KBS TEKNISK RAPPORT 110

In situ experiments on nuclide migration in fractured crystalline rocks

Ove Landström
Carl-Erik Klockars
Karl-Erik Holmberg
Stefan Westerberg

Studsvik Energiteknik and
The Geological Survey of Sweden July 1978

KÄRN - BRÄNSLE - SÄKERHET

POSTADRESS: Kärnbränslesäkerhet, Fack. 102 40 Stockholm. Telefon 08-67 95 40

IN SITU EXPERIMENTS ON NUCLIDE MIGRATION IN FRACTURED CRYSTALLINE ROCKS

Ove Landström
Carl-Erik Klockars
Karl-Erik Holmberg
Stefan Westerberg

Studsvik Energiteknik and
The Geological Survey of Sweden juli 1978

I slutet av rapporten har bifogats en förteckning över av KBS hittills publicerade tekniska rapporter i denna serie.

CONTENTS

IN SITU EXPERIMENTS ON NUCLIDE MIGRATION IN FRACTURED CRYSTALLINE ROCKS

By
O Landström[x], C-E Klockars[xx], K-E Holmberg[x] and
S Westerberg[x]

[x] Studsvik Energiteknik AB, 611 82 Nyköping, Sweden

[xx] The Geological Survey of Sweden, Vretgränd 18,
753 22 Uppsala, Sweden

1. INTRODUCTION

The migration rate of a nuclide with groundwater in geological media is lowered, as compared to the water movement, by different reactions, e.g. ion exchange, adsorption, precipitation and mineralization. The retardation of a nuclide "i" is usually expressed by the retardation factor K_i, which is defined as the ratio between the water velocity u_p (in pores) and the velocity u_i of the nuclide and related to the mass distribution coefficient K_d ($m^3 \cdot kg^{-1}$) by the equation

$$K_i = \frac{u_p}{u_i} = 1 + K_d \cdot \frac{\rho}{\varepsilon} \qquad (1)$$

where ρ is the bulk density (kg m^{-3}) of the dry porous medium and ε is the porosity. Equation (1) is valid for porous geological media such as sand and unconsolidated sediments, whereas for fractured rocks the following equation is often used:

$$K_i = \frac{u_p}{u_i} = 1 + K_a \cdot R_f \qquad (2)$$

where K_a is the surface distribution coefficient ($m^3 \cdot m^{-2}$) and R_f is the surface-to-volume ratio of the fractures.

The retardation factor K_i is usually calculated from K_d and K_a values determined in laboratory experiments with rock or soil samples. Such samples cannot, however, in all respects be representative of the migration media. Migration experiments carried out "in situ" are therefore an important complement to laboratory studies.

In the present paper are reported the results and experience of the first two of a series of field experiments carried out in natural non-disturbed fractures of crystalline rocks. The aim of the first series was to study the migration of some selected radionuclides and to develop suitable methods and techniques for such studies. The aim of the second series was to test the effect of bentonite injection into rock fractures on the radionuclide migration. The experiments were carried out in co-operation between the Geological Survey of Sweden and Studsvik Energiteknik AB.

2. GEOLOGY OF THE TEST AREA

The experimental site is situated close to the Baltic Sea and about 90 km south of Stockholm. The rocks in this area, which are mainly of Precambrian age, are described by Lundström (1976).

The migration experiments were performed in a large outcrop of migmatitic-gneissic granite. A map of the fractures in the rock surface is shown in fig 1 (from Bjurstedt et al, 1975). Also horizontal fractures were observed in the core of a diamond-drilled borehole, marked as K3 in fig 1. Many of the fractures are filled with calcite and chlorite.

3. HYDROLOGICAL TESTS AND SELECTED TRACER FLOW PATHS

Eight boreholes with a diameter of 115 mm were drilled in the outcrop area and different borehole investigations (including pumping tests, water pressure tests, visual TV logging, resistivity and radioactivity measurements, and ^{82}Br tracer tests) were carried out in order to delineate

the hydrogeological conditions and to find flow paths, suitable for the migration experiments. Three boreholes, marked B2, B7 (observation holes) and B8 (injection hole) in figures 1 and 2 were selected for the experiments. Fig 3 shows the results of sectional permeability determinations in these boreholes, reflecting the fractured nature of the rock.

Two flow paths could be simultaneously utilized in the experiments; one between B8 and B2 (the main flow path) and another between B8 and B7, the distance between the boreholes being 51 and 22 metres, respectively (fig 2). When pumping in B2 (at a depth of 65 metres)with a constant rate of 0.1 litre/second, the peak of the ^{82}Br pulse was recorded at B2 about 40 hours after injection in B8 (fig 4). The corresponding time between B8 and B7 was about 10 hours (fig 4). Special tests with ^{82}Br revealed that the water enters borehole B7 via a fracture zone at 70 metres depth and flows upwards the hole, leaving it through a main fracture zone at about 40 metres depth, probably discharging into the Baltic Sea.

In fig 2 is marked the ground water level (related to the mean sea level) measured on 1977-03-22 at stationary conditions with a pumping rate of 0.1 litre/second. The hydraulic gradient is thus 0.05 between B8 and B2 and 0.11 between B8 and B7. The water pumped from the borehole B2 was allowed to discharge into the Baltic Sea. Neither the detailed configuration of the fracture system nor the distribution of fracture widths are, of course, known. The TV logging revealed one fracture apperently about 1 cm wide in the injection zone of B8, but it is not known how far this width may persist.

4. MIGRATION STUDIES

4.1 Elements studied and radionuclides used

The present study comprised the following elements: selenium, technetium, tin, cesium. iodine, neodymium and strontium. Long-lived nuclides of these elements are present in highly radioactive waste (Table I); neodymium being used as a "stand-in" for the elements americium - curium.

In Table II are listed the isotopes used in the experiments, their nuclear characteristics and MPC values. In addition to the waste elements, one of the macroelements in the groundwater, sodium, was represented by the isotope ^{24}Na. In all the different injections ^{82}Br was used as reference tracer and assumed to follow the water flow with negligible retention.

4.2 Injection procedure

The radionuclides were dissolved in 5 - 10 litres of groundwater, taken from borehole B2, and pumped down between two rubber packers enclosing the high permeability zone at about 72 m depth in borehole B8 (see figures 2 and 3). The nuclides were then forced out into the fractures by rinsing with totally 30 litres of groundwater, spread over three successive operations.

Several radionuclides were usually simultaneously injected. The combinations of radionuclides and injected activities used in the three principal field studies are listed in Table III.

4.3 Radioactivity measurements

The gamma activity of pumped water from borehole B2 was continuously recorded with a Ge(Li) detector. This allowed selective measurements of simultaneously injected isotopes, as illustrated in fig 5 which shows a gamma spectrum measured in connection with the studies of ^{82}Br, ^{131}I and ^{99m}Tc. The net peak areas of the 554.3 keV (^{82}Br), 364.5 keV (^{131}I) and 140.4 KeV (^{99m}Tc) gamma-rays were recorded for the concentration analysis.

Water samples were regularly taken from borehole B2 for calibration and check of the field analysis and for laboratory measurements of those nuclides which emit gamma-rays of too low energy to be measured in the field, e. g. ^{131}Cs.

Also ^{85}Sr was mostly analysed in the laboratory because of interference from the 510 keV gamma-ray in the natural background radiation. In borehole B7 water sampling was made at a level just above the water inflow at 70 metres and analysis was carried out in the laboratory.

The laboratory measurements were mainly based on gamma spectrometry, using a Ge(Li) detector. In the case of very low activity the samples were concentrated by evaporation and measured in a "4 π" geometry using a well-type Ge(Li) detector. The ^{131}Cs activity was measured with a Si(Li) detector after preconcentration and precipitation.

4.4 Results of the migration experiments

In figures 6 - 11 are shown curves of the measured concentration versus migration time for the different nuclides. The concentrations are related to C_o, which is the tracer concentration in the injected solution. The 22 m flow path is denoted "B8 - B7" and the 51 m flow path "B8 - B2". The measured activities are corrected for radioactive decay and are thus valid for the time of injection.

4.5 Complementary laboratory experiments

Batch experiments and column tests were performed for planning of the field experiments. Complementary laboratory experiments, briefly described in the sequel, were also carried out as an aid to the interpretation of the field data. The results are used in the discussion of the field data later on.

Dried drill cuttings from boreholes B8 and B7 were used, having the following grain size distribution:

Fraction	0.04 - 0.17	81 weight per cent
	0.02 - 0.04	12 "-
	0.01 - 0.02	5 "-
	0.001- 0.01	1 "-

The groundwater used in the experiments was taken from borehole B2 and had the following main composition:

Ca	36	mg/litre	HCO_3	240	mg/litre
Mg	10	"	SiO_2	14	"
Na	45	"	pH	7.45	
K	5.5	"	Conductivity	385	µS/cm
Cl	11	"			
SO_4	14	"			

Aliquots of the solutions injected on 1977-03-11 (Table III) were diluted as follows:

A	1 part with 9 parts of groundwater
B	1 part with 4 parts of groundwater and 5 parts of deionized water
C	1 part with 9 parts of deionized water

Batch experiments were performed by shaking different amounts of drill cuttings (15, 50, 150 and 500 g/litre) with solutions A, B and C. After a contact time of two hours the slurries were centrifuged and the activity of the centrifugate measured for K_d calculations. Separate samples of solutions A, B and C were also centrifuged in order to determine the fractions of added activities which were still in solution. The following observations were made:

- Tin is completely hydrolyzed and no K_d could therefore be determined for Sn^{4+}.
- Most of selenium was precipitated before coming into contact with the cuttings. The soluble selenium was only slightly sorbed on the grains with a K_d of the order of 0 - 3 ml/g.
- Neodymium precipitates to some extent when mixed with the groundwater. The K_d values are thus somewhat uncertain.
- Strontium did not precipitate. A K_d value of 1.5 ml/g was obtained (mean of 5 determintations).

Additional K_d determinations (for I^-, SeO_3^{2-} and Cs^+) were made using groundwater without extra carriers. The results are listed in Table IV together with values obtained in the experiments described above.

4.6 Comments on the results of the field migration experiments

Technetium

Owing to the short half-life of ^{99m}Tc, only the beginning of the breakthrough curve for the flow path B8 - B2 could be recorded, whereas the whole concentration curve was recorded for the shorter flow path B8 - B2, fig 6. As expected, the migration rate for technetium injected as TcO_4^- is the same as that for bromine, i. e. technetium is transported without any observable retention. This is contrary to the results obtained in Oak Ridge for various American rock samples; an appreciable retardation of technetium was observed which is believed to be due to reduction of initially deposited TcO_4^- ions (Carleson, 1978).

Iodine

In fig 7 the breakthrough curve of I^- is compared to that of Br^- for the flow path B8 - B2. The slightly lower maximum of the iodine curve indicates a weak sorption of iodine. Similar results were obtained for the flow path B8 - B7. This indicates a slight difference between the field and the laboratory results (K_d = 0, Table IV).

Sodium

The sodium concentration curve for the flow path B8 - B2, shown in fig 8, is very much the same as that of iodine, i. e. a somewhat lower maximum and longer tail as compared to the bromine curve. The sorption process is probably ion exchange which, however, should be weak in view of the relatively high concentrations of calcium and magnesium in the water.

Strontium

As seen from figures 9 and 10, strontium was retarded by a factor of about 6 in both flow paths as compared to bromine. This compares well with the retardation factors of 6 and 3, respectively, which were calculated by Neretnieks (1977) from K_d values determined on drill-cuttings in two laboratories: Allard (1977) and Table IV in this report. The K_d values were recalculated to K_a values assuming spherical grains. Neretnieks obtained fissure date by extending the fracture model of Snow (1968) to assume a normal frequency distribution for the channel width. Fitting the experimental and computed residence time distributions gave a mean fissure width of 0.063 mm with a standard deviation of 0.021 mm for the flow path B8 - B7.

Tin

Applying the results of our laboratory experiments, Sn^{4+} might be expected to partly or completely precipitate in the borehole by hydrolysis. A K_d value of 250 ml/g was reported for desert soil (Burkholder et al 1976). With the exception of some very low activity of ^{113}Sn during the first seven hours in borehole B7, no tin activity was detected until about 20 days later when the beginning of a breakthrough was observed simultaneously with the arrival of selenium activity (fig 11). This seems to indicate either that the tin precipitate, which might be a selenium compound, has a certain solubility or that tin migrates in a chemical form, other than Sn^{4+}, e. g. in colloidal form.

Selenium

Selenium as SeO_3^{2-} is known to form precipitates with Sn^{4+} and under certain conditions also with Ca^{2+}, which complicates the interpretation. Selenium was injected partly as precipitates and partly in solution as SeO_3^{2-}. In borehole B7 as well as in B2 selenium arrived simultaneously with bromine (fig 11). The concentration decreased rapidly to almost zero and increased again after about 20 days in a way similar

to that of tin. This indicates different migration rates of selenium depending on its chemical form. The fact that selenium and tin arrive close together in their second pulse suggests their migration in a similar chemical form. The batch experiments gave values of K_d for selenium equal to zero when the injected solution (with carriers) was used, and a value of 2.4 for selenium without carriers, cf Table IV.

Neodymium

Neodymium could not be detected during an observation time of 60 days. This is explained by the short half-life of ^{147}Nd and the high K_d values (Table IV), which means a strong retention of neodymium. Very high values for the neodymium K_d, in the range of 1 600 - 4 000 ml/g were obtained for granitic material (Allard, 1977). Our laboratory experiments showed that some neodymium precipitated, probably as hydroxide or carbonate, which will initially lower the concentration available for migration. A much larger activity has thus to be injected in order to demonstrate a complete concentration curve for neodymium in the fractures investigated.

Cesium

Cesium could not be detected during an observation time of 60 days. This is explained, in a similar way as for neodymium, by the high K_d value (Table IV) which means a retention for cesium sufficiently strong to allow the complete decay of the ^{131}Cs radioactivity before arriving at the observation boreholes.

4.7 Dispersion coefficient and mean transit time

The dispersion coefficient and the mean transit time for ^{82}Br and ^{85}Sr in the flow path B8 - B2 were calculated using the method given by Lenda and Zuber (1970). The calculations were based on the following assumptions: radial flow, instantaneous injection and infinite medium.

In Table V are listed calculated values of the transit time t_o, the dispersion coefficient D_x and the dimensionless parameter $D_x/v \cdot x$; v and x being defined in equation (3) below.

The dispersion coefficient and the mean transit time were also estimated for ^{82}Br and ^{99m}Tc in the flow path B8 - B7 using the same methods and assumptions as for the B8 - B2 flow path above. The values 3.6 m^2/h and 18.8 h were obtained for both ^{82}Br and ^{99m}Tc.

By solving the dispersion equation for the case if instantaneous injection, using the Laplace Transform method, the solution reads (Lenda and Zuber, 1970):

$$\frac{c'_x \; x}{m} = \frac{1}{\sqrt{4 \frac{D_x}{v \cdot x} \left(\frac{t}{t_o} \right)^3}} \cdot \exp \left[- \frac{(1 - t/t_o)^2}{4 \frac{D_x}{v \cdot x} \cdot \frac{t}{t_o}} \right] \quad (3)$$

where

c'_x	linear tracer concentration
m	total mass (activity) injected
D_x	longitudinal dispersion coefficient
v	mean pore velocity of conveying fluid
x	injection to observation distance
t_o	mean transit time of tracer
t	time variable

By inserting the calculated values for t_o and D_x into equation (3) the theoretical breakthrough curves were calculated and are compared to the experimental values in the figures 12 and 13. Fairly good agreement for the leading as well as for the tailing part was obtained for the ^{85}Sr curve, whereas for ^{82}Br there is good agreement only for the leading part of the curve.

5. BENTONITE EXPERIMENTS

The aim of this second experimental series was to test how effectively the injection of bentonite into rock fractures could further retard any released nuclides. To get comparable data bentonite was injected into the same fracture zones of borehole B8 (figures 2 and 3) as were utilized for the migration study. For the same reason previously studied radionuclides were used.

5.1 Bentonite injection procedure

Slurries of bentonite were injected between rubber packers into narrow sections (2 to 4 metres) of the borehole and with successively increasing concentration of bentonite and applied pressure (Nilsson, 1977). Totally about 2 000 kg (dry weight) of bentonite was injected. Of this amount, 1 400 kg, corresponding to about 20 m^3 of bentonite slurries, was injected into the high permeability zone below 71 metres. In this case bentonite reached as far as to borehole B8 as well as to borehole B7.

In a final operation, bentonite was injected in high concentrations and with high pressure from the ground surface; i. e. the whole length of the borehole was included. Before the subsequent tracer tests the wall of the borehole was cleaned with a wire brush and rinsed by water flushing.

5.2 Radionuclide injection procedure

The radionuclides were injected into the lower part of the borehole, endeavouring to get them concentrated in the fracture zone at the 72 metres level. Before the injection of tracers a sealed plastic tube was placed in the borehole, in which a spectrometer borehole probe could be operated for control of any activity loss. The borehole loggings did thus not influence the water movements.

Two isotope tracers, ^{82}Br and ^{85}Sr, were used and injected in two separate runs. 3.2 mCi of ^{82}Br was first injected in order to check the injection procedure. After the decay of most of the ^{82}Br activity, 0.87 mCi of ^{85}Sr was injected. As all bromine activity was observed to remain in the borehole in the first run, indicating watertight fractures, the simultaneous injection of ^{82}Br (as a reference tracer for the water movement) was considered unnecessary in the second run. "During the summer 1978 measurements of the watertable were performed. The watertable was approx. +1.1 m in B2, + 1.4 in B7 and + 10.4 m in B8 (compare fig 2)."

Other experimental conditions were the same as in the previous migration study, e. g. water was pumped from borehole B2 at a constant rate of 0.1 litre/second.

5.3 Radioactivity measurements

The possible migration of tracer activity from borehole B8 was controlled in two ways:

- Samples of pumped water were regularly taken from the observation borehole B2 and analysed in the laboratory by similar methods to those used in the migration study.
- The remaining tracer activity in the injection hole B8 was selectively measured with a borehole gamma ray spectrometer; the ^{82}Br analysis based on the gamma energies 554 keV and the ^{85}Sr analysis on the 514 keV gamma-ray. Background activity, measured before the radionuclide injection, was subtracted from the bromine and strontium energy interval values.

The borehole spectrometer was energy-calibrated using suitable radioisotope sources. The calibration was checked before and after each logging run by recording characteristic energy peaks of the tracers. This is illustrated in fig 14, which shows the ^{85}Sr spectrum measured at the fracture zone level. The lower energy peak might be due to ^{75}Se which precipitated in connection with the previous migration study.

5.4 Results and discussion

Neither ^{82}Br nor ^{85}Sr could be detected in water samples from borehole B2. The detection limits for ^{82}Br and ^{85}Sr were 50 pCi/litre and 12 pCi/litre, respectively. These results were confirmed by the results of borehole measurements in the injection hole B8; no loss of tracer activity from the borehole could be observed. In Table VI are listed the results of successive borehole measurements of the integrated ^{82}Br activity in the depth interval 69 - 73.5 metres, which includes the highly permeable zone utilized for injection in the previous migration experiments but now filled up with bentonite.

The corresponding values of integrated ^{85}Sr activity for the interval 69 - 73.5 metres are listed in Table VII. In this case the observation time is considerably longer and therefore more interesting. Similarly to ^{82}Br, the variation of the values is within the estimated errors; typical sources of error being temperature effects on the borehole probe, background variation, statistical fluctuations of radiation, probe position determination, etc. Moreover, the strontium concentration in the borehole fluid could also change with time without any real loss of activity from the borehole, e. g. by diffusion and by sorption on bentonite, which is present in fissure openings, on the borehole wall and sedimented to the bottom of the hole. The concentration - depth curves of ^{85}Sr from two measurements with six months' time difference are shown in fig 15.

The migration rate observed for strontium after the bentonite injection is at least 135 times slower than the rate of the groundwater.

6. SUMMARY AND CONCLUSIONS

Nuclide migration in fractured rocks was studied in field experiments in a granite-gneissic outcrop within the Studsvik research centre area. Radionuclides representing long-lived fission products of the elements selenium, technetium, tin, cesium, iodine, neodymiun and strontium were injected into a fracture zone intersecting one of the testholes at a depth of 72 metres below the ground surface. Concentration-time curves of activities arriving at the pumping borehole were measured. The distance between the boreholes was 51 metres and the pumping rate 0.1 litre/s. The mean transit time and the dispersion coefficient for water were calculated to be 57 h and 8.8 m^2/h, respectively. A shorter flow path (22 metres) could be utilized by intermittent sampling in a third borehole.

The radioactivity measurement techniques included gamma-spectrometric borehole logging, continuous activity measurements of pumped water and water sampling followed by laboratory analysis. Different combinations of radionuclides were injected simultaneously and selectively registered by gamma-ray spectrometry using a Ge(Li) detector in the field as well as in the laboratory.

Technetium and iodine travelled as anions with the same velocity as that of water. Strontium was retarded by a factor of about 6. Neither cesium nor neodymium could be detected. This is in agreement with their high retardation factors, estimated from mass distribution constants, determined in the laboratory. Selenium was partly and tin probably almost completely precipitated when injected into the borehole, which complicated the interpretation. A selenium pulse of short duration arrived simultaneously with the bromine pulse. About 20 days later the beginning of a second breakthrough of selenium and a first breakthrough of tin was observed in the shorter flow path.

In a second series of experiments it was shown that the fracture system surrounding the injection borehole could be effectively grouted with bentonite. Subsequent tracer tests with strontium-85 showed that after more than twelve months all the injected activity still remained in the borehole. It was found that bentonite injection is a very effective way of reducing the radionuclide migration through strongly fractured rock.

REFERENCES

ALLARD, B, KIPATSI, H and RYDBERG, J
Sorption av långlivade radionuklider i lera och berg
KBS Teknisk Rapport 55, Stockholm 1977

BJURSTEDT, S, SUKOTJO, S and BROTZEN, O
Karakteristik av hällområden
SGU Berggrundsbyrån, 1975 (in Swedish)

BURKHOLDER, H C, CLONINGER, M O, BAKER, D A and JANSEN, G
Nuclear Technology 31 (1976) p. 202

CARLESON, G.
Personal communication

KJELLBERT, N
Radioactive inventories in PWR spent fuel and high-level waste calculated by use of the origen code
KBS-report 01, Stockholm 1977

LENDA, A and ZUBER, A
Tracer dispersion in groundwater experiments. Isotope Hydrology, Proc symp Vienna 9 - 13 March, 1970
IAEA, VIENNA, 1970, p. 619 - 641

LUNDSTRÖM, I
Description to the map of solid rocks Nyköping SO,
Sveriges Geologiska Undersökning, Serie Af Nr 114, 1976
English summary

NERETNIEKS, I
Retardation of escaping nuclides from a final depository
KBS-report 30, Stockholm 1977

NILSSON, T
Working report. Stabilisator AB 1977 (in Swedish)

SNOW, D T
Rock Fracture Spacings, Openings and Porosities,
Soil Mech Found Div, AIChE, 94 (1968) SMI p. 73 - 91

WIVSTAD, I
Swedish utilities design "completely safe" disposal route, Nucl. Eng. Int. 23 (1978) 266 p. 45 - 48

TABLE I Activities of some important fission products in highly radioactive waste after 100 and 1 000 years. From Kjellbert, N (1977)

Nuclide	$T_{1/2}$ years	Activity (Ci/ton uranium) after 100 years	1 000 years
^{79}Se	65 000	0.39	0.39
^{90}Sr	28.1	6 500	-
^{93}Zr-^{93m}Nb	$1.5 \cdot 10^6$	1.9	1.9
^{99}Tc	210 000	14	14
^{107}Pd	$7 \cdot 10^6$	0.12	0.12
^{126}Sn-^{126m}Sb-^{126}Sb	100 000	0.57	0.56
^{129}I	$17 \cdot 10^6$	0.038	0.038
^{135}Cs	$3 \cdot 10^6$	0.25	0.25
^{137}Cs-^{137m}Ba	30	11 000	-
^{151}Sm	87	570	0.44

TABLE II Isotope tracer used

Element studied	Isotope used	Half-life	Gamma energies used in measurements	MPC - Public water
			keV	µCi/cc
Sodium	^{24}Na	15 h	1 369	$3 \cdot 10^{-5}$
Selenium	^{75}Se	120 d	265	$3 \cdot 10^{-4}$
Bromium	^{82}Br	35 h	554 - 777	$4 \cdot 10^{-5}$
Strontium	^{85}Sr	64 d	514	$1 \cdot 10^{-4}$
Technetium	^{99m}Tc	6 h	142	$3 \cdot 10^{-3}$
Tin	^{113}Sn	115 d	392	$8 \cdot 10^{-5}$
Iodine	^{131}I	8 d	365	$3 \cdot 10^{-7}$
Cesium	^{131}Cs	9.7 d		$9 \cdot 10^{-4}$
Neodymium	^{147}Nd	11.1 d	531	$6 \cdot 10^{-5}$

TABLE III Combination of injected isotopes

Injection number	Isotopes injected	Chemical form (and amount of carriers)	Activity injected mCi	Amount of solution litres
4 1977-02-09	^{82}Br	NH_4Br (1 g)	2.44	11.8
	^{99m}Tc	TcO_4^-	12.9	
	^{131}I	NaI	0.92	
5 1977-03-11	^{82}Br	NH_4Br (1 g)	2.4	5.6
	^{75}Se	H_2SeO_3 (345 mg)	1.85	
	^{85}Sr	$SrCl_2$ (100 mg)	0.65	
	^{113}Sn	$SnCl_4$ (158 mg)	0.90	
	^{147}Nd	$Nd(NO_3)_3$ (1 g)	2.15	
6 1977-03-22	^{82}Br	NH_4Br (1 g)	1.66	5.6
	^{24}Na	NaCl	1.65	
	^{131}Cs	CsCl	5	

TABLE IV Laboratory determinations of the mass distribution coefficient, K_d

Element	Isotope used	K_d (ml/g)
Strontium	^{85}Sr	1.5 (5)
Neodymium	^{147}Nd	44 (4)
Iodine	^{131}I	0
Selenium	^{75}Se	2.4
Cesium	^{134}Cs	560 (2)

TABLE V Mean transit times (t_o), dispersion coefficient (D_x) and the parameter $D_x/v\ x$

Isotope	t_o hours	D_x m^2/h	$\frac{D_x}{v\ x}$
^{82}Br	57	8.8	0.152
^{85}Sr	398	16.2	0.28

TABLE VI Total activity of ^{82}Br in the depth interval 69 - 73.5 metres of borehole B8

Hours after injection	27	45	95	142	167
Activity, mCi	0.463	0.501	0.429	0.482	0.486

TABLE VII Total activity of ^{85}Sr in the depth interval 69 - 73.5 metres of borehole B8

Days after injection	43	47	57	62	68	111	229	374
Activity, mCi	0.336	0.361	0.379	0.345	0.362	0.362	0.366	0.389

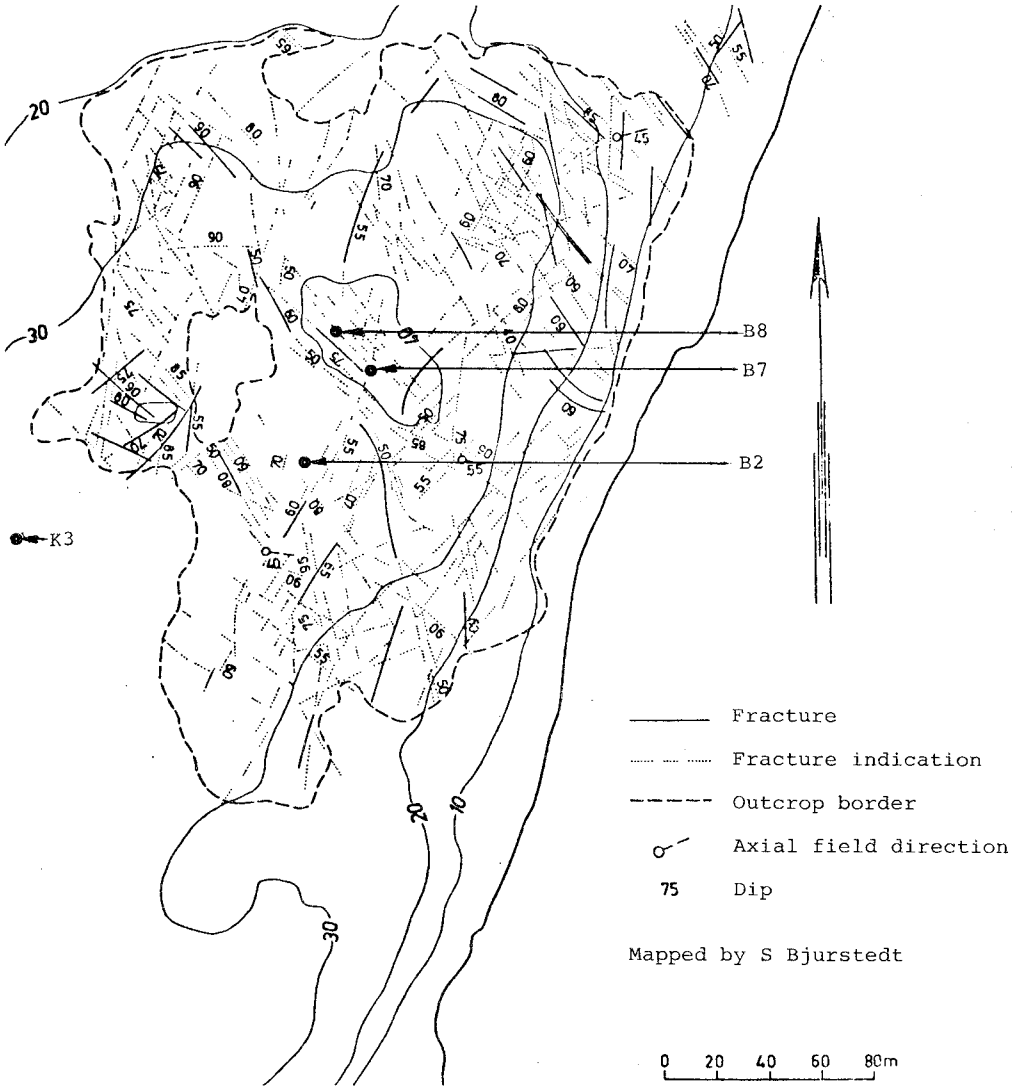

Fig 1. FRACTURE MAP OF THE EXPERIMENTAL AREA AND BOREHOLE POSITIONS

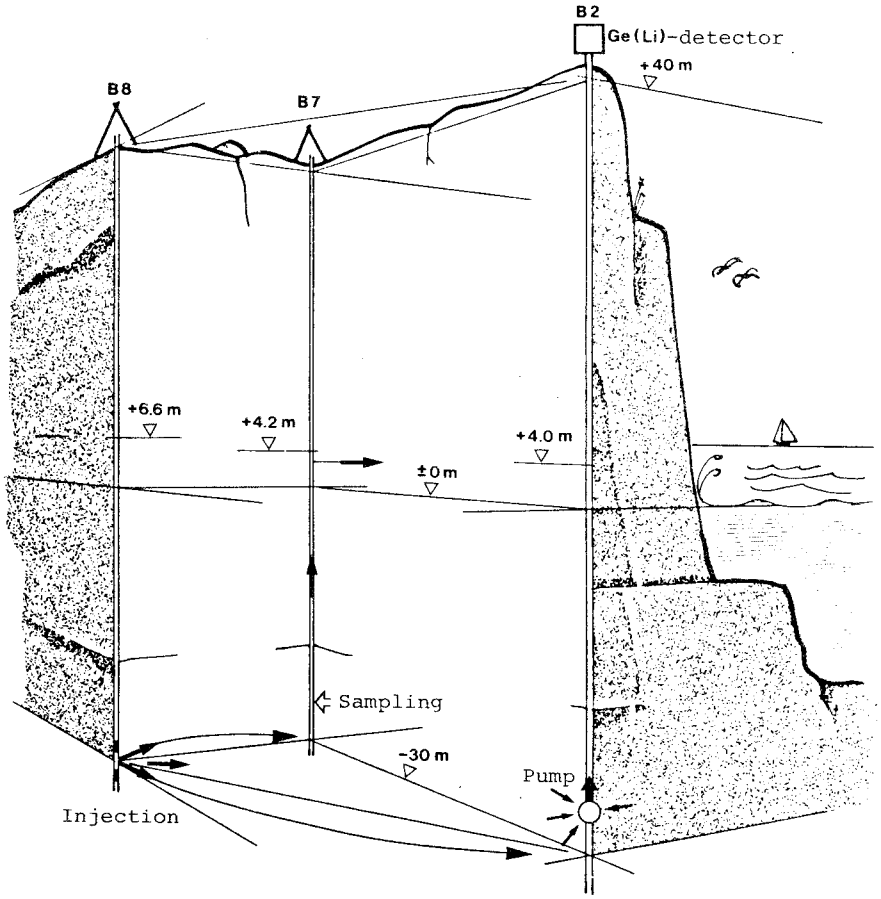

FIG 2. CUTAWAY VIEW OF THE "IN SITU" EXPERIMENTAL AREA

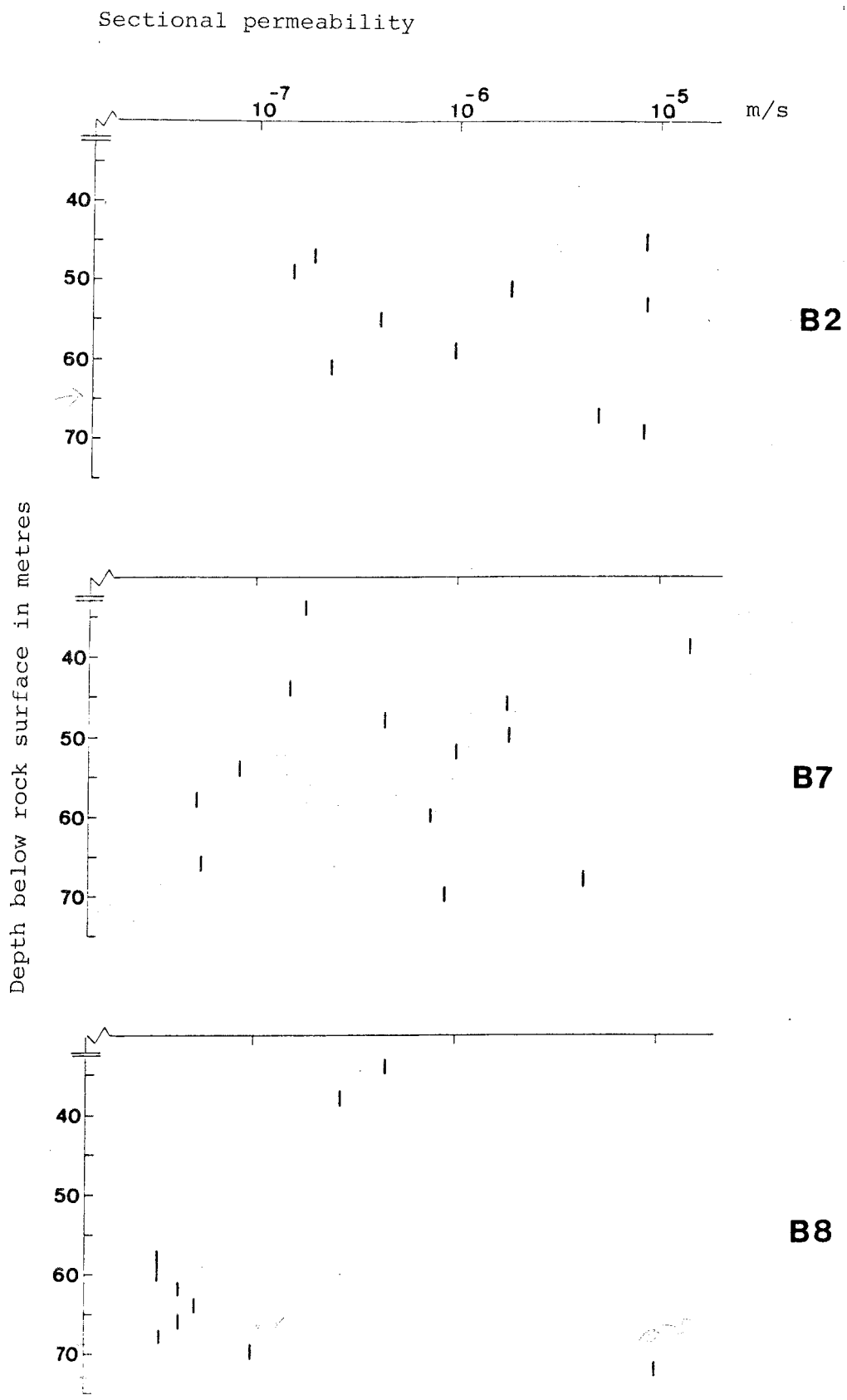

Fig 3 Permeability measurements of 2 metre sections in boreholes B2, B7 and B8. Limit of sensitivity: $2.5 \cdot 10^{-8}$ m/s.

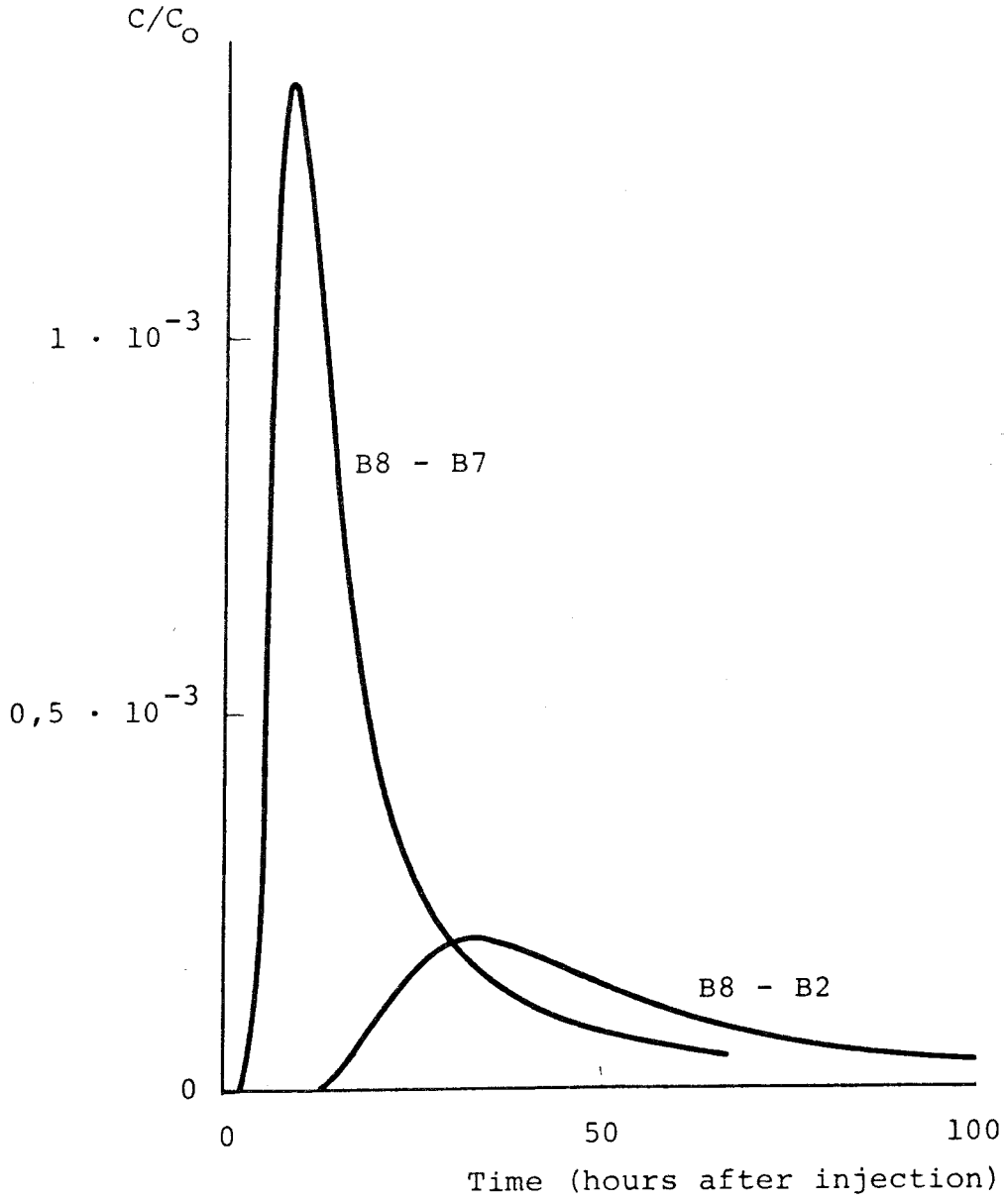

FIG 4. CONCENTRATION CURVES OF ^{82}Br FOR THE TWO FLOW PATHS

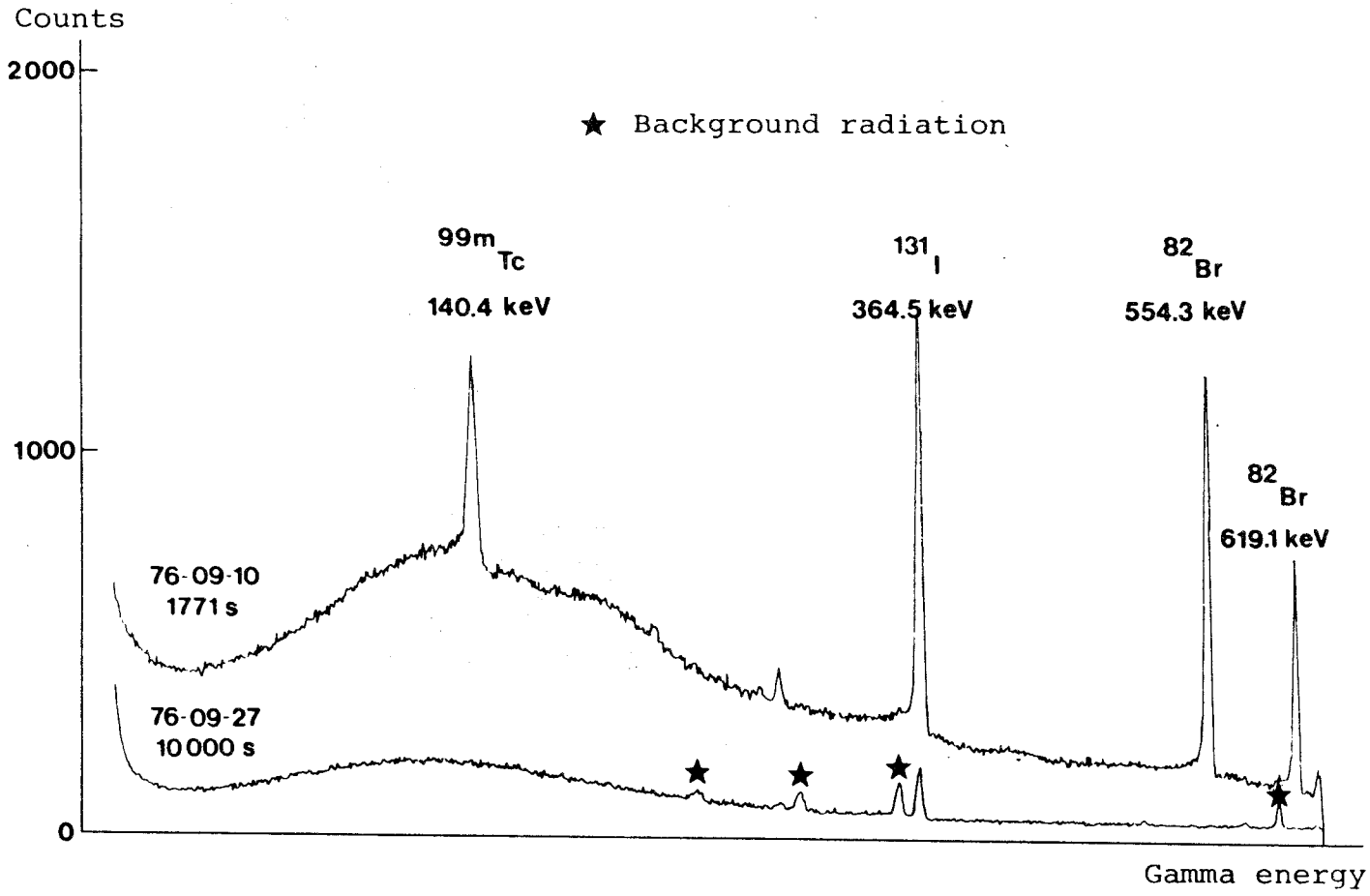

FIG 5. GAMMA SPECTRA, MEASURED WITH THE Ge(Li) DETECTOR AT BOREHOLE B2

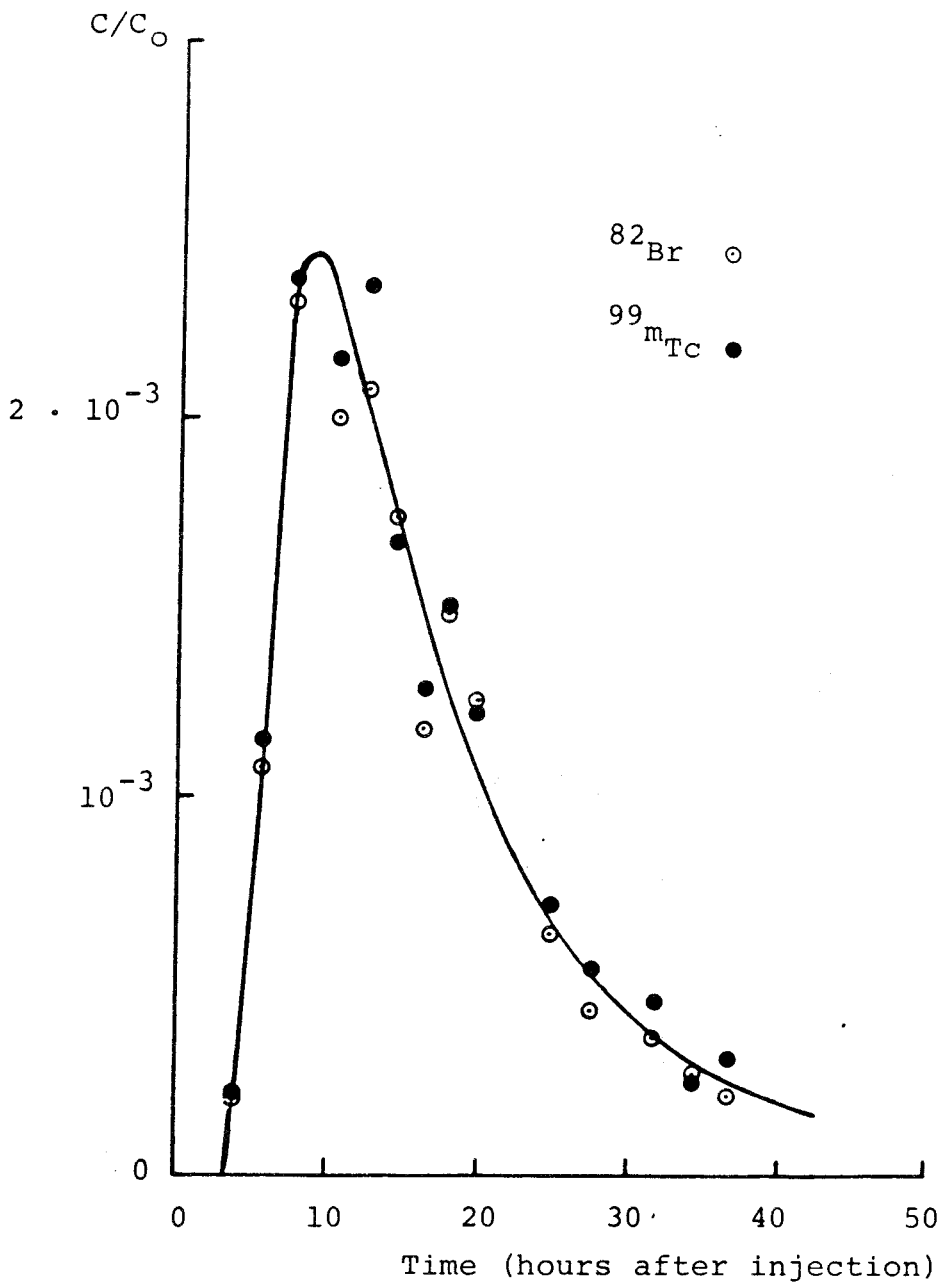

FIG 6. CONCENTRATION CURVES OF ^{82}Br AND ^{99m}TC FOR THE FLOW PATH B8 - B7

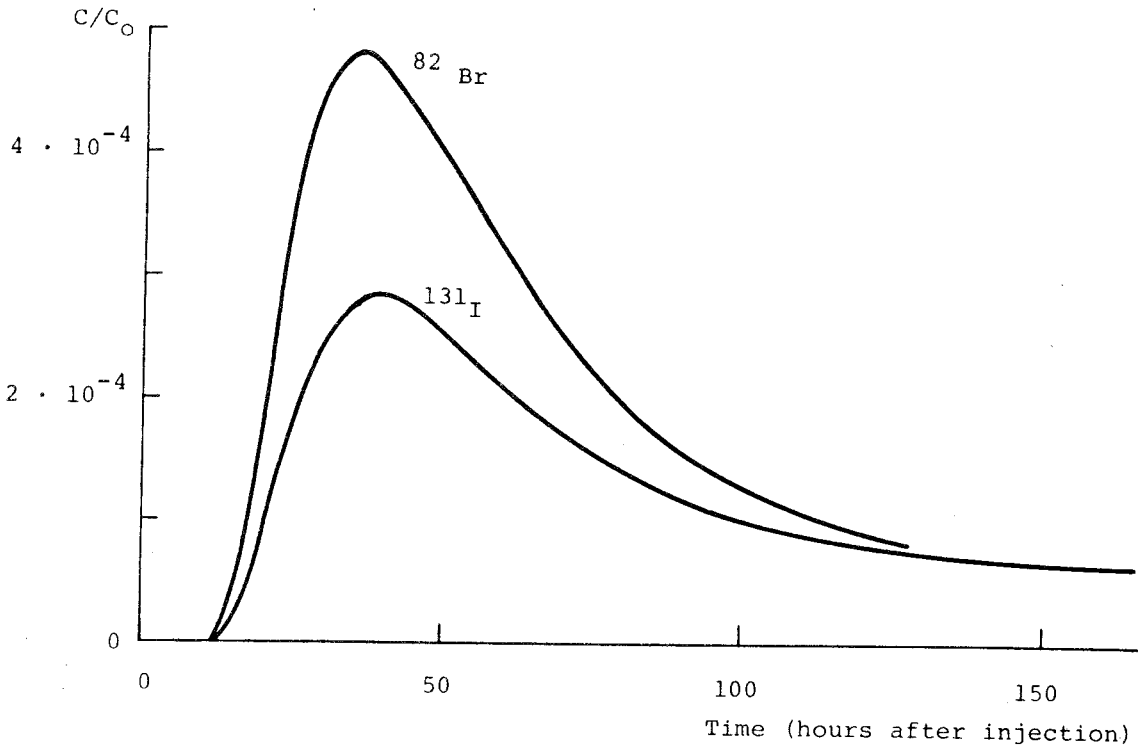

FIG 7. CONCENTRATION CURVES OF ^{82}Br AND ^{131}I FOR THE FLOW PATH B8 - B2

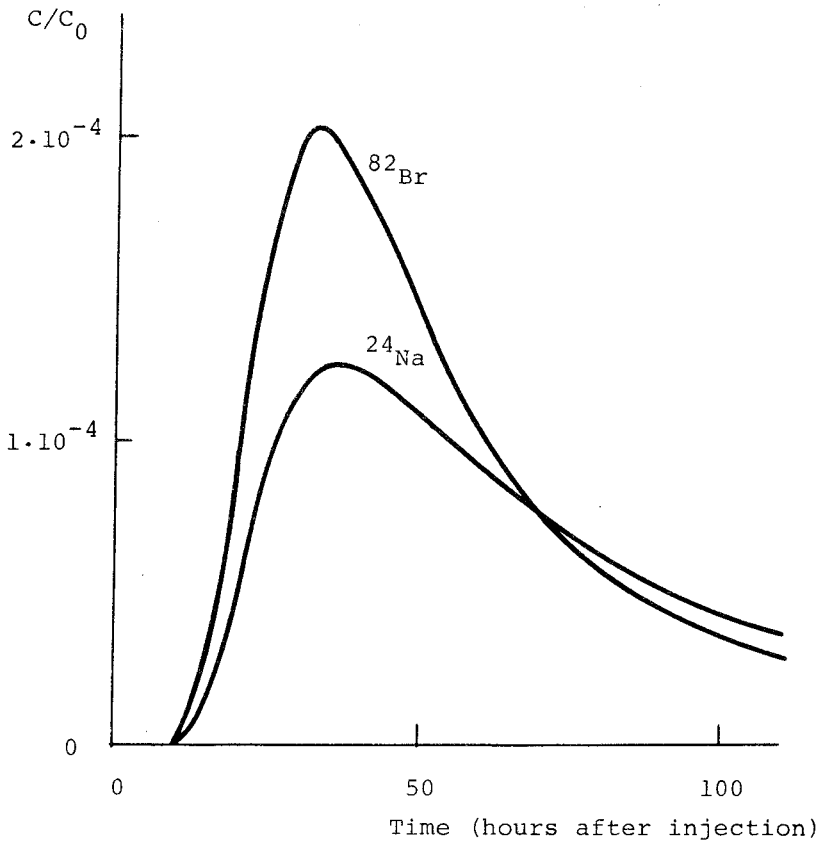

FIG 8. CONCENTRATION CURVES OF ^{82}Br AND ^{24}Na
FOR THE FLOW PATH B8 - B2

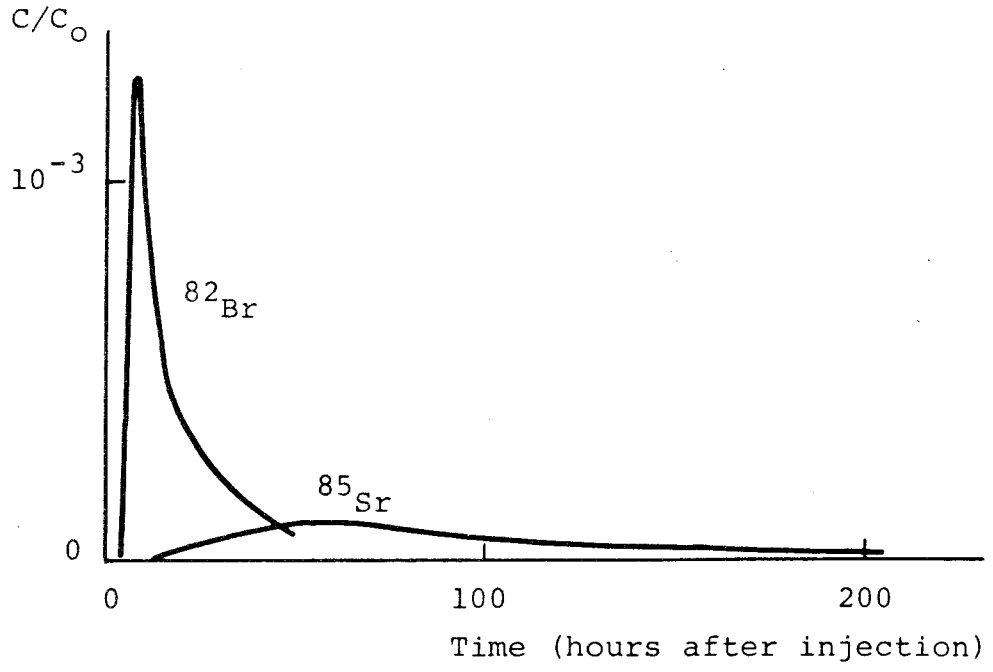

FIG 9. CONCENTRATION CURVES OF ^{82}Br AND ^{85}Sr FOR THE FLOW PATH B8 - B7

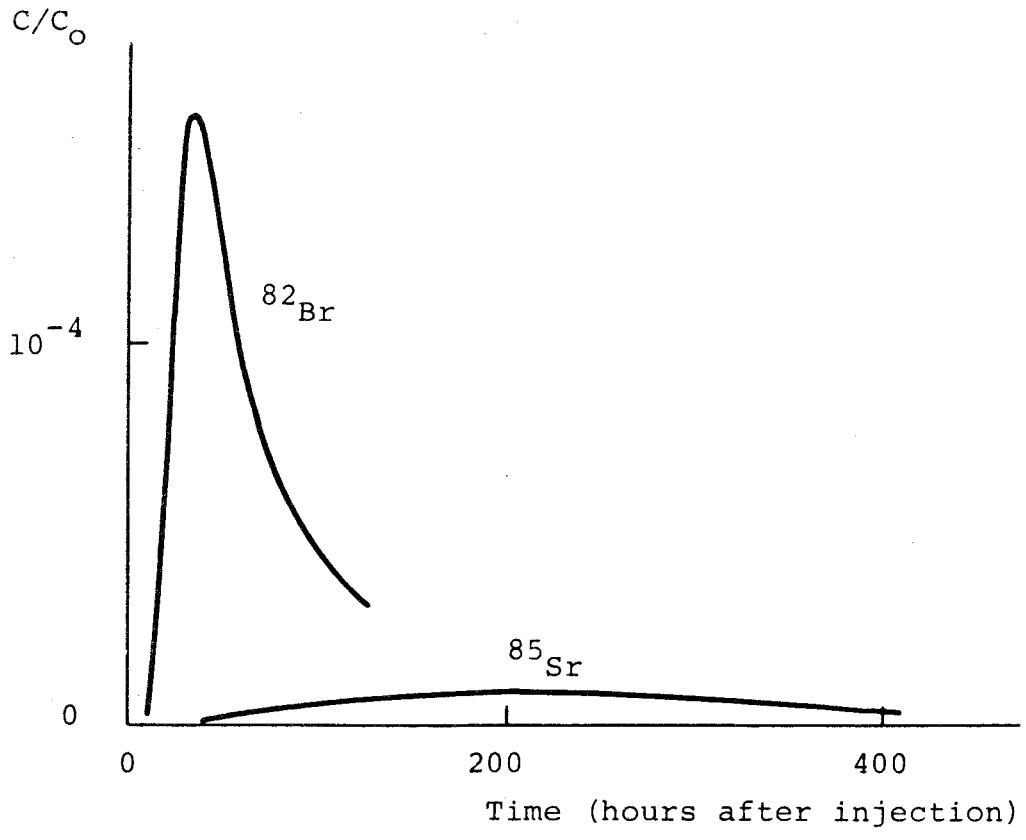

FIG 10. CONCENTRATION CURVES OF ^{82}Br AND ^{85}Sr FOR THE FLOW PATH B8 - B2

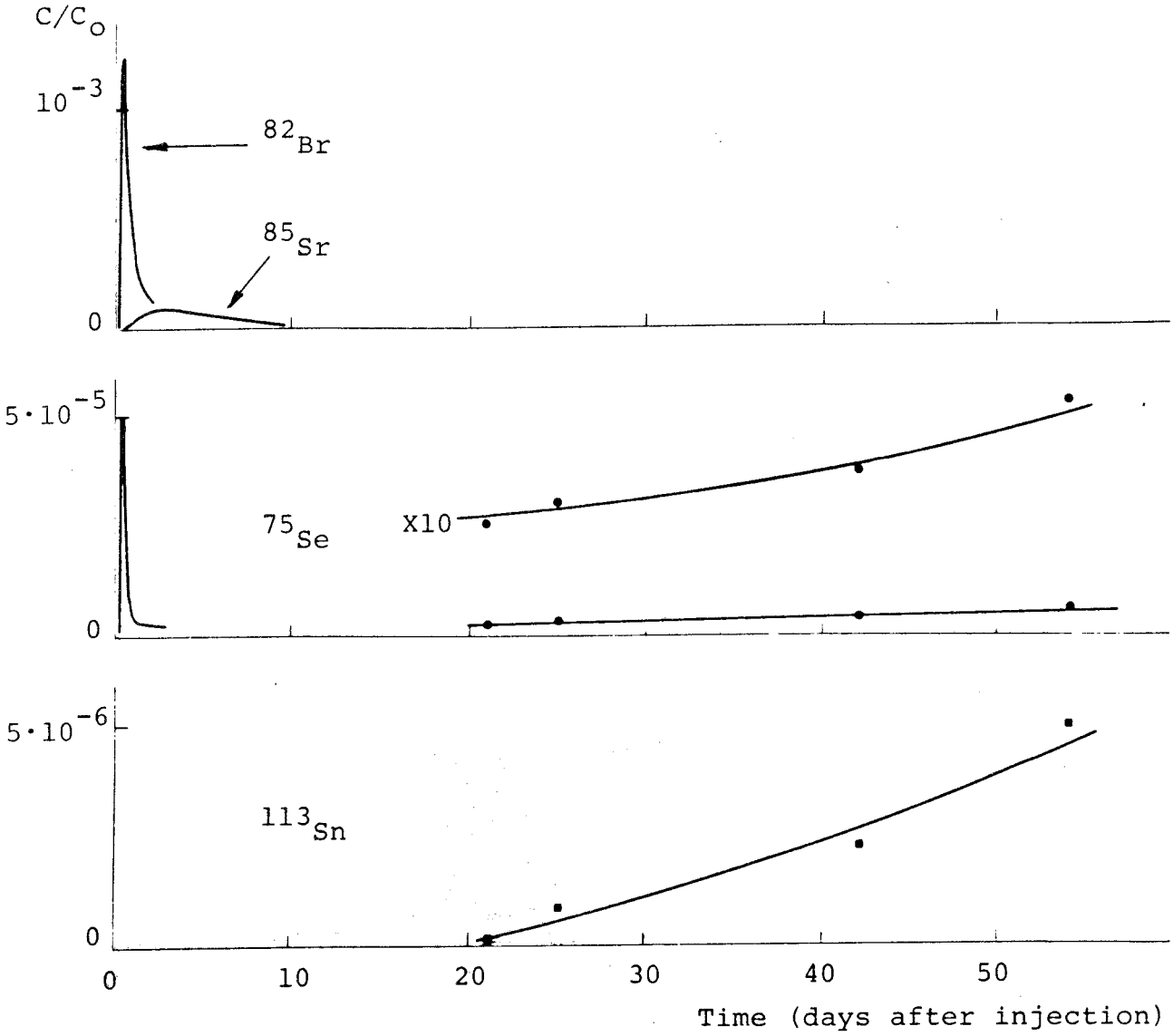

FIG 11. CONCENTRATION CURVES OF ^{82}Br, ^{85}Sr, ^{75}Se AND ^{113}Sn FOR THE FLOW PATH B8 - B7

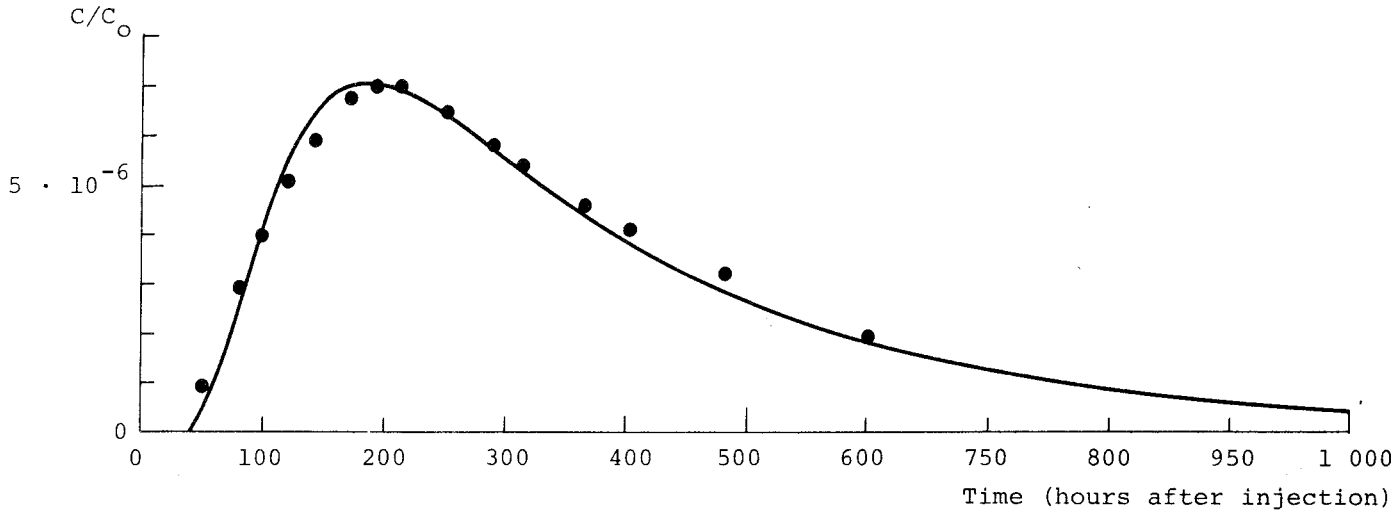

FIG 12. THEORETICAL CURVE AND EXPERIMENTAL POINTS FOR ^{85}Sr IN PATHWAY B8 - B2

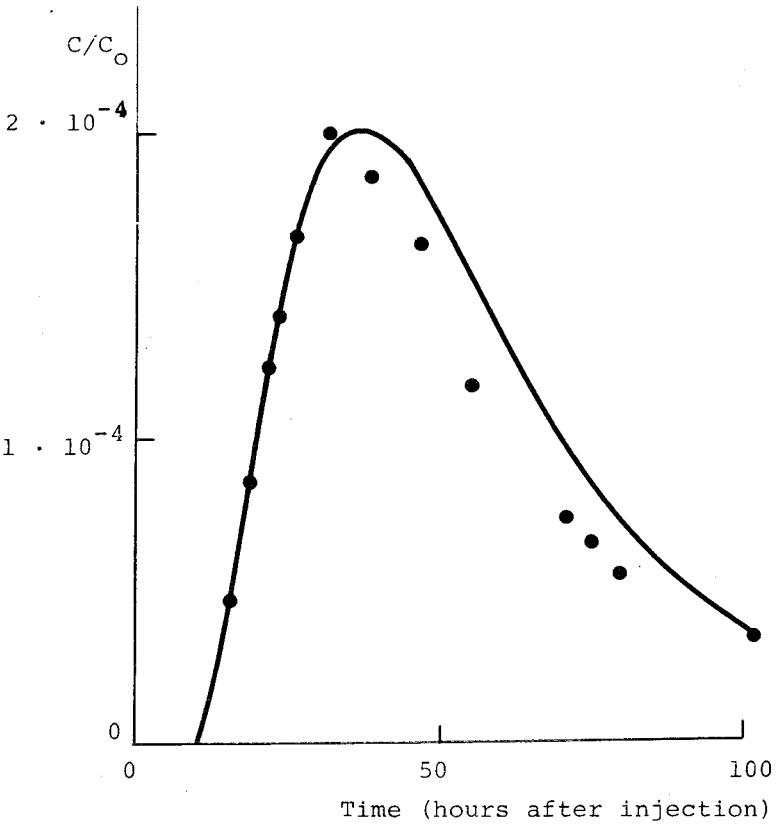

FIG 13. THEORETICAL CURVE AND EXPERIMENTAL POINTS FOR ^{82}Br IN PATHWAY B8 - B2

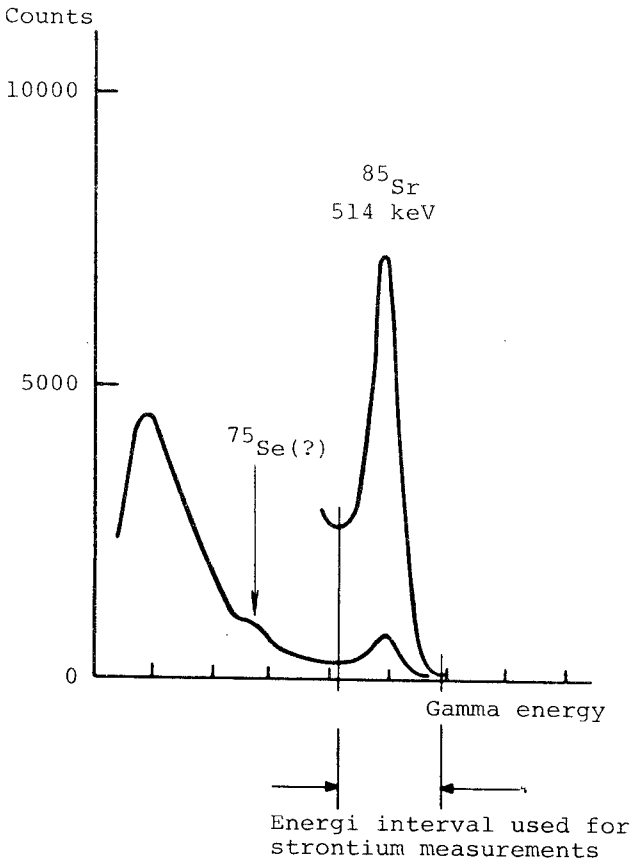

FIG 14. GAMMA SPECTRUM MEASURED AT 72 M LEVEL IN BOREHOLE B8. NaI DETECTOR Ø 1/2" x 1".

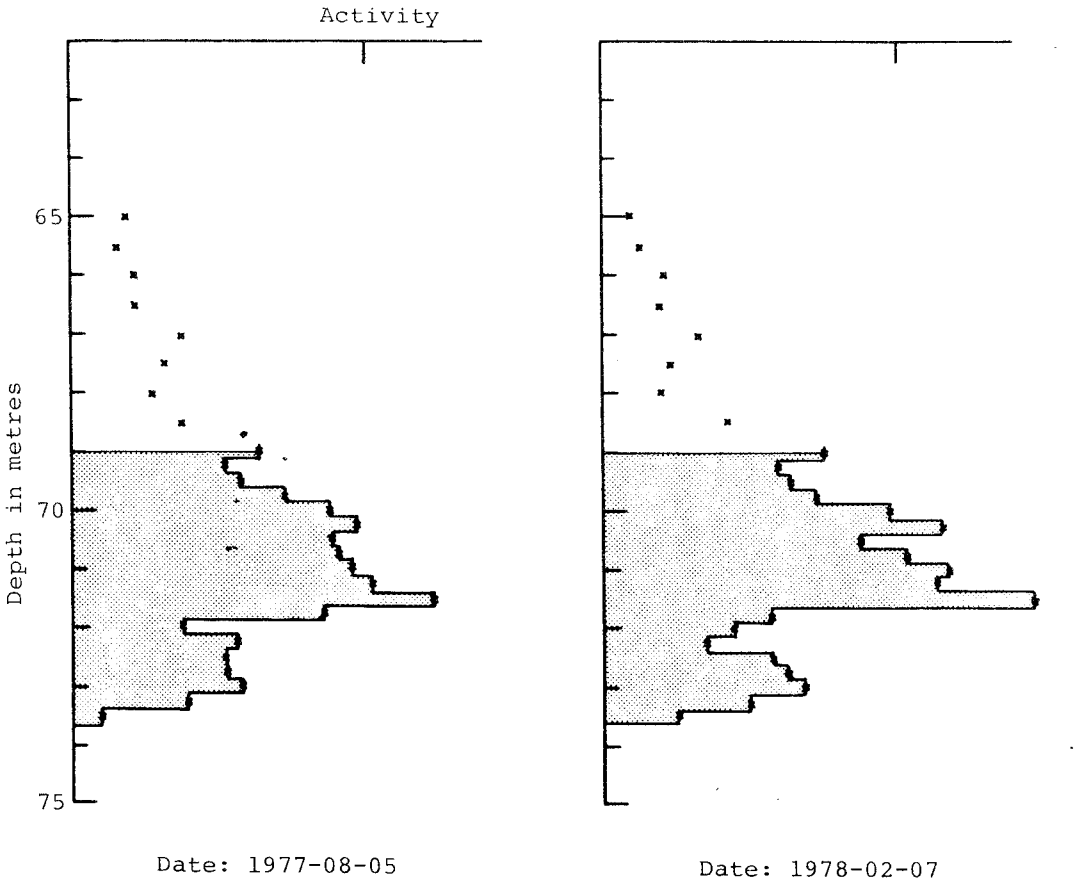

FIG 15. LOGGING DIAGRAM OF ^{85}Sr ACTIVITY (CORRECTED FOR RADIOACTIVE DECAY) IN BOREHOLE B8 AT TWO MEASUREMENT TIMES. SHADED AREAS: TOTAL ACTIVITY LISTED IN TABLE VII.

FÖRTECKNING ÖVER KBS TEKNISKA RAPPORTER

01 Källstyrkor i utbränt bränsle och högaktivt avfall från en PWR beräknade med ORIGEN
Nils Kjellbert
AB Atomenergi 77-04-05

02 PM angående värmeledningstal hos jordmaterial
Sven Knutsson
Roland Pusch
Högskolan i Luleå 77-04-15

03 Deponering av högaktivt avfall i borrhål med buffertsubstans
Arvid Jacobsson
Roland Pusch
Högskolan i Luleå 77-05-27

04 Deponering av högaktivt avfall i tunnlar med buffertsubstans
Arvid Jacobsson
Roland Pusch
Högskolan i Luleå 77-06-01

05 Orienterande temperaturberäkningar för slutförvaring i berg av radioaktivt avfall, Rapport 1
Roland Blomqvist
AB Atomenergi 77-03-17

06 Groundwater movements around a repository, Phase 1, State of the art and detailed study plan
Ulf Lindblom
Hagconsult AB 77-02-28

07 Resteffekt studier för KBS
Del 1 Litteraturgenomgång
Del 2 Beräkningar
Kim Ekberg
Nils Kjellbert
Göran Olsson
AB Atomenergi 77-04-19

08 Utlakning av franskt, engelskt och kanadensiskt glas med högaktivt avfall
Göran Blomqvist
AB Atomenergi 77-05-20

09 Diffusion of soluble materials in a fluid filling a porous medium
Hans Häggblom
AB Atomenergi 77-03-24

10 Translation and development of the BNWL-Geosphere Model
Bertil Grundfelt
Kemakta Konsult AB 77-02-05

11 Utredning rörande titans lämplighet som korrosionshärdig kapsling för kärnbränsleavfall
Sture Henriksson
AB Atomenergi 77-04-18

12 Bedömning av egenskaper och funktion hos betong i samband med slutlig förvaring av kärnbränsleavfall i berg
Sven G Bergström
Göran Fagerlund
Lars Rombén
Cement- och Betonginstitutet 77-06-22

13 Urlakning av använt kärnbränsle (bestrålad uranoxid) vid direktdeponering
Ragnar Gelin
AB Atomenergi 77-06-08

14 Influence of cementation on the deformation properties of bentonite/quartz buffer substance
Roland Pusch
Högskolan i Luleå 77-06-20

15 Orienterande temperaturberäkningar för slutförvaring i berg av radioaktivt avfall
Rapport 2
Roland Blomquist
AB Atomenergi 77-05-17

16 Översikt av utländska riskanalyser samt planer och projekt rörande slutförvaring
Åke Hultgren
AB Atomenergi augusti 1977

17 The gravity field in Fennoscandia and postglacial crustal movements
Arne Bjerhammar
Stockholm augusti 1977

18 Rörelser och instabilitet i den svenska berggrunden
Nils-Axel Mörner
Stockholms Universitet augusti 1977

19 Studier av neotektonisk aktivitet i mellersta och norra Sverige, flygbildsgenomgång och geofysisk tolkning av recenta förkastningar
Robert Lagerbäck
Herbert Henkel
Sveriges Geologiska Undersökning september 1977

20 Tektonisk analys av södra Sverige, Vättern - Norra Skåne
Kennert Röshoff
Erik Lagerlund
Lunds Universitet och Högskolan Luleå september 1977

21 Earthquakes of Sweden 1891 - 1957, 1963 - 1972
Ota Kulhánek
Rutger Wahlström
Uppsala Universitet september 1977

22 The influence of rock movement on the stress/strain situation in tunnels or bore holes with radioactive consisters embedded in a bentonite/quartz buffer mass
Roland Pusch
Högskolan i Luleå 1977-08-22

23 Water uptake in a bentonite buffer mass
A model study
Roland Pusch
Högskolan i Luleå 1977-08-22

24 Beräkning av utlakning av vissa fissionsprodukter och aktinider från en cylinder av franskt glas
Göran Blomqvist
AB Atomenergi 1977-07-27

25 Blekinge kustgnejs, Geologi och hydrogeologi
Ingemar Larsson KTH
Tom Lundgren SGI
Ulf Wiklander SGU
Stockholm, augusti 1977

26 Bedömning av risken för fördröjt brott i titan
Kjell Pettersson
AB Atomenergi 1977-08-25

27 A short review of the formation, stability and cementing properties of natural zeolites
Arvid Jacobsson
Högskolan i Luleå 1977-10-03

28 Värmeledningsförsök på buffertsubstans av bentonit/pitesilt
Sven Knutsson
Högskolan i Luleå 1977-09-20

29 Deformationer i sprickigt berg
Ove Stephansson
Högskolan i Luleå 1977-09-28

30 Retardation of escaping nuclides from a final depository
Ivars Neretnieks
Kungliga Tekniska Högskolan Stockholm 1977-09-14

31 Bedömning av korrosionsbeständigheten hos material avsedda för kapsling av kärnbränsleavfall. Lägesrapport 1977-09-27 samt kompletterande yttranden.
Korrosionsinstitutet och dess referensgrupp

32 Egenskaper hos bentonitbaserat buffertmaterial
Arvid Jacobsson
Roland Pusch
Högskolan i Luleå 1978-06-10

33 Required physical and mechanical properties of buffer masses
Roland Pusch
Högskolan i Luleå 1977-10-19

34 Tillverkning av bly-titan kapsel
Folke Sandelin AB
VBB
ASEA-Kabel
Institutet för metallforskning
Stockholm november 1977

35 Project for the handling and storage of vitrified high-level waste
Saint Gobain Techniques Nouvelles October, 1977

36 Sammansättning av grundvatten på större djup i granitisk berggrund
Jan Rennerfelt
Orrje & Co, Stockholm 1977-11-07

37 Hantering av buffertmaterial av bentonit och kvarts
Hans Fagerström, VBB
Björn Lundahl, Stabilator
Stockholm oktober 1977

38 Utformning av bergrumsanläggningar
Alf Engelbrektson, VBB
Arne Finné, KBS
Stockholm december 1977

39 Konstruktionsstudier, direktdeponering
ASEA-ATOM
Västerås

40 Ekologisk transport och stråldoser från grundvattenburna radioaktiva ämnen
Ronny Bergman
Ulla Bergström
Sverker Evans
AB Atomenergi 1977-12-20

41 Säkerhet och strålskydd inom kärnkraftområdet.
Lagar, normer och bedömningsgrunder
Christina Gyllander
Siegfried F Johnson
Stig Rolandson
AB Atomenergi och ASEA-ATOM 1977-10-13

42 Säkerhet vid hantering, lagring och transport av använt kärnbränsle och förglasat högaktivt avfall
Ann-Margret Ericsson
Kemakta november 1977

43 Transport av radioaktiva ämnen med grundvatten från ett bergförvar
Bertil Grundfelt
Kemakta november 1977

44 Beständighet hos borsilikatglas
Tibor Lakatos
Glasteknisk Utveckling AB

45 Beräkning av temperaturer i ett envånings slutförvar i berg för förglasat radioaktivt avfall Rapport 3
Roland Blomquist
AB Atomenergi 1977-10-19

46 Temperaturberäkningar för slutförvar för använt bränsle
Taivo Tarandi
Vattenbyggnadsbyrån Stockholm 1978

47 Teoretiska studier av grundvattenrörelser
John Stokes
Roger Thunvik
Inst för kulturteknik KTH maj 1978

48 The mechanical properties of the rocks in Stripa, Kråkemåla,Finnsjön and Blekinge
Graham Swan
Högskolan i Luleå 1977-09-14

49 Bergspänningsmätningar i Stripa gruva
Hans Carlsson
Högskolan i Luleå 1977-08-29

50 Lakningsförsök med högaktivt franskt glas i Studsvik
Göran Blomqvist
AB Atomenergi november 1977

51 Seismotechtonic risk modelling for nuclear waste disposal in the Swedish bedrock
F Ringdal
H Gjöystdal
E S Husebye
Royal Norwegian Council for scientific and industrial research

52 Calculations of nuclide migration in rock and porous media, penetrated by water
H Häggblom
AB Atomenergi 1977-09-14

53 Mätning av dissusionshastighet för silver i lera-sand-blandning
Bert Allard
Heino Kipatsi
Chalmers tekniska högskola 1977-10-15

54 Groundwater movements around a repository

54:01 Geological and geotechnical conditions
Håkan Stille
Anthony Burgess
Ulf E Lindblom
Hagconsult AB september 1977

54:02 Thermal analyses
Part 1 Conduction heat transfer
Part 2 Advective heat transfer
Joe L Ratigan
Hagconsult AB september 1977

54:03 Regional groundwater flow analyses
Part 1 Initial conditions
Part 2 Long term residual conditions
Anthony Burgess
Hagconsult AB oktober 1977

54:04 Rock mechanics analyses
Joe L Ratigan
Hagconsult AB september 1977

54:05 Repository domain groundwater flow analyses
Part 1 Permeability perturbations
Part 2 Inflow to repository
Part 3 Thermally induced flow
Joe L Ratigan
Anthony S Burgess
Edward L Skiba
Robin Charlwood

54:06 Final report
Ulf Lindblom et al
Hagconsult AB oktober 1977

55 Sorption av långlivade radionuklider i lera och berg,
Del 1
Bert Allard
Heino Kipatsi
Jan Rydberg
Chalmers tekniska högskola 1977-10-10

56 Radiolys av utfyllnadsmaterial
Bert Allard
Heino Kipatsi
Jan Rydberg
Chalmers tekniska högskola 1977-10-15

57 Stråldoser vid haveri under sjötransport av kärnbränsle
Anders Appelgren
Ulla Bergström
Lennart Devell
AB Atomenergi 1978-01-09

58 Strålrisker och högsta tillåtliga stråldoser för människan
Gunnar Walinder
FOA 4 november 1977

59 Tectonic Lineaments in the Baltic from Gävle to Simrishamn
Tom Flodén
Stockholms Universitet 1977-12-15

60 Förarbeten för platsval, berggrundsundersökningar
Sören Scherman

Berggrundvattenförhållande i Finnsjöområdets nordöstra del
Carl-Erik Klockars
Ove Persson
Sveriges Geologiska Undersökning januari 1978

61 Permeabilitetsbestämningar
Anders Hult
Gunnar Gidlund
Ulf Thoregren

Geofysisk borrhålsmätning
Kurt-Åke Magnusson
Oscar Duran
Sveriges Geologiska Undersökning januari 1978

62 Analyser och åldersbestämningar av grundvatten på stora djup
Gunnar Gidlund
Sveriges Geologiska Undersökning 1978-02-14

63 Geologisk och hydrogeologisk grunddokumentation av Stripa försöksstation
Andrei Olkiewicz
Kenth Hansson
Karl-Erik Almén
Gunnar Gidlund
Sveriges Geologiska Undersökning februari 1978

64 Spänningsmätningar i Skandinavisk berggrund - förutsättningar resultat och tolkning
Sten G A Bergman
Stockholm november 1977

65 Säkerhetsanalys av inkapslingsprocesser
Göran Carleson
AB Atomenergi 1978-01-27

66 Några synpunkter på mekanisk säkerhet hos kapsel för kärnbränsleavfall
Fred Nilsson
Kungl Tekniska Högskolan Stockholm februari 1978

67 Mätning av galvanisk korrosion mellan titan och bly samt mätning av titans korrosionspotential under γ-bestrålning
3 st tekniska PM
Sture Henrikson
Stefan Poturaj
Maths Åsberg
Derek Lewis
AB Atomenergi januari-februari 1978

68 Degraderingsmekanismer vid bassänglagring och hantering av utbränt kraftreaktorbränsle
Gunnar Vesterlund
Torsten Olsson
ASEA-ATOM 1978-01-18

69 A three-dimensional method for calculating the hydraulic gradient in porous and cracked media
Hans Häggblom
AB Atomenergi 1978-01-26

70 Lakning av bestrålat UO_2-bränsle
Ulla-Britt Eklund
Roland Forsyth
AB Atomenergi 1978-02-24

71 Bergspricktätning med bentonit
Roland Pusch
Högskolan i Luleå 1977-11-16

72 Värmeledningsförsök på buffertsubstans av kompakterad bentonit
Sven Knutsson
Högskolan i Luleå 1977-11-18

73 Self-injection of highly compacted bentonite into rock joints
Roland Pusch
Högskolan i Luleå 1978-02-25

74 Highly compacted Na bentonite as buffer substance
Roland Pusch
Högskolan i Luleå 1978-02-25

75 Small-scale bentonite injection test on rock
Roland Pusch
Högskolan i Luleå 1978-03-02

76 Experimental determination of the stress/strain situation in a sheared tunnel model with canister
Roland Pusch
Högskolan i Luleå 1978-03-02

77 Nuklidvandring från ett bergförvar för utbränt bränsle
Bertil Grundfelt
Kemakta konsult AB, Stockholm 1978-08-31

78 Bedömning av radiolys i grundvatten
Hilbert Christenssen
AB Atomenergi 1978-02-17

79 Transport of oxidants and radionuclides through a clay barrier
Ivar Neretnieks
Kungl Tekniska Högskolan Stockholm 1978-02-20

80 Utdiffusion av svårlösliga nuklider ur kapsel efter kapselgenombrott
Karin Andersson
Ivars Neretnieks
Kungl Tekniska Högskolan Stockholm 1978-03-07

81 Tillverkning av kopparkapsel för slutförvaring av använt bränsle
Jan Bergström
Lennart Gillander
Kåre Hannerz
Liberth Karlsson
Bengt Lönnerberg
Gunnar Nilsson
Sven Olsson
Stefan Sehlstedt
ASEA, ASEA-ATOM juni 1978

82 Hantering och slutförvaring av aktiva metalldelar
Bengt Lönnerberg
Alf Engelbrektsson
Ivars Neretnieks
ASEA-ATOM, VBB, KTH Juni 1978

83 Hantering av kapslar med använt bränsle i slutförvaret
Alf Engelbrektsson
VBB Stockholm april 1978

84 Tillverkning och hantering av bentonitblock
VBB
ASEA
ASEA-ATOM
Gränges Mineralprocesser
Juni 1978

85 Beräkning av kryphastigheten hos ett blyhölje innehållande en glaskropp under inverkan av tyngdkraften
Anders Samuelsson

Förändring av krypegenskaperna hos ett blyhölje som följd av en mekanisk skada
Göran Eklund
Institutet för Metallforskning september 1977 - april 1978

86 Diffusivitetsmätningar av metan och väte i våt lera
Ivars Neretnieks
Christina Skagius
Kungl Tekniska Högskolan Stockholm 1978-01-09

87 Diffusivitetsmätningar i våt lera Na-lignosulfonat, Sr^{2+}, Cs^{+}
Ivars Neretnieks
Christina Skagius
Kungl Tekniska Högskolan Stockholm 1978-03-16

88 Ground water chemistry at depth in granites and gneisses
Gunnar Jacks
Kungl Tekniska Högskolan Stockholm april 1978

89 Inverkan av glaciation på en deponeringsanläggning belägen i urberg 500 m under markytan
Roland Pusch
Högskolan i Luleå 1978-03-16

90 Koppar som kapslingsmaterial för icke upparbetat kärnbränsleavfall - bedömning ur korrosionssynpunkt
Lägesrapport 1978-03-31
Korrosionsinstitutet och dess referensgrupp

91 Korttidsvariationer i grundvattnets trycknivå
Lars Y Nilsson
Kungliga Tekniska Högskolan Stockholm september 1977

92 Termisk utvidgning hos granitoida bergarter
Ove Stephansson
Högskolan i Luleå april 1978

93 Preliminary corrosion studies of glass ceramic code 9617 and a sealing frit for nuclear waste canisters
I D Sundquist
Corning Glass Works 78-03-14

94 Avfallsströmmar i upparbetningsprocessen
Birgitta Andersson
Ann-Margret Ericsson
Kemakta mars 1978

95 Separering av C-14 vid upparbetningsprocessen
Sven Brandberg
Ann-Margret Ericsson
Kemakta mars 1978

96 Korrosionsprovning av olegerat titan i simulerade deponeringsmiljöer för upparbetat kärnbränsleeavfall
Sture Henrikson
Marian de Pourbaix
AB Atomenergi 1978-04-24

97 Colloid chemical aspects of the "confined bentonite concept"
Jean C Le Bell
Ytkemiska Institutet 1978-05-07

98 Sorption av långlivade radionuklider i lera och berg
Del 2
Bert Allard
Heino Kipatsi
Börje Torstenfelt
Chalmers Tekniska Högskola 1978-04-20

99 Lakning av högaktivt franskt glas
Lägesrapport 1978-06-01
Göran Blomqvist
AB Atomenergi 1978-06-19

100 Dos och dosinteckning från grundvattenburna radioaktiva ämnen vid slutförvaring av använt kärnbränsle
Ronny Bergman
Ulla Bergström
Sverker Evans
AB Atomenergi

101 Utläckning av Ni-59 från ett bergförvar
Ivars Neretnieks
Karin Andersson
Kungl Tekniska Högskolan Stockholm 1978-04-24

102 Metod att bocka bestrålade bränslestavar
Torsten Olsson
ASEA-ATOM 1978-03-29

103 Some aspects on colloids as a means for transporting radio nuclides
Ivars Neretnieks
Kungl Tekniska Högskolan Stockholm 1978-08-08

104 Finit elementanalys av bentonitfyllt bergförvar
Ove Stephansson
Kenneth Mäki
Tommy Groth
Per Johansson
Högskolan i Luleå

105 Neutroninducerad aktivitet i bränsleelementdetaljer
Nils Kjellbert
AB Atomenergi 1978-03-30

106 Strålningsnivå och till vatten deponerad strålningsenergi utanför kapslar i slutförvaret
Klas Lundgren
ASEA-ATOM 1978-05-29

107 Blyinfodrad titankapsel för upparbetat och glasat kärnbränsleavfall - Bedömning ur korrosionssynpunkt
Korrosionsinstitutet och dess referensgrupp. Slutrapport 1978-05-25

108 Criticality in a spent fuel repository in wet crystalline rock
Peter Behrenz
Kåre Hannerz
ASEA-ATOM 1978-05-30

109 Lakningsbar spaltaktivitet
Lennart Devell
Rolf Hesböl
AB Atomenergi

110 In situ experiments on nuclide migration in fractured crystalline rocks
Ove Landström
Carl-Erik Klockars
Karl-Erik Holmberg
Stefan Westerberg
Studsvik Energiteknik and
The Geological Survey of Sweden juli 1978

111 Nuklidhalter i använt LWR-bränsle och i högaktivt avfall från återcykling av plutonium i PWR
Nils Kjellbert
Studsvik Energiteknik AB 1978-07-26

112 Säkerhetsanalys av hanteringsförfarandet vid inkapsling av utbränt bränsle i kopparkapsel
Erik Nordesjö
ASEA-ATOM 1978-03-20

113 Studier av keramiska material för inkapsling av högaktivt avfall
Lennart Hydén et al
ASEA-ATOM september 1978

114 γ-radiolysis of organic compounds and α-radiolysis of water
Hilbert Christensen
Studsvik Energiteknik AB 1978-09-07

115 Accelererad utlösning av uran från α-aktivt UO_2
Gösta Nilsson
Studsvik Energiteknik AB 1978-04-27

116 Lakning av Al_2O_3 under simulerande deponeringsbetingelser
Britt-Marie Svensson
Lennart Dahl
Studsvik Energiteknik AB 1978-06-02

117 Lakning av Al_2O_3 i dubbeldestillerat vatten
Britt-Marie Svensson
Göran Blomqvist
Studsvik Energiteknik AB 1978-05-29

118 Slutrapport Al_2O_3 kapsel
Korrosionsinstitutet och dess referensgrupp

119 Slutförvaring av aktiverade ståldetaljer i betong
Lars Rombén
Kyösti Tuutti
Cement- och Betonginstitutet 1978-07-14

120 Some notes in connection with the KBS studies of final disposal of spent fuel
Ivars Neretnieks
Kungl Tekniska Högskolan september 1978