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A Simple Model for Describing Radon Migration and Entry Into Houses

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ABSTRACT

An approximate analytical solution to describe radon transport in soil having uniform properties is applied to the interaction of a soil depressurization system with radon emission to the atmosphere. The study addresses the question of whether soil depressurizing mitigation systems are likely to significantly increase the local ambient radon levels by increasing the emission rate from the soil. While the model predicts that the operation of a soil depressurization system usually increases the total emission rate, this increase does not appear to be significant except for soils with high permeabilities. This is true because the decrease in emission rate from the soil surface tends to compensate for the increase in emission rate by the mitigation system unless the soil permeability is quite high. For permeabilities below 2×10^{-11} m^2, the increase in total emission rate of a single mitigation system and its sphere of influence is less than 1%. Even for permeabilities greater than 4×10^{-10} m^2, the increase in total emission rate associated with a single house and its sphere of influence is probably not greater than 50%. A 50% increase in the emission rate from a single mitigation system does not translate into a 50% increase in the ambient radon level. If only 10% of the soil surface in a community with permeability greater than 4×10^{-10} m^2 is associated with operating mitigation systems, the local ambient level might be expected to increase by about 5%.

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

INTRODUCTION

A large number of radon mitigation systems have been installed in U. S. houses during the past few years. One of the more effective mitigation techniques uses active soil depressurization to reverse the direction of flow of soil gas through the building substructure and to flush high concentrations of radon from beneath the building. In many instances, high radon concentrations have been measured in the exhaust of the mitigation system. In some instances, the high radon concentrations combined with the relatively high flow rates generated by the mitigation system have given rise to concern for the safety of individuals exposed to these emissions. Some of these exhausts are released under or near decks where the occupants of the house could receive appreciable exposures. In other instances, the exhausts are released near ground level where children may be prone to play. Even where the exhausts are extended to the eaves of the houses, there is concern that downwash may result in occupant exposure. The EPA has had inquiries from individuals about potential exposures from the exhausts of a neighbor's mitigation system.

Most of these situations relate to the concern about potential exposure to a few individuals as a result of increased concentrations at very specific locations. The local concentration near a mitigation system exhaust might become quite high if the mechanisms for dispersing the radon in the atmosphere, such as air movement, were inhibited by physical obstructions or, temporarily, by a temperature inversion. Concentrations near a mitigation system exhaust will depend strongly on the dispersion processes. The present paper will not address the question of dispersion of the radon in the atmosphere. It will be assumed that radon emitted to the atmosphere is effectively dispersed in such a way that only the average radon concentration increases.

A related question that is frequently asked is whether communities with hundreds or thousands of mitigation systems may actually increase the ambient radon level resulting in increased average exposure for the members of the community. Some have taken the issue further by coining the term "mining" of radon to describe the high emission rate from mitigation systems. The purpose of the present document is to explore the effects of active soil depressurization systems on the total radon emissions to the atmosphere.

MODEL DESCRIPTION

In order to explore the influence of soil depressurization systems on total radon emissions to the atmosphere, the interaction of a model house with gas transport in the soil will be described. For convenience, and to avoid lengthy numerical analysis, simplifying assumptions will be used to obtain analytical solutions to the transport equations.

A number of sources in the literature (1-4) emphasize that pressure driven flow of soil gas into the house is the dominant radon entry process in most houses. Consequently, the present formulation will use the conceptual arrangement illustrated in figure 1. This figure depicts a basement house that is depressurized (by a temperature difference, wind effects, or mechanical appliances) relative to the ambient air. The resulting pressure difference serves as a driving force to cause air to flow downward through the soil and enter the basement through openings in the substructure. The dominant entry route in many basements is the perimeter wall/floor crack. In some houses, the dominant entry route is a perimeter drain tile that connects directly to a sump that, in turn, is open to the interior of the basement. Both these situations will be modeled (1-3, 5) as flow into an isolated cylinder buried at basement depth below the surface.

In order to determine the net effect of the mitigation system on radon emission, two processes must be considered. While increased emissions through the system exhausts are frequently observed, little has been said about the effects of the system on the emissions from the surface of the soil surrounding the house.

Emission of radon from the surface of the soil occurs by molecular diffusion of radon through the soil gas contained in the pores of the soil. However, when air flows down through the soil the radon concentration in the soil gas is diluted and the concentration gradient is modified. Consequently, radon emission from the surface of the soil is reduced by increased flow through the house and mitigation system. The net effect on radon emission will be determined by the difference in the increased emissions through the mitigation system and the decreased emissions from the surface of the soil.

Emission of radon through the house and/or the mitigation system will be computed using expressions developed in reference 1. The emission rate through the house or mitigation system is given by

$$E_m = \int C v \, da, \tag{1}$$

where E_m is the emission rate (Bq/s), C is the local radon activity concentration (Bq/m^3) in the soil gas, and v (m/s) is the velocity of the soil gas. The integration is taken over the surface of the cylinder which represents the entry route into the house or the mitigation system. The activity concentration at the surface of the cylinder (1) is given by

$$C(\phi) = \frac{G}{\lambda}\left\{1 - \exp\left(\frac{-\lambda \epsilon \mu h^2 \ln(2h/b)}{k|P_c|}\left[\frac{1 - \phi\cot\phi}{\sin^2\phi}\right]\right)\right\} \tag{2}$$

where

$C(\phi)$ = the radon activity concentration (Bq/m^3) at angle ϕ,
ϕ = the polar angle measured from the vertical axis of the cylinder,
G = the emanation rate (Bq/m^3/s) of radon from soil particles,
λ = the radon decay constant (s^{-1}),
exp = the exponential function,
ϵ = the soil porosity,
h = the depth of the basement (m),
ln = the natural logarithm,
b = the radius of the cylinder (m),
k = the permeability of the soil, and
P_c = the pressure (Pa) in the cylinder relative to atmosphere.

Equation (2) does not apply when $\phi = 0$ because of a local singularity. The gas velocity at the surface of the cylinder is given by

$$v = \frac{k|P_c|h}{b\mu\ln(2h/b)}\left(\frac{1}{h-b\cos\phi}\right), \tag{3}$$

where v is the velocity, μ is the kinematic viscosity of the soil gas, and the other parameters are as previously described. It is a relatively straight forward matter to numerically evaluate equation (1) using equations (2) and (3). While equation (3) represents a rigorous result, equation (2) is a rigorous solution of the transport equations only when the contributions from diffusion are negligible. While this approximation is adequate for relatively large values of soil permeability, the permeability in many localities is not that large.

Perhaps the simplest way to estimate the local effect of diffusion on the entry of radon into the buried cylinder would be to compute the gradient of the activity concentration at the surface of the cylinder and integrate the resulting diffusive flux over the surface of the cylinder. This result would not be rigorously correct because the concentration gradient would not be self-consistent. That is, the influence of the diffusive process on the concentration gradient would not be accurately reflected.

However, since the calculation is easy to do, it seems worthwhile to incorporate this approximation.

The normal gradient of the concentration evaluated at the surface of the cylinder is given by

$$\nabla C_n = \frac{G\epsilon\mu h^2}{bk|P_c|}\left(\frac{1-\phi\cot\phi}{\sin^2\phi}\right)\exp\left(\frac{-\lambda\epsilon\mu h^2 \ln(2h/b)}{k|P_c|}\left[\frac{1-\phi\cot\phi}{\sin^2\phi}\right]\right) \quad , \tag{4}$$

where ∇ is the gradient operator. The diffusive flux is given by

$$J_d = -D_e \nabla C_n \quad , \tag{5}$$

where J_d is the diffusive flux and D_e is the effective diffusion coefficient. This flux is to be integrated over the surface of the cylinder,

$$E_d = \int -D_e \nabla C_n da \quad . \tag{6}$$

and the result added to equation (1). E_d represents the change in the emission rate from the house or mitigation system due to diffusion at the surface of the cylinder.

In the region near the surface of the soil, the flow will be nearly vertical. In a limited region near the soil surface, the problem will be treated as if it were one dimensional for purposes of computing activity concentration and migration. With these assumptions, the transport equation becomes

$$D_e \frac{d^2C}{dy^2} - \frac{v}{\epsilon}\frac{dC}{dy} - \lambda C + G = 0 \quad . \tag{7}$$

Equation (7) has the solution

$$C(y) = \frac{G}{\lambda}\left\{1 - \exp\left(-\left[\sqrt{\left(\frac{v}{2\epsilon D_e}\right)^2 + \frac{\lambda}{D_e}} - \frac{v}{2\epsilon D_e}\right] y\right)\right\} \quad . \tag{8}$$

Since we consider only a narrow range of y near the surface, y = 0, the velocity can be considered to be independent of y. It has been assumed that C(0) = 0. The diffusive flux at the surface of the soil is given by

$$J_D = -D_e \frac{dC}{dy} = -\frac{D_e G}{\lambda}\left[\sqrt{\left(\frac{v}{2\epsilon D_e}\right)^2 + \frac{\lambda}{D_e}} - \frac{v}{2\epsilon D_e}\right] \quad . \tag{9}$$

The total emission rate of radon from the surface of the soil would be obtained by integrating the flux (equation 9) over all the surface. Since the surface is very large, it can be seen that the integral would yield a very large number. The influence of the mitigation system on the emission rate would be contained in the relatively small differences in very large numbers. Since this approach would require extreme accuracy in evaluating the integrals, the following rationale is adapted.

It is known from reference 1 that the velocity at the surface of the soil decreases approximately as the reciprocal of the square of the distance from the house. Consequently, the practical influence of the house and mitigation system on radon emission from the soil is limited to quite finite distances. Let us call the area of the soil surface for which the house and mitigation system influence the emission rate the house's "sphere of influence." This sphere of influence will be characterized by its maximum distance from the house. Reference 1 shows that the fraction of total flow occurring within a distance s of the house is given by

$$s = h \tan\left(\frac{\pi}{2}\frac{Q(s)}{Q_T}\right) \quad , \tag{10}$$

where s is the distance from the house, Q(s) is the flow through the area between the house and the boundary located at distance s, and Q_T is the total flow. The sphere of influence could be defined, for instance, as the area within a distance, s, of the house through which 95% of the total flow passes. With this definition, a basement 2 m deep would have a sphere of influence that lies within about 25 m of the house. In the present calculations, this convention will be adapted so that the integrations over the soil surface will extend to 25 m. The emission rate from the surface becomes

$$E_s = L\int J_D dx, \tag{11}$$

where E_s is the emission rate from the surface of the soil within the house's sphere of influence, L is the length of the cylinder, and x is the distance from the house along the surface. The total emission rate (E_T) of radon into the atmosphere is given by

$$E_T=E_m+E_d+E_s. \tag{12}$$

RESULTS

In order to apply and interpret the above developments, some idealizations are required. First, a model house is described. It is assumed that the basement walls, floor, and common joints are tightly sealed against air flow, except that the sump has been left open. There is a complete loop of drain tile around the base of the house. This drain tile is connected to the sump which was designed to remove the water collected by the drain tiles. This description depicts an efficient radon entry path into the basement. Since the basement is frequently at lower pressure than the atmosphere, the sump and, consequently, the drain tiles are also at reduced pressures. This results in convective flow of air from the surface through the soil into the tile and ultimately into the basement. Under these circumstances, radon entry into the house can be computed by computing the radon entry into the drain tile. These assumptions were at the heart of the method for computing radon entry rate presented in reference 1.

This idealization for radon entry is now extended to describe the interaction of the mitigation system with the soil. Suppose the mitigation system installed in this model house consists of a collection pipe sealed in the sump with the mitigation fan and exhaust located on the roof. In this case, the mitigation system becomes an integral part of the sump and therefore is coupled directly to the drain tile system. It is easy to imagine that the mitigation system could be made to simulate the natural conditions of radon entry simply by adjusting the fan speed until the pressure difference in the drain tiles relative to atmosphere is the same as when the mitigation system was not present. It is reasonable to assume that the radon emission rate from the exhaust under these conditions would be the same as the radon entry rate into the basement when the mitigation system was absent. Herein lies the essence of the present approach for describing the interaction of the mitigation system with the soil.

It is assumed that the operation of the mitigation system can be treated as an extension of the natural entry process. This extension is reflected in the mathematical formulation by the pressure difference. This assumes that the radon entry rate into the drain tiles (and consequently out the system exhaust) would be the same as if the depressurization had occurred by reducing the pressure in the basement (for instance, with a blower door).

While the idealized model described here is a very specific case in which radon entry into a buried tube can be used to describe radon entry into a particular type of basement, it is believed that the formulation can be applied for other basement construction details. For instance, if there is no drain tile, but there is a perimeter crack at the wall/floor joint, it is believed that entry through the crack can be simulated by flow into an appropriately sized cylinder. In reference 1, it is shown that the model is not very sensitive to the diameter of the cylinder.

The total emission rate in equation (12) was evaluated for a model basement house having 144 m^2 of floor area in contact with soil. The length of the perimeter drain tile around the basement is 50 m. Values of the parameters used to characterize the soil properties are listed in Table 1. Figure 2 shows the normalized total emission rate as a function of pressure for four values of soil permeability. The emission rates have been normalized to the values at zero pressure. The emission rate from the exhaust is taken to be zero when the pressure is zero. Consequently, all the emission is from the surface of the soil when the pressure is zero. This total emission rate represents all the emissions from the mitigation system and the soil within the assumed sphere of influence of the house. Although the calculations were done for rather modest values of radium content in the soil (emanation rate), the normalized values are independent of the source strength. Of course, these calculations assume that the radium is uniformly distributed in the soil and that the transport properties of the soil are uniform. From Figure 2 it can be seen that the mitigation system produces very little increase in the total emission rate when the soil permeability is less than about 2×10^{-11} m^2. For a permeability of 7.8×10^{-11} m^2 the increase in total emissions is about 5% at 10 Pa and 30% at 40 Pa. Even at the rather high permeability of 3.9×10^{-10} m^2, the increase is about 38% at 10 Pa and 245% at 40 Pa. There probably are few localities with permeabilities higher than 4×10^{-10} m^2.

Figure 3 shows normalized emission rates as a function of pressure for the individual emission sources, the soil surface, and the mitigation system. Note that, while the emission rate from the mitigation system starts at zero for zero pressure and increases with increasing pressure difference, the emission rate at the surface of the soil starts at a maximum at zero pressure and decreases with increasing pressure. This is a direct reflection of the influence of the air flow at the soil surface on the concentration gradient. Note that the two phenomena approximately compensate each other. In fact the total emission rate increases by less that 1% over the pressure range to 40 Pa, while the individual rates change by about 10%.

Figure 4 shows normalized emission rate as a function of pressure for the individual rates as well as for the total emission rate. These curves represent a soil permeability of 1.6×10^{-11} m^2. While the individual emission rates vary by about 25% over the pressure range, the total emission rate varies by less than 4%. This result indicates that the changes in the two emission processes almost compensate for each other.

In figure 5 the two emission rates are equal at about 26 Pa. While the individual rates have changed by about 50%, the total emission rate has only increased by about 18%. However, as the permeability increases, the mitigation system emissions begin to be more important. At a permeability of 3.9×10^{-10} m^2, the variations in the emission rates are somewhat more dramatic as seen in figure 6. The individual rates are equal at about 6 Pa, while the total emission rate is more nearly linear over the pressure range. The emission rate from the surface of the soil at 40 Pa is only about 20% of its initial value. Remember that this effect only applies over the house's sphere of influence. In fact most of the decrease in emissions occurs near the house.

At the very high permeability of 2×10^{-9} m^2, the emissions are totally dominated by the mitigation system above pressures of about 10 Pa as shown in figure 7. Although the factor of 6 increase in emission rate due to the mitigation system is very impressive, it probably is not realistic. First of all, few soils have such high permeabilities. Secondly, a mitigation system could not maintain such high pressures at the flow rates that would result from such high permeabilities. For the permeabilities of 3.9×10^{-10} m^2 and 2×10^{-9} m^2 in figures 6 and 7, respectively, a pressure difference greater than 10 Pa probably could not be maintained by the mitigation system. The increases in the total emission rates would then be limited to about 50% and 300% for permeabilities of 3.9×10^{-10} m^2 and 2×10^{-9} m^2, respectively.

It must be remembered that a particular increase applies only to a given house and its sphere of influence. These emissions will be mixed with all the ambient air. Since the sphere of influence of installed mitigation systems is likely to cover only a small fraction of the total soil surface, the increase of the ambient radon level will increase by a smaller fraction than those associated with individual mitigation systems. For instance, if only 10% of the surface of the soil in a given community is associated with mitigation systems, then the ambient radon concentrations would increase by only 10% of the increase of the average individual mitigation system. Even for the high permeabilities discussed above, this would translate into the range 5 - 30% increase in ambient levels. This range of increased ambient radon levels should be compared with typical natural variations of 300% (10 - 30 Bq/m^3) that occur from one location to another.

CONCLUSIONS

It has been argued that radon entry into many basement houses can be estimated by calculating radon entry into a buried cylinder which simulates either perimeter drain tiles or wall/floor cracks. It has been further argued that this model can be extended to simulate the interaction of the depressurization system with radon in the soil. The primary advantage of this simulation is that analytical solutions can be obtained to describe the radon migration and entry. This paper addresses the question of whether soil depressurization systems significantly increase the ambient radon concentrations. While the model predicts that the total emission rate from the house and its sphere of influence is almost always increased by the operation of a soil depressurization system, the increase is not significant (less than 1% increase per mitigation system) for soil permeabilities below about 2×10^{-11} m^2. As the permeability increases so does the total emission rate. However, the pressure difference that the mitigation system can sustain decreases as the permeability increases. Consequently, the maximum increase in the total emission from a house and its sphere of influence due to the operation of a depressurization system is probably not more than 50%. In cases of unusually high permeability (2×10^{-9} m^2) the increase per house could be 300%. Even the higher rates of increased emissions would lead to average ambient levels smaller than typical indoor radon levels.

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TABLE 1. Values of the parameters used to perform the calculations in this paper

Parameter	Baseline value	Range of variation
k	1.6×10^{-11} m^2	$1 \times 10^{-15} - 2 \times 10^{-9}$ m^2
P_c	4 Pa	0 - 40 Pa
D_e	2.0×10^{-6} m^2/s	$1 \times 10^{-6} - 4 \times 10^{-6}$ m^2/s
μ	1.7×10^{-5} kg/m/s	
ϵ	0.5	
G	0.0334 Bq/m^3/s	
λ	2.11×10^{-6}	
b	0.0508 m	
h	2.0 m	
L	50. m	

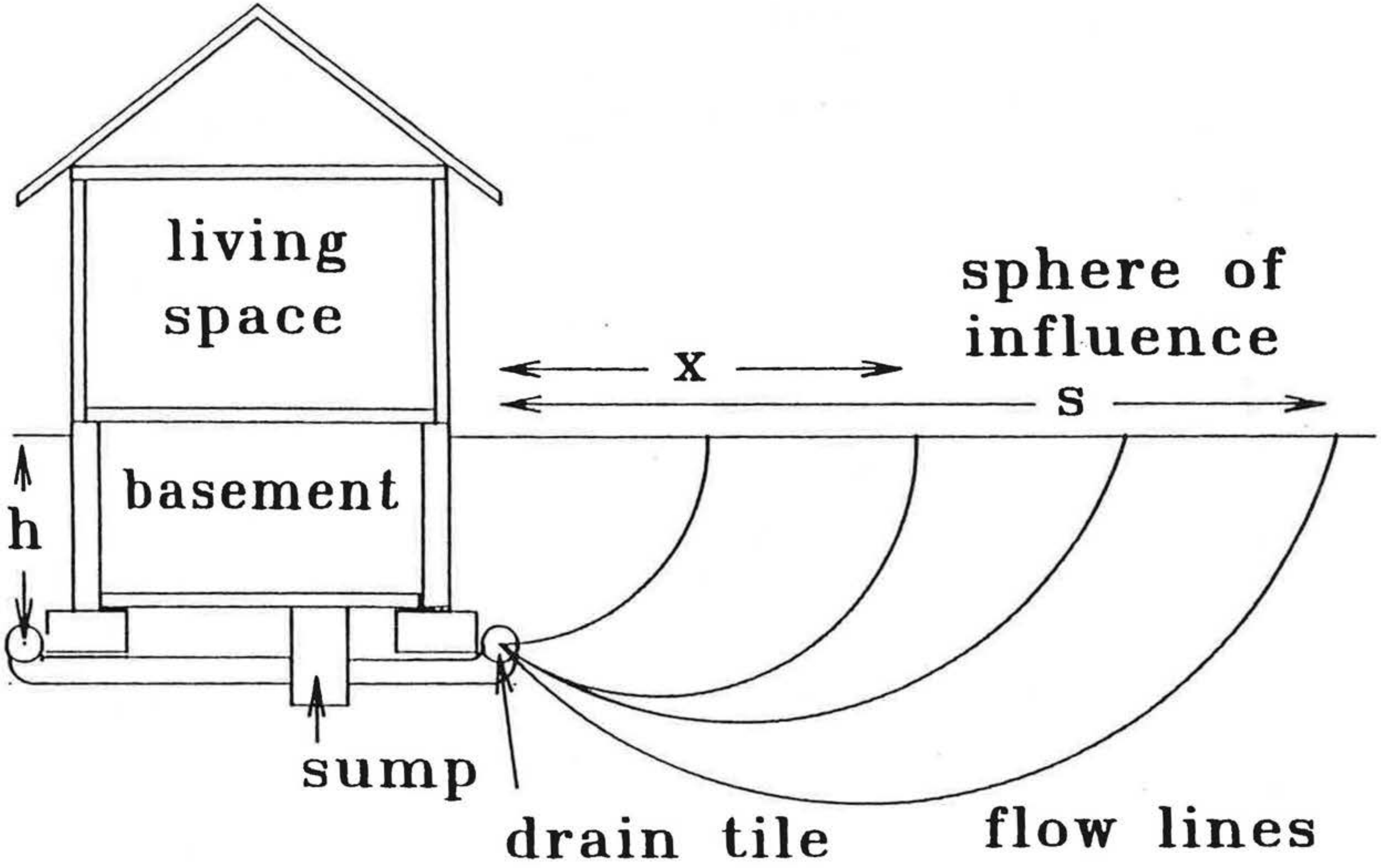

Figure 1. The house soil system showing the air flow pattern

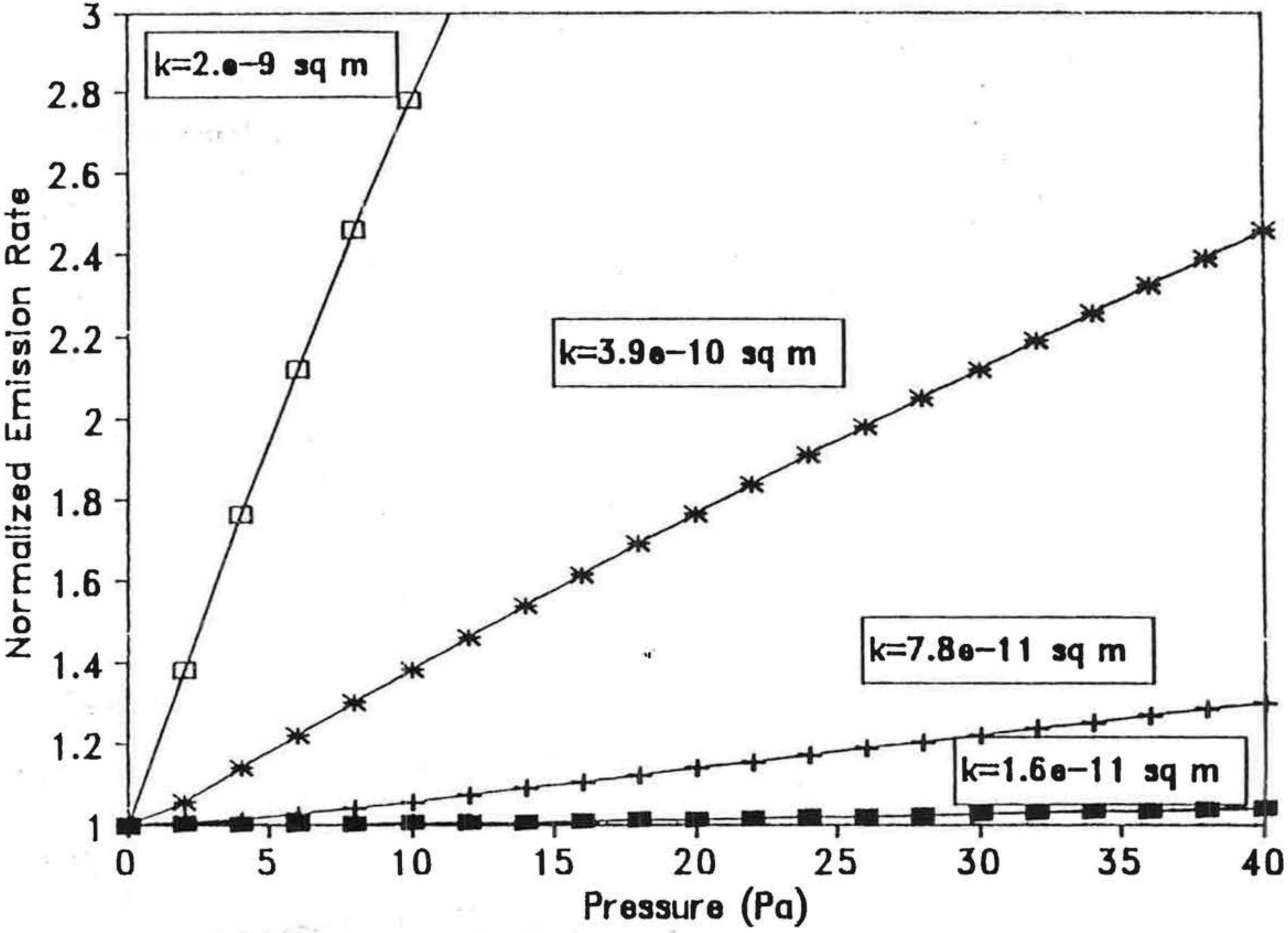

Figure 2. Normalized emission rates as a function of pressure for four values of permeability

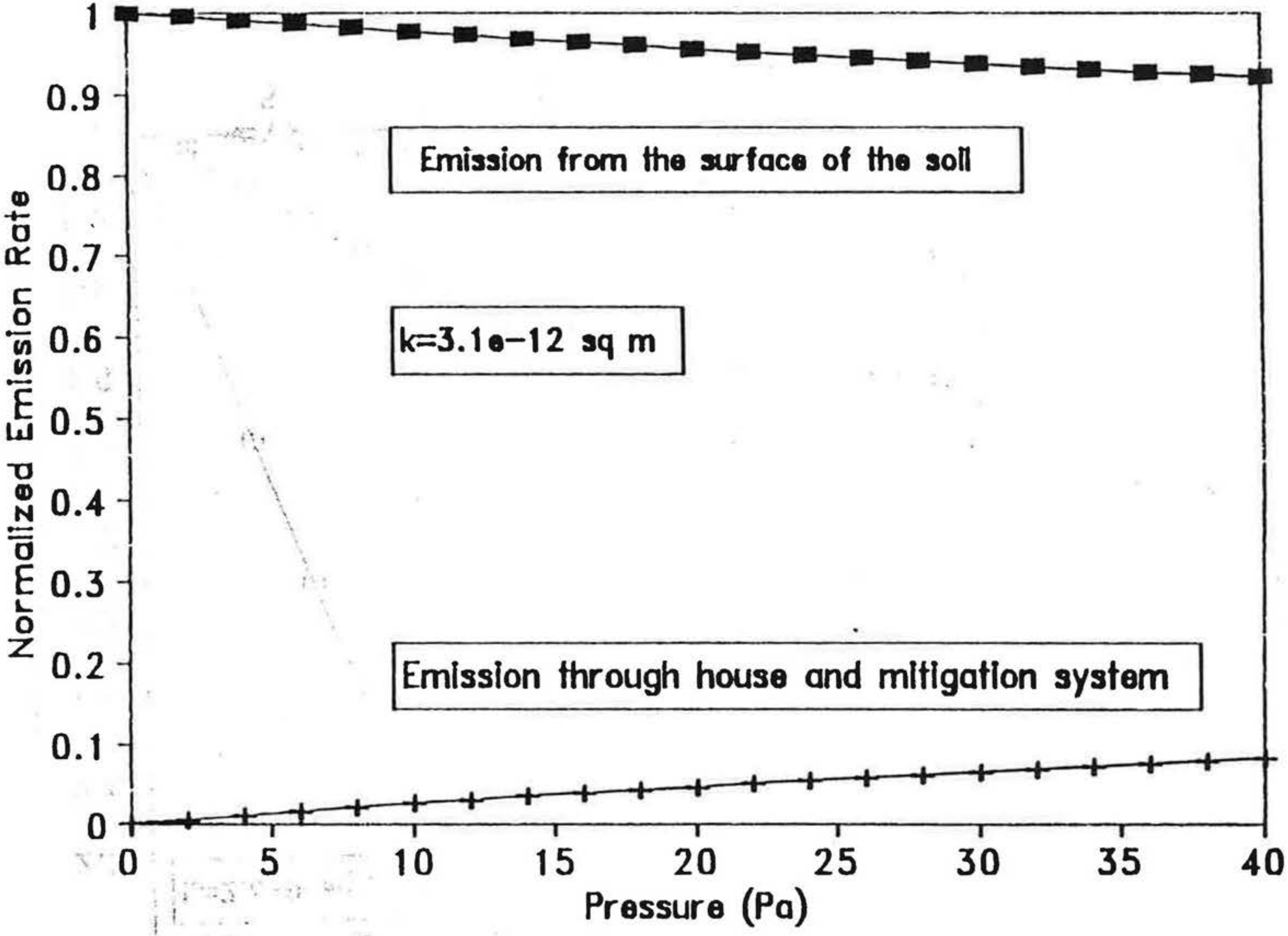

Figure 3. Normalized emission rates as a function of pressure for the two individual emission sources with permeability of 3.2×10^{-12} m^2

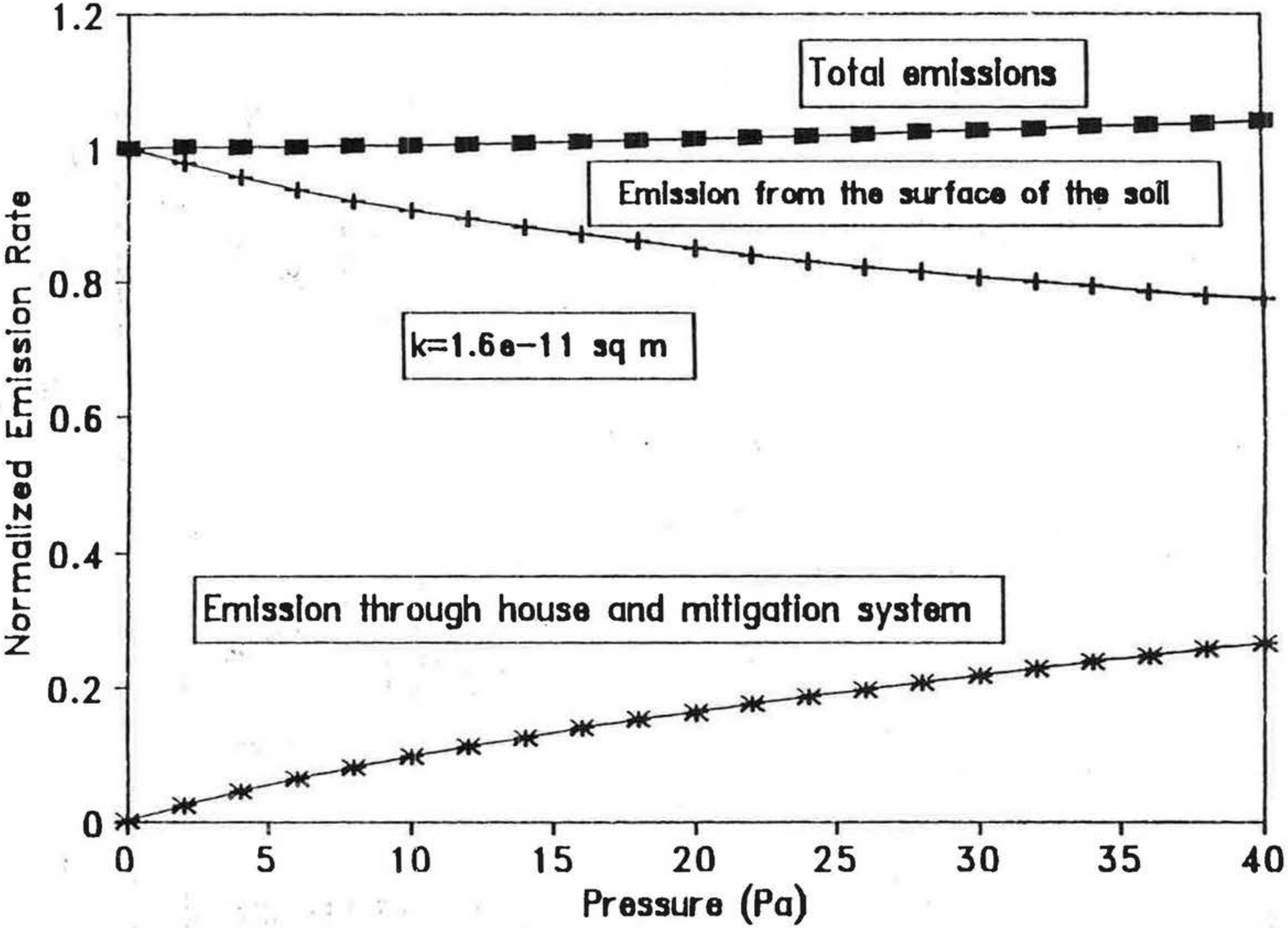

Figure 4. Normalized emission rates as a function of pressure for individual emission sources and their total with permeability of 1.6×10^{-11} m^2

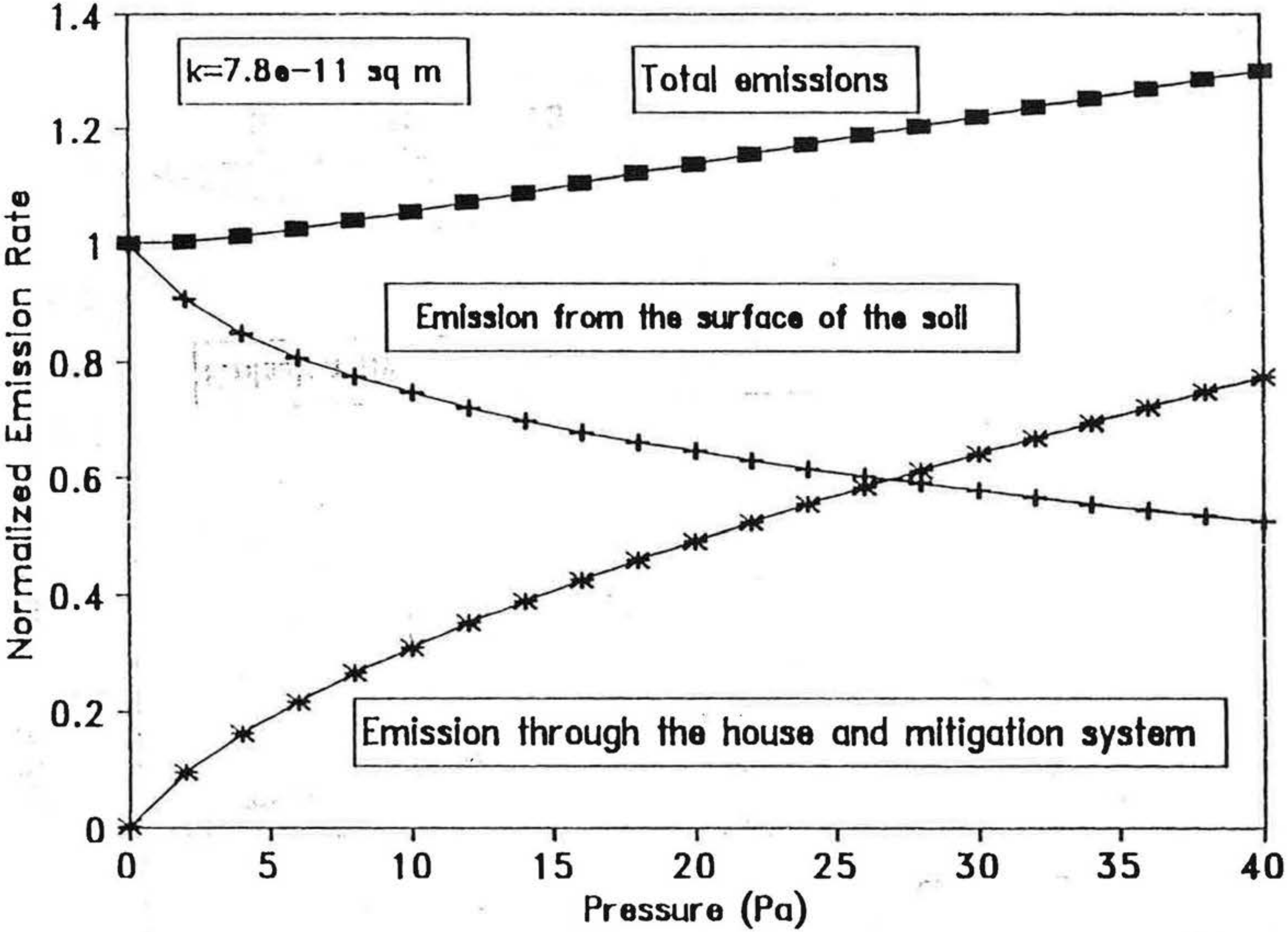

Figure 5. Normalized emission rates as a function of pressure for individual emission sources and their total with permeability of 7.8 x 10^{-11} m^2

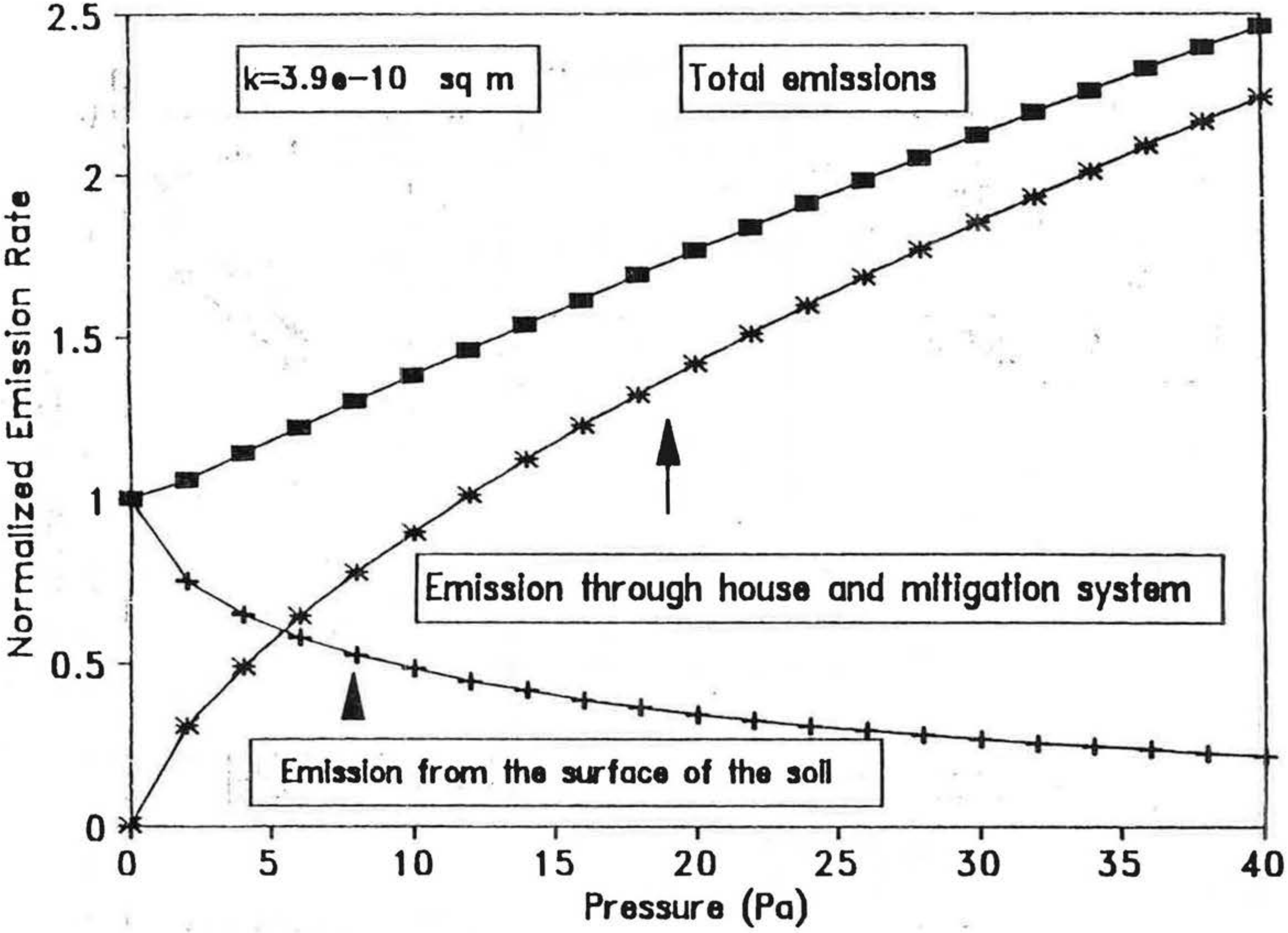

Figure 6. Normalized emission rates as a function of pressure for individual emission sources and their total with permeability of 3.9×10^{-10} m^2

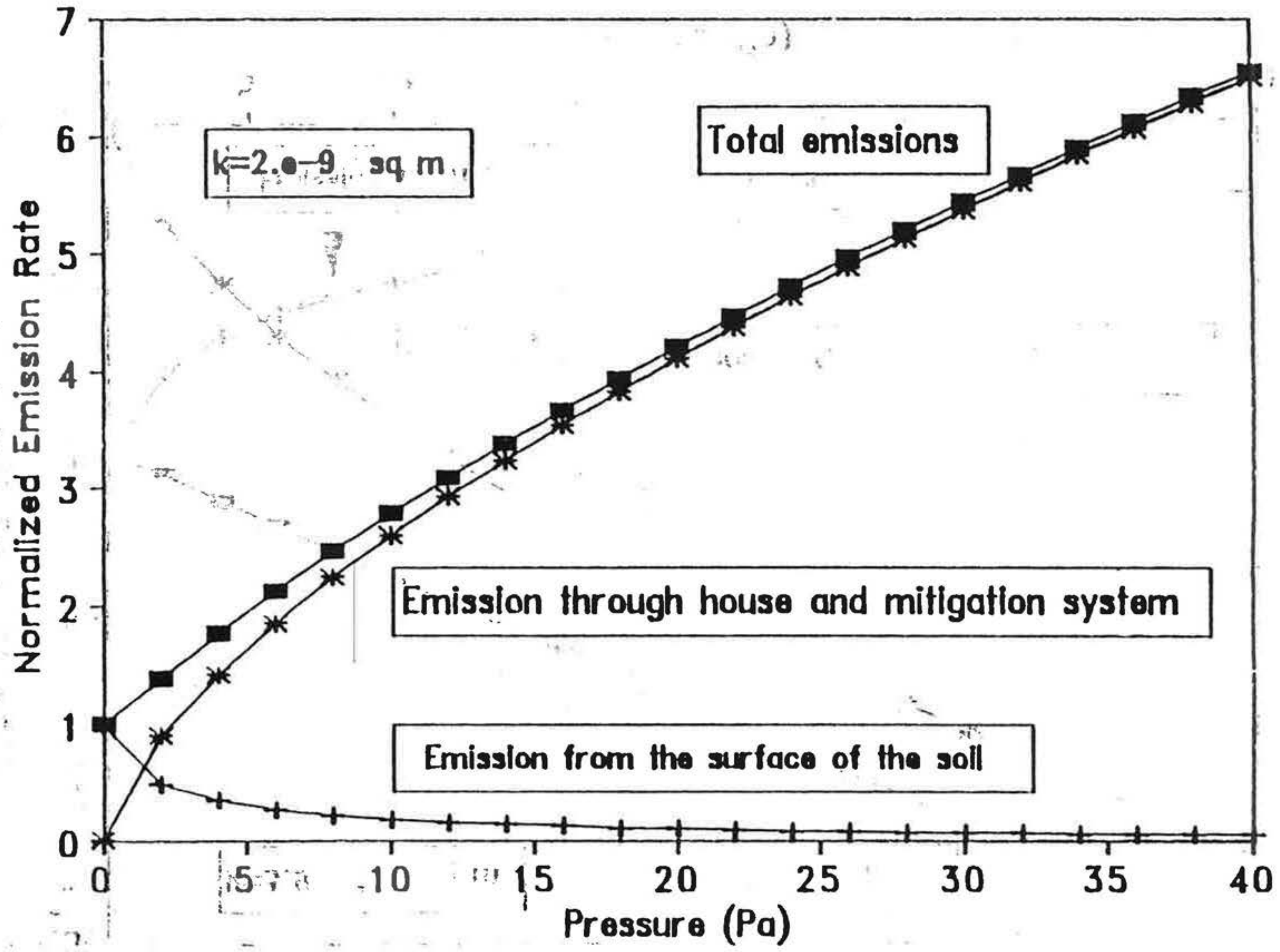

Figure 7. Normalized emission rates as a function of pressure for individual emission sources and their total with permeability of 2.0×10^{-9} m^2