5) is valid that the slab of rock between two fissures will never be saturated.

5. COMPUTED CASES

Table 2 gives the data for the cases presented in this paper. The cases are divided in two main groups. In the first, all the fissures have equal width which implies that there is no channeling and no hydrodynamic dispersion. These are the cases 1-8. The second group assumes a strong channeling with $\sigma_\ell = 0.221$.

6. PRESENTATION OF RESULTS

For every case the effluent fraction n_i^x/N_{oi} of each nuclide have been calculated at various distances x and for times up to a maximum of 10^9 years. Figures 1-8 show the breakthrough curves at 1000 m distance for all those nuclides which have a c_f/c_o larger than 10^{-9} at any time.

It can be seen that in case 1 with no channeling only I-129 will arrive with a release rate higher than 10^{-13} of the original inventory per year (Figure 1). The same case with severe channeling is shown in figure 4 (case 13).

Another type of plot is shown in figures 9-26. They have been constructed by plotting the maximum points in figures 1-8 (and many more) versus distance. They thus show the maximum fraction of the original content of the inventory which can reach a certain distance at any time. At all other times the fraction will be less (or equal).

7. DISCUSSION

The hydraulic conductivity K_p, hydraulic gradient i and the fissure spacing S influence the results in the same way. All three parameters are part of the group

$$\alpha = \frac{S^2 \cdot K_p^2 \cdot i^2}{D_e} \qquad (26)$$

The effective diffusivity is also included in this group.

The four entities influence the results only through this group and need thus not be considered separately.

There is an inherent assumption which may not be valid when the fissure spacing is small or when the nuclide sorbs poorly (small $K_d\rho_p$). The assumption is that the penetration depth of the nuclide into the rock from the surface of the fissure is smaller than half the distance between fissures. Penetration depths for various $K_d\rho_p$ values have been calculated (Neretnieks 1980).

For $K_d\rho_p$ values around 100 m^3/m^3 (Cs, Sr, Tc) about $5 \cdot 10^4$ years will suffice to penetrate 0.5 and about $1.2 \cdot 10^8$ will be needed to penetrate 25 m. For radium and the actinides with $K_d\rho_p \sim 10^3$ (Pa, U, Pu) it takes 10 times longer to penetrate the same depths and for Th, Am and Cm with $K_d\rho_p \sim 10^4$ and larger it will take $\sim 5 \cdot 10^6$ and $1.2 \cdot 10^{10}$ years to penetrate 0.5 and 25 m respectively. Iodide with $K_d\rho_p = 0.005$ will need $\sim$ 2.5 years to penetrate 0.5 m and 6200 years to penetrate 25 m.

The analysis will not be valid for iodide except for the very short times. The presented curves will underestimate the effluent concentration for iodide. For most of the other nuclides the larger fissure spacing 50 m will not infringe upon the assumption whereas a smaller fissure spacing 1 m will invalidate the results for Cs-135 and Tc-99 for a high hydraulic conductivity ($K_p = 10^{-7}$ m/s fig 3 and figure 12). For smaller hydraulic conductivities, 10^{-8}, these nuclides will become unimportant at distances over 1000 m. It is very doubtful, however, if fissures with equal widths and hydraulic conductivities may be spaced as closely as 1 m. The cases with equal fissure widths ($\sigma_\ell = 0$) should more be seen as cases for single large fissures. The fissure spacing S would then mean that if such fissures were placed at distances S the average permeability of such a rock mass would become K_p.

For a rock mass with varying fissure widths (and thus conductivities) the faster fissures will dominate the breakthrough curves. As these larger fissures make up a small fraction of all fissures they will be much more widely spaced than S. The easy and more interesting part of the breakthrough curves may thus not seriously violate the assumption.

The results from these calculations can be compared to those in KBS 1978 concerning the direct deposition of spent fuel. Case 21 has the same t_o and Δt and sorption coefficients K_d as the main case in KBS 1978. Practically the same water flowrate is used, $U_o = 3 \cdot 10^{-4}$ $m^3/m^2 \cdot$ year in case 21 and $2 \cdot 10^{-4}$ $m^3/m^2 \cdot$ year in KBS 1978. The fissure spacing is the same S = 1 m. The water velocity as such does not influence the results for the sorbing nuclides. The distance is not defined in KBS 1978 but is much larger than 1000 m.

This type of comparison is quite misleading, however. In KBS 1978 the computed retardation factors were based on the assumptions of surface sorption. The retardation factor R_i was calculated from

$$R_i = 1 + \frac{a\,K_{ai}}{\varepsilon_f} (1-\varepsilon_f)$$

where

a = specific surface $\left|\frac{m^2}{m^3 \text{ rock}}\right|$

K_{ai} = surface sorption coefficient $|m|$

ε_f = flow porosity of bedrock

The flow porosity of the bedrock was taken to be 10^{-5}. The use of this porosity in the present study would lead to an equivalent migration path length of 60 000 m instead of 1 000 m to obtain the residence time of 3 000 years used in (KBS 1978). Under such conditions the present model would predict that no nuclide except I-129 would reach the biosphere in significant amounts.

It should also be noted that the impact of channeling is severe. A comparison of case 1 and 13 shows that in case 1 (figures 1 and 9) only I-129 and U-238 travel past a 100 m mark in any appreciable amount. In this case the fissures are assumed to be of equal width and no dispersion is assumed (In KBS 1978 the dispersion was for all practical purposes neglected).

With severe channeling - case 13 - figure 23 shows that practically all the nuclides studied will be observable at the 100 m point. Even at a distance of 1 000 m, 9 nuclides will arrive with a release larger than 10^{-14}/year of the original inventory.

8. USE OF RESULTS

The results in this study can be used to assess the influence of some important entities on the migration of the most important radionuclides. They may also under some circumstances be used to indicate what effluent rates to the biosphere to expect. The possible combinations of input-parameter values arevast and only a few selected combinations were used. The initial canister breakthrough time t_o was taken to be short in most cases in order to include the shortlived nuclides. Any case can be recalculated to another t_o by accounting for the decay. This is done by multiplying the release by $e^{-\lambda_i(t_o^2 - t_o^1)}$ for every individual nuclide t_o^2 is the new breakthrough time and t_o^1 is the time for which the results are available.

Cases 1-8 apply to no channeling or single fissure cases. They may be used to indicate the release from an individual fissure. One application would be to study transport in an odd large fracture. If the K_p, i, S and D_e values for the case of interest can be found in table 2, the results can be applied in a straightforward manner. When the K_p, i, S, and D_e values cannot be found the combination α (see equation 26) is determined, and the cases having α nearest to the desired case are used.

As an example consider a case where a fissure is expected at every 100 m. The bedrock with these fissures has an average hydraulic conductivity $K_p = 10^{-9}$ m/s. In this rock a 2 m straddle packer test would give a section with $K_p = 0.5 \cdot 10^{-7}$ m/s when the fissure was found, assuming that the rest of the rock is tight. For $i = 0.003$ m/m and $D_e = 10^{-13}$m/s we obtain $\alpha = 0.910^{-6}$ m^2/s. In table 3 we find that case 3 is nearest, $\alpha = 10^{-6}$ m^2/s. For a leach time of $3 \cdot 10^4$ years figures 3 and 12 can be used.

For the single fissure case it is very easy to calculate the breakthrough using the equation (9). It is easily done using a pocket calculator and a table of values of the error function.

When channeling is to be included, cases 13-25 can be used in the same way as examplified for the single channel case. As can be seen by comparing cases 1 and 13 or 4 and 17, 16 and 20 etc. it is evident that for the same average hydraulic conductivity of the bedrock, same fissure spacing etc., a variation of fissure widths will lead to a strong increase in release rates.

The channeling parameter chosen $\sigma_\ell = 0.221$ probably is on the high side for large distances. There is, however, no experimental evidence at present to really assess the channelling or dispersion mechanisms over large distances in fissured bedrock.

Case 21, figures 7 and 23, has about the same basic values of S, K_p and i as those used in the KBS II (1978) safety analysis for spent fuel. The travel distance was not defined in that study.

Table 3 gives a comparison between the KBS II (1978) results and the results from case 21 for 1000 m and 5000 distances. The inventory of radionuclides in 10^4 tonnes of 10^5 years old spent fuel as given in table 8-2 in KBS II 1978 is used for the calculations. Iodide is not included as the calculations do not apply for a non-sorbing nuclide at these very long contact times.

Whereas the KBS II 1978 study predicted releases in the mCi range for some nuclides, this model predicts maximum releases of at most some 10:s of µCi. It should be noted that in the present model a very strong channeling has been assumed.This was not included in KBS II (1978).

Nuclide	Halflife $T_{\frac{1}{2}}$ years	Volume sorption coefficient $K_d\rho_p$ a) m^3/m^3
Sr-90	28.8	43
Tc-99	212 000	135
I-129	$17 \cdot 10^6$	0.005 b)
Cs-135	$3 \cdot 10^6$	170
Cs-137	30.2	170
Ra-226	1 600	1 350
Th-229	7 340	6 480
Th-230	80 000	6 480
Pa-231	32 500	1 620 c)
U-233	162 000	3 240
U-234	247 000	3 240
U-238	$4.51 \cdot 10^9$	3 240
Np-237	$2.14 \cdot 10^6$	3 240
Pu-238	86	810
Pu-239	24 400	810
Pu-240	6 580	810
Pu-241	13.2	810
Pu-242	379 000	810
Am-241	458	86 000
Am-242-m	152	86 000
Am-243	7 370	86 000
Cm-244	17.6	43 000 d)
Cm-245	9 300	23 000

Table 1. Nuclides considered in this study.
No chain decay is accounted for.

a) Nuclear fuel safety project (1978), vol.II Technical report, Stockholm.

b) $K_d \rho_p$ equal to porosity of granite matrix.

c) Assumed half that of U. Calculated only for case 13.

d) See J.Geophys.Res. 85, 1980, p 4379. Half of value for Am-243

		No channeling $\sigma_\ell = 0$								Channeling $\sigma_\ell = 0.221$								
Case		1	2	3	4	5	6	7	8	13	16	17	18	20	21	23	24	25
α	m^2/s	10^{-10}	10^{-4}	10^{-6}	10^{-8}	10^{-10}	10^{-10}	10^{-10}	10^{-10}	10^{-10}	10^{-8}	10^{-12}	10^{-10}	10^{-10}	10^{-10}	$2.2 \cdot 10^{-10}$	$2.2 \cdot 10^{-8}$	$2.2 \cdot 10^{-6}$
K_p	m/s	10^{-9}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-9}	10^{-9}	10^{-9}	10^{-9}	10^{-8}	10^{-10}	10^{-9}	10^{-9}	10^{-9}	10^{-10}	10^{-9}	10^{-8}
i	m/m	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.003	0.003	0.003
S	m	1	1	1	1	1	1	1	1	1	1	1	1	1	1	50	50	50
t_o	years	40	40	40	40	5000	5000	5000	40	40	40	40	5000	5000	10^5	0.1	0.1	0.1
Δt	years	$3 \cdot 10^4$	$3 \cdot 10^4$	$3 \cdot 10^4$	$3 \cdot 10^4$	$3 \cdot 10^4$	$3 \cdot 10^5$	$3 \cdot 10^6$	10^9	$3 \cdot 10^4$	$3 \cdot 10^4$	$3 \cdot 10^4$	$3 \cdot 10^4$	$3 \cdot 10^6$	$5 \cdot 10^5$	10^9	10^9	10^9
Figure no:		1,9	2,10,11	3,12	1,13	14	15	16	17	4,18	19	20	5,21	6,22	7,23	8,24	25	26

$D_e = 10^{-12}$ m^2/s for all cases

Table 2. Data for the cases presented.
Cases 1 and 13 are the central cases without and with channeling.

Nuclide	Radioactivity per 10^4 tonnes after 10^5 years	Maximum inflow to recipient area		
		Case 21 1000 m	Case 21 5000 m	KBS II (1978)
	Ci	Ci/yr	Ci/yr	Ci/yr
Cs-135	2 500	$3 \cdot 10^{-6}$	$8 \cdot 10^{-8}$	$3 \cdot 10^{-4}$
Tc -99	100 000	$3 \cdot 10^{-5}$	$5 \cdot 10^{-7}$	$2 \cdot 10^{-5}$
U-238	3 100	$3 \cdot 10^{-7}$	$9 \cdot 10^{-9}$	$6 \cdot 10^{-3}$
Pu-242	13 000	10^{-6}	$1.3 \cdot 10^{-8}$	$<< 10^{-9}$
Np-237	11 000	$3 \cdot 10^{-7}$	$6 \cdot 10^{-9}$	10^{-10}
U-234	14 000	10^{-7}	$8 \cdot 10^{-10}$	$6 \cdot 10^{-3}$
U-233	3 800	$2 \cdot 10^{-8}$	$2 \cdot 10^{-10}$	10^{-10}
Th-230	9 000	$2 \cdot 10^{-9}$	$3 \cdot 10^{-11}$	$3 \cdot 10^{-3}$
Pu-239	200 000	$2 \cdot 10^{-8}$	$2 \cdot 10^{-10}$	n.a.
Ra-226	1 600	n.a.*	n.a.*	$3 \cdot 10^{-3}$

* Ra-226 is a daughter of Th 230 and will in these circumstances be very near radioactive equilibrium with Th-230. The Ra-226 activity would then be of the same magnitude as Th-230 activity.

Table 3. Maximum inflow of activity to recipient area from a repository with 10 000 tonnes of spent fuel. Case 21 $K_p = 10^{-9}$ m/s, i = 0.01 m/m, $D_e = 10^{-12} m^2/s$, S = 1 m, $t_o = 10^5$ years, $\Delta t = 5 \cdot 10^5$ years.

NOTATION

a	specific surface	m^2/m^3 fluid
c	concentration in the liquid	mol/m^3
c_o	initial concentration in the liquid	mol/m^3
c_f	concentration in the liquid in a fissure	mol/m^3
c_p	concentration in the liquid in a pore	mol/m^3
c_s	concentration on the solid	mol/m^2
D_a	apparent diffusivity $D_a = D_e/K_d\rho_p$	m^2/s
D_e	effective diffusivity $= D_p\varepsilon_p$	m^2/s
D_L	dispersion coefficient	m^2/s
D_p	diffusivity in micropores	m^2/s
G	see equation 8	
g	gravitational constant	m/s^2
H	see equations 10 and 13	
i	hydraulic gradient	m/m
K_a	surface sorption coefficient	m
$K_d\rho_p$	volume sorption coefficient	m^3/m^3
K_p	hydraulic conductivity	m/s
n	nuclide release rate at repository	Ci/ton, year
n^x	nuclide release rate at distance x	Ci/ton, year
R	retardation factor due to surface sorption	-
Q	flow rate	m^3/s
$\bar{Q}$	mean flow rate	m^3/s
Q_t	flow rate carrying tracer	m^3/s
R	retardation factor	-
S	fissure spacing	m
t	time	s
t_o	time at which leaching of waste starts	s
t_w	water residence time	s
Δt	time for dissolution of waste	s
U_f, U	fluid velocity in a fissure	m/s
U_o	water flux	m^3/m^2
x	distance in flow direction	m
z	distance into rock matrix	m
α	see equation 26	-
δ	fissure width	m

ε_f	porosity considering fissure volume only	-
ε_p	porosity of rock matrix excluding fissures	-
λ	radioactive decay constant	s^{-1}
μ	mean fissure width	m
ν	viscosity of fluid (water)	m^2/s
ρ	density of rock matrix	kg/m^3
σ_ℓ	standard deviation of the logarithm of fissure widths	-

Subscript

i	nuclide i or fissure i
o	at time = 0

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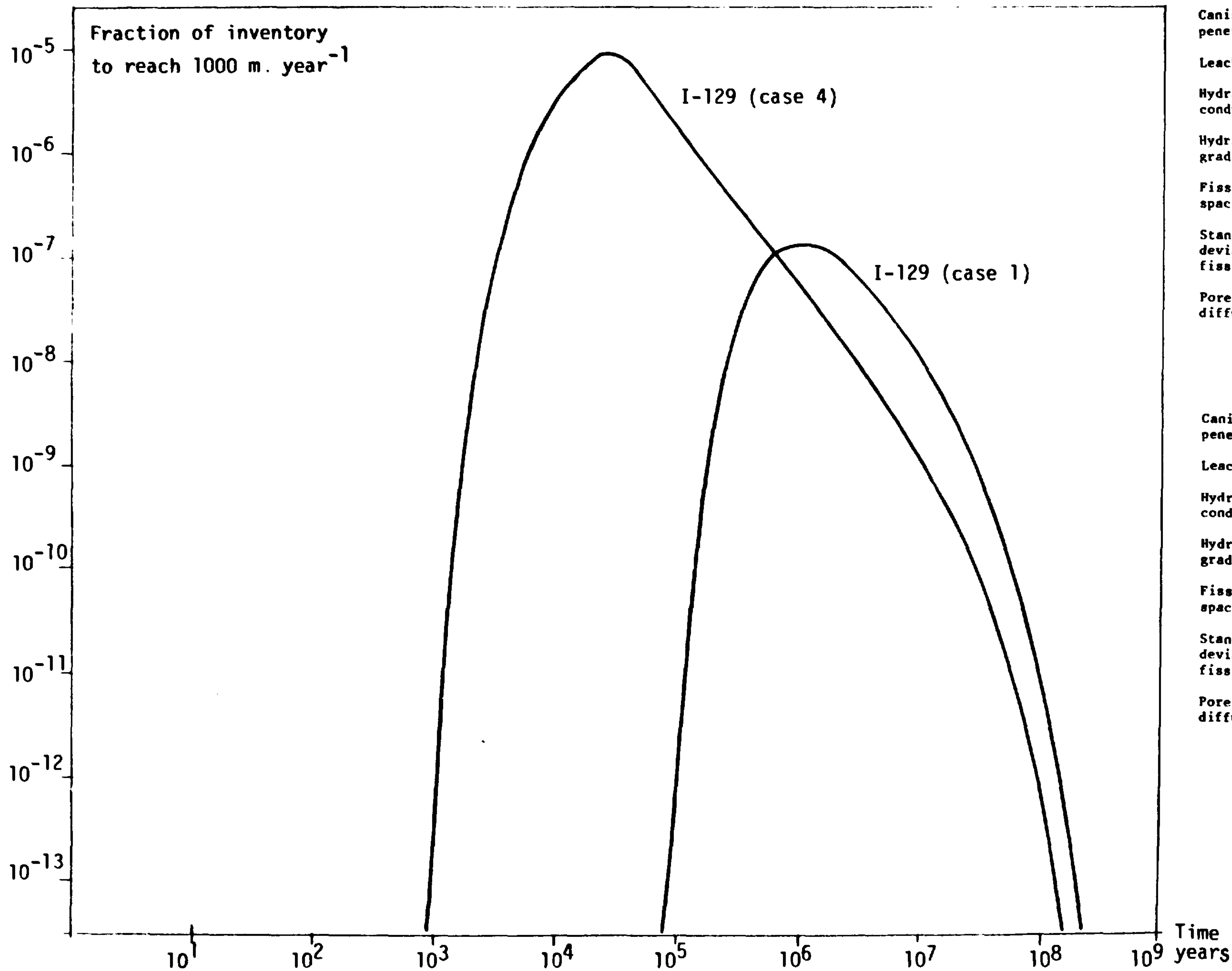
IN/Esp



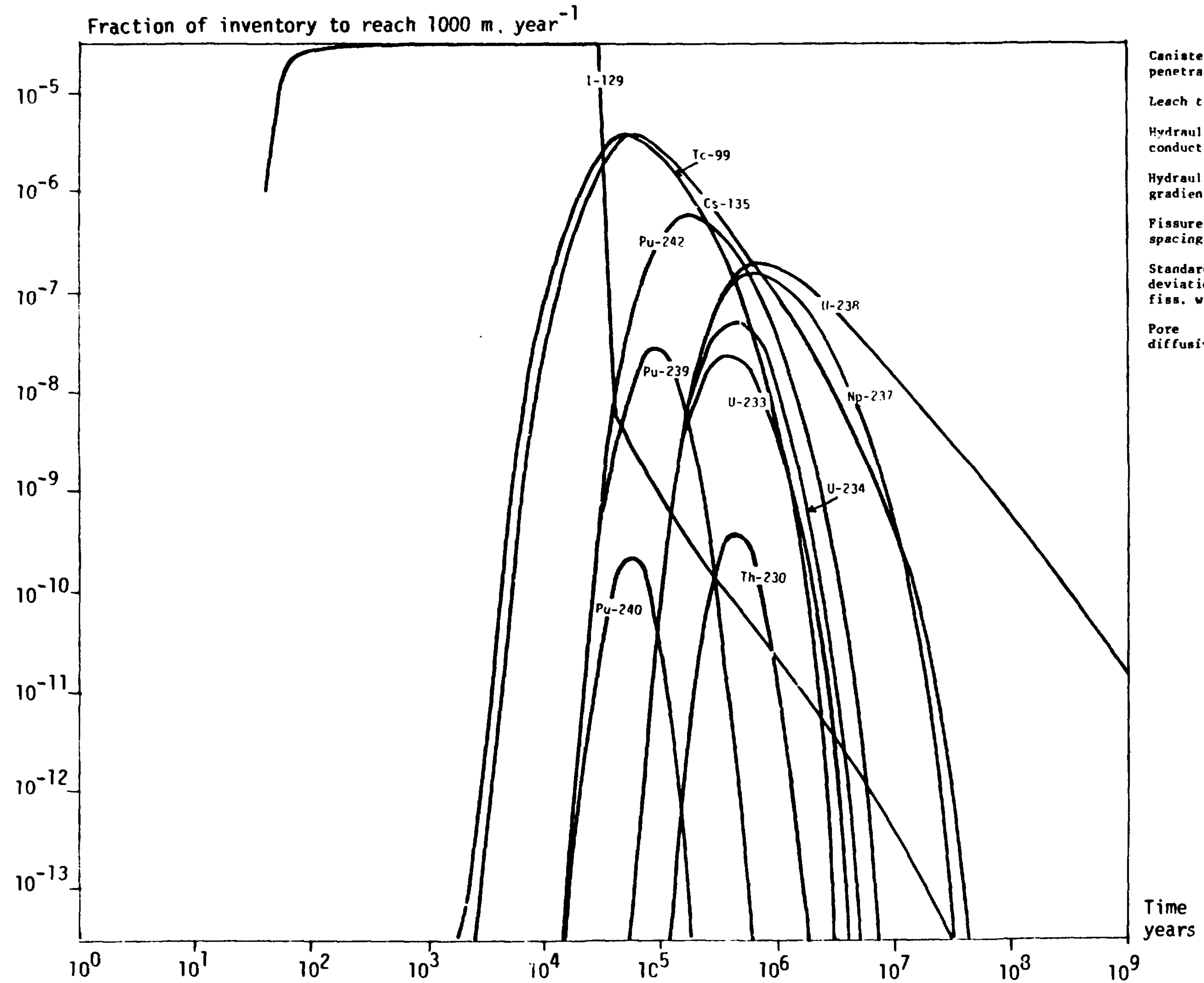
Canister penetration	t_o	40	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0	-
Pore diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Case 1

Canister penetration	t_o	40	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-8}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0	-
Pore diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2

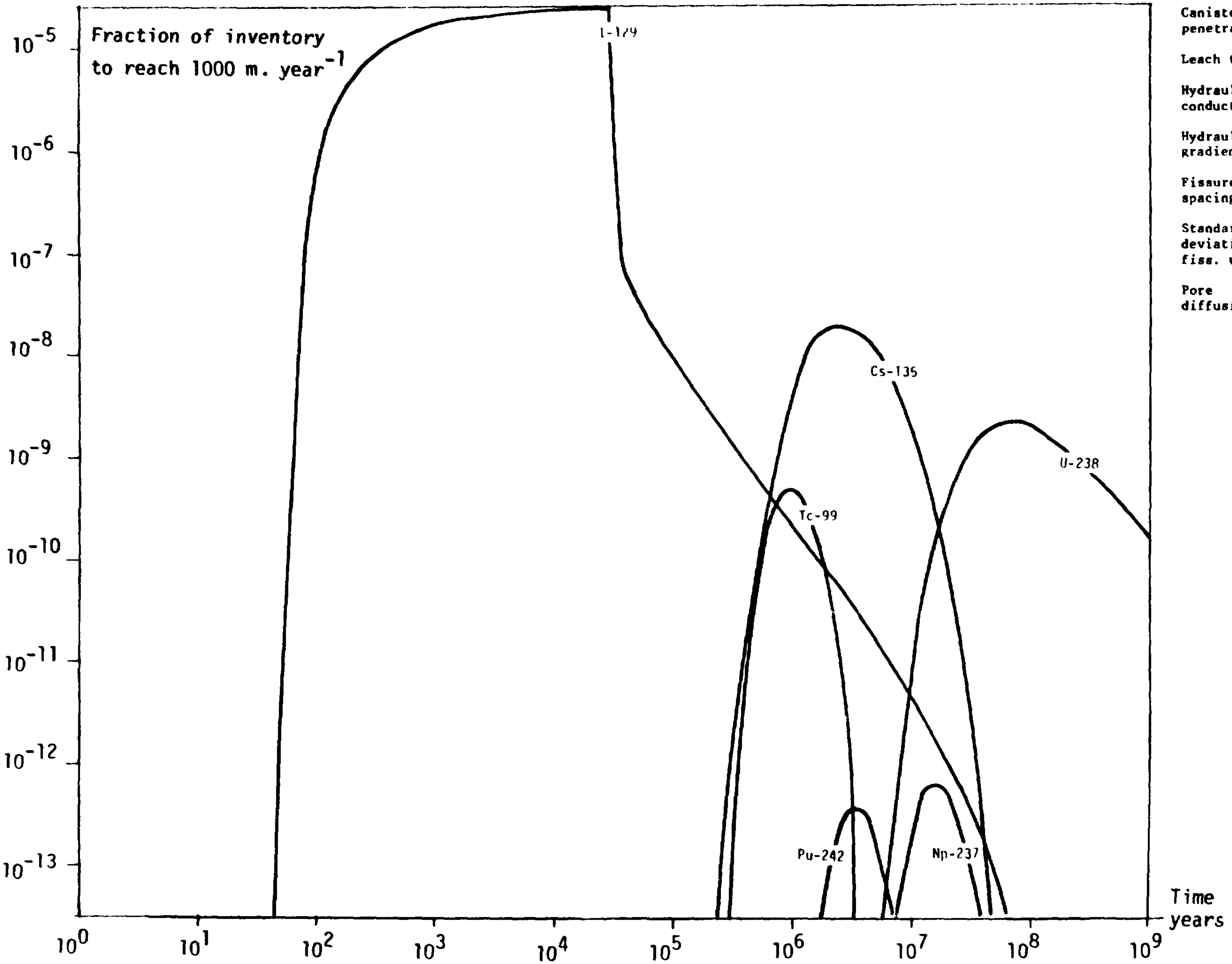
Case 4

Figure 1



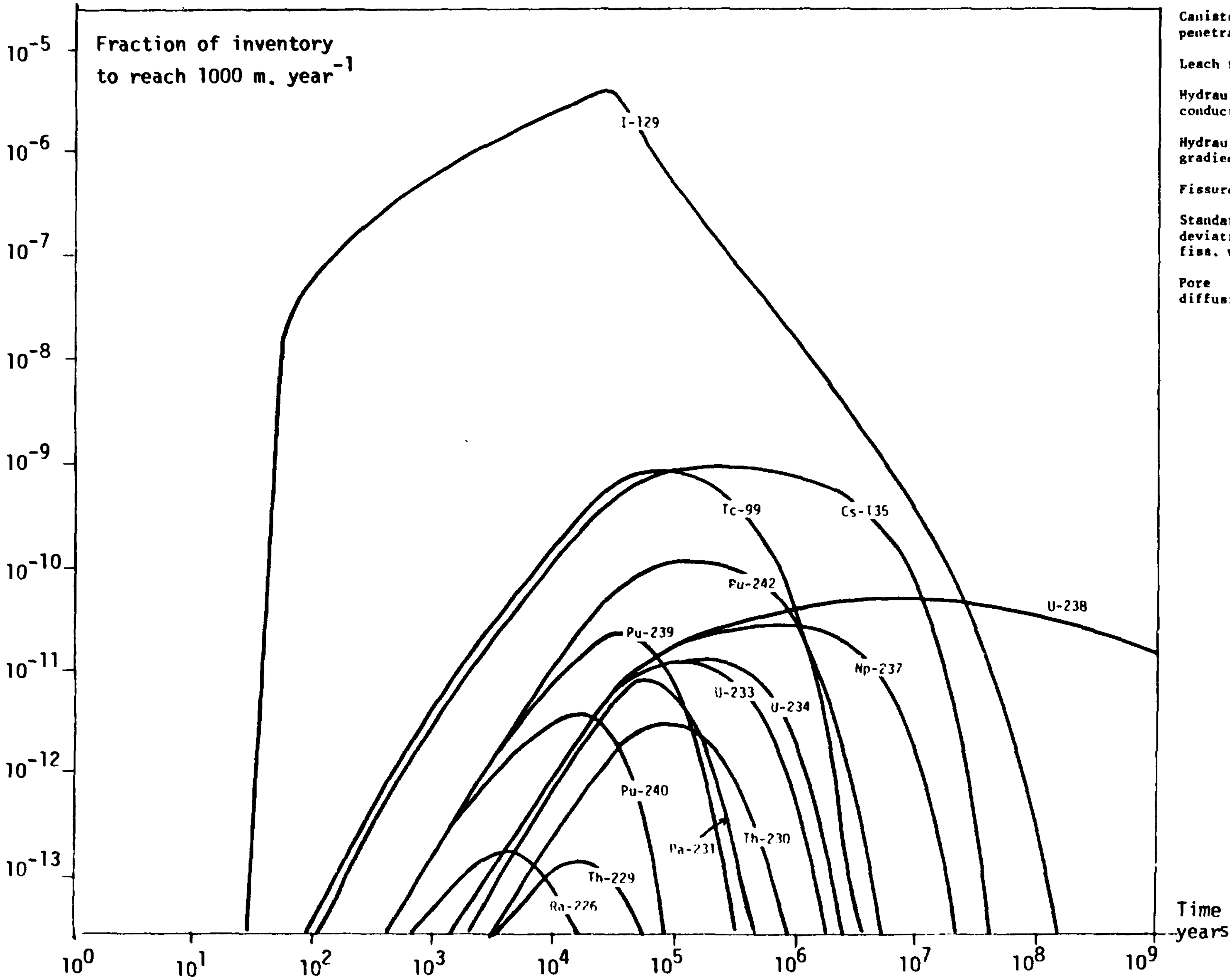
Canister penetration	t_o	40	years
Leach time	Δt	$3 \cdot 10^{4}$	years
Hydraulic conductivity	K_p	10^{-6}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0	-
Pore diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 2



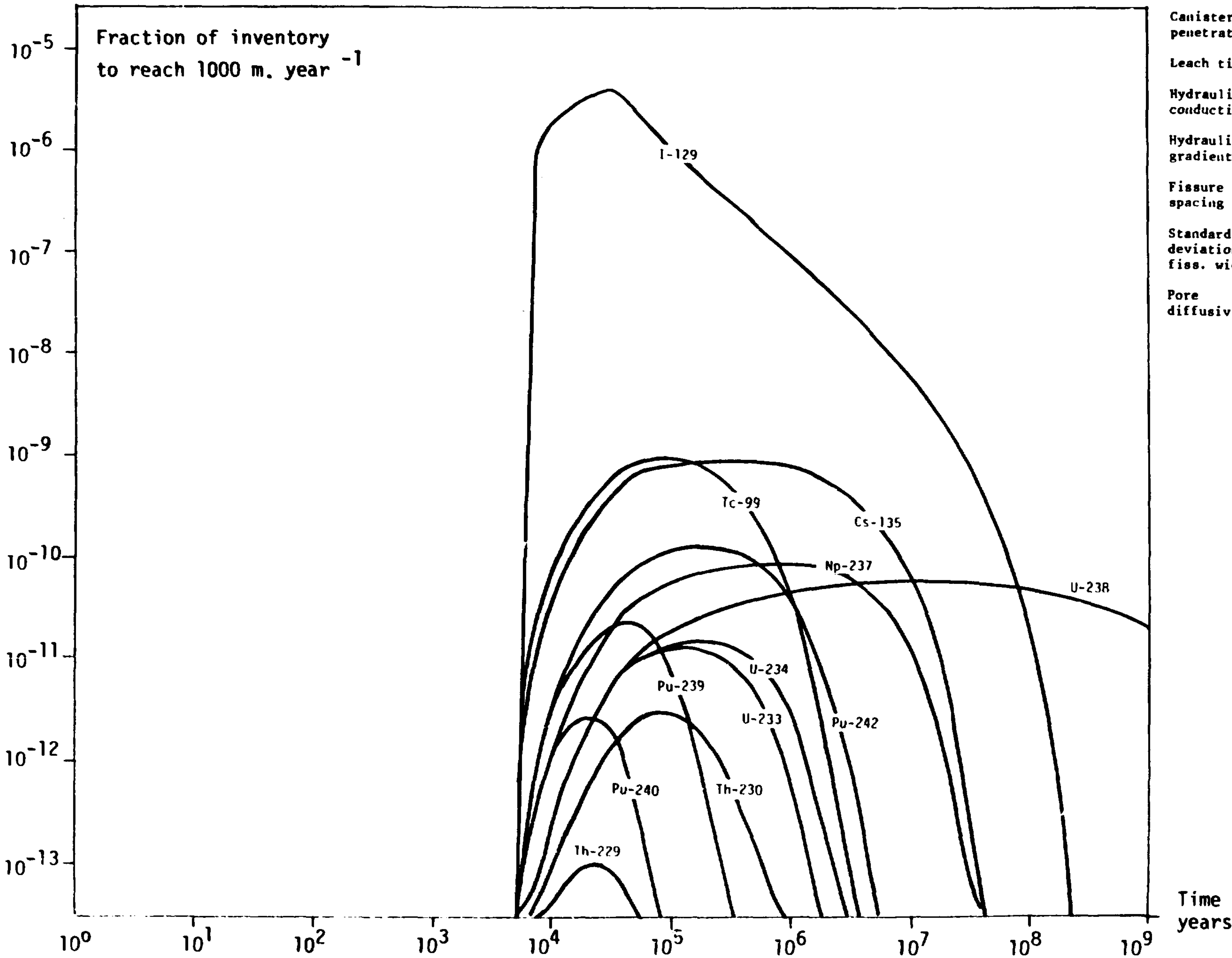
Canister penetration	t_o	40	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-7}	years
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0	-
Pore diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 3



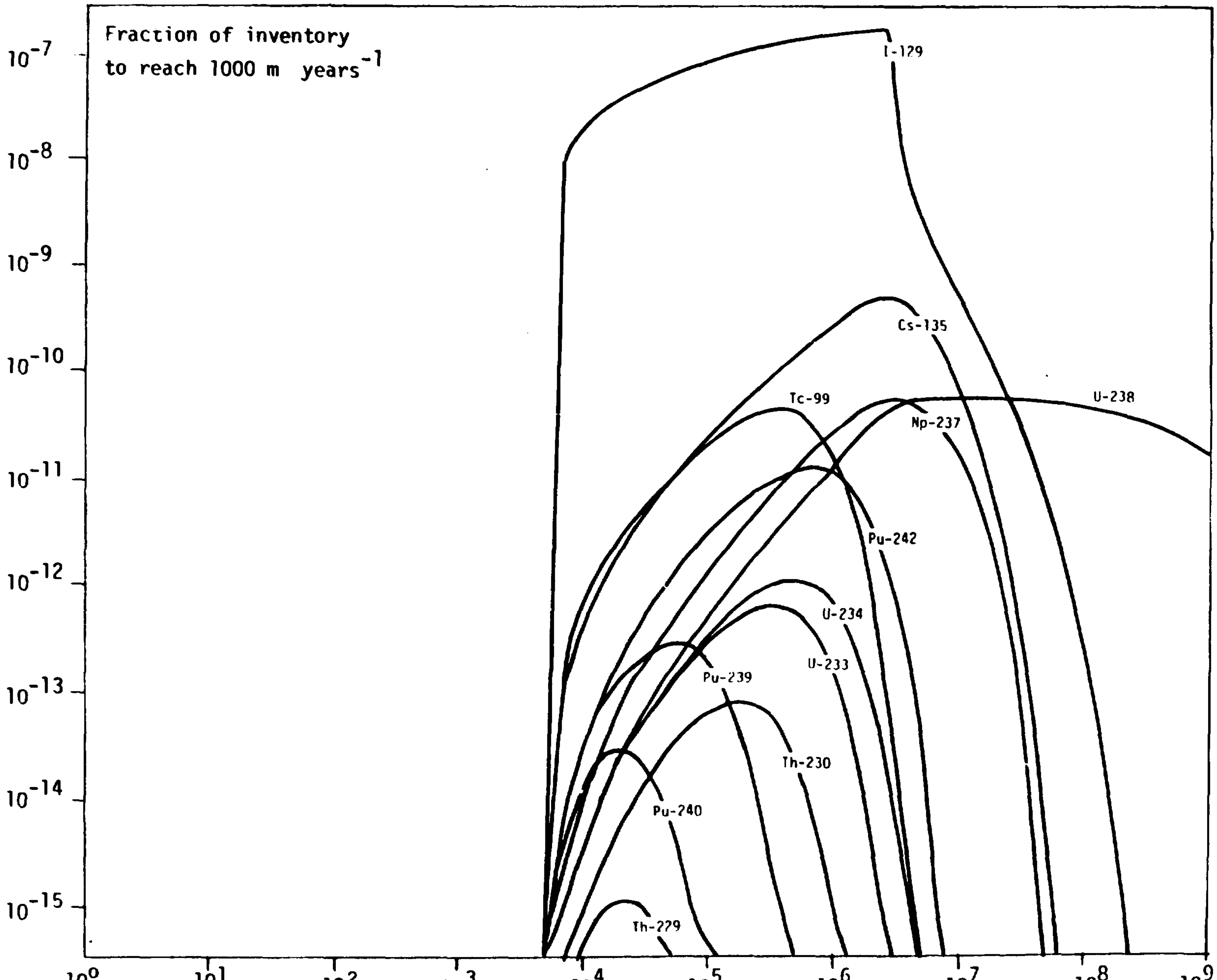
Canister penetration	t_σ	40	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0.221	-
Pore diffusivity	$D_p \epsilon_p$	10^{-12}	m^2/s

Figure 4



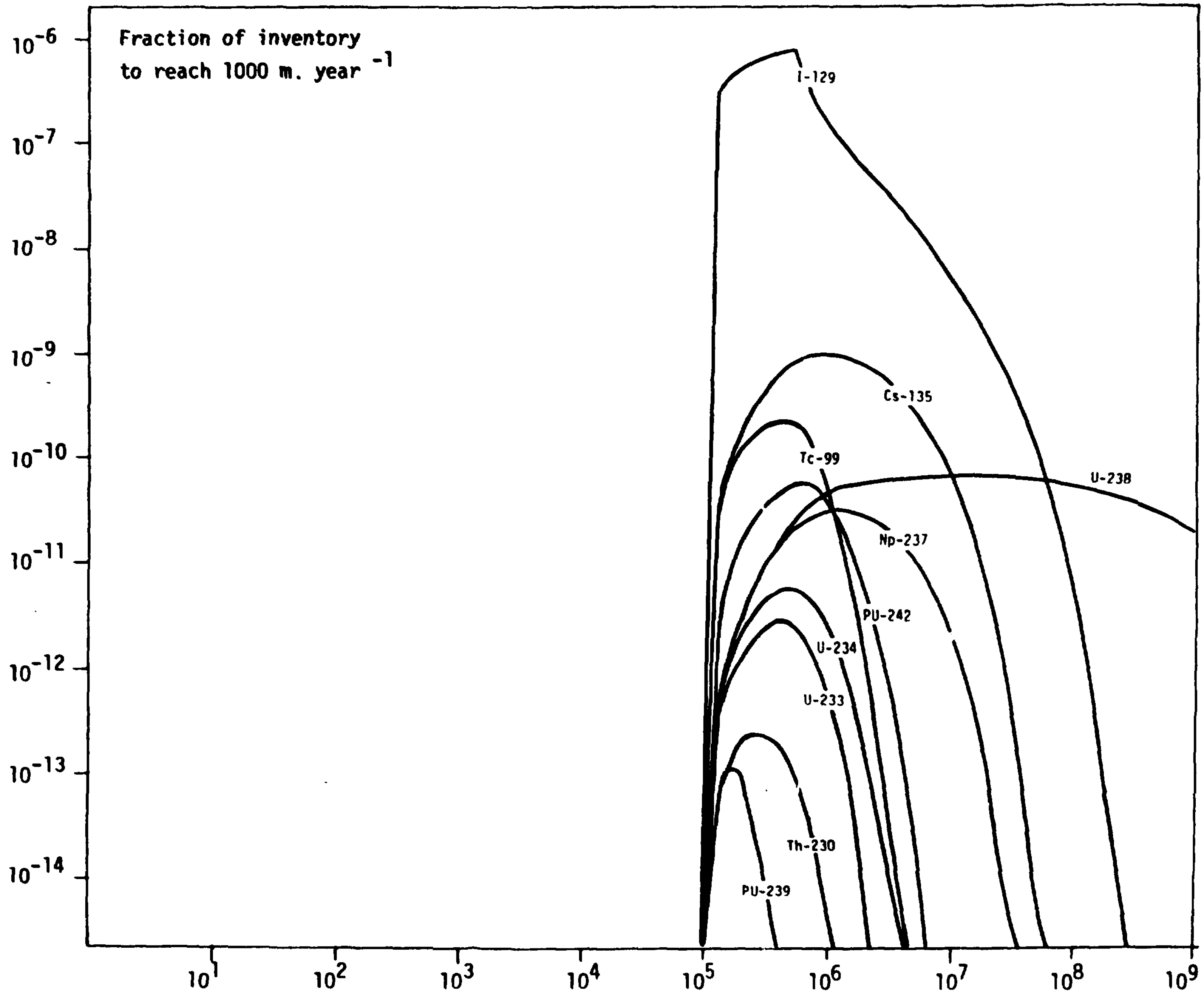
Canister penetration	t_o	5000	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0.221	-
Pore diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 5



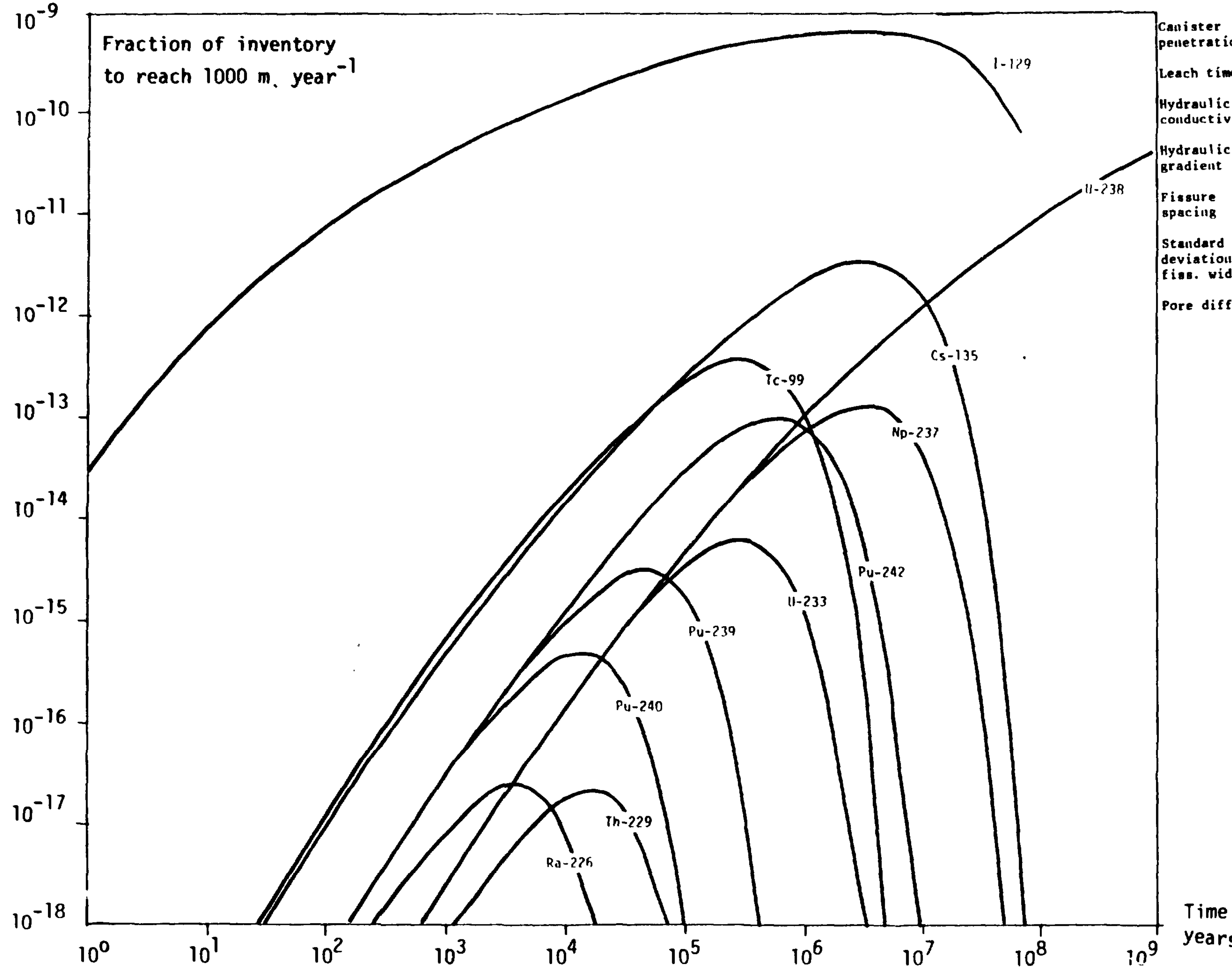
Canister penetration	t_o	5000	years
Leach time	Δt	$3 \cdot 10^6$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0.221	-
Pore diffusivity	$D_p \epsilon_p$	10^{-12}	m^2/s

Figure 6



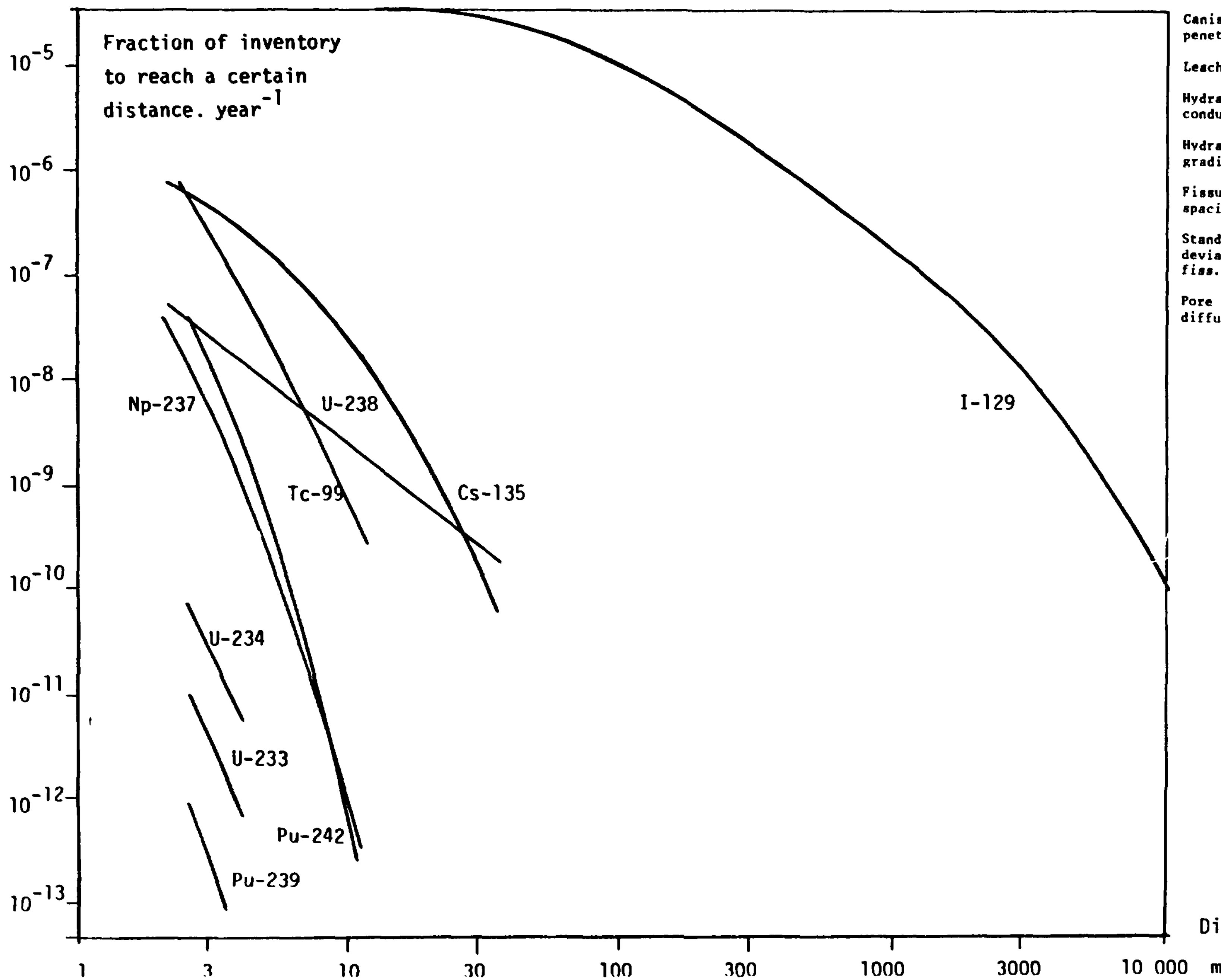
Canister penetration	t_o	10^5	years
Leach time	Δt	$5 \cdot 10^5$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0.221	-
Pore diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 7



Canister penetration	t_o	0.1	years
Leach time	Δt	10^9	years
Hydraulic conductivity	K_p	10^{-10}	m/s
Hydraulic gradient	i	0.003	m/m
Fissure spacing	S	50	m
Standard deviation fiss. width	σ	0.221	-
Pore diffusivity	$D_p \epsilon_p$	10^{-12}	m^2/s

Figure 8



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
Standard deviation fiss. width	σ	0	-
Pore diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 9

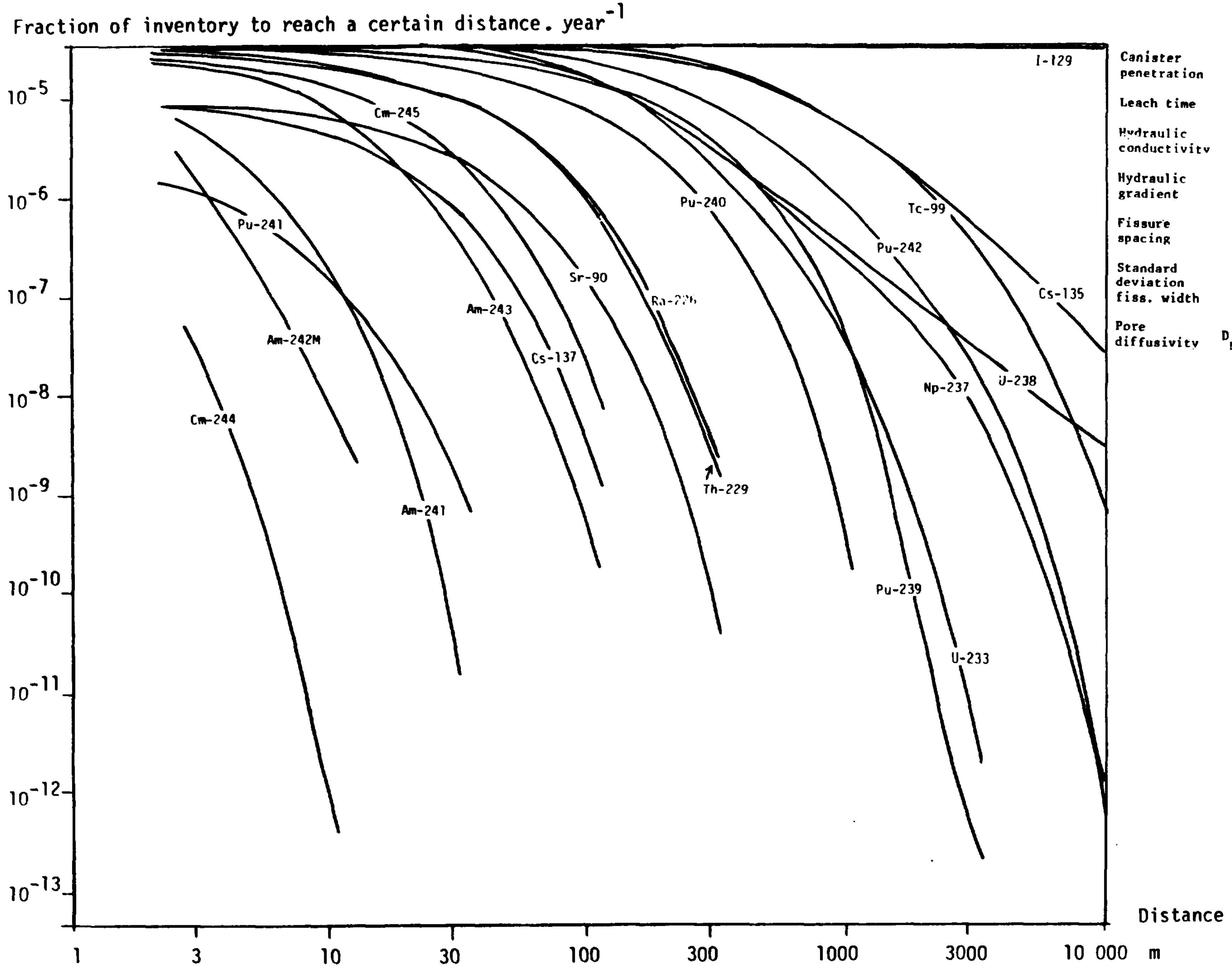
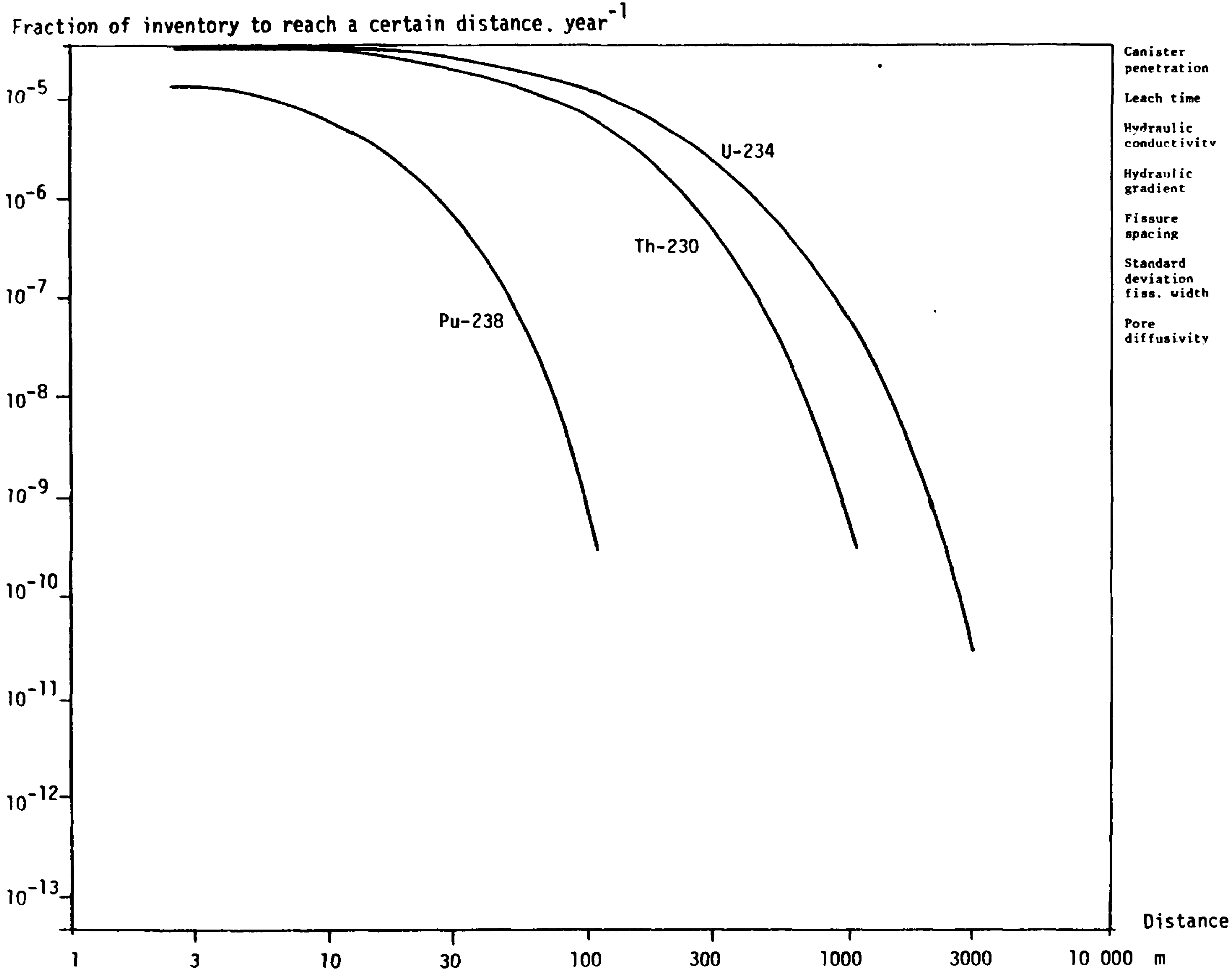


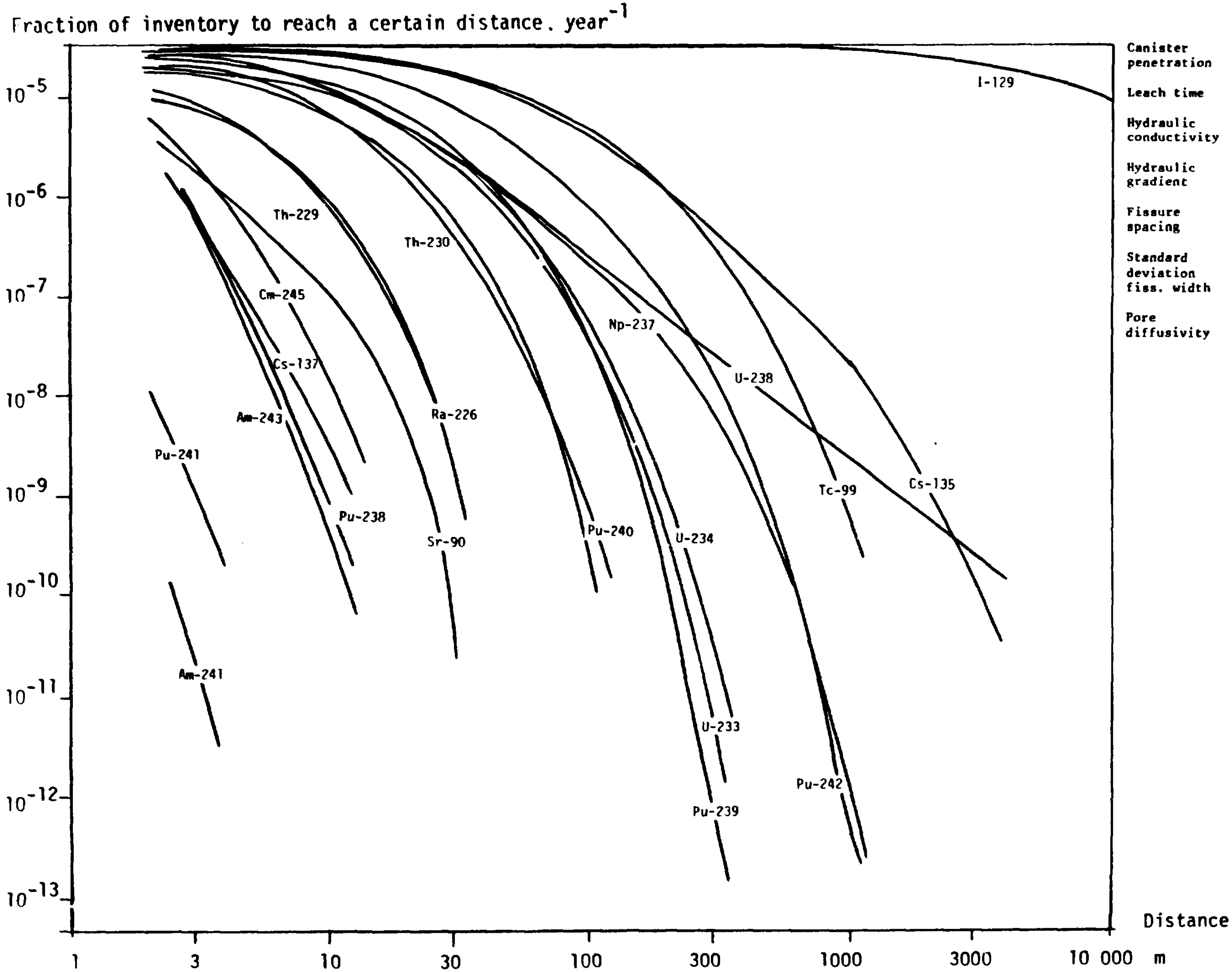
Figure 10

Continued on Figure 11



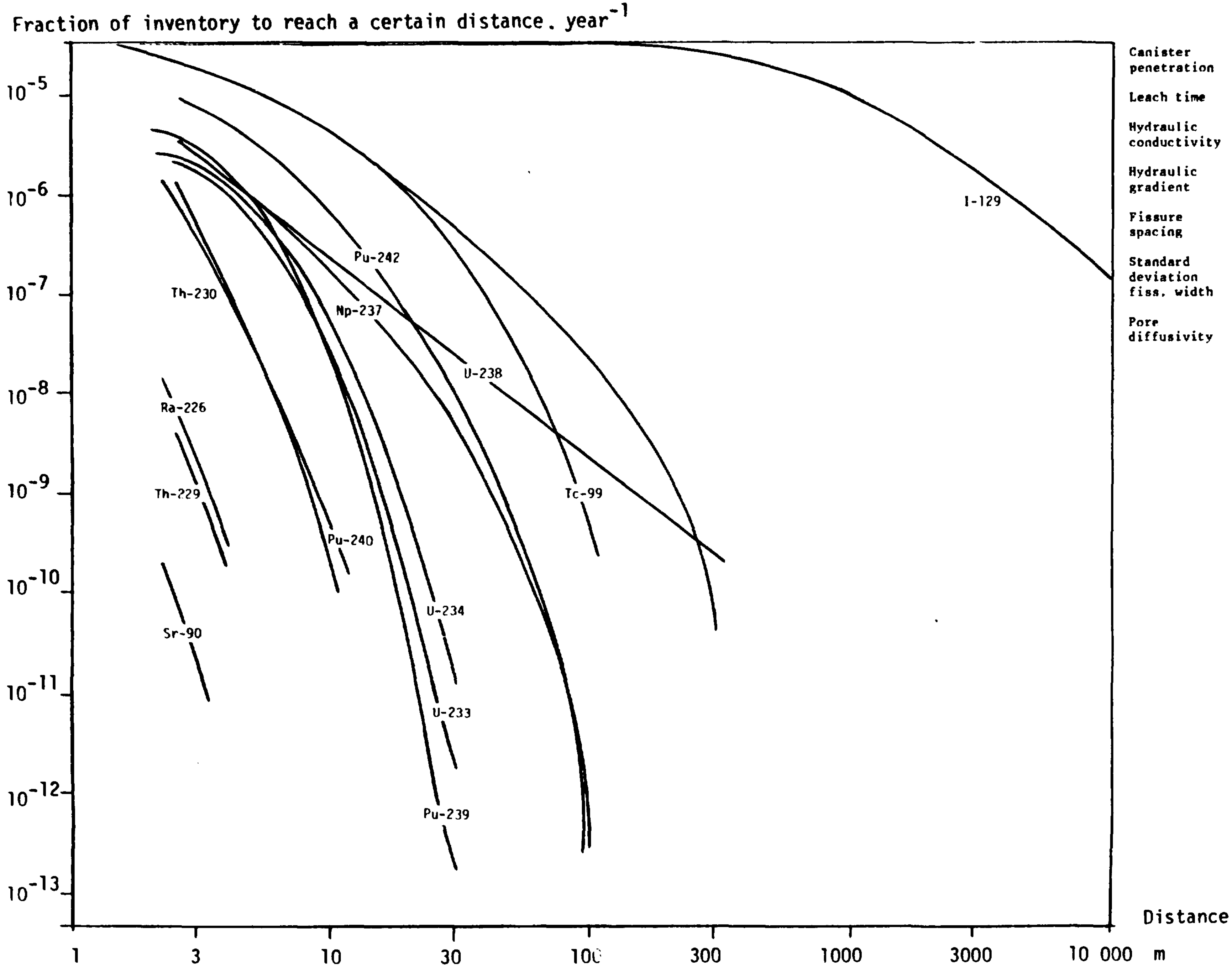
Canister penetration	t_o	40	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-6}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0	-
Pore diffusivity	$D_p \epsilon_p$	10^{-12}	m^2/s

Figure 11



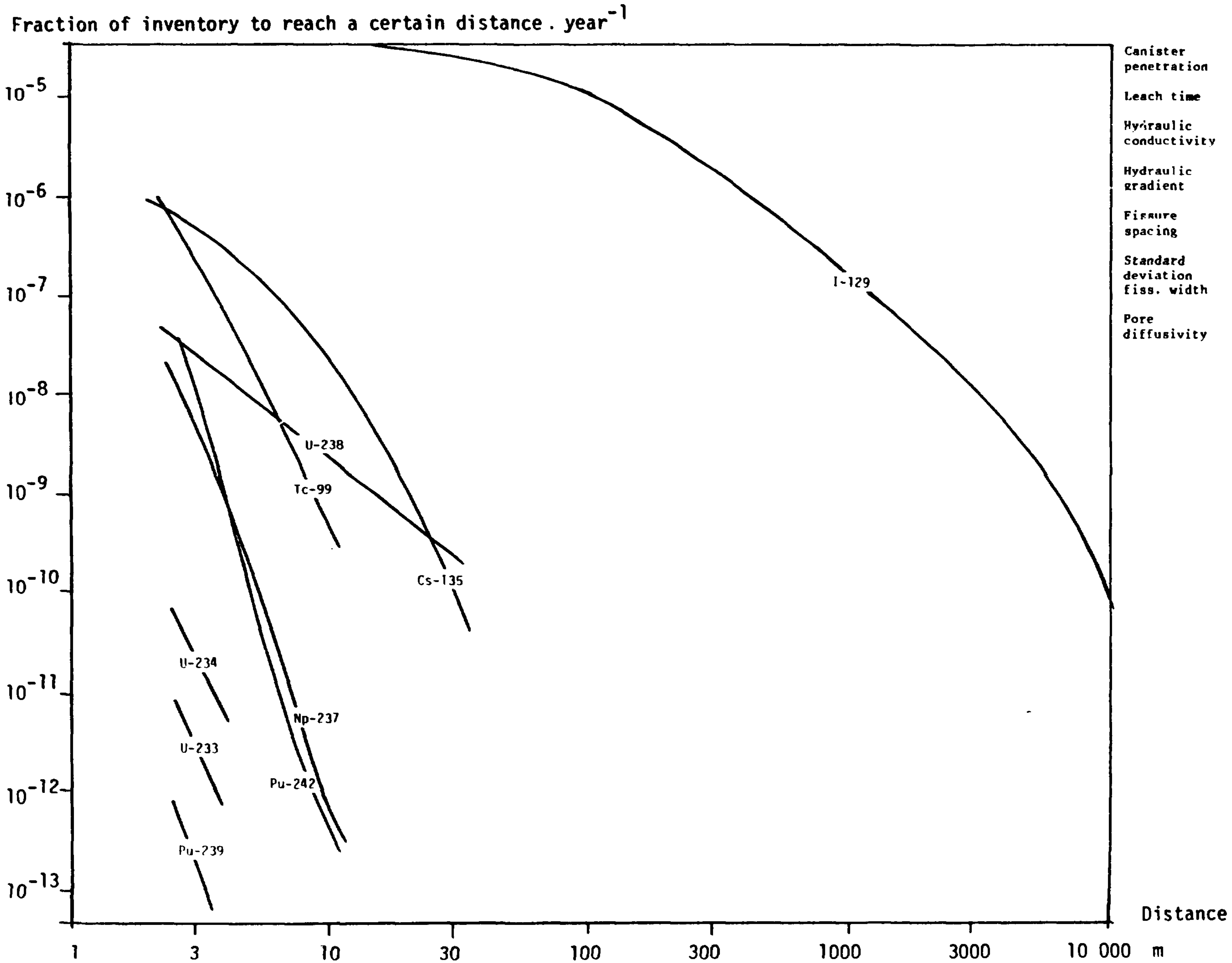
Canister penetration	t_o	40	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-7}	years
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0	-
Pore diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 12



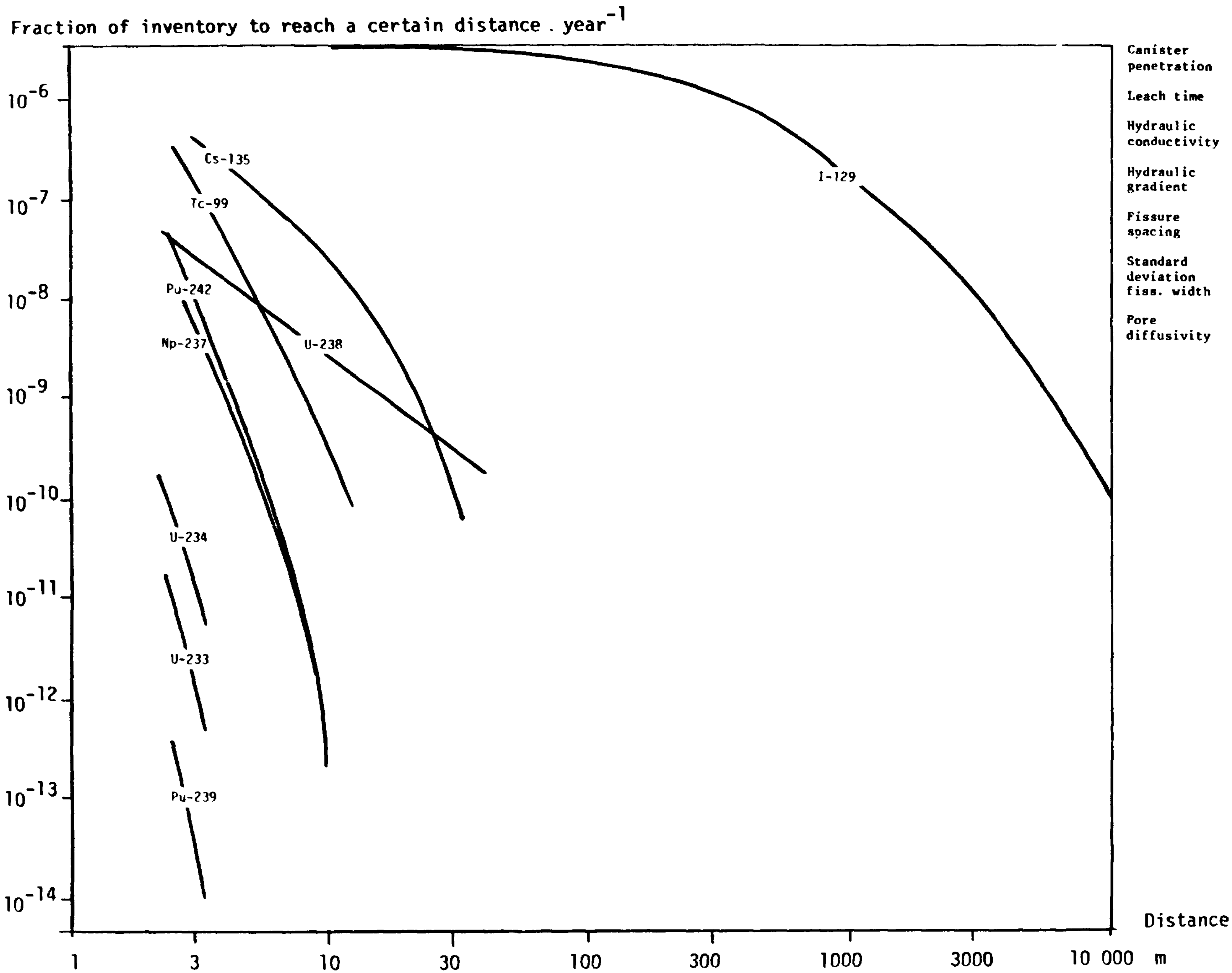
Canister penetration	t_o	40	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-8}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0	-
Pore diffusivity	$D_p \epsilon_p$	10^{-12}	m^2

Figure 13



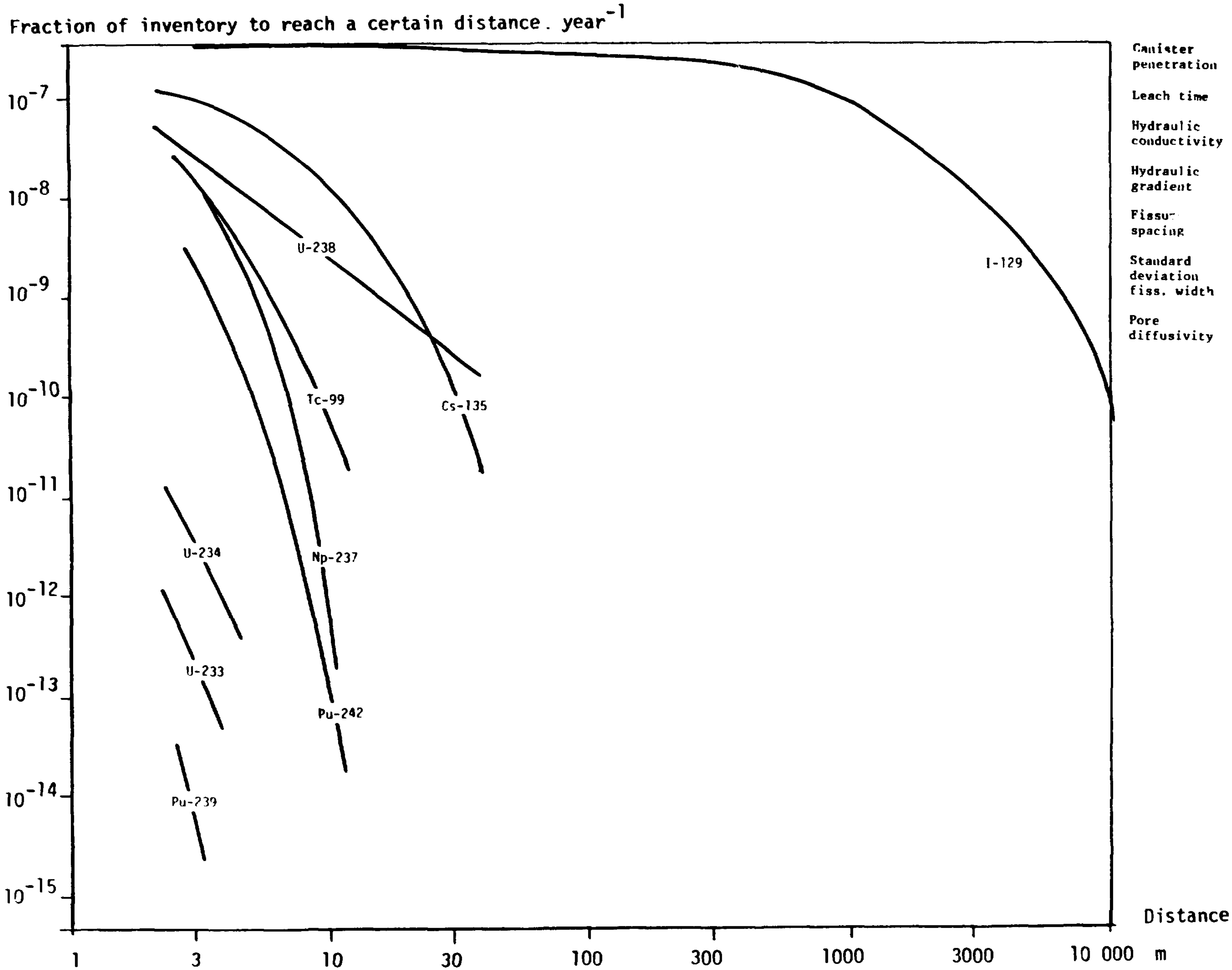
Canister penetration	t_o	5000	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0	-
Pore diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 14



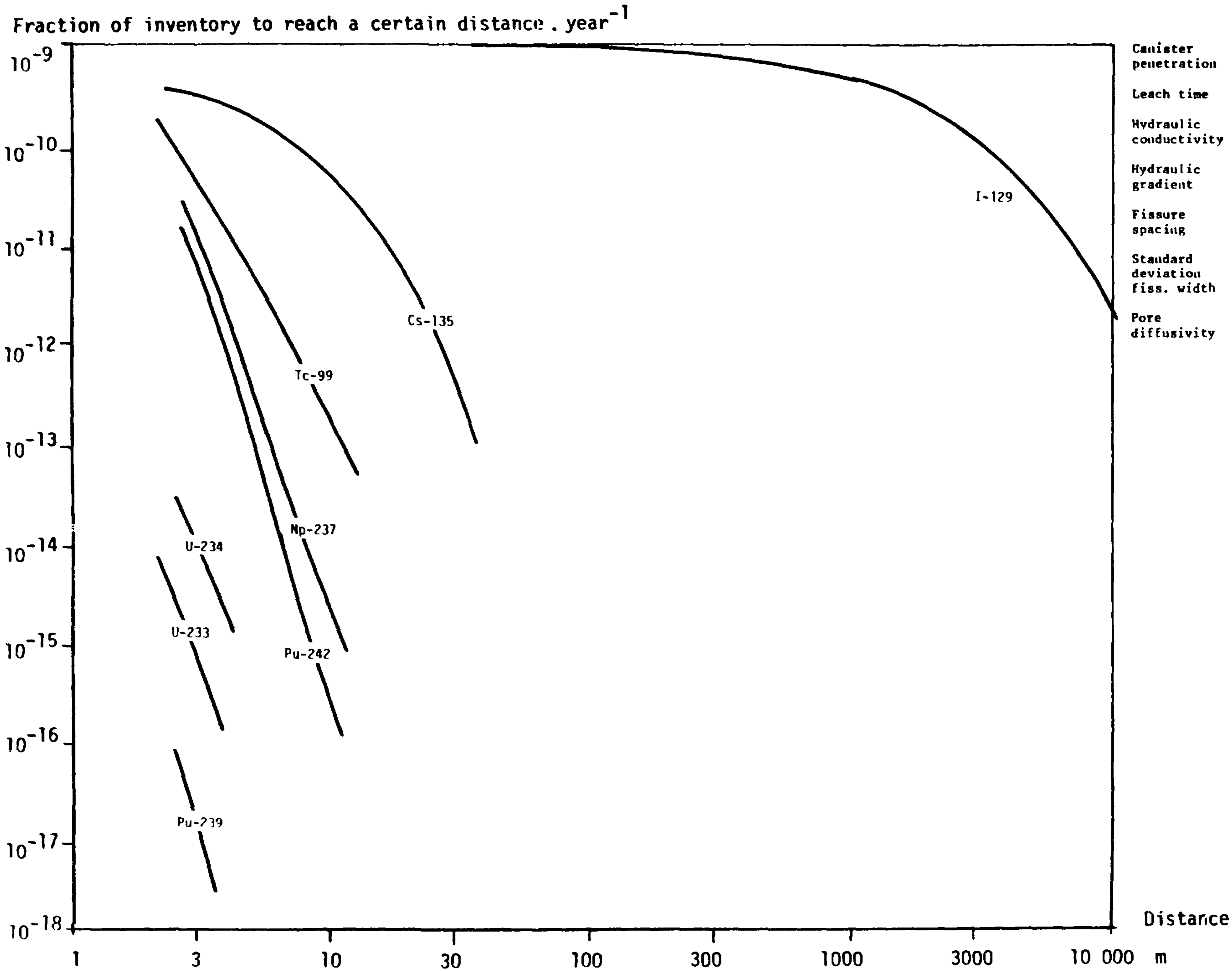
Canister penetration	t_o	5000	years
Leach time	Δt	$3 \cdot 10^5$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0	-
Pore diffusivity	$D_p \epsilon_p$	10^{-12}	m^2/s

Figure 15



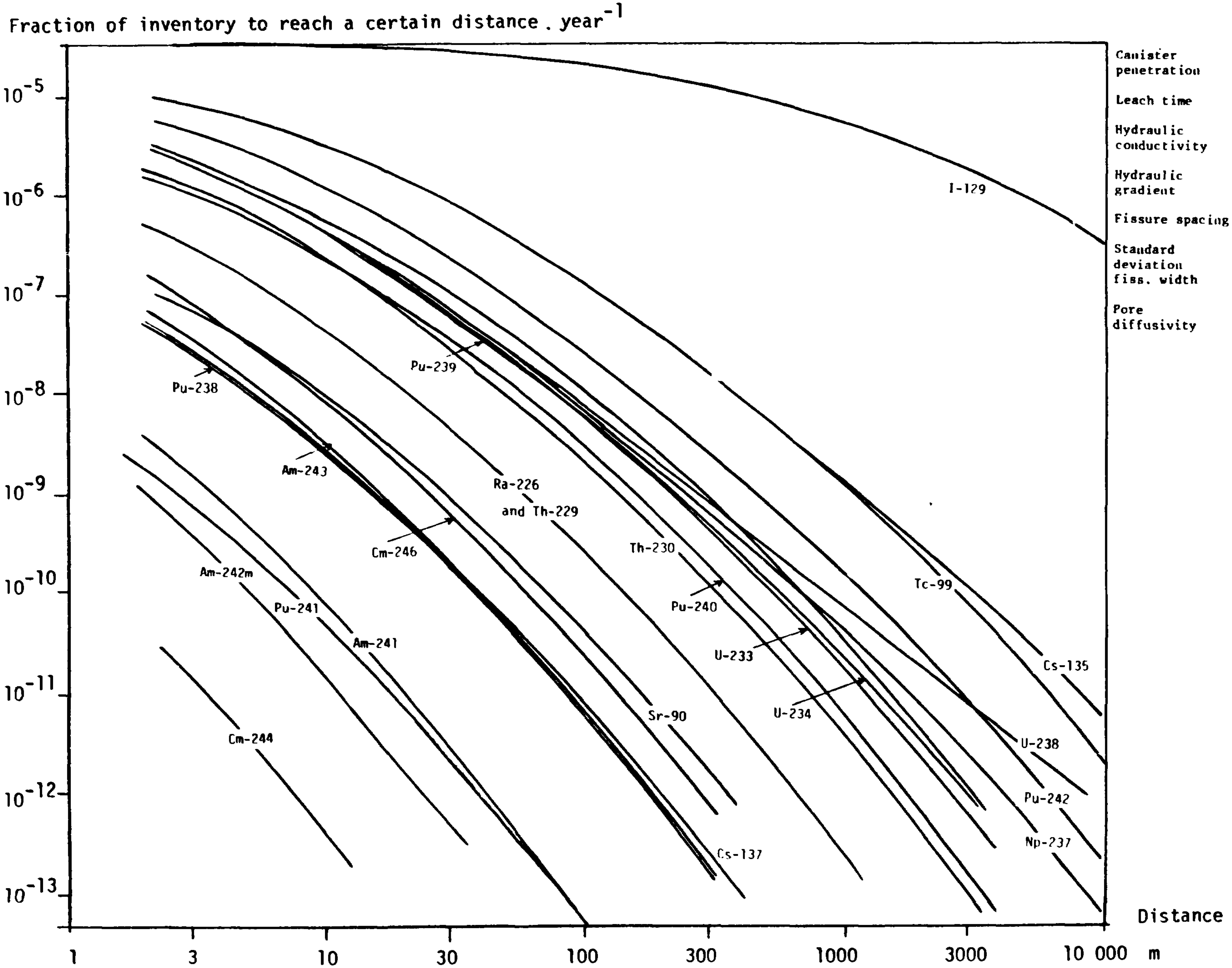
Canister penetration	t_o	5000	years
Leach time	Δt	$3 \cdot 10^6$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0	-
Pore diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 16



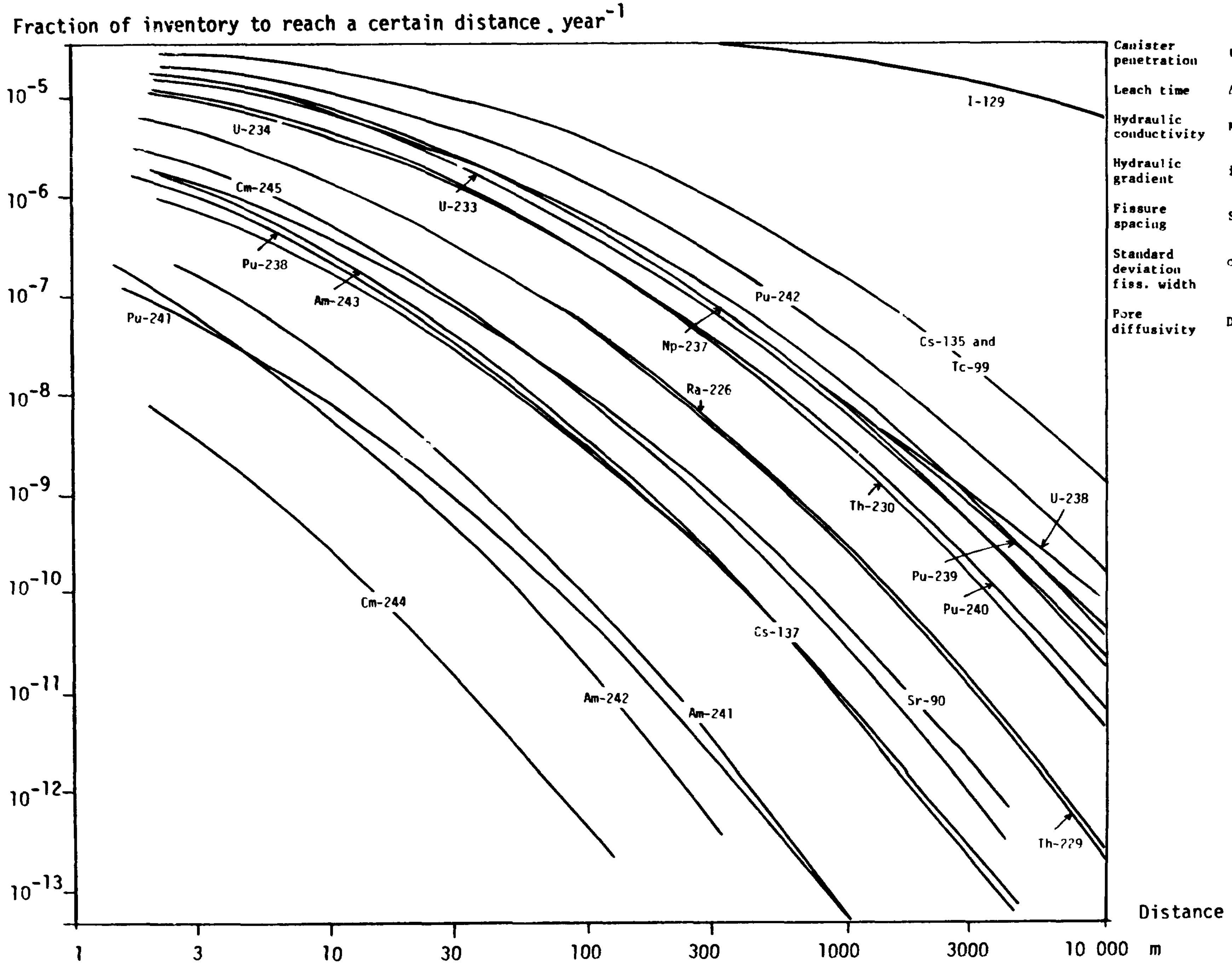
Canister penetration	t_o	40	years
Leach time	Δt	10^{9}	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0	-
Pore diffusivity	$D_p \epsilon_p$	10^{-12}	m^2/s

Figure 17



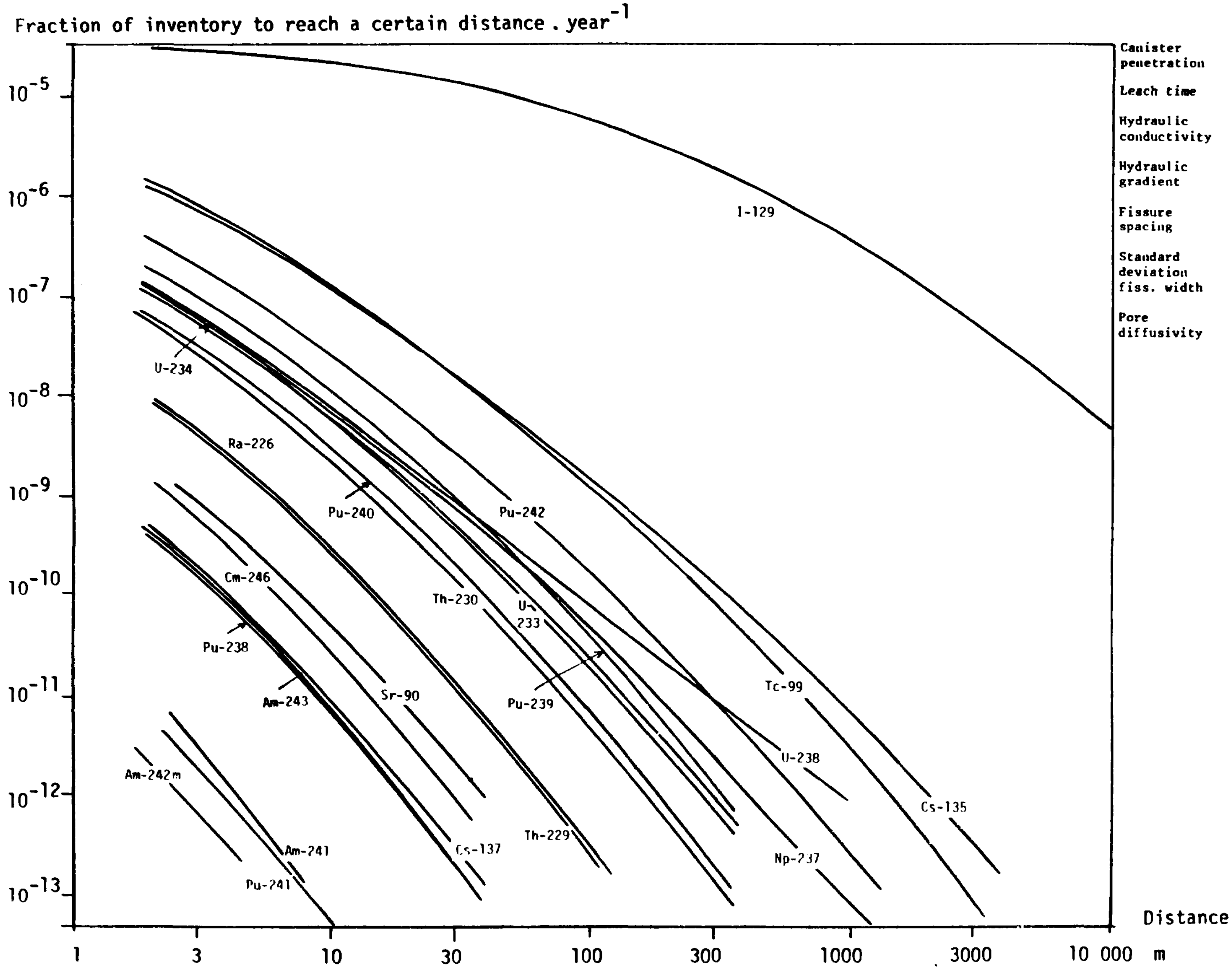
Canister penetration	t_0	40	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0.221	-
Pore diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 18



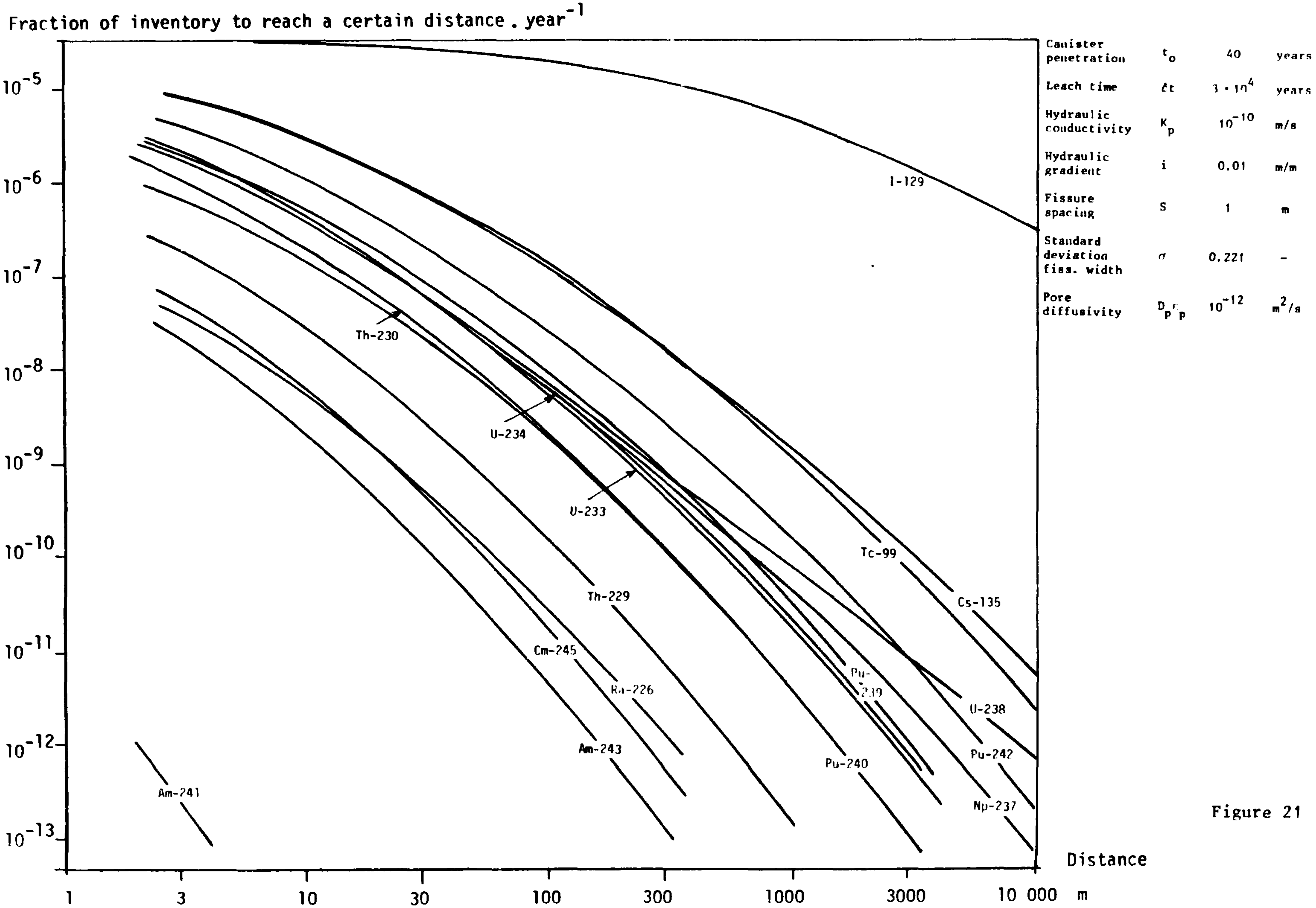
Canister penetration	t_o	40	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-8}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0.221	-
Pore diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 19



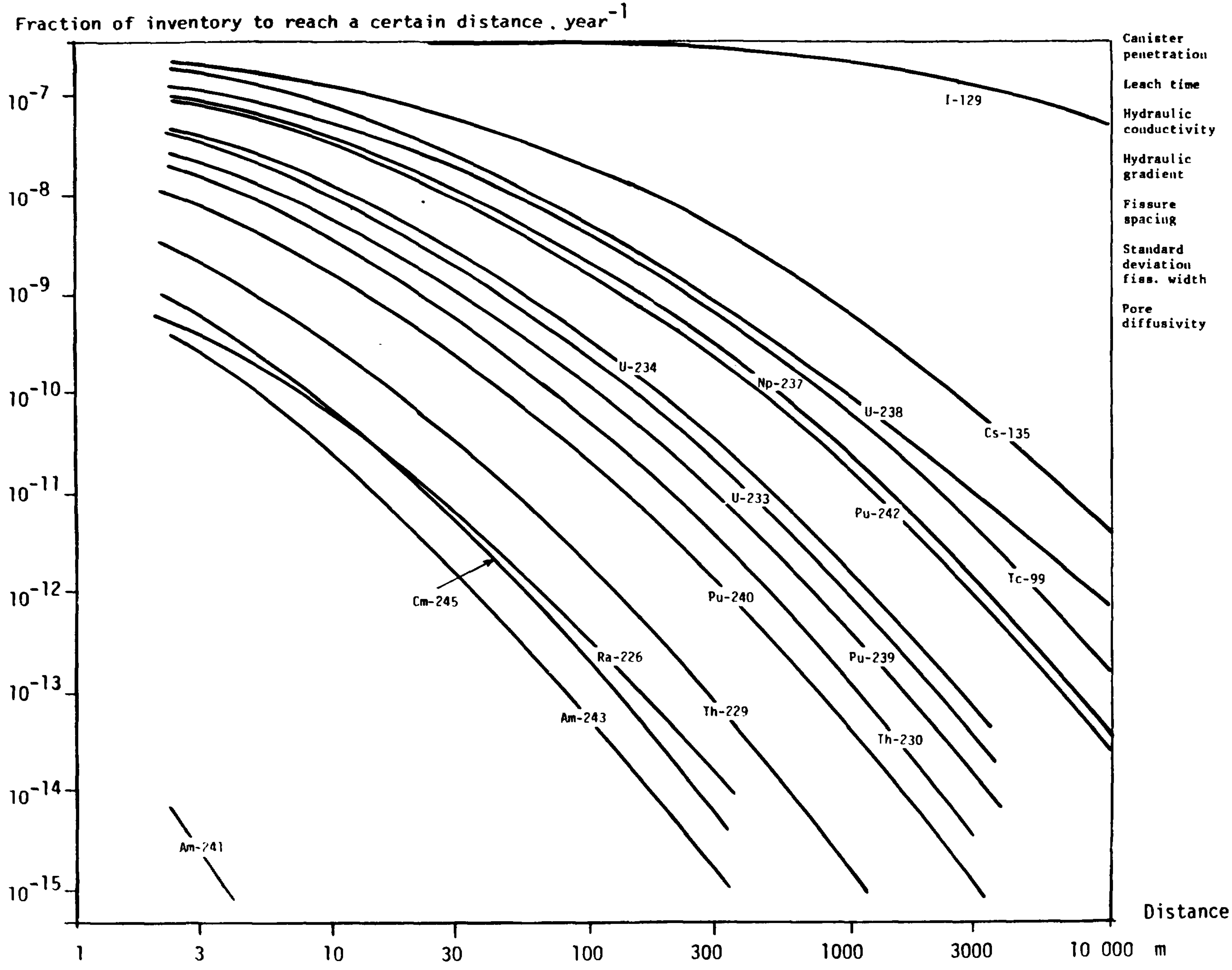
Canister penetration	t_o	40	years
Leach time	Δt	$3 \cdot 10^4$	years
Hydraulic conductivity	K_p	10^{-10}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0.221	-
Pore diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 20



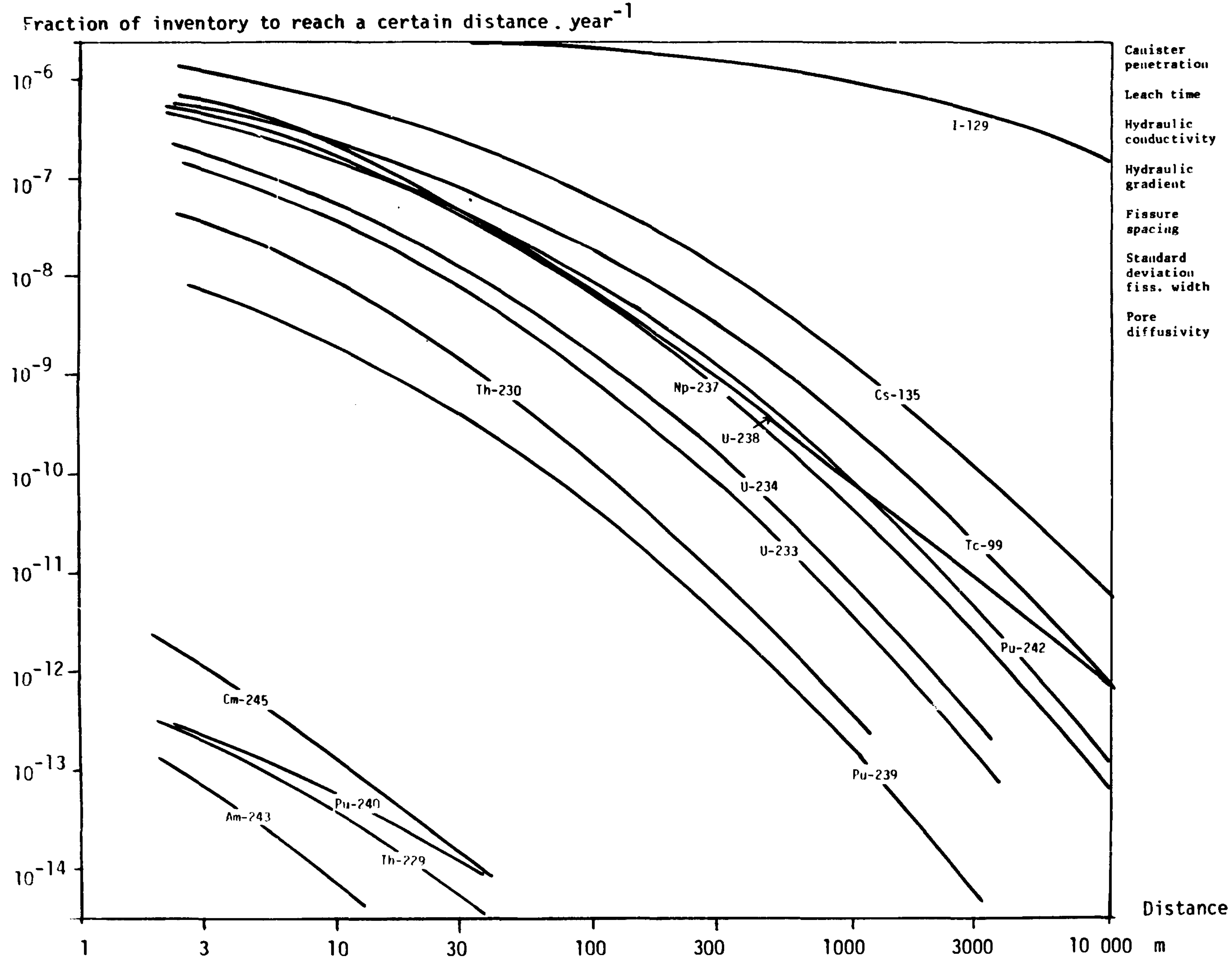
Fraction of inventory to reach a certain distance, year^{-1}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
I-129
Th-230
U-234
U-233
Tc-99
Cs-135
Th-229
Cm-245
Ra-226
Pu-239
U-238
Pu-242
Am-243
Pu-240
Np-237
Am-241
Distance
1
3
10
30
100
300
1000
3000
10 000 m
Canister penetration t_o 40 years
Leach time Δt $3 \cdot 10^4$ years
Hydraulic conductivity K_p 10^{-10} m/s
Hydraulic gradient i 0.01 m/m
Fissure spacing S 1 m
Standard deviation fiss. width σ 0.221 -
Pore diffusivity $D_p \epsilon_p$ 10^{-12} m^2/s

Figure 21



Canister penetration	t_o	5000	years
Leach time	Δt	$3 \cdot 10^6$	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.01	m/m
Fissure spacing	S	1	m
Standard deviation fiss. width	σ	0.221	-
Pore diffusivity	$D_p c_p$	10^{-12}	m^2/s

Figure 22



Canister penetration	t_o	10^5	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
Standard deviation fiss. width	σ	0.221	-
Pore diffusivity	$D_p c_p$	10^{-12}	m^2/s

Figure 23

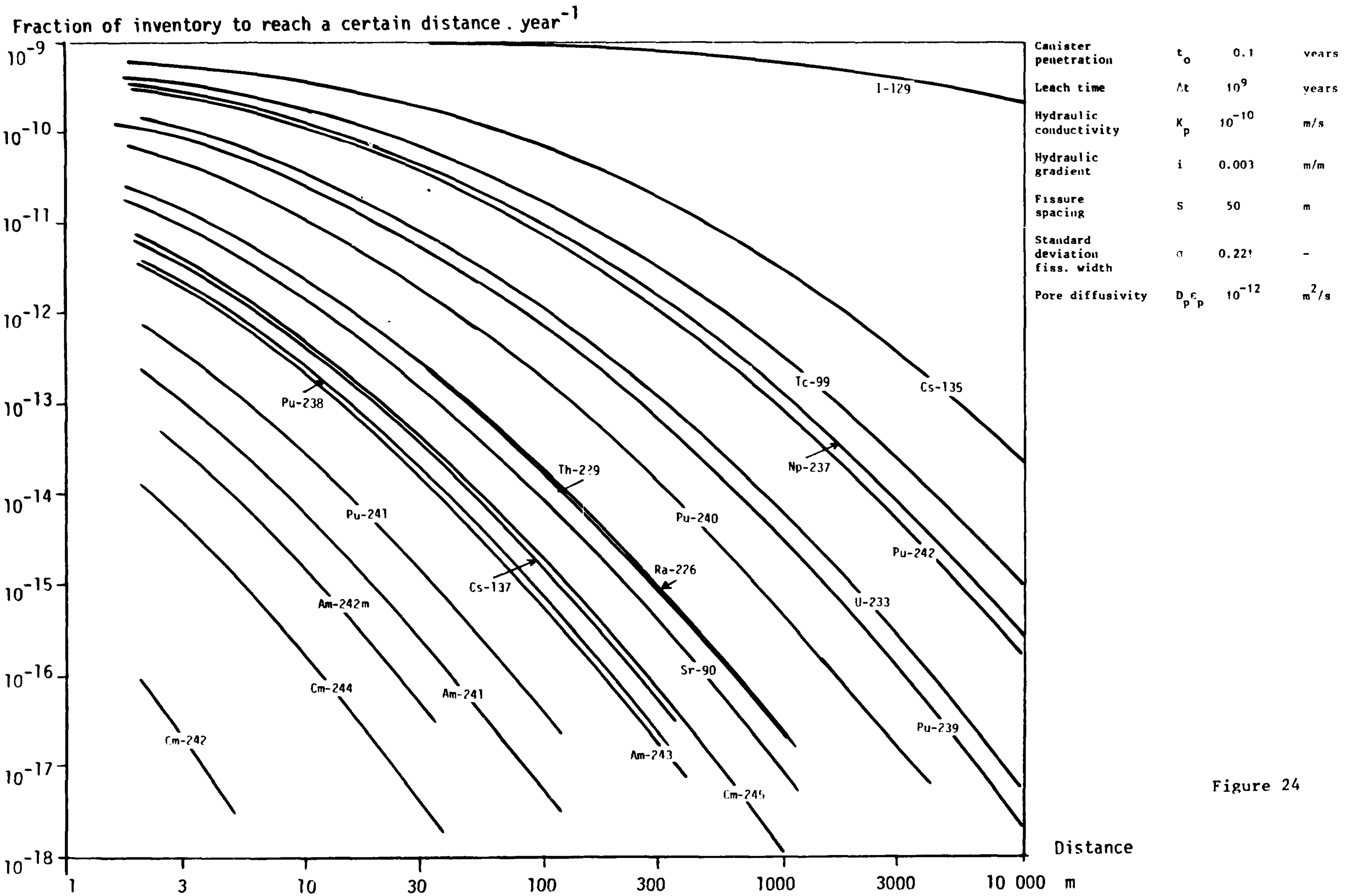
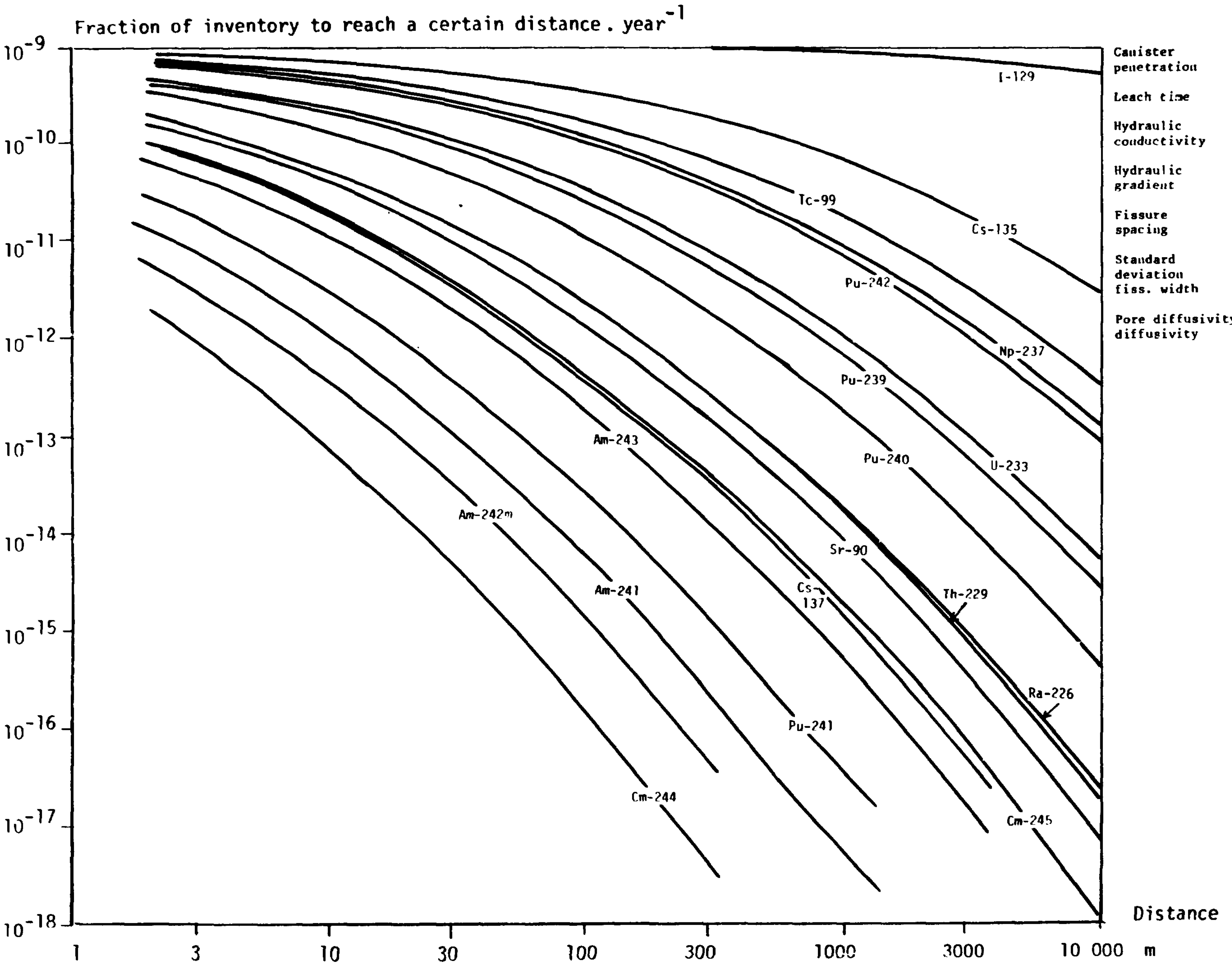
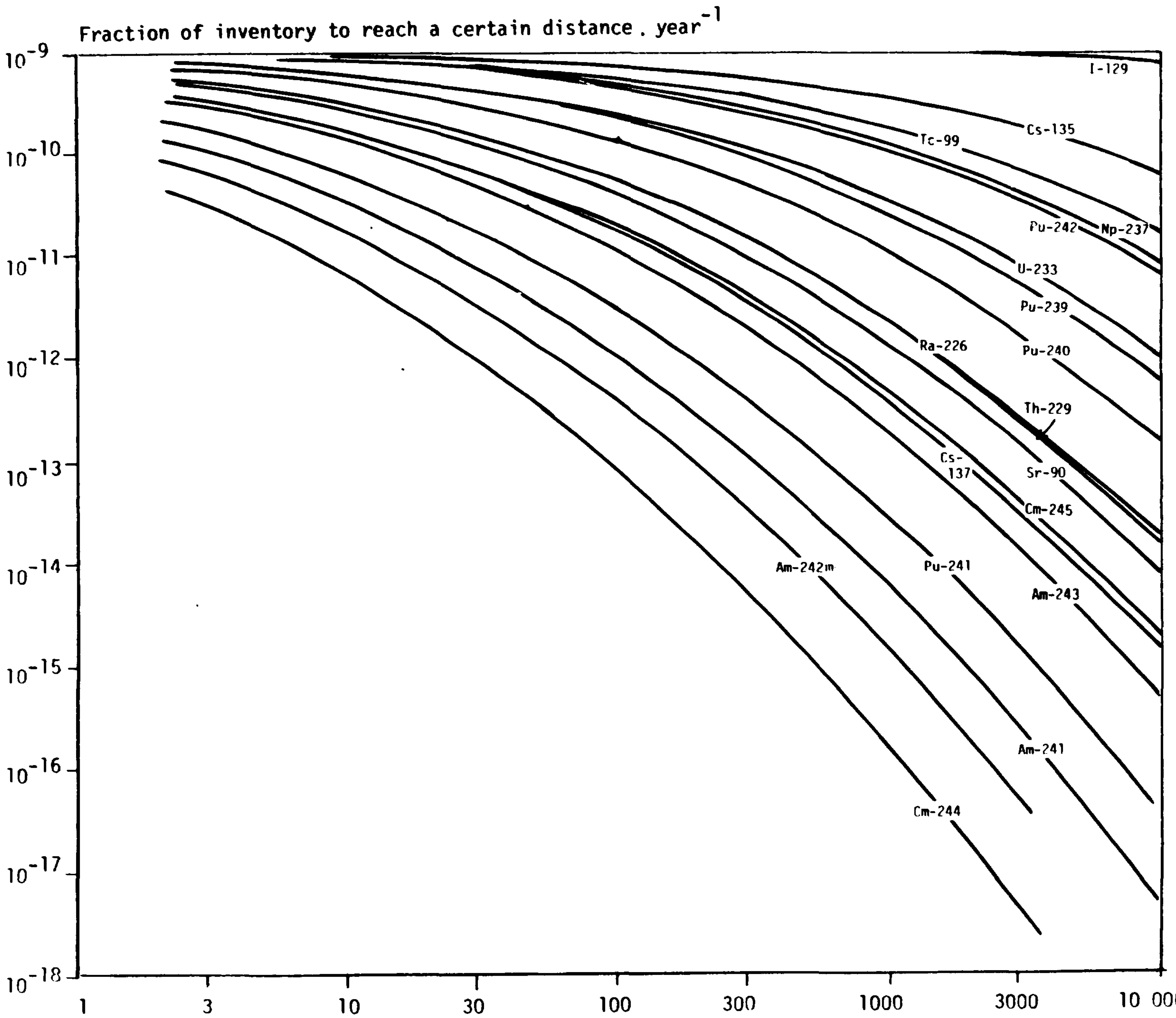

Fraction of inventory to reach a certain distance . year^{-1}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
I-129
Cs-135
Tc-99
Np-237
Pu-242
U-233
Pu-239
Pu-240
Ra-226
Sr-90
Cm-245
Th-229
Am-243
Cs-137
Pu-238
Pu-241
Am-241
Am-242m
Cm-244
Cm-242
Distance
1
3
10
30
100
300
1000
3000
10 000 m
Canister penetration t_o 0.1 years
Leach time Δt 10^9 years
Hydraulic conductivity K_p 10^{-10} m/s
Hydraulic gradient i 0.003 m/m
Fissure spacing S 50 m
Standard deviation fiss. width σ 0.221 -
Pore diffusivity $D_p \epsilon_p$ 10^{-12} m^2/s

Figure 24



Canister penetration	t_o	0.1	years
Leach time	Δt	10^9	years
Hydraulic conductivity	K_p	10^{-9}	m/s
Hydraulic gradient	i	0.003	m/m
Fissure spacing	S	50	m
Standard deviation fiss. width	σ	0.221	-
Pore diffusivity diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 25



Canister penetration	t_o	0.1	years
Leach time	Δt	10^9	years
Hydraulic conductivity	K_p	10^{-8}	m/s
Hydraulic gradient	i	0.003	m/m
Fissure spacing	S	50	m
Standard deviation fiss. width	σ	0.221	-
Pore diffusivity	$D_p \varepsilon_p$	10^{-12}	m^2/s

Figure 26

FÖRTECKNING ÖVER KBS TEKNISKA RAPPORTER

TR 82-03 Migration of radionuclides in fissured rock: Some calculated results obtained from a model based on the concept of stratified flow and matrix diffusion
Ivars Neretnieks
Royal Institute of Technology
Department of Chemical Engineering
Stockholm, Sweden, October 1981

TR 82-04 Radionuclide chain migration in fissured rock - The influence of matrix diffusion
Anders Rasmuson *
Akke Bengtsson **
Bertil Grundfelt **
Ivars Neretnieks *
April, 1982

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Stockholm, Sweden

TR 82-05 Migration of radionuclides in fissured rock - Results obtained from a model based on the concepts of hydrodynamic dispersion and matrix diffusion
Anders Rasmuson
Ivars Neretnieks
Royal Institute of Technology
Department of Chemical Engineering
Stockholm, Sweden, May 1982

TR 82-06 Numerical simulation of double packer tests Calculation of rock permeability
Carol Braester
Israel Institute of Technology, Haifa, Israel
Roger Thunvik
Royal Institute of Technology
Stockholm, Sweden, June 1982

TR 82-07 Copper/bentonite interaction
Roland Pusch
Division Soil Mechanics, University of Luleå
Luleå, Sweden, 1982-06-30

TR 82-08 Diffusion in the matrix of granitic rock Field test in the Stripa mine Part 1
Lars Birgersson
Ivars Neretnieks
Royal Institute of Technology
Department of Chemical Engineering
Stockholm, Sweden, July 1982