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AUSTRALIAN NUCLEAR SCIENCE AND TECHNOLOGY ORGANISATION

LUCAS HEIGHTS RESEARCH LABORATORIES

THE ERROR INTRODUCED INTO A WATER DENSITY MEASUREMENT DUE TO THE PRESENCE OF A WATER DENSITY GRADIENT

by

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ABSTRACT

A multigroup diffusion code has been used to calculate the thermal neutron flux resulting from a neutron source in a homogeneous soil system in which there is a linear water density gradient. A relative neutron count rate is obtained by integrating the thermal flux over the volumes of different detectors in that flux. By repeating the calculation in the same soil system containing water at a constant density equal to that pertaining to the measuring point in the gradient system, the change in flux due to the gradient can be determined.

The magnitude of the effect is mainly a function of the soil density, the slope of the water density gradient, the proximity of the gradient to the detector and the water density. The mass absorption coefficient and the mass scattering coefficient have very little influence on this effect.

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ERRORS; HUMIDITY; MOISTURE GAGES; MULTIGROUP THEORY; NEUTRON FLUX; SOILS; THERMAL NEUTRONS; WATER

EDITORIAL NOTE

The Australian Nuclear Science and Technology Organisation replaced the Australian Atomic Energy Commission on 27 April 1987. Reports issued after April 1987 have the prefix ANSTO with no change of the symbol (E, M, S or C) or numbering sequence.

CONTENTS

(Continued)

1. INTRODUCTION

A neutron moisture meter consists of a probe containing a source of fast neutrons and a slow neutron detector, plus electronic apparatus to generate the necessary power supplies and to amplify and present the signals generated by the detector.

When the probe is lowered into a borehole, the fast neutrons emitted by the source collide with the atoms of the surrounding medium and may be slowed down by sharing their energy with these atoms, or absorbed by them. Some of the scattered neutrons will return to the detector and, for a given soil, the number returning will be a function of the amount of water present because hydrogen has a large neutron scattering cross section.

It has been shown [Ritchie and Wilson 1984] that the response of a neutron moisture probe is a function of the following parameters:

(i) The total water density ω in g cm^{-3}. This includes water of crystallisation or any other bound water.

(ii) The dry soil density ρ in g cm^{-3}.

(iii) The thermal neutron mass absorption coefficient defined as $S_a = \Sigma_a/\rho$ cm^2 g^{-1}, where Σ_a is the thermal macroscopic absorption cross section of the dry soil (not including that of any bound water).

(iv) The thermal neutron mass scattering coefficient defined as $S_s = \Sigma_s/\rho$ cm^2g^{-1}, where Σ_s is the macroscopic scattering cross section of the dry soil (not including bound water).

For the most part, the functions describing the effect of the parameters are non-linear and non-independent. For example, the function describing the effect of the soil density on the thermal flux at the detector changes with the water density. As the neutrons returning to the detector are from all parts of the surrounding 'volume of importance', it is implied that any inhomogeneity within this volume must affect the count rate. In this case, the inhomogeneity examined is the water density.

It would not be practical or perhaps even possible to conduct an experiment with sufficiently spatially constant soil parameters and a constant water density gradient so that the effect being studied is not perturbed. For this reason a calculational technique was developed from the methods used previously [Ritchie and Wilson 1984]. The soil is not specified by name or type, only by its nuclear parameters S_a and S_s and its density ρ. The water density gradient is introduced by having a sequence of thin layers of soil, each layer containing a slightly different water density than its neighbour. The resulting flux distribution was then compared with that calculated for a similar soil with a constant water density equal to that of the measuring point in the gradient situation.

2. MODELLING THE GRADIENT

The computer code MIRANDA [Robinson 1977] was used to generate neutron cross sections for different soils and these together with the soil density ρ, defined the solid material. The code POW [Pollard 1974] was then used to model this geometry and fill the geometrical regions with a mixture of the chosen soil and differing quantities of water to produce the gradient (**figure 1**), to introduce the neutron source and calculate the resulting neutron flux. **Figure 2** shows a water density profile the length of which is always limited to 20 cm because it became apparent that water at distances greater than this was having very little effect on the count rate.

The probe was considered to be a point neutron source with a coincident detector denoted by S/D (source/detector) or a BF_3 counter (see **figure 6**) with a neutron source with its centre on the same axis and 5 cm from the end of the counter. The length of the counter was varied in some cases. The neutron source was given the spectrum of a Ra-Be source [Ritchie and Wilson 1984], but other source type spectra are unlikely to produce significantly different results.

With the source in the gradient system at a water density of 0.25 g cm^{-3} (**figure 3**), the resulting flux at the source/detector or BF_3 system was calculated for a range of soil parameters, water density gradients and gradient proximities and compared with the fluxes calculated for similar soils with no water density gradients.

3. RESULTS

3.1 Proximity of the Gradient

Figure 3 shows the position of the source/detector with respect to the water density profile. In situation A, the source sits at the bottom of the gradient. On one side the soil, containing water at a constant density of 0.25 g cm^{-3}, stretches off to infinity, on the other the water density increases linearly to 0.4 g cm^{-3} over a distance of 20 cm (rate of change +0.0075 g cm^{-4}) and then remains constant at 0.4 g cm^{-3}. In situation B, the source sits at a water density of 0.25 g cm^{-3} but on one side the water density falls to 0.2125 g cm^{-3} over 5 cm and then remains constant, and on the other side the water density rises to 0.3625 g cm^{-3} over 15 cm and then remains constant. In each of the five cases, the water density at the source/detector is 0.25 g cm^{-3} and the density gradient is constant at 0.0075 g cm^{-4}.

The spatial variations of the thermal flux arising from a source at each of the positions A to E of **figure 3** are shown at A to E of **figure 4**. Overall, A has the highest mean water density and E the lowest. This is reflected by the decreasing fluxes of **figure 4**. The relative thermal fluxes calculated for each situation are given in **table 1**.

In the presence of a water density gradient, not only does the magnitude of the flux change but also the position of the flux peak moves with respect to the source. It no longer coincides with the source but lies on the high water side at a distance depending upon the source position relative to the gradient. The maximum peak displacement (**figure 5**) occurs when the source is near the centre of the gradient, approximately equivalent to position C of **figure 3**.

These changes in the flux will cause changes in the detector count rate and, because of the peak movement, the changes will be different for different detector geometries. **Figure 6** shows the ratio ϕ_G/ϕ_H plotted against the distance of the source from the centre of the gradient. ϕ_G is defined as the flux at the detector when in a water gradient, and ϕ_H the flux at the detector when in the same soil system having a constant water density equal to that at the source position in the gradient system. **Figure 6** also shows the relative count rate changes which would be registered by BF_3 counters of different lengths. These data are acquired by integrating the flux over the length of the counter at its position relative to the source. For the soil parameters and gradient shown, flux changes of up to 6 per cent are obtained for a point detector and somewhat more for the BF_3 counters. These figures are typical. It is shown later that the changes can be greater or less depending on other soil parameters. The details of the flux peak movements and the ratio ϕ_G/ϕ_H for various detectors are given in **table 2**. **Figure 7** shows that where the source/detector is off the gradient, ϕ_G/ϕ_H returns to 1.0 when the source/detector is about 25 cm from the centre of the gradient.

3.2 Water Density Gradient Effect at Various Dry Soil Densities

Decreasing the soil density moves the thermal flux peak further into the high water region and further reduces the flux at the detector, but not as much as might be expected becauses the peak broadens. **Figures 8** to **10** show the fluxes for different soil absorption and scattering coefficients with the gradient symmetrical about the source/detector (**figure 3**, position c).

Because of the rather flat peaks, the peak positions were determined by fitting the peak region to the equation

$$\phi = a + bx + cx^2$$

and differentiating to find the point of zero flux gradient.

Figures 11a to **c** show the peak movement. The calculated fluxes and peak positions at constant mass absorption coefficient but different dry soil densities and mass scattering coefficients are given in **tables 3** to **14**. **Figure 12** shows the effect of the proximity of the gradient at different dry soil densities for a point source and detector. Note how the error in the calculated water density can be significantly larger than that shown in **figure 6**. If a linear relationship existed between the thermal flux at the detector and the water density there would be a zero error at the centre of a linear water density gradient. The curvature of this relationship is the source of the error. **Figure 13** shows how the dry soil density affects the ratio ϕ_G/ϕ_H with the source/detector at the centre of the gradient (position C). ϕ_G/ϕ_H and the displacements of the flux peaks are detailed in **table 15**.

3.3 Water Density Gradient Effects at Different Mass Absorption and Mass Scattering Coefficients

In the homogeneous case these parameters affect the thermal flux at the detector [Ritchie and Wilson 1984]. Using a symmetrical water density gradient to produce the greatest flux peak movement, a set of calculations was made at various dry soil densities, mass absorption and mass scattering coefficients. Some of the calculated thermal neutron fluxes are shown in **figures 14 to 16** plotted from the data throughout **tables 3 to 14.** Selected curves are plotted in **figure 17** to emphasise the effects on the flux of the absorption and scattering coefficients at different values of these parameters. **Figures 18** to **20** show the movement of the flux peak with changing absorption and scattering coefficients from data throughout **tables 3 to 14.** An examination of these results, particularly **table 15,** shows that the mass absorption and scattering coefficients only have a weak effect on the peak movement and specially on the ratio ϕ_G/ϕ_H compared with the density effect (**table 15**). Because of the relatively small importance of these cross-section effects they are not considered further.

3.4 The Effect of the Slope of the Water Density Gradient

A series of flux calculations was made with different symmetrical water density gradients with all other soil parameters fixed (ρ = 1.667 g cm^{-3}, S_a = 6.305 × 10^{-3} cm^2 g^{-1}, S_s = 0.12 cm^2 g^{-1}). **Figure 21** shows the changes in flux shape and amplitude as the density gradient increases from 0.00375 to 0.02 g cm^{-4}. **Figure 22** shows the peak movement and **figure 23** the ratio ϕ_G/ϕ_H. The slope of the water density gradient is one of the more important factors, having a significant effect on the probe signal. Values of ϕ at the detector, ϕ_G/ϕ_H and the displacement of the flux peak are given in **table 16**.

4. DISCUSSION

It is clear from the above that the presence of a water density gradient can have a significant effect on the thermal flux at the detector of a neutron moisture probe, causing a false water density to be recorded. If the point A of **figure, 6, 12, 13,** and **23** is moved to its extreme position with changes of soil density and gradient slope it can be seen that if the source/detector is at the beginning or the end of a gradient the error can be very large, say 30-40 per cent. The proximity of the gradient, the soil density and the slope of the gradient are the important factors. Mass absorption and mass scattering coefficients have little importance. A method of correcting for this perturbation is given in Wilson [1988].

5. REFERENCES

Pollard, J.P. [1974] - AUS module POW - A general purpose 0, 1 and 2D multigroup neutron diffusion code including feed back-free kinetics. AAEC/E269.

Ritchie, A.I.M., Wilson, D.J. [1984] - Investigation of the response of a neutron moisture meter using a multigroup, two-dimensional diffusion code. AAEC/E579.

Robinson, G.S. [1977] - AUS module MIRANDA - a data preparation code based on multiregion resonance theory. AAEC/E410.

Wilson, D.J. [1988] - Correcting the error in neutron moisture probe measurements caused by a water density gradient. ANSTO/E674.

TABLE 1
RELATIVE THERMAL FLUX IN A SOIL WITH A MOISTURE CONCENTRATION GRADIENT OF SLOPE OF 0.0075 g cm^{-4}

Dry soil density ρ = 1.6667 g cm^{-3}

Mass absorption coefficient S_a = 6.305×10^{-3} cm^{-2} g^{-1}

Mass scattering coefficient S_s = 0.109 cm^{-2} g^{-1}

The source/detector (S/D) is always at the point where the water density is 0.25 g cm^{-3}

Distance from Centre of Gradient (cm)	Gradient Situation (see figures 2 and 3) A	B	C	D	E
	Relative Flux				
-21.5	3523	2240	1400	870	550
-20.5	3888	2416	1500	940	590
-19.5	4158	2603	1619	1020	630
-18.5	4437	2798	1746	1090	675
-17.5	4708	3003	1881	1170	720
-16.5	4978	3218	2026	1260	770
-15.5	5240	3440	2179	1386	830
-14.5	5485	3671	2343	1461	900
-13.5	5707	3908	2517	1575	970
-12.5	5895	4150	2704	1698	1050
-11.5	6040	4396	2901	1831	1125
-10.5	6133	4644	3112	1975	1214
S/D→					
- 9.5	6171	4891	3336	2131	1312
- 8.5	6154	5138	3581	2306	1424
- 7.5	6086	5572	3843	2500	1549
- 6.5	5970	5578	4119	2713	1689
- 5.5	5813	5738	4404	2944	1844
	S/D→				
- 4.5	5620	5839	4692	3194	2015
- 3.5	5398	5876	4973	3459	2202
- 2.5	5152	5852	5236	3739	2405
- 1.5	4889	5774	5466	4030	2625
- 0.5	4612	5648	5645	4327	2861
		S/D→			
0.5	4328	5481	5762	4624	3112
1.5	4041	5280	5811	4911	3377
2.5	3753	5052	5796	5177	3653
3.5	3469	4803	5724	5407	3936
4.5	3191	4538	5601	5584	4222
			S/D→		
5.5	2922	4262	5434	5694	4503
6.5	2663	3980	5231	5732	4769
7.5	2415	3695	4996	5702	5008
8.5	2180	3411	4738	5609	5203
9.5	1959	3131	4459	5459	5335
				S/D→	
10.5	1750	2856	4165	5258	5390
11.5	1550	2593	3867	5020	5366
12.5	1380	2345	3572	4758	5276
13.5	1230	2114	3284	4480	5136
14.5	1080	1899	3008	4196	4958
15.5	950	1701	2744	3911	4751
16.5	830	1530	2496	3630	4524
17.5	730	1360	2263	3637	4286
18.5	640	1200	2047	3094	4041
19.5	560	1070	1847	2842	3794
20.5	490	940	1662	2604	3549
21.5	430	850	1500	2380	3309
22.5	380	770	1350	2170	3076
23.5	350	720	1200	1974	2851

TABLE 2
MAGNITUDE OF RELATIVE THERMAL NEUTRON FLUX CHANGE IN A SYSTEM WITH A WATER CONCENTRATION GRADIENT ϕ_G COMPARED WITH A HOMOGENEOUS SYSTEM ϕ_H AND THE DISPLACEMENT OF THE FLUX PEAK†

ω Range (g cm^{-3})	Gradient Situation (figures 3 & 4)	Peak Disp. (cm)	ϕ_G/ϕ_H			
			Point Det.	6 cm† Det.	12 cm† Det.	17 cm† Det.
0.25-0.4	A	0.7	1.059	1.064	1.071	1.078
0.2125-0.3625	B	1.7	0.996	0.999	1.003	1.008
0.175-0.325	C	1.9	0.982	0.984	0.983	0.983
0.1375-0.2875	D	1.5	0.973	0.971	0.967	0.960
0.115-0.265			0.958	0.948	0.941	0.931
0.1-0.25	E	0.7	0.923	0.921	0.913	0.904

† *e.g.* as seen by a 6, 12 or 17 cm long BF_3 counter

Soil parameters:

ρ 1.667 g cm^{-3}, S_a 6.305 x 10^{-3} cm^2 g^{-1}, S_s 0.12 cm^2 g^{-1}

TABLE 3
RELATIVE THERMAL FLUX IN SOIL WITH A WATER CONCENTRATION GRADIENT

Slope = 0.0075 g cm^{-4}

Effect of dry soil density ρ

Mass absorption coefficient $S_a = 1.7088 \times 10^{-3}$ cm^2 g^{-1}

Mass scattering coefficient $S_s = 0.109$ cm^2 g^{-1}

Distance from Centre of Gradient (cm)	Dry Soil Density ρ (g cm^{-3})				
	0.5	1.0	1.3333	1.6667	2.0
	Relative Flux				
-10.5	28035	39021	46103	52988	59648
- 9.5	29133	40858	48520	56054	63432
- 8.5	30305	42819	51101	59333	67484
- 7.5	31542	44883	53819	62787	71758
- 6.5	32829	47026	56637	66369	76195
- 5.5	34149	49212	59508	70016	80712
- 4.5	35477	51398	62371	73645	85200
- 3.5	36786	53529	65146	77147	89519
- 2.5	38037	55532	67732	80387	93487
- 1.5	39186	57323	70007	83195	96882
- 0.5	40182	58806	71834	85386	99454
0.5	40983	59901	73106	86815	101021
1.5	41561	60569	73772	87423	101512
2.5	41909	60808	73841	87238	100980
3.5	42028	60635	73349	86320	99523
4.5	41923	60074	72340	84741	97247
5.5	41600	59149	70860	82576	94265
6.5	41069	57892	68959	79900	90686
7.5	40341	56332	66686	76789	86613
8.5	39427	54500	64089	73311	82144
9.5	38340	52426	61216	69534	77366
10.5	37092	50139	58108	65515	72358
Distance of Peak from Centre of Gradient (cm)	3.531	2.580	2.123	1.767	1.480

TABLE 4
RELATIVE THERMAL FLUX IN SOIL WITH A WATER CONCENTRATION GRADIENT

Slope = 0.0075 g cm^{-4}

Effect of dry soil density ρ

Mass absorption coefficient $S_a = 6.305 \times 10^{-3}$ cm^2 g^{-1}

Mass scattering coefficient $S_s = 0.109$ cm^2 g^{-1}

Distance from centre of Gradient (cm)	Dry Soil Density ρ (g cm^{-3})				
	0.5	1.0	1.3333	1.6667	2.0
	Relative Flux				
-10.5	21924	26266	28808	31120	33217
- 9.5	22902	27752	30661	33363	35871
- 8.5	23954	29359	32673	35808	38775
- 7.5	25072	31073	34824	38429	41900
- 6.5	26244	32871	37084	41191	45201
- 5.5	27452	34724	39416	44044	48619
- 4.5	28675	36895	41768	46921	52069
- 3.5	29887	38435	44072	49733	55435
- 2.5	31051	40178	46240	52361	58565
- 1.5	32126	41747	48160	54657	61264
- 0.5	33063	43052	49709	56453	63312
0.5	33821	44021	50789	57621	64548
1.5	34374	44619	51357	58113	64917
2.5	34717	44849	51430	57965	64483
3.5	34852	44729	51045	57240	63343
4.5	34784	44284	50247	56009	61600
5.5	34520	43541	49081	54341	59357
6.5	34069	42527	47592	52306	56707
7.5	33442	41269	45824	49965	53736
8.5	32650	39795	43819	47376	50520
9.5	31704	38129	41612	44590	47126
10.5	30615	36297	39238	41651	43605
Distance of Peak from Centre of Gradient (cm)	3.665	2.657	2.159	1.769	1.460

TABLE 5
RELATIVE THERMAL FLUX IN SOIL WITH A WATER CONCENTRATION GRADIENT

Slope = 0.0075 g cm^{-4}

Effect of dry soil density ρ

Mass absorption coefficient $S_a = 12.61 \times 10^{-3}$ cm^2 g^{-1}

Mass scattering coefficient $S_s = 0.109$ cm^2 g^{-1}

Distance from Centre of Gradient (cm)	Dry Soil Density ρ (g cm^{-3})				
	0.5	1.0	1.3333	1.6667	2.0
	Relative Flux				
-10.5	16888	18051	18838	19571	20227
- 9.5	17735	19228	20244	21212	22110
- 8.5	18655	20518	21793	23032	24210
- 7.5	19640	21909	23471	25013	26507
- 6.5	20678	23383	25256	27128	28970
- 5.5	21756	24916	27118	29340	31557
- 4.5	22854	26477	29013	31596	34201
- 3.5	23946	28021	30886	33823	36810
- 2.5	25000	29494	32658	35919	39257
- 1.5	25976	30822	34232	37754	41372
- 0.5	26828	31923	35493	39177	42960
0.5	27517	32734	36357	40077	43880
1.5	28020	33222	36788	40415	44093
2.5	28334	33397	36808	40234	43666
3.5	28461	33278	36456	39598	42698
4.5	28407	32891	35777	38577	41285
5.5	28180	32263	34815	37234	39520
6.5	27790	31419	33610	35630	37482
7.5	27247	30385	32202	33818	35242
8.5	26560	29184	30624	31843	32858
9.5	25739	27837	28906	29746	30378
10.5	24794	26364	27073	27556	27838
Distance of Peak from Centre of Gradient (cm)	3.702	2.595	2.054	1.651	1.333

TABLE 6
RELATIVE THERMAL FLUX IN SOIL WITH A WATER CONCENTRATION GRADIENT

Slope = 0.0075 g cm^{-4}

Effect of dry soil density ρ

Mass absorption coefficient $S_a = 18.91 \times 10^{-3}$ cm^2 g^{-1}

Mass scattering coefficient $S_s = 0.109$ cm^2 g^{-1}

Distance from Centre of Gradient (cm)	Dry Soil Density ρ (g cm^{-3})				
	0.5	1.0	1.3333	1.6667	2.0
	Relative Flux				
-10.5	13699	13635	13818	14034	14236
- 9.5	14445	14609	14949	15325	15688
- 8.5	15262	15687	16210	16774	17330
- 7.5	16141	16860	17589	18368	19147
- 6.5	17074	18111	19068	20087	21117
- 5.5	18045	19422	20623	21901	23206
- 4.5	19039	20764	22217	23766	25361
- 3.5	20032	22099	23801	25620	27507
- 2.5	20992	23376	25307	27374	29529
- 1.5	21883	24528	26645	28910	31280
- 0.5	22660	25479	27709	30090	32579
0.5	23286	26170	28422	30814	33302
1.5	23741	26572	28754	31050	33417
2.5	24022	26698	28730	30843	32996
3.5	24132	26569	28392	30260	32133
4.5	24080	26211	27783	29365	30921
5.5	23872	25651	26945	28219	29442
6.5	23520	24914	25916	26876	27766
7.5	23031	24022	24729	25382	25953
8.5	22415	22996	23416	23774	24050
9.5	21653	21854	21999	22085	22093
10.5	20841	20612	20497	20334	20107
Distance of Peak from Centre of Gradient (cm)	3.679	2.494	1.933	1.533	1.215

TABLE 7
RELATIVE THERMAL FLUX IN SOIL WITH A WATER CONCENTRATION GRADIENT

Slope = 0.0075 g cm^{-4}

Effect of dry soil density ρ

Mass absorption coefficient $S_a = 1.7088 \times 10^{-3}$ cm^2 g^{-1}

Mass scattering coefficient $S_s = 0.12$ cm^2 g^{-1}

Distance from Centre of Gradient (cm)	Dry Soil Density ρ (g cm^{-3})				
	0.5	1.0	1.3333	1.6667	2.0
	Relative Flux				
-10.5	29916	41293	49192	56889	64337
- 9.5	30270	43276	51836	60279	68557
- 8.5	31500	45391	54657	63902	73075
- 7.5	32798	47616	57626	67717	77841
- 6.5	34147	49924	60702	71671	82785
- 5.5	35529	52276	63833	75694	87815
- 4.5	36919	54625	66950	79690	92808
- 3.5	38287	56909	69965	83539	97601
- 2.5	39592	59051	72765	87085	101988
- 1.5	40787	60957	75214	90139	105713
- 0.5	41819	62521	77159	92489	108491
0.5	42643	63658	78483	93976	110116
1.5	43229	64326	79129	94534	110513
2.5	43572	64525	79115	94203	109750
3.5	43673	64276	78483	93056	107950
4.5	43538	63607	77284	91179	105240
5.5	43174	62[illegible]9	75575	88661	101754
6.5	42592	61[illegible]5	73413	85593	97622
7.5	41805	59400	70855	82060	92966
8.5	40824	57378	67956	78143	87898
9.5	39664	55104	64769	73918	82520
10.5	38339	52610	61343	69452	76921
Distance of Peak from Centre of Gradient (cm)	3.428	2.444	1.979	1.628	1.343

TABLE 8
RELATIVE THERMAL FLUX IN SOIL WITH A WATER CONCENTRATION GRADIENT

Slope = 0.0075 g cm^{-4}

Effect of dry soil density ρ

Mass absorption coefficient $S_a = 6.305 \times 10^{-3}$ cm^2 g^{-1}

Mass scattering coefficient $S_s = 0.12$ cm^2 g^{-1}

Distance from Centre of Gradient (cm)	Dry Soil Density ρ (g cm^{-3})				
	0.5	1.0	1.3333	1.6667	2.0
	Relative Flux				
-10.5	22765	27801	30749	33423	35838
- 9.5	23791	29404	32775	35901	38794
- 8.5	34896	31137	34973	38602	42031
- 7.5	26069	32984	37322	41497	45513
- 6.5	27296	34920	39790	44545	49193
- 5.5	28562	36914	42333	47693	53001
- 4.5	29842	38925	44895	50864	56841
- 3.5	31108	40898	47400	53956	60582
- 2.5	32323	42763	49749	56838	64049
- 1.5	33441	44434	51819	59339	67018
- 0.5	34412	45812	53470	61270	69237
0.5	35191	46820	54597	62489	70523
1.5	35753	47420	55152	62944	70821
2.5	36093	47617	55158	62680	70207
3.5	36212	47434	54661	61775	68802
4.5	36117	46902	53712	60312	66730
5.5	35817	46049	52364	58375	64110
6.5	35623	44906	50671	56041	61054
7.5	34644	43507	48682	53385	57662
8.5	33794	41880	46444	50472	54021
9.5	32784	40056	43999	47361	50207
10.5	31628	38059	41385	44100	46281
Distance of Peak from Centre of Gradient (cm)	3.556	2.520	2.012	1.633	1.327

TABLE 9
RELATIVE THERMAL FLUX IN SOIL WITH A WATER CONCENTRATION GRADIENT

Slope = 0.0075 g cm^{-4}

Effect of dry soil density ρ

Mass absorption coefficient $S_a = 12.61 \times 10^{-3}$ cm^2 g^{-1}

Mass scattering coefficient $S_s = 0.12$ cm^2 g^{-1}

Distance from Centre of Gradient (cm)	Dry Soil Density ρ (g cm^{-3})				
	0.5	1.0	1.3333	1.6667	2.0
	Relative Flux				
-10.5	17534	19109	20110	21020	21819
- 9.5	18423	20378	21646	22833	23915
- 8.5	19388	21769	23339	24842	26254
- 7.5	20420	23267	25171	27028	28813
- 6.5	21509	24854	27120	29363	31559
- 5.5	22637	26505	29151	31805	34441
- 4.5	23786	28182	31217	34293	37287
- 3.5	24927	29840	33254	36745	40290
- 2.5	26027	31416	35177	39046	43005
- 1.5	27042	32831	36876	41049	45337
- 0.5	27025	33996	38223	42582	47061
0.5	28634	34839	39125	43521	48019
1.5	29146	35329	39543	43826	48169
2.5	29456	35475	39506	43549	47596
3.5	29569	35303	39060	42766	46416
4.5	29492	34842	38258	41559	44746
5.5	29234	34122	37149	40004	42692
6.5	28806	33174	35782	38170	40349
7.5	28217	32025	34200	36119	37797
8.5	27480	30701	32443	33903	35105
9.5	26605	29228	30543	31568	32327
10.5	25602	27624	28528	29141	29501
Distance of Peak from Centre of Gradient (cm)	3.595	2.459	1.919	1.524	1.207

TABLE 10
RELATIVE THERMAL FLUX IN SOIL WITH A WATER CONCENTRATION GRADIENT

Slope = 0.0075 g cm^{-4}

Effect of dry soil density ρ

Mass absorption coefficient $S_a = 18.91 \times 10^{-3}$ cm^2 g^{-1}

Mass scattering coefficient $S_s = 0.12$ cm^2 g^{-1}

Distance from Centre of Gradient (cm)	Dry Soil Density ρ (g cm^{-3})				
	0.5	1.0	1.3333	1.6667	2.0
	Relative Flux				
-10.5	14221	14434	14751	15071	15352
- 9.5	15005	15485	15987	16496	16967
- 8.5	15861	16647	17364	18095	18794
- 7.5	16783	17910	18869	19854	20818
- 6.5	17760	19258	20484	21752	23013
- 5.5	18778	20669	22181	23754	25341
- 4.5	19818	22113	23919	25812	27743
- 3.5	20855	23546	25644	27855	30131
- 2.5	21857	24913	27279	29783	32378
- 1.5	22784	26142	28724	31462	34311
- 0.5	23589	27148	29862	32735	35725
0.5	24234	27866	30606	33490	35477
1.5	24696	28268	30925	33694	36536
2.5	24973	28368	30850	33403	35987
3.5	25071	28192	30430	32693	34945
4.5	24998	27769	29714	31641	33518
5.5	24762	27130	28752	30319	31803
6.5	24374	26302	27586	28787	29881
7.5	23845	25312	26256	27099	27821
8.5	23186	24183	24795	25297	25676
9.5	22405	22936	23231	23418	23488
10.5	21512	21586	21584	21485	21284
Distance of Peak from Centre of Gradient (cm)	3.573	2.362	1.810	1.412	1.097

TABLE 11
RELATIVE THERMAL FLUX IN SOIL WITH A WATER CONCENTRATION GRADIENT

Slope = 0.0075 g cm^{-4}

Effect of dry soil density ρ

Mass absorption coefficient $S_a = 1.7088 \times 10^{-3}$ cm^2 g^{-1}

Mass scattering coefficient $S_s = 0.13$ cm^2 g^{-1}

Distance from Centre of Gradient (cm)	Dry Soil Density ρ (g cm^{-3})				
	0.5	1.0	1.3333	1.6667	2.0
	Relative Flux				
-10.5	30048	43261	51873	60273	68402
- 9.5	31249	45374	54719	63954	73016
- 8.5	32531	47626	57755	67887	77956
- 7.5	33882	49994	60949	72027	83166
- 6.5	35286	52448	64256	76317	88571
- 5.5	36723	54947	67619	80677	94066
- 4.5	38167	57440	70963	85005	99516
- 3.5	39585	59861	74192	89165	104740
- 2.5	40937	62125	77183	92987	109505
- 1.5	42173	64131	79786	96260	113526
- 0.5	43236	65766	81534	98749	116486
0.5	44078	66939	83200	100282	118156
1.5	44672	67603	83825	100789	118457
2.5	45009	67764	83731	100318	117476
3.5	45093	67445	82968	98956	115351
4.5	44931	66678	81595	96803	112236
5.5	44530	65497	79676	93962	108285
6.5	43903	63942	77276	90535	103646
7.5	43064	62049	74460	86619	98458
8.5	42025	59858	71289	82305	92848
9.5	40801	57406	67822	77678	86930
10.5	39408	54729	64113	72813	80803
Distance of Peak from Centre of Gradient (cm)	3.341	2.335	1.869	1.518	1.235

TABLE 12
RELATIVE THERMAL FLUX IN SOIL WITH A WATER CONCENTRATION GRADIENT

Slope = 0.0075 g cm^{-4}

Effect of dry soil density ρ

Mass absorption coefficient S_a 6.305×10^{-3} cm^2 g^{-1}

Mass scattering coefficient S_s 0.13 cm^2 g^{-1}

Distance from Centre of Gradient (cm)	Dry Soil Density ρ (g cm^{-3})				
	0.5	1.0	1.3333	1.6667	2.0
	Relative Flux				
-10.5	23490	29130	32431	35419	38105
- 9.5	24559	30837	34611	38108	41334
- 8.5	25708	32682	36976	41038	44870
- 7.5	26929	34646	39502	44179	48676
- 6.5	28206	36705	42155	47486	52698
- 5.5	29521	38824	44887	50898	56860
- 4.5	30854	40958	47637	54337	61054
- 3.5	32104	43049	50321	57680	65135
- 2.5	33423	45021	52832	60788	68906
- 1.5	34579	46781	55034	63473	72118
- 0.5	35578	48223	56776	65523	74487
0.5	36376	49264	57941	66783	75814
1.5	36945	49864	58481	67198	76038
2.5	37281	50030	58423	66824	75254
3.5	37386	49790	57820	65751	73600
4.5	37267	49176	56732	64073	71220
5.5	36935	48223	55218	61887	68253
6.5	36401	46965	53338	59281	64825
7.5	35677	45438	51149	56339	61049
8.5	34776	43676	48703	53134	67025
9.5	33711	41709	46045	49731	52834
10.5	32495	39567	43218	46184	48546
Distance of Peak from Centre of Gradient (cm)	3.469	2.408	1.903	1.526	1.222

TABLE 13
RELATIVE THERMAL FLUX IN SOIL WITH A WATER CONCENTRATION GRADIENT

Slope = 0.0075 g cm^{-4}

Effect of dry soil density ρ

Mass absorption coefficient $S_a = 12.61 \times 10^{-3}$ cm^2 g^{-1}

Mass scattering coefficient $S_s = 0.13$ cm^2 g^{-1}

Distance from Centre of Gradient (cm)	Dry Soil Density ρ (g cm^{-3})				
	0.5	1.0	1.3333	1.6667	2.0
	Relative Flux				
-10.5	18090	20023	21212	22274	23194
- 9.5	19015	21374	22864	24239	25482
- 8.5	20019	22854	24684	26419	28035
- 7.5	21094	24448	26655	28790	30831
- 6.5	22226	26136	28750	31323	33831
- 5.5	23399	27890	30932	33971	36982
- 4.5	24591	29671	33150	36668	40251
- 3.5	25775	31429	35335	39323	43371
- 2.5	26915	33096	37392	41808	46328
- 1.5	27964	34588	39202	43961	48855
- 0.5	28874	35808	40624	45591	50700
0.5	29600	36679	41557	46563	51688
1.5	30118	37168	41961	46833	51776
2.5	30425	37287	41870	46463	51063
3.5	30526	37066	41336	45544	49685
4.5	30428	36537	40420	44166	47775
5.5	30142	35734	39177	42416	45455
6.5	29679	34691	37662	40372	42832
7.5	29051	33438	35924	38104	39998
8.5	28269	32006	34005	35669	37028
9.5	27346	30419	31943	33118	33982
10.5	26293	28701	29768	30486	30903
Distance of Peak from Centre of Gradient (cm)	3.508	2.350	1.868	1.422	1.110

TABLE 14
RELATIVE THERMAL FLUX IN SOIL WITH A WATER CONCENTRATION GRADIENT

Slope = $0.0075\ g\ cm^{-4}$

Effect of dry soil density ρ

Mass absorption coefficient $S_a = 18.91 \times 10^{-3}\ cm^2\ g^{-1}$

Mass scattering coefficient $S_s = 0.13\ cm^2\ g^{-1}$

Distance from Centre of Gradient (cm)	Dry Soil Density ρ ($g\ cm^{-3}$)				
	0.5	1.0	1.3333	1.6667	2.0
	Relative Flux				
-10.5	14671	15125	15559	15968	16314
- 9.5	15487	16243	16887	17511	18076
- 8.5	16378	17480	18368	19245	20070
- 7.5	17337	18824	19986	21153	22279
- 6.5	18353	20257	21722	23211	24677
- 5.5	19411	21757	23546	25383	27222
- 4.5	20491	23290	25413	27615	29848
- 3.5	21567	24810	27264	29828	32457
- 2.5	22605	26257	29014	31912	34907
- 1.5	23564	27553	30554	33718	37005
- 0.5	24393	28607	31756	35073	38520
0.5	25053	29349	32526	35854	39295
1.5	25521	29750	32831	36025	39296
2.5	25795	29825	32708	35653	38627
3.5	25881	29604	32210	34826	37417
4.5	25789	29122	31397	33630	35791
5.5	25528	28411	30321	32145	33859
6.5	25109	27501	29032	30442	31712
7.5	24545	26424	27573	28578	29428
8.5	23846	25203	25980	26602	27066
9.5	23023	23862	24284	24554	24671
10.5	22086	22417	22508	22458	22273
Distance of Peak from Centre of Gradient (cm)	3.483	2.253	1.713	1.315	1.001

TABLE 15
THE EFFECT OF A WATER DENSITY GRADIENT ON THE THERMAL FLUX AT A POINT DETECTOR

Mass scattering coefficient $S_s = 0.12\ cm^2\ g^{-1}$

Soil mass Absorption coefficient ($cm^2\ g^{-1} \times 10^3$)		Dry Soil Density ρ ($g\ cm^{-3}$) 0.5	1.00	1.3333	1.667	2.00
	ϕ_H	43837	64746	79536	95011	111157
1.71	ϕ_G	41819	62521	77159	92489	108491
	ϕ_G/ϕ_H	0.9540	0.9656	0.9701	0.9735	0.9760
	ϕ_H	36109	47482	55158	62987	70991
6.305	ϕ_G	34412	45812	53470	61270	69237
	ϕ_G/ϕ_H	0.9530	0.9648	0.9694	0.9727	0.9753
Peak Displacement (cm)		3.556	2.520	2.012	1.633	1.237
	ϕ_H	29300	35225	39422	43770	48253
12.61	ϕ_G	27925	33996	38223	42582	47061
	ϕ_G/ϕ_H	0.9531	0.9651	0.9696	0.9729	0.9753
	ϕ_H	24742	28121	30792	33646	36631
18.91	ϕ_G	23589	27148	29862	32735	35725
	ϕ_G/ϕ_H	0.9540	0.9654	0.9698	0.9729	0.9753

TABLE 16
EFFECT OF SLOPE OF GRADIENT ON THERMAL NEUTRON FLUX AT DETECTOR

Gradient ($g\ cm^{-4}$)	φ (Detector)	ϕ_G / ϕ_H	Disp. of Peak
0.00375	62285	0.9889	0.640
0.00500	61977	0.9840	0.911
0.00750	61270	0.9727	1.633
0.01000	60435	0.9595	2.324
0.01250	59465	0.9441	2.959
0.01500	58346	0.9263	3.537
0.01750	57053	0.9058	4.031
0.02000	55538	0.8817	4.466

Homogeneous case $\phi_H = 62987$

Soil parameters:

$\rho = 1.667\ g\ cm^{-3}$, $S_a = 6.305 \times 10^{-3}\ cm^{-2}\ g^{-1}$ $S_s = 0.12\ cm^{-2}\ g^{-1}$

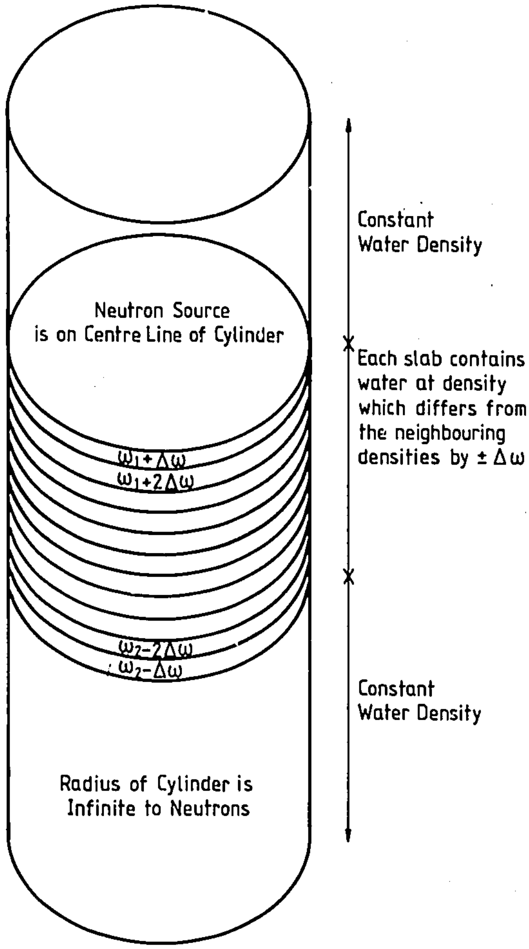


Figure 1 Structure for the water density gradient calculations

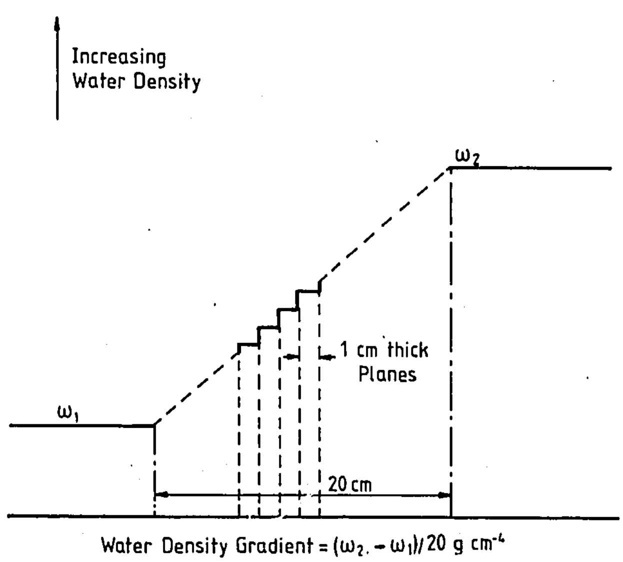


Figure 2 Structure for the water density gradient calculations

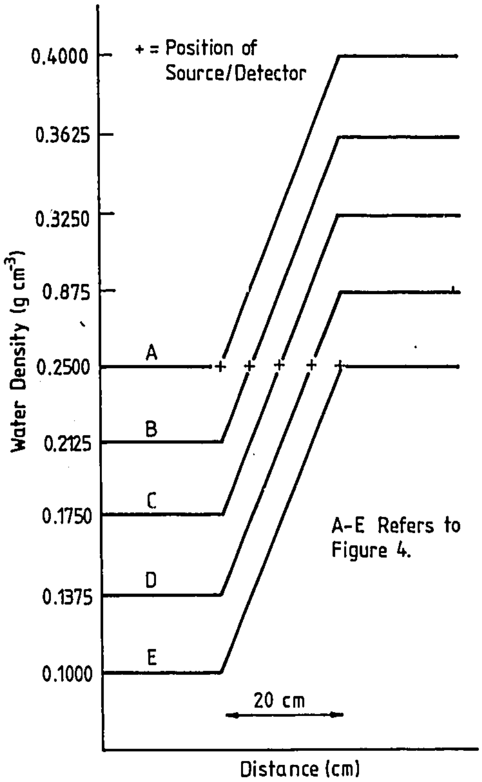


Figure 3 The position of the source relative to the water density gradient

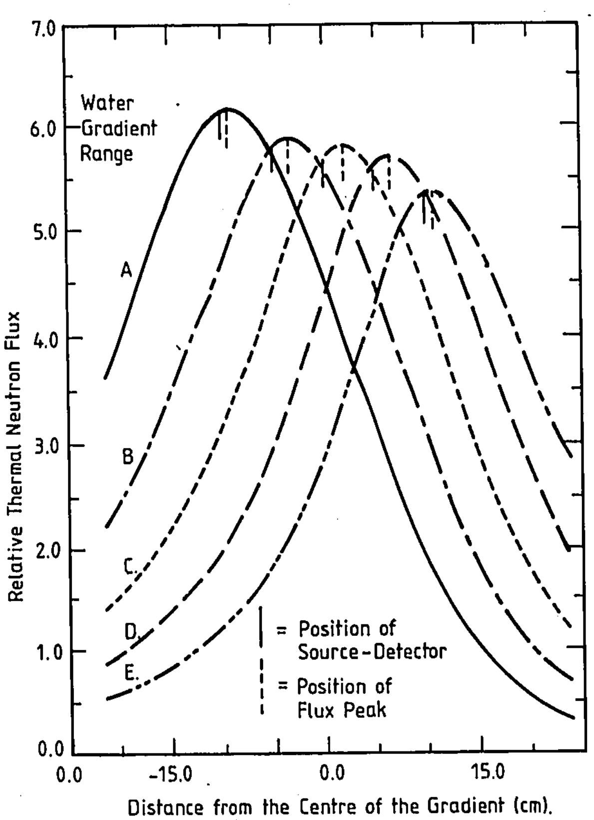


Figure 4 Thermal flux in a constant water gradient ; the effect of the gradient range

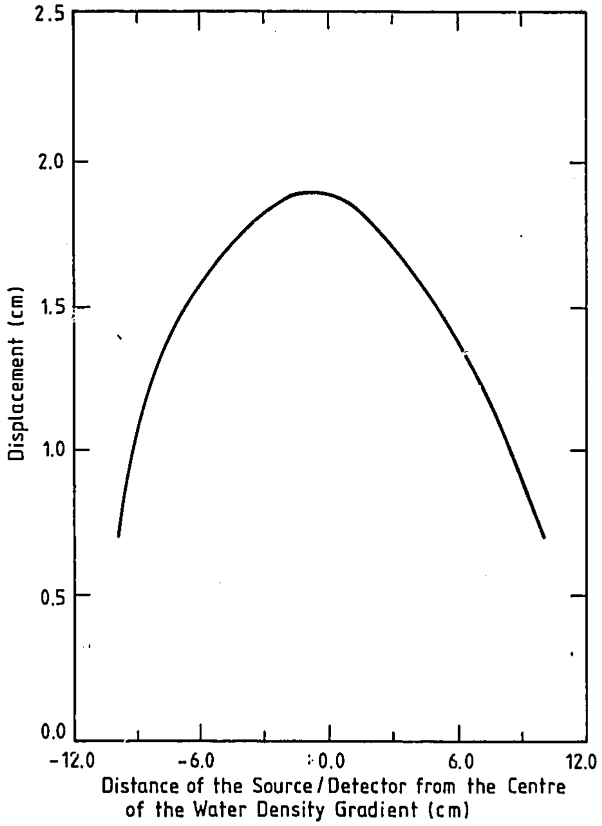


Figure 5 Displacement of the flux peak due to a linear water density gradient

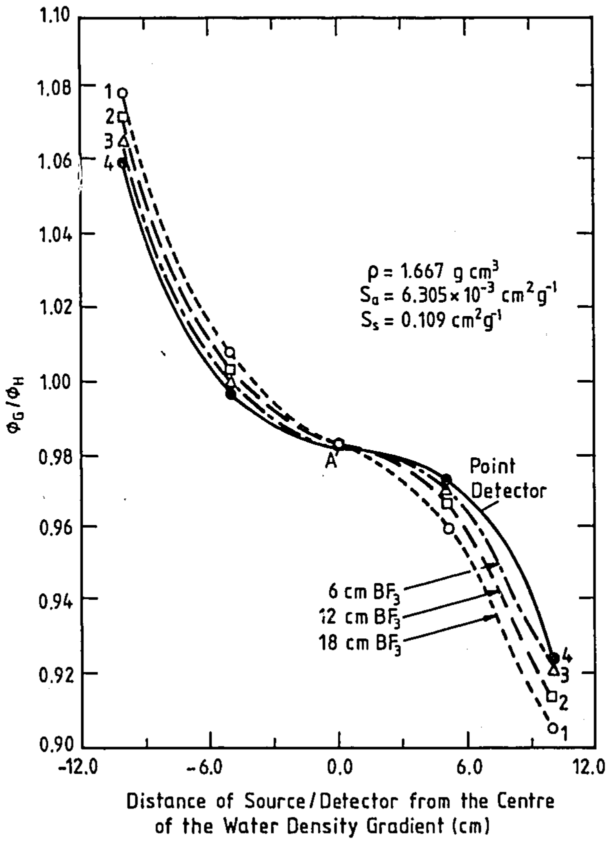


Figure 6 The variation of ϕ_G/ϕ_H due to a water density gradient

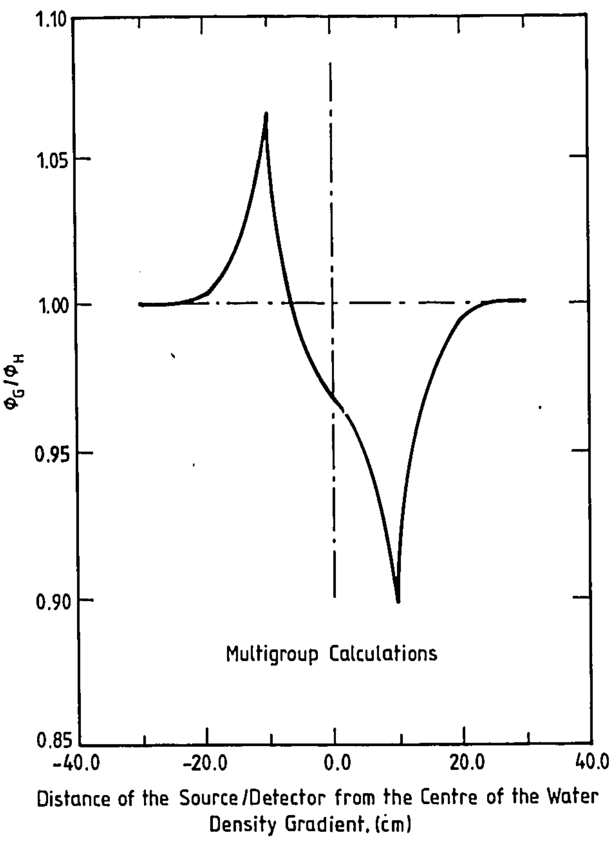
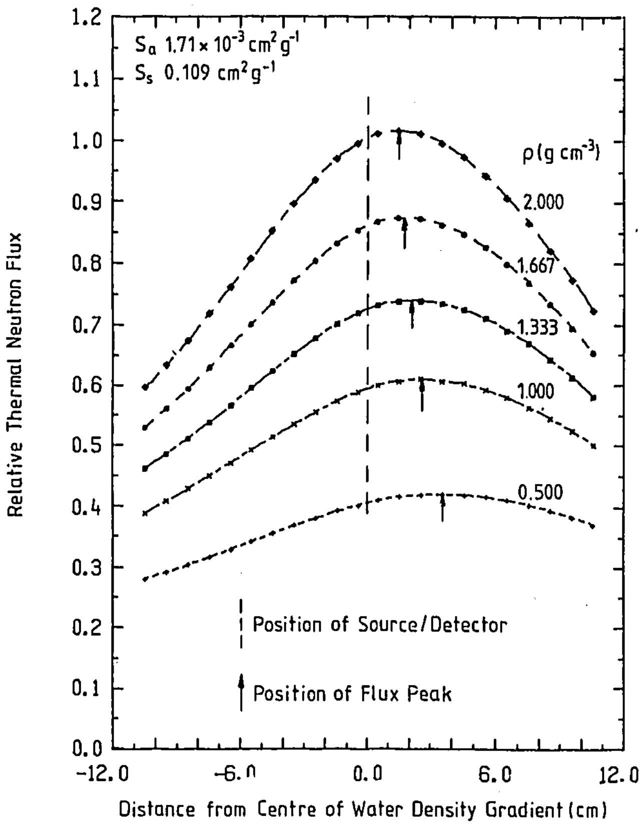


Figure 7 The extended effect of the water density gradient

(a)



(b)

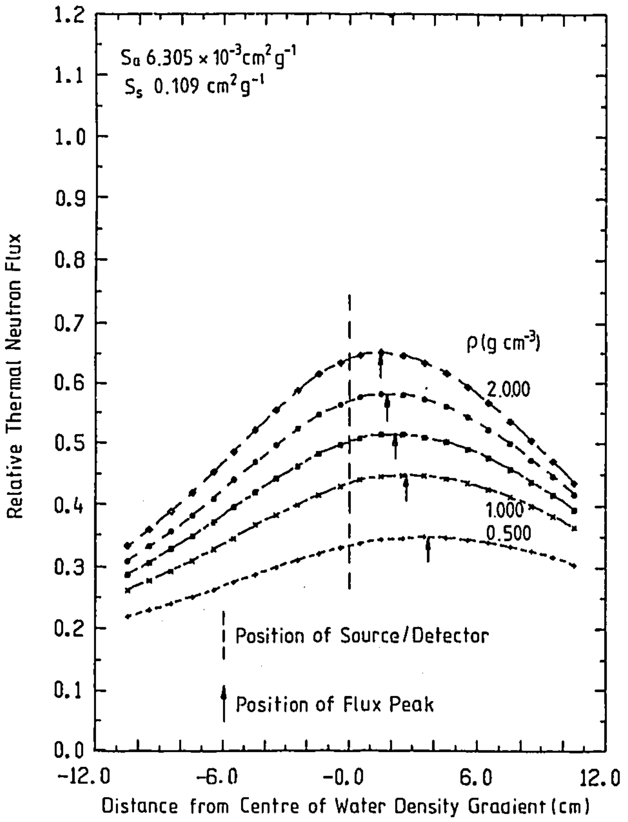
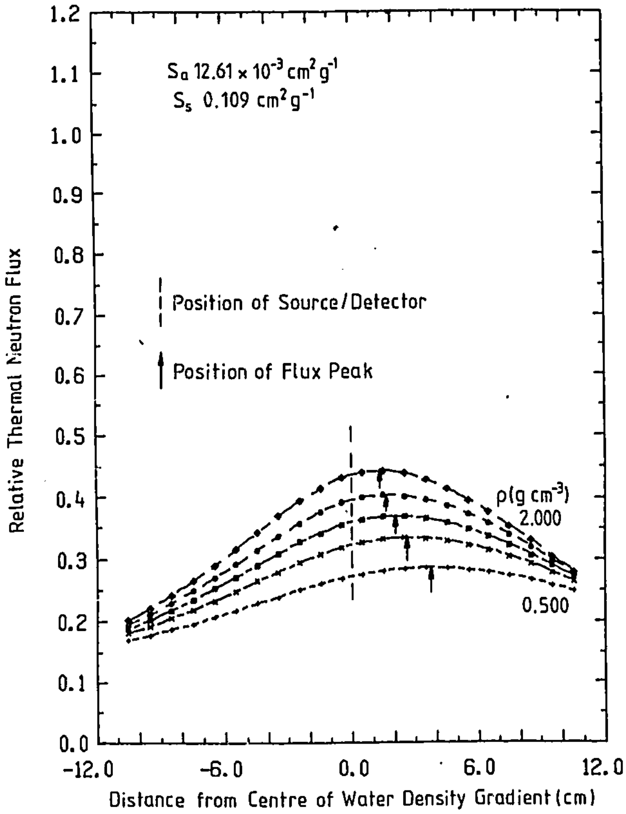


Figure 8 The effect of soil density in the presence of a water density gradient (S_s = 0.109 cm^2 g^{-1}): (a) S_a = 1.71 x 10^{-3} cm^2 g^{-1}; (b) S_a = 6.305 x 10^{-3} cm^2 g^{-1}.

(c)



(d)

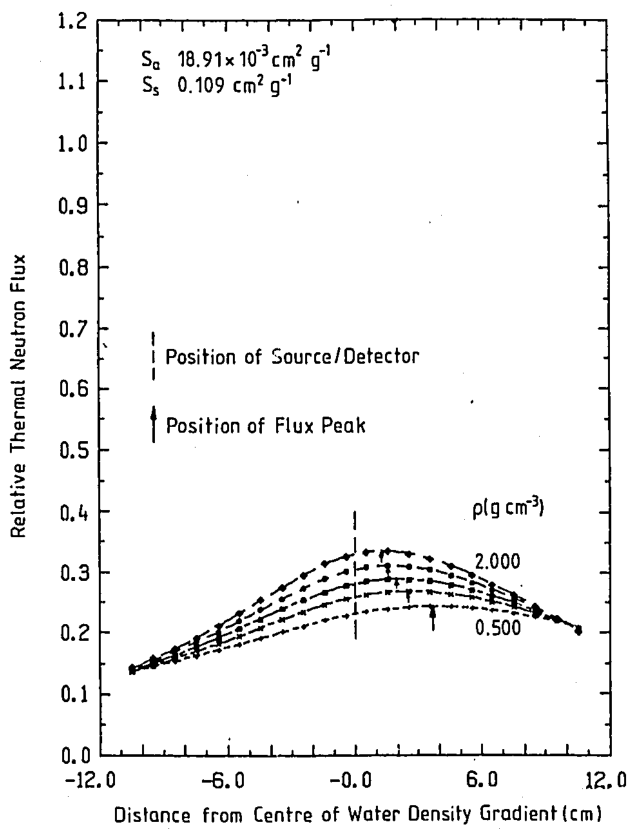
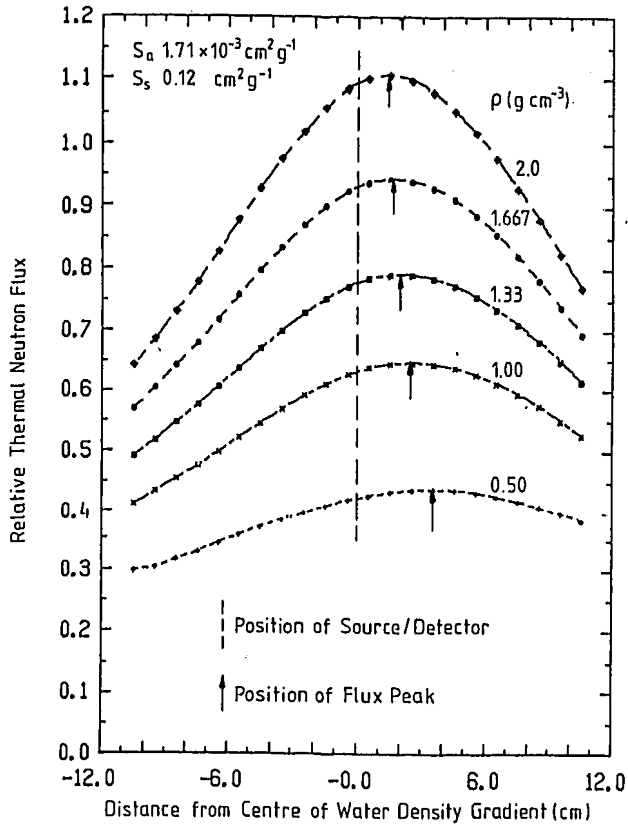


Figure 8 (continued) (c) $S_a = 12.61 \times 10^{-3}$ cm^2 g^{-1}; (d) $S_a = 18.91 \times 10^{-3}$ cm^2 g^{-1}

(a)



(b)

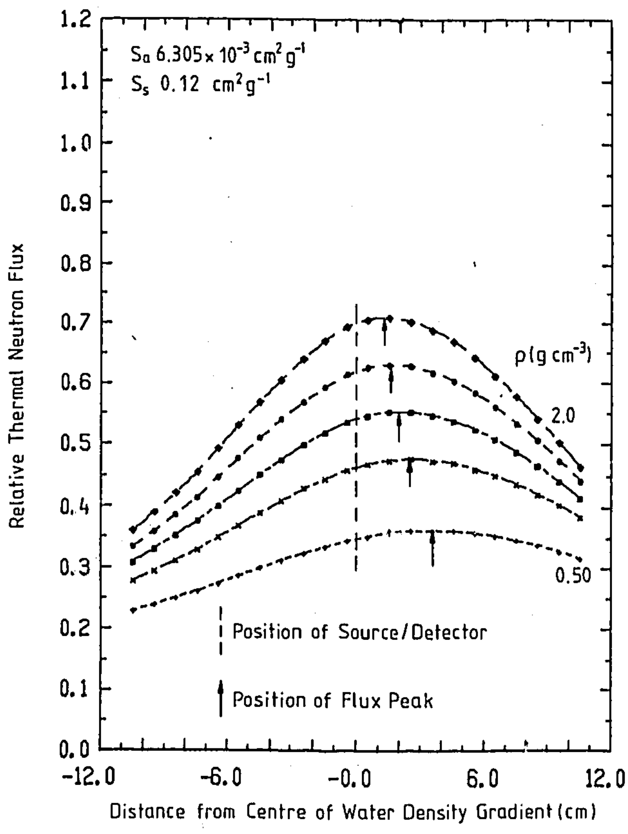
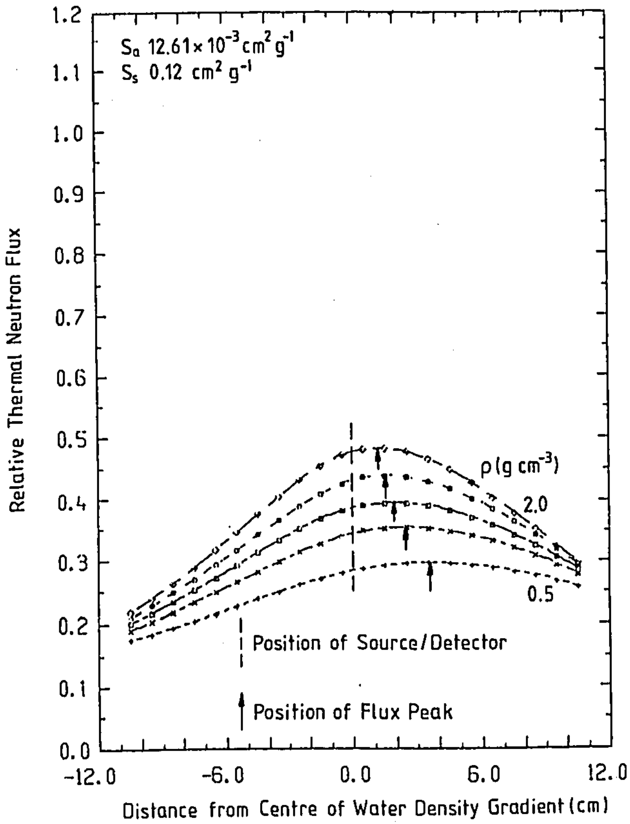


Figure 9 The effect of soil density in the presence of a water density gradient ($S_s = 0.12$ cm^2 g^{-1}): (a) $S_a = 1.71 \times 10^{-3}$ cm^2 g^{-1}; (b) $S_a = 6.305 \times 10^{-3}$ cm^2 g^{-1}.

(c)



(d)

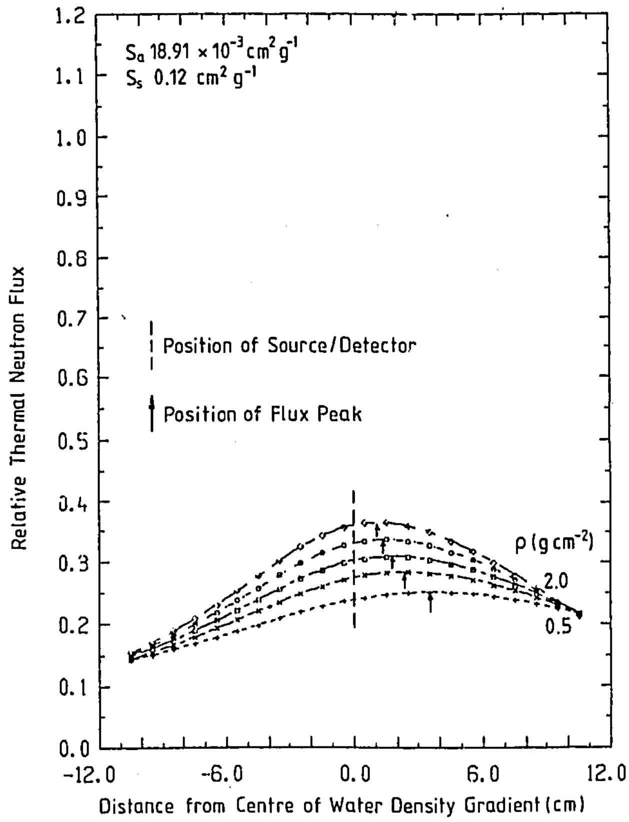
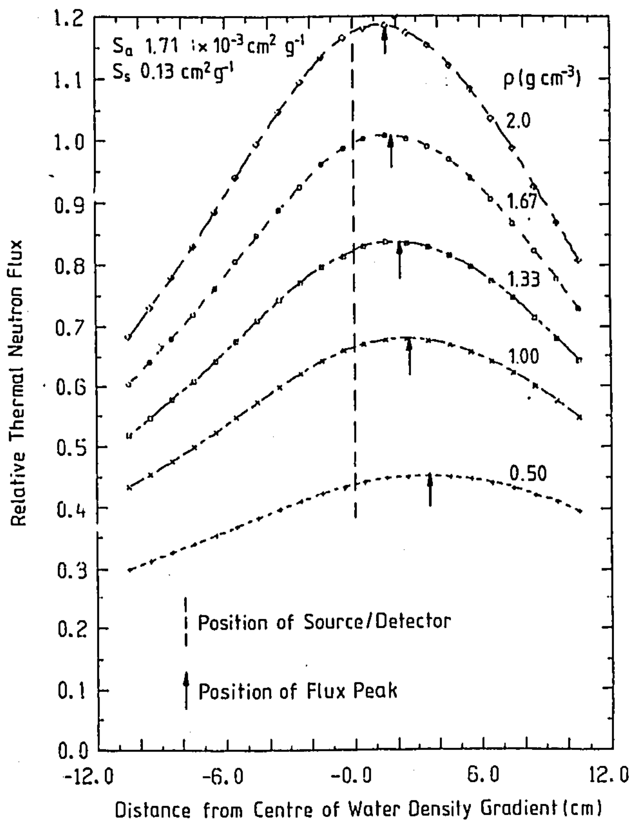


Figure 9 (continued) (c) $S_a = 12.61 \times 10^{-3}$ cm^2 g^{-1}; (d) $S_a = 18.91 \times 10^{-3}$ cm^2 g^{-1}.

(a)



(b)

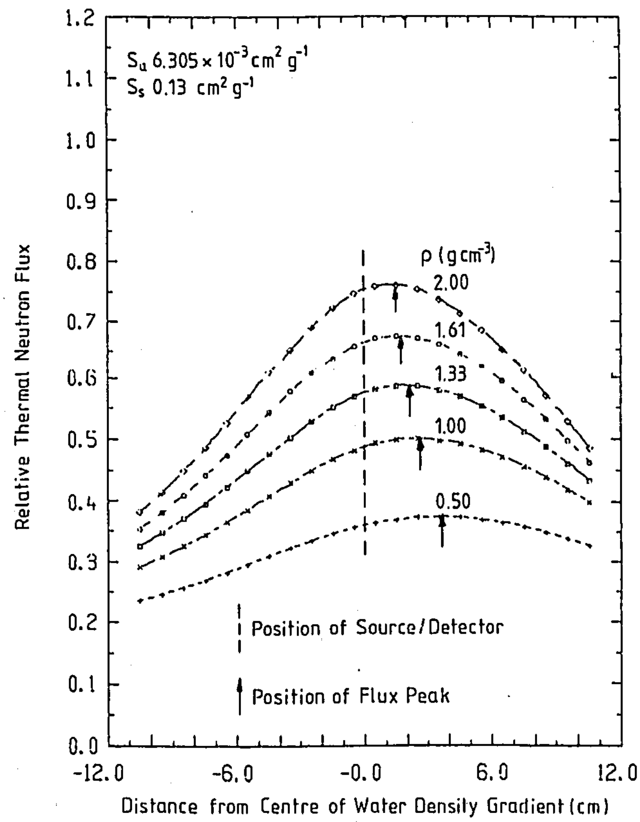
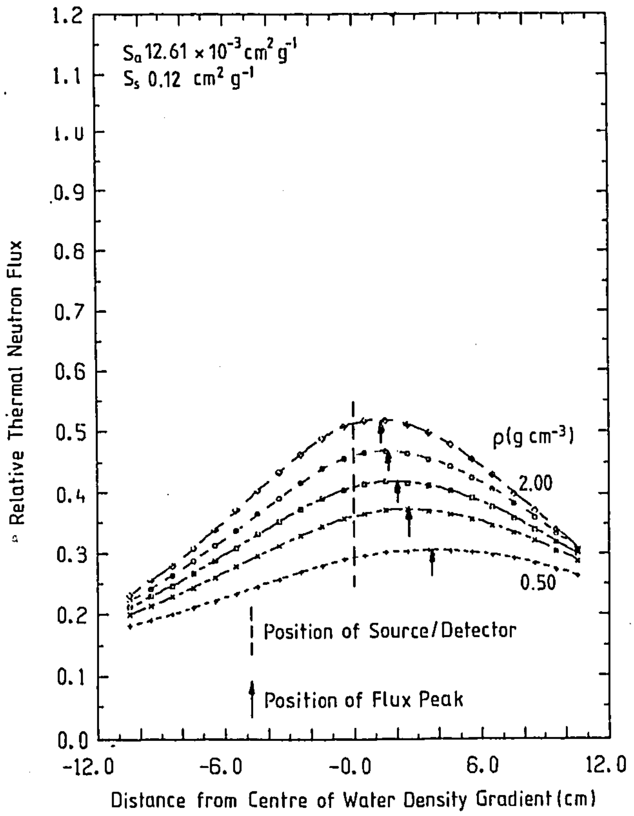


Figure 10 The effect of soil density in the presence of a water density gradient ($S_s = 0.13$ cm^2 g^{-1}): (a) $S_a = 1.71 \times 10^{-3}$ cm^2 g^{-1}; (b) $S_a = 6.305 \times 10^{-3}$ cm^2 g^{-1}.

(c)



(d)

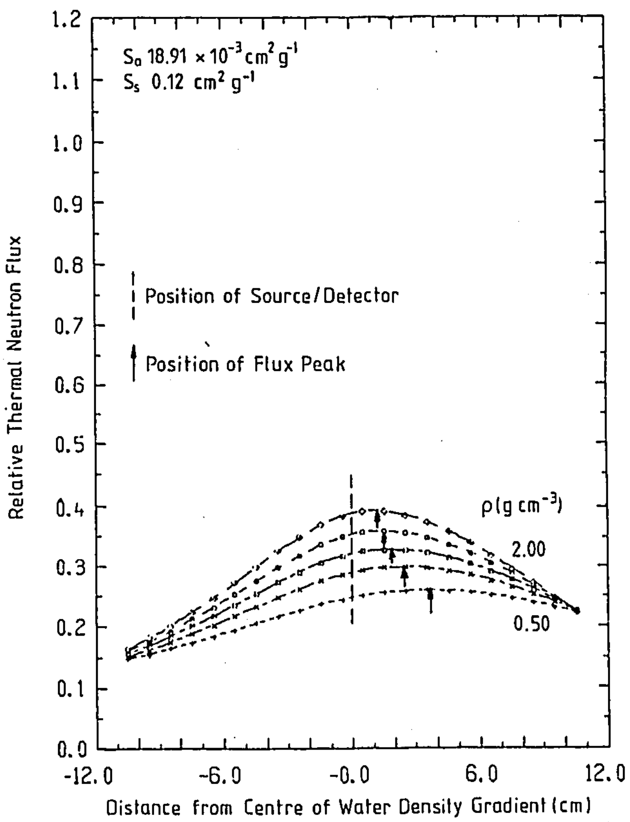


Figure 10 (continued) (c) $S_a = 12.61 \times 10^{-3}$ cm^2 g^{-1}; (d) $S_a = 18.91 \times 10^{-3}$ cm^2 g^{-1}.

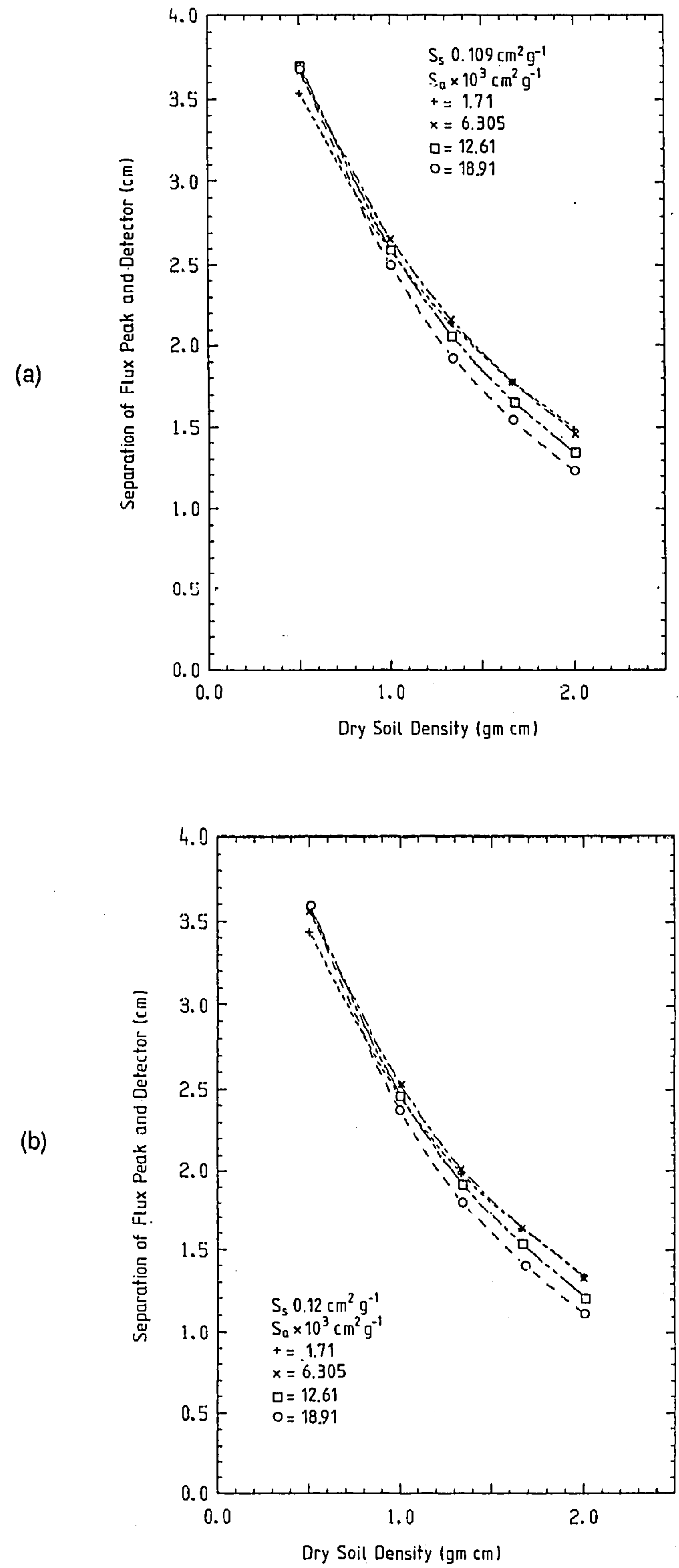


Figure 11 The effect of soil density on the peak flux position in the presence of a water density gradient: (a) S_s = 0.109 $cm^2 g^{-1}$; (b) S_s = 0.12 $cm^2 g^{-1}$.

(c)

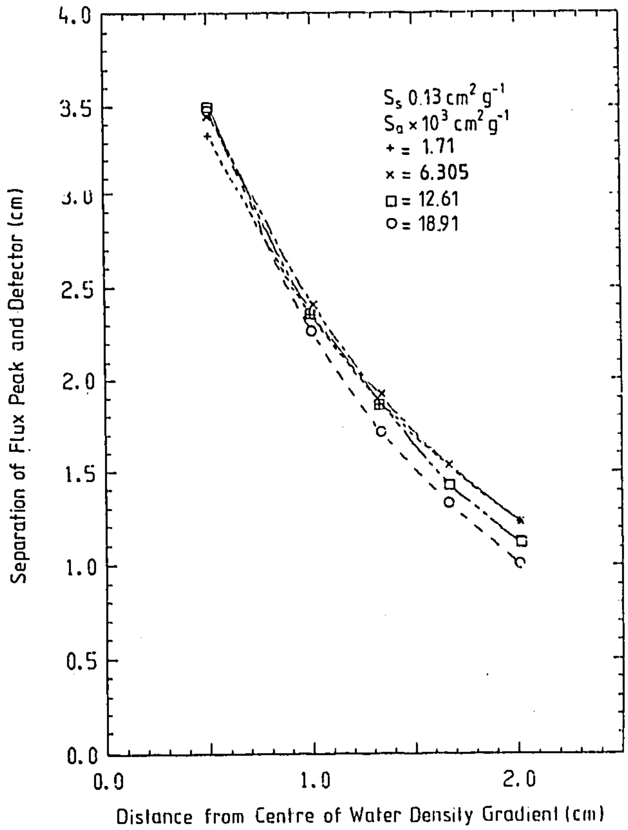


Figure 11 (continued) (c) $S_s = 0.13\ cm^2\ g^{-1}$.

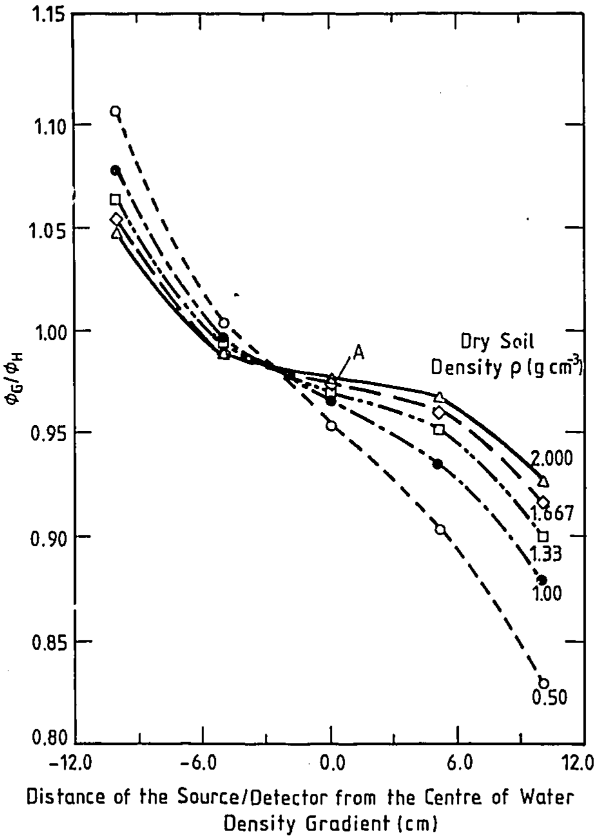


Figure 12 The effect of the proximity of the water density gradient at different dry soil densities

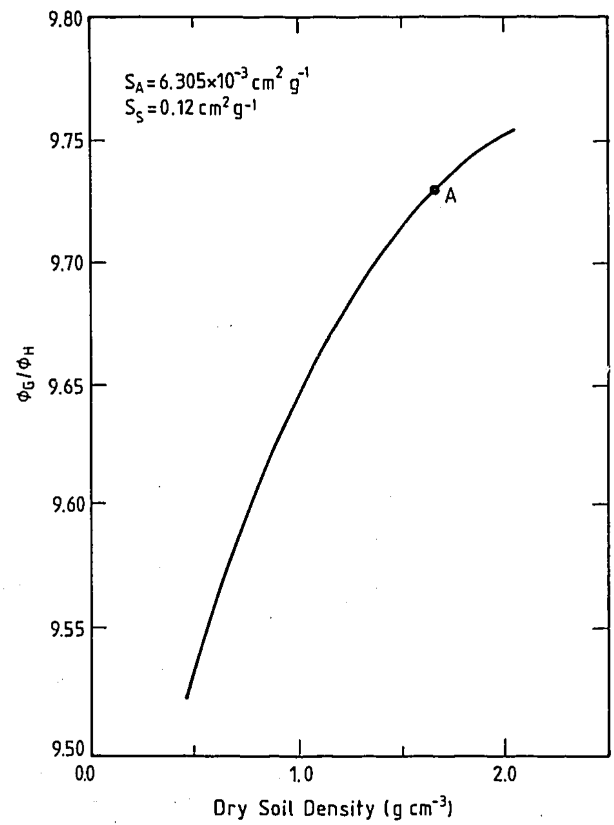
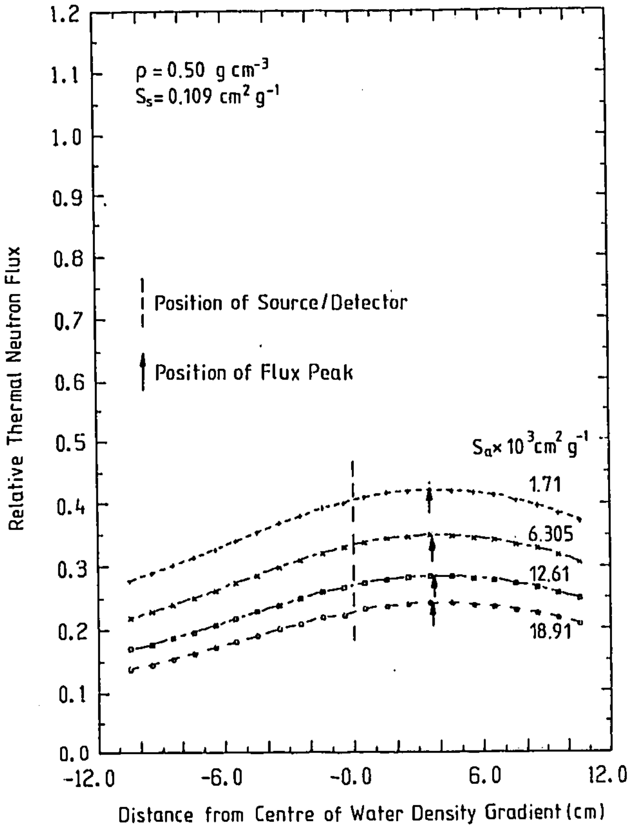


Figure 13 The influence of the dry soil density on the ratio ϕ_G/ϕ_H with the source/detector at the centre of the gradient

(a)



(b)

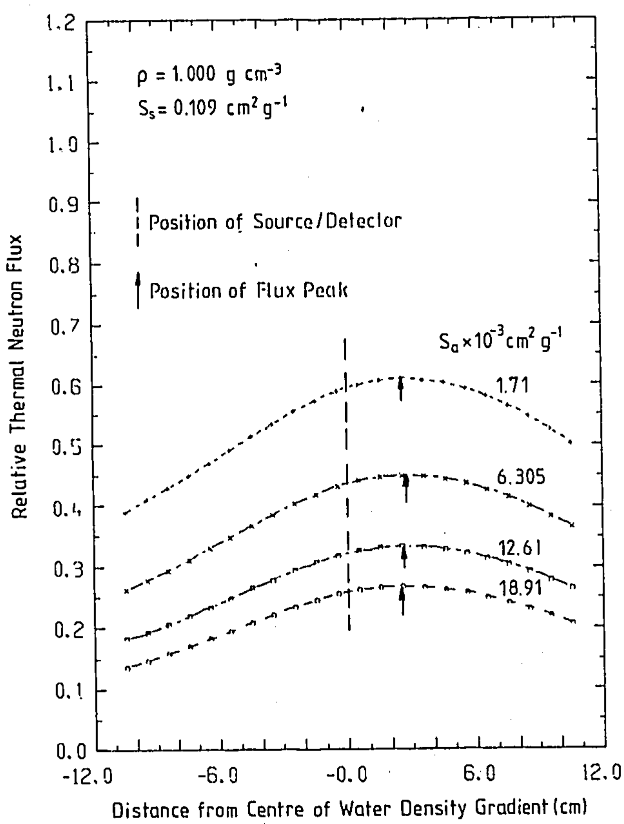
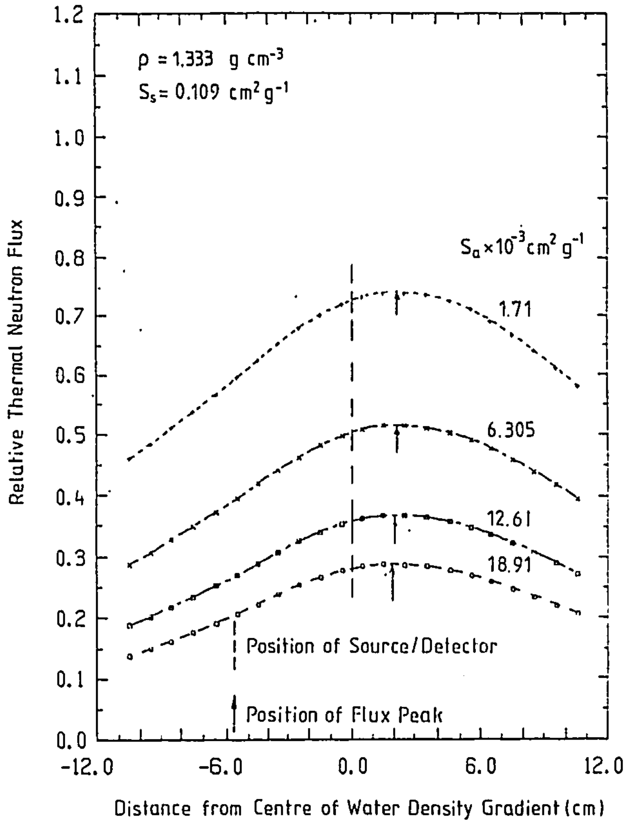


Figure 14 The effect of the mass absorption coefficient and dry soil density on the flux and peak flux position in the presence of a water density gradient (S_s = 0.109 $cm^2\ g^{-1}$): (a) ρ = 0.500 g cm^{-3}; (b) ρ = 1.000 g cm^{-3}.

(c)



(d)

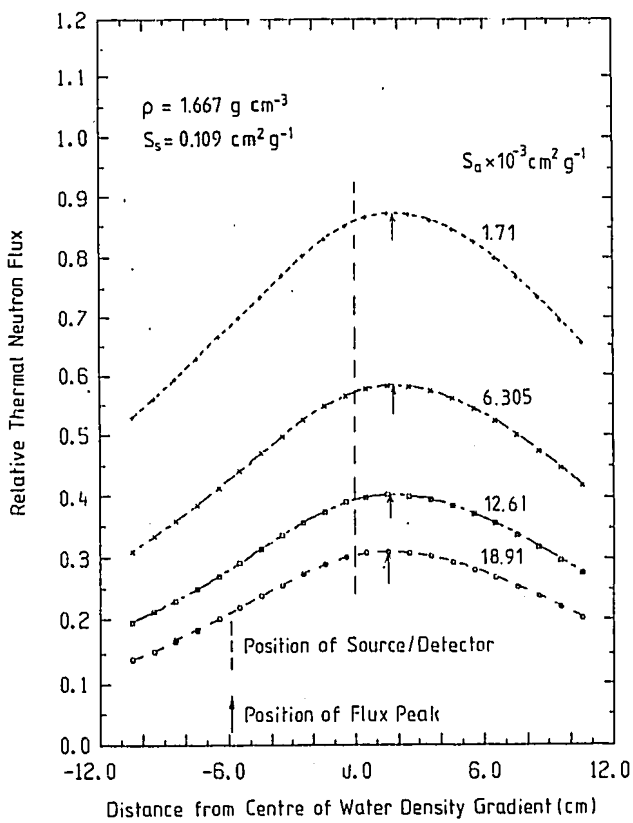


Figure 14 (continued) (c) $\rho = 1.333$ g cm^{-3}; (d) $\rho = 1.667$ g cm^{-3}.

(e)

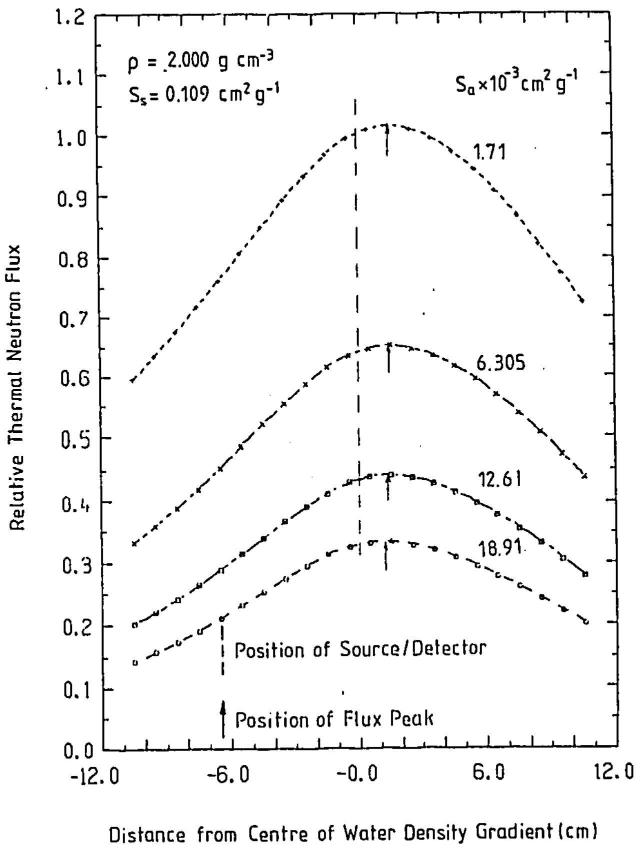


Figure 14 (continued) (e) $\rho = 2.000 \text{ g cm}^{-3}$

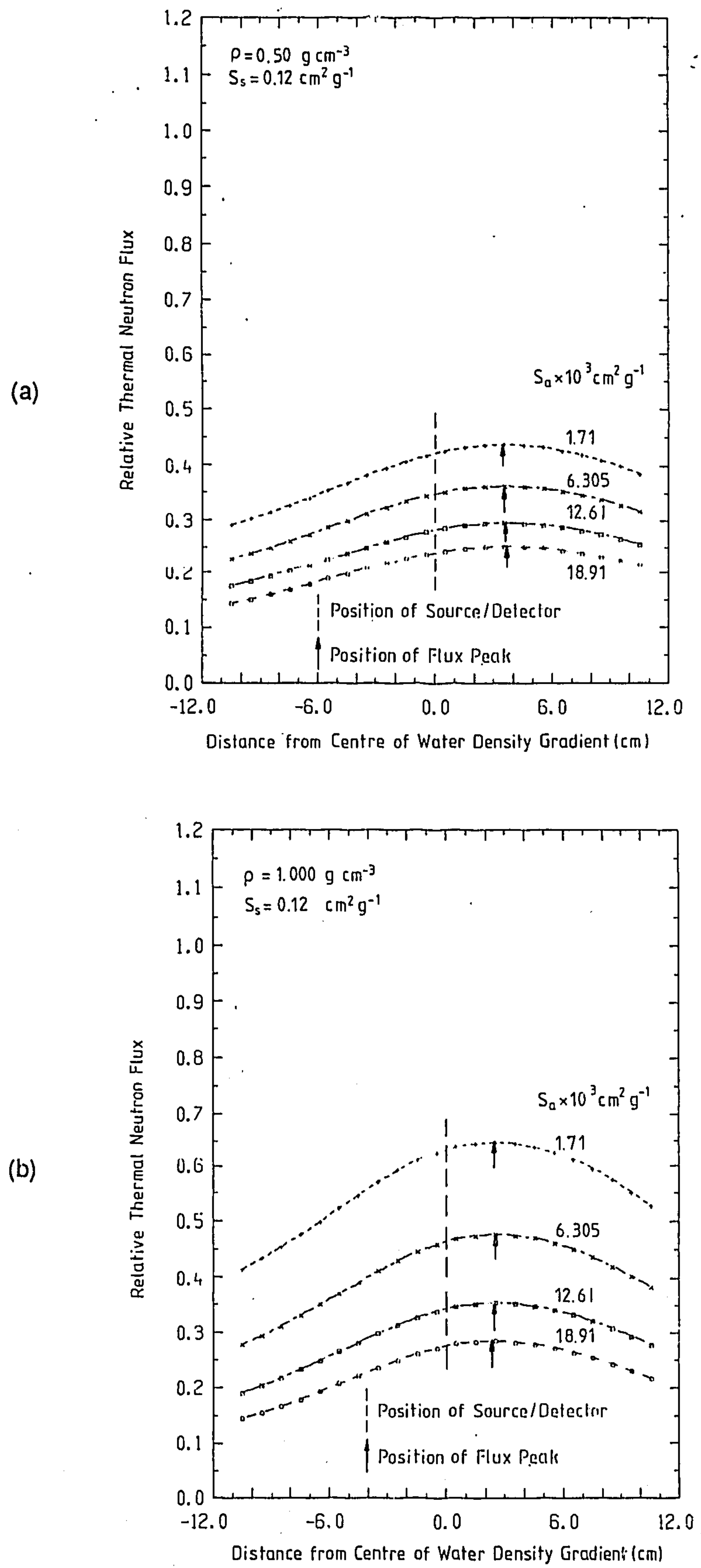
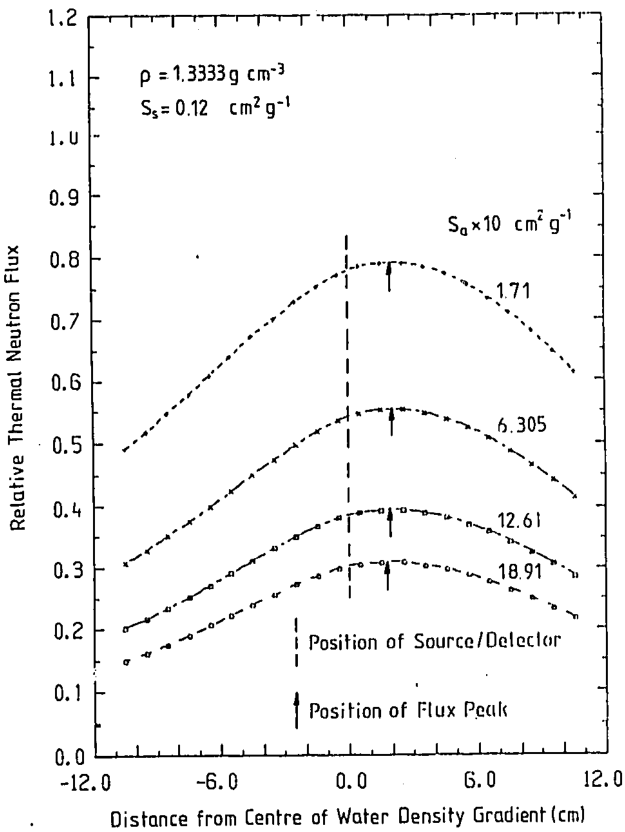


Figure 15 The effect of the mass absorption coefficient on the flux and peak flux position in the presence of a water density gradient ($S_s = 0.12$ cm^2 g^{-1}): (a) $\rho = 0.500$ g cm^{-3}; (b) $\rho = 1.000$ g cm^{-3}.

(c)



(d)

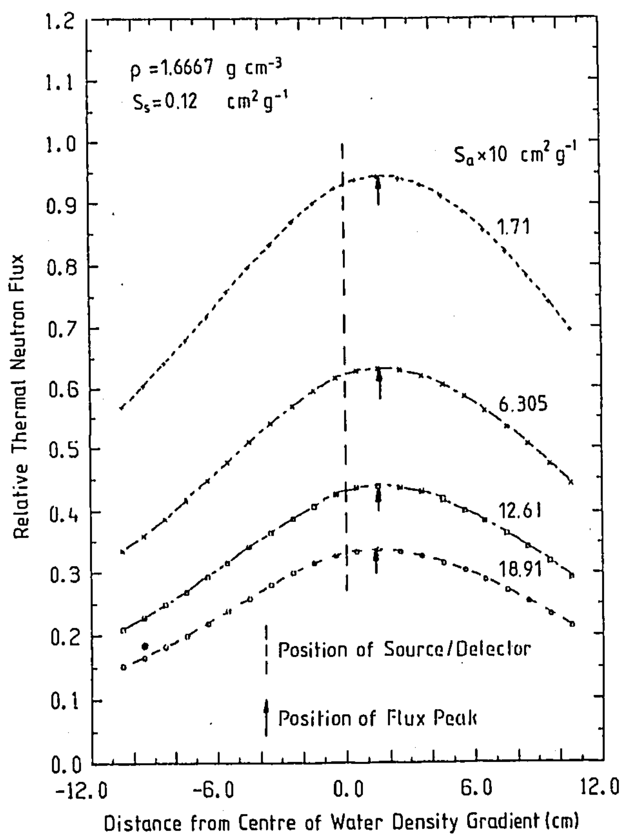


Figure 15 (continued) (c) $\rho = 1.333$ g cm^{-3}; (d) $\rho = 1.667$ g cm^{-3}.

(e)

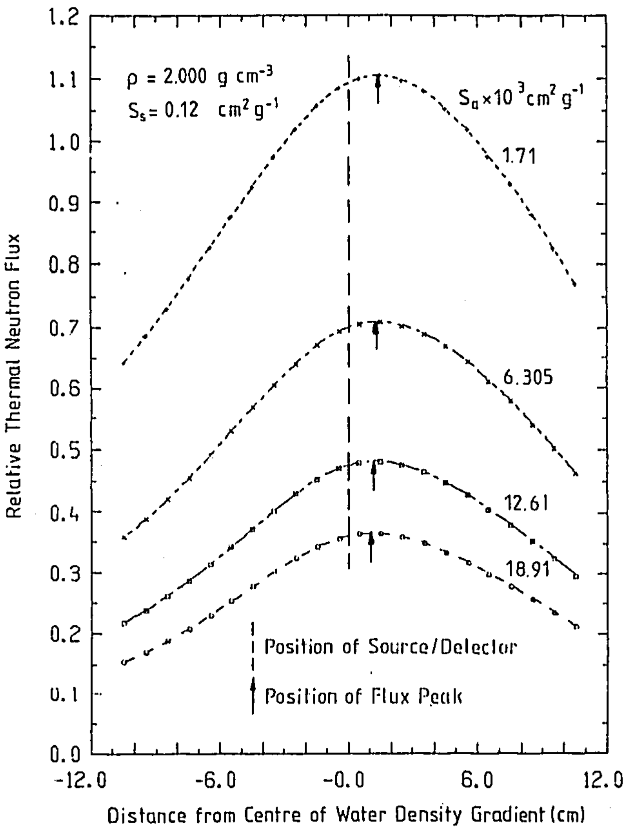
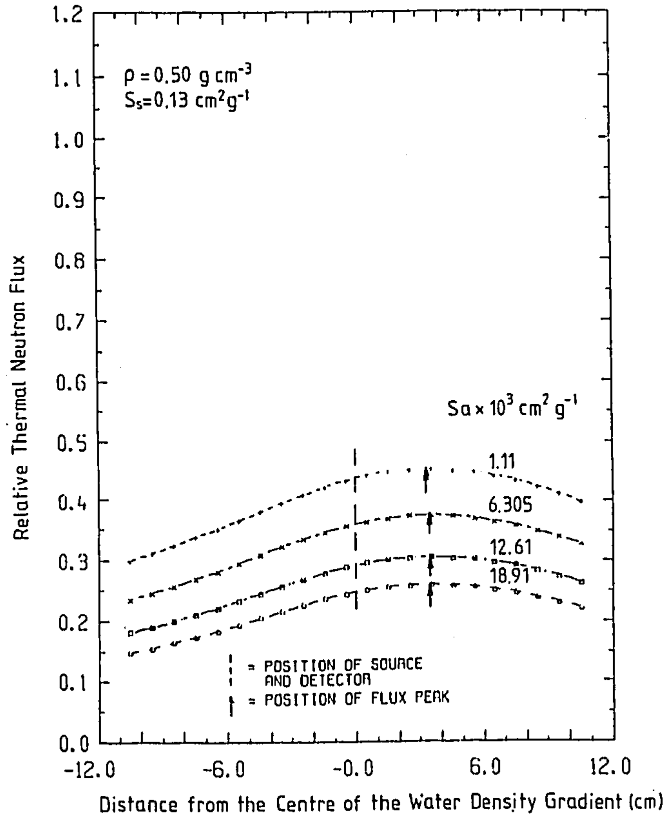


Figure 15 (continued) (e) $\rho = 2.000$ g cm^{-3}.

(a)



(b)

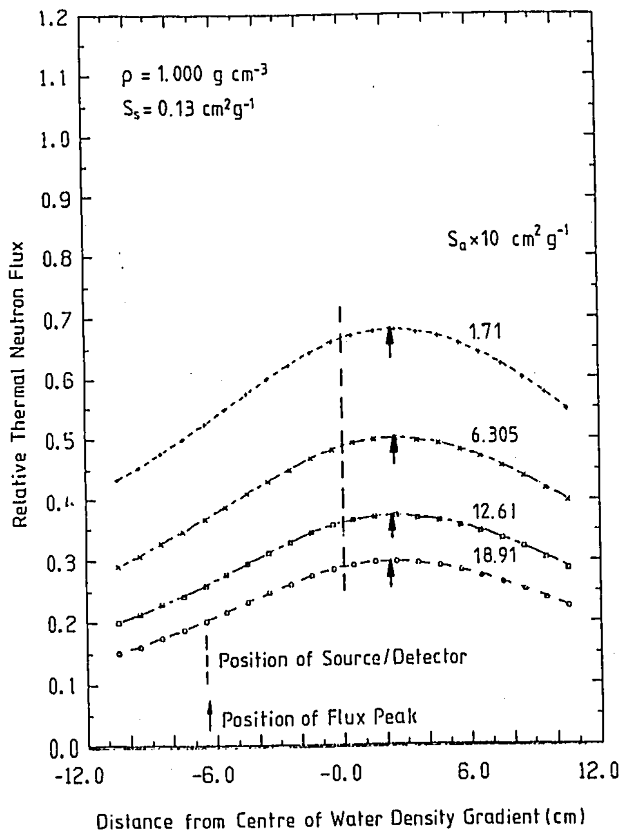
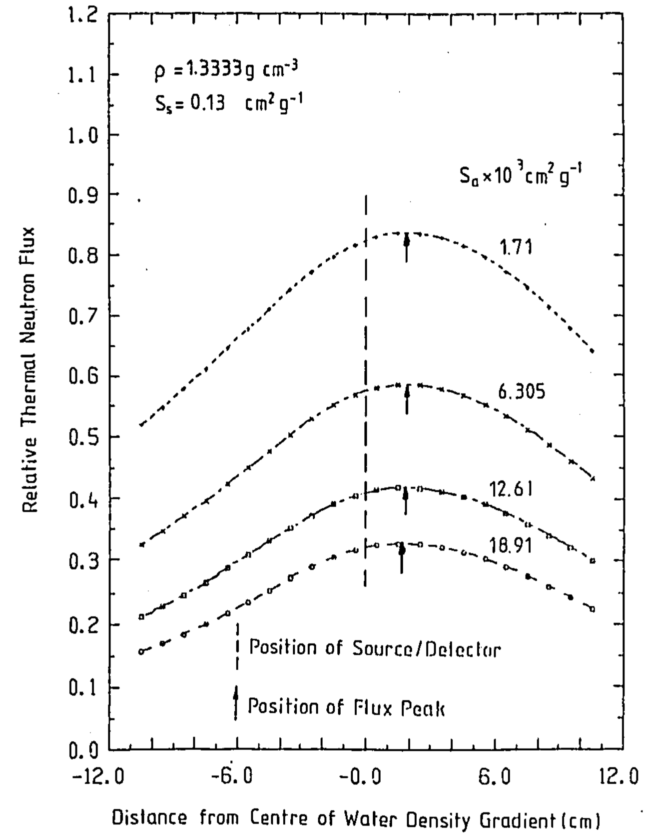


Figure 16 The effect of the mass absorption coefficient on the flux and peak flux position in the presence of a water density gradient ($S_s = 0.13\ cm^2\ g^{-1}$): (a) $\rho = 0.500\ g\ cm^{-3}$; (b) $\rho = 1.000\ g\ cm^{-3}$.

(c)



(d)

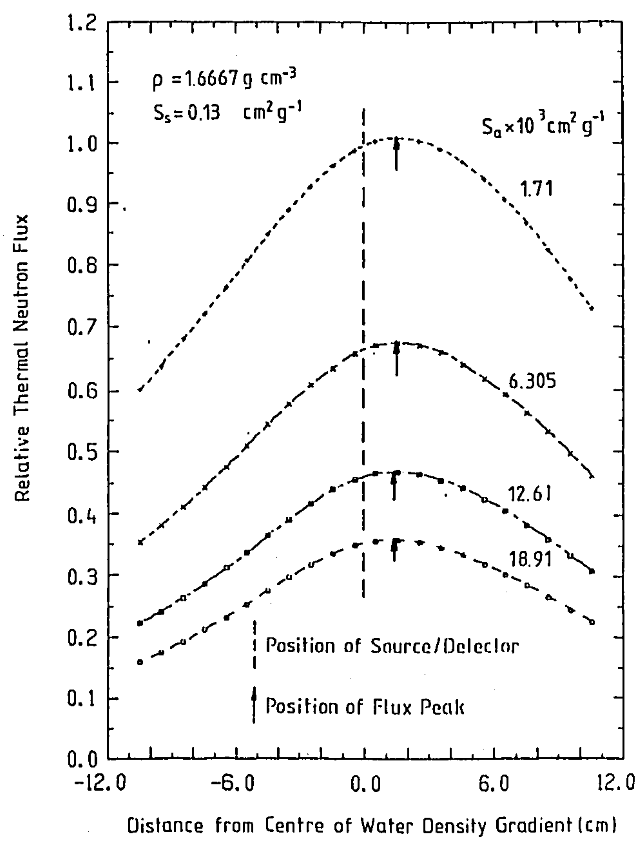


Figure 16 (continued) (c) $\rho = 1.333$ g cm^{-3}; (d) $\rho = 1.667$ g cm^{-3}.

(e)

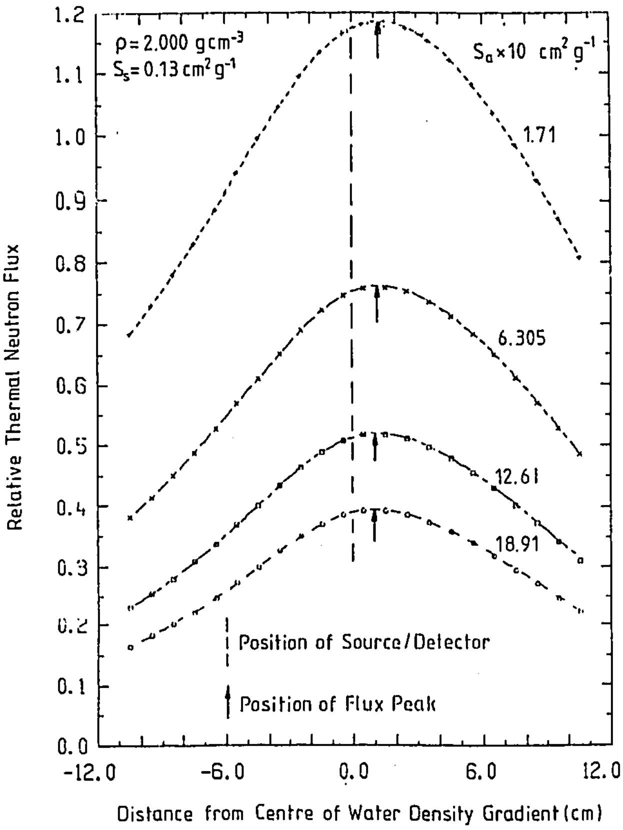


Figure 16 (continued) (e) $\rho = 2.000$ g cm^{-3}

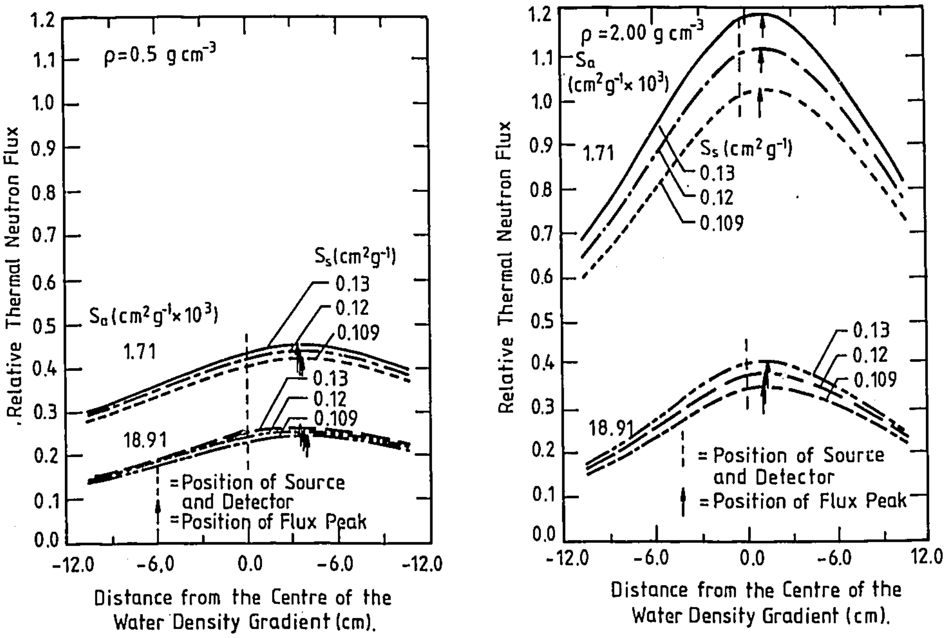


Figure 17 The effect of the mass absorption and scattering coefficients on the peak flux position in the presence of a water density gradient

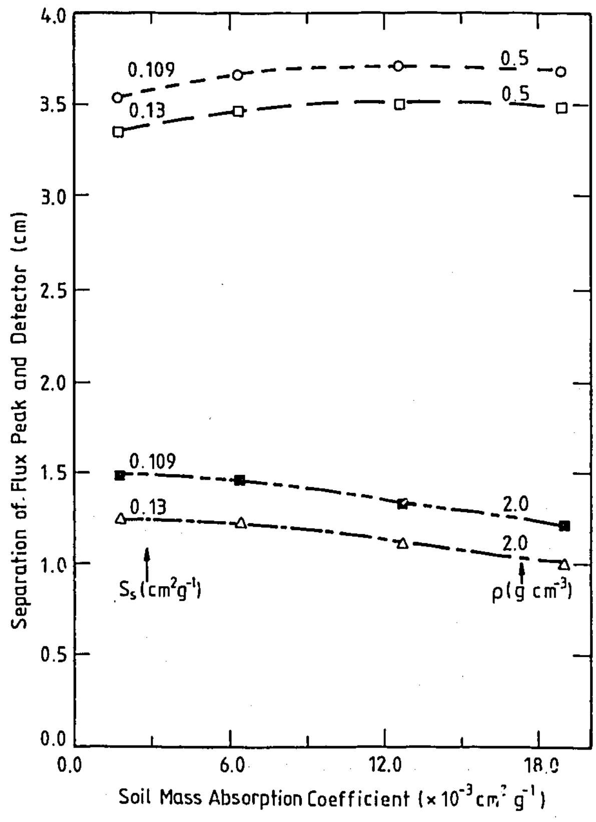


Figure 18 The effect of the mass absorption coefficient on the peak flux position in the presence of a water density gradient

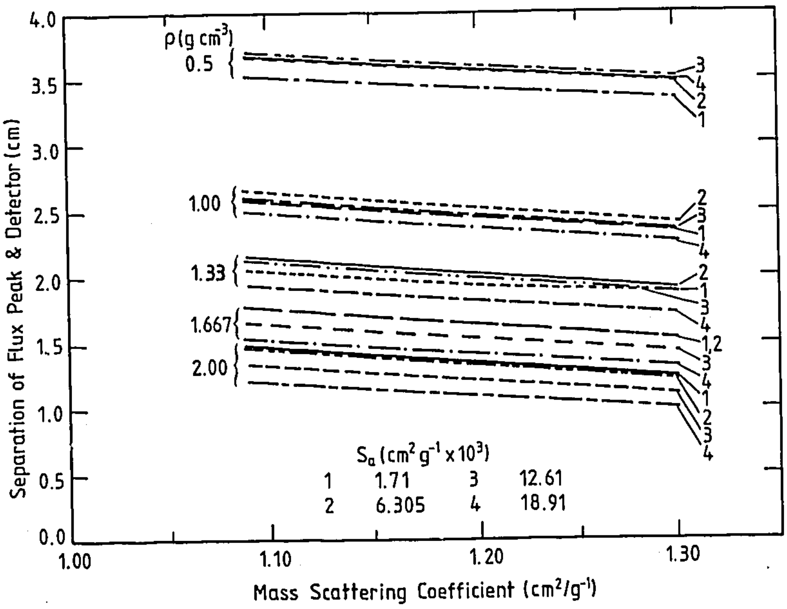


Figure 19 The effect of the mass scattering coefficient on the peak flux position in the presence of a water density gradient

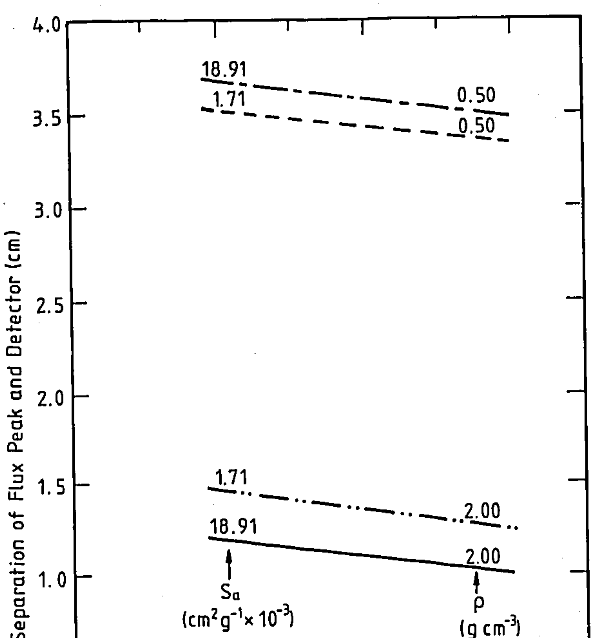


Figure 20 The effect of the mass scattering coefficient on the peak flux position in the presence of a water density gradient

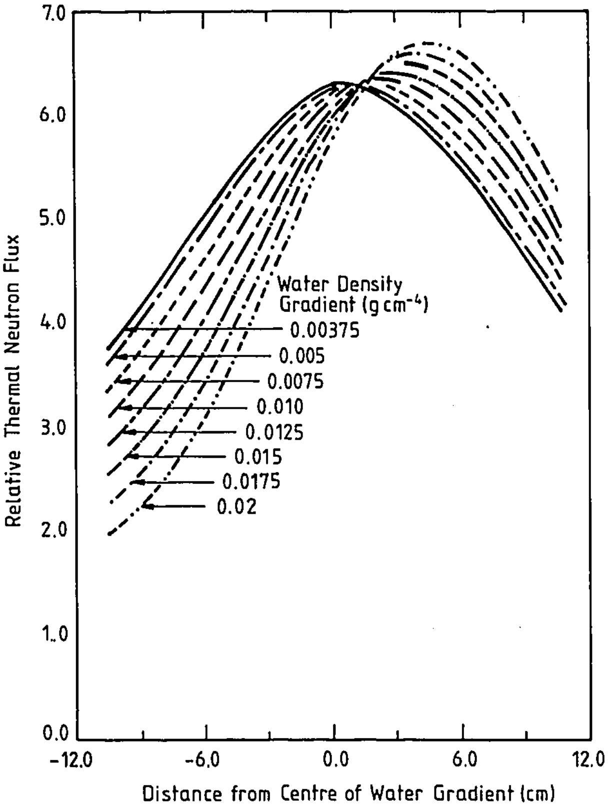


Figure 21 The effect of the water density gradient on the thermal neutron flux

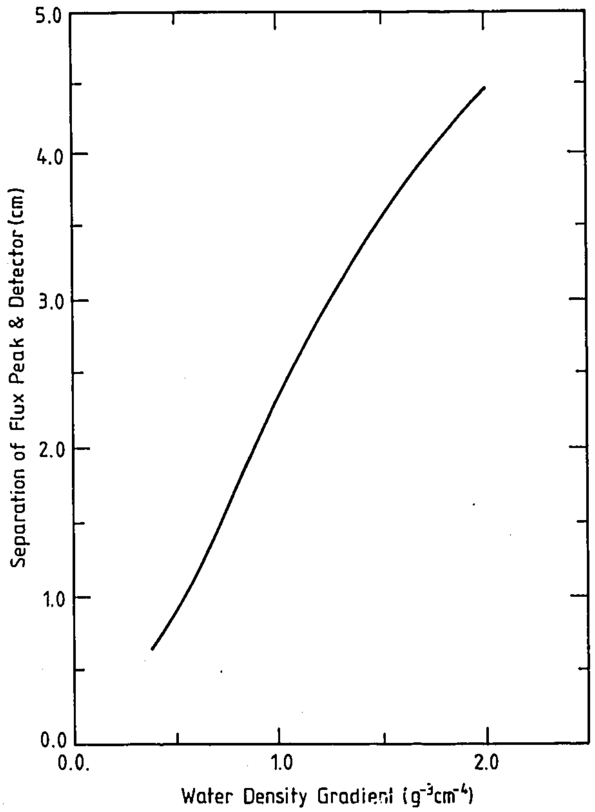


Figure 22 The effect of the water density gradient on the position of the peak flux

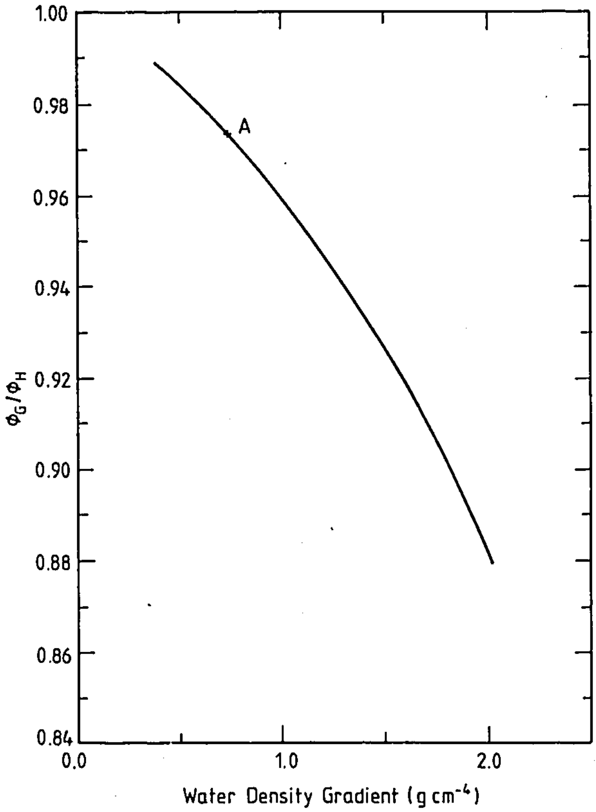


Figure 23 The effect of the water density gradient on ϕ_G/ϕ_H